WEATHERING AND TRANSPORT OF SEDIMENT IN THE CHEYENNE RIVER BASIN, EASTERN WYOMING*

by

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ABSTRACT

The weathering and fluvial transport stages of a sedimentation sequence of the Cheyenne River in Eastern Wyoming are discussed. The river heads in east-central Wyoming, crosses several rock units in its eastward path before reaching the Angostura Reservoir in southwestern South Dakota. The drainage area of the Cheyenne River above the Angostura Reservoir comprises about 9000 square miles.

Weathering profiles of the rock units traversed by the river in this drainage area were sampled to determine their respective contributions to the sediment load. Among these formations are the lithologically diverse Chadron, Brule, Fort Union, Lance, Pierre, and Spearfish. The textural and mineralogical analyses of the weathered outcrops were compared with those of sediment samples collected at gauging stations operated by the Water Resources Division of the U.S. Geological Survey.

X-ray diffraction studies of the weathered rock profiles and of the suspended sediment indicate a diverse clay mineral assemblage in the $2-1\mu$ diameter size fraction. Kaolinite, illite, and vermiculite occur along with quartz and feldspar. However, the $<1\mu$ size fraction of the suspended sediment contained only montmorillonite. The kaolinite content of the $2-1\mu$ size fraction of the suspended sediment increased in the direction of flow, at the expense of vermiculite and illite.

The computed and observed amounts of sediment contributions by the various rock units show a fairly good fit; the data indicate the importance of defining mineral composition in terms of discrete size separates, even under 2μ diameter. The increase in kaolinite content in the $2-1\mu$ size fraction of the suspended sediment may be due to bank contribution downstream from the gauging stations. The montmorillonite content of the $<1\mu$ size fraction is unchanged by transport.

INTRODUCTION

THE processes involved in fluvial sedimentation are of immediate concern to geologists and engineers engaged in problems of river mechanics. These processes are responsible for the weathering, transport and continental deposition of material derived from rocks. The type, amount, and

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mode of deposition of this material are of major significance in river basins, especially in the Western States, where water control and distribution determine the limits of ecologic communities.

Limited precipitation in these western areas is the most important factor in the design of proper water conservation practices. An integral part of most conservation programs is reservoirs, both large and small. Because of the high concentrations of sediment often delivered to the reservoirs along with the water, provision must be made for sediment storage. Therefore, the unit cost of water can be very high in basins where erosion is severe.

Upland and erosion sedimentation may be controlled either by vegetation, conservation structures or a combination of both. Semi-arid climates limit the effectiveness of vegetation in erosion control and various structures are used as a means of retaining sediment and water. There is a large area to be covered by such control practices, therefore, it is pertinent to be able to pinpoint sediment source areas so that maximum benefit may be derived from control structures.

Sediment movement from upland slopes to stream flood plains or reservoir deltas is a complex process. This problem of reservoir sedimentation acquired practical significance, following the construction of the Angostura Dam on the Cheyenne River near Hot Springs, South Dakota. The Angostura Dam was completed in 1949 and studies were initiated in 1950 to delineate major sources of sediment upstream from the reservoir. The investigation was cooperative between the U.S. Bureau of Reclamation and the U.S. Geological Survey. Gauging stations for measuring suspended sediment and stream flow were constructed on the Cheyenne River and three major tributaries: Lance, Beaver, and Hat Creeks (see Fig. 1). Measurements of suspended-sediment load at the gauging stations were supplemented by field studies of upland sediment movement into small reservoirs.

These studies, conducted from 1950–1954, indicate that sediment is not transported from upland slopes to stream channels as a single uninterrupted event. The amount of sediment that is delivered to the streams is a function of the erodibility of the parent material, physical features of the drainage basin, runoff characteristics of the area, and the precipitation distribution during the period of study.

The suspended-sediment data from the gauging stations and the sedimentation rates measured in small reservoirs were used to study the characteristics of transported material. Accordingly, we decided to determine the usability of the mineralogy of the fines in suspended sediment as a means of assessing quantitatively the sediment contributions of various tributaries to the master stream. A secondary objective was to determine, if possible, the relative sediment contributions of the several geologic formations that are exposed within the drainage basin. Thirdly, the study represented a detailed investigation into a sedimentation sequence that includes weathering–erosion–fluviatile transport.
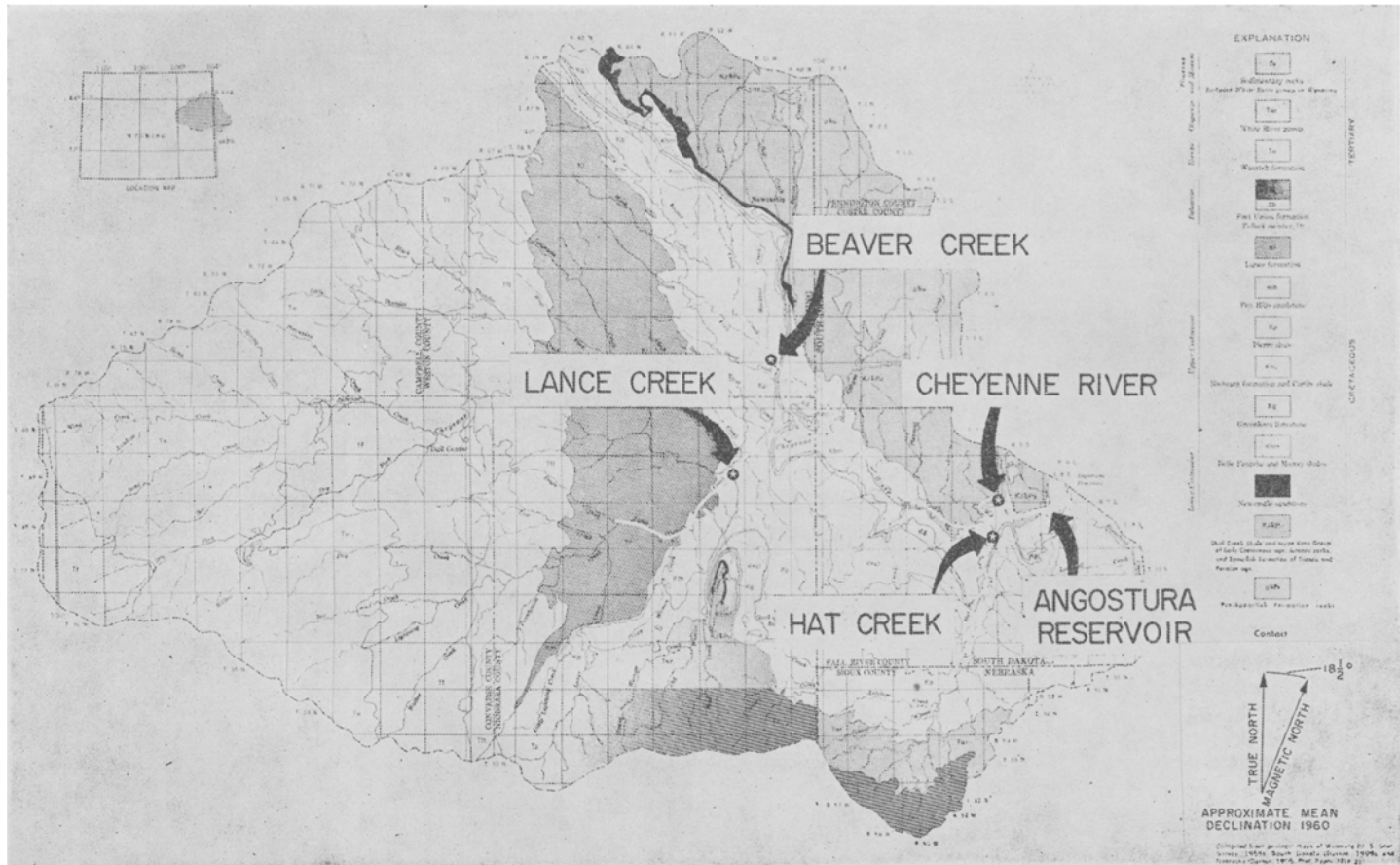
FIGURE 1.—Generalized geologic map of Cheyenne River basin above the Angostura Reservoir, Wyoming, South Dakota, and Nebraska.

SETTING

Topography

Only the part of the Cheyenne River basin lying upstream from the Angostura Reservoir, South Dakota, is considered in this report. This drainage area is approximately 9000 square miles including portions of three states: southwestern South Dakota, northwestern Nebraska, and eastern Wyoming. The basin is bounded generally by the parallels 42° 50' and 44° 10' north latitude and the meridians 103° 30' and 106° west longitude. The distance from the Angostura Reservoir to the western drainage divide is 133 miles, while the widest north–south extent of the basin is 92 miles (see Fig. 1).

About 50 miles from the western divide, the South Fork and the Dry Fork of the Cheyenne River join to form the Cheyenne River. From this junction the river flows eastward to within a few miles of the Angostura Reservoir, where its course is deflected to the southeast by the Black Hills.

Geology and Soils

Soil formation in the Cheyenne River basin has been confined to the producing of a thin superficial mantle of residual weathered bedrock on the slopes and upland areas and to moderately thick deposits of alluvium along the stream flood plains and valley floors. The soils are young and closely reflect the lithology of the underlying rock units.

The Black Hills in the eastern part of the basin are composed chiefly of folded sedimentary rocks along the hill flanks, with a core of igneous and metamorphic rocks in the central part of the uplift. The sedimentary rocks exposed in this locality include all formations from the Minnelusa Formation of Pennsylvanian and Permian age to the Pierre Shale of Late Cretaceous age.

The escarpment along the southern boundary of the Cheyenne River basin is formed by the Brule and Chadron Formations of the White River Group of Oligocene age, capped by the resistant Arikaree Sandstone of Miocene age and the grit and limestone beds of the Ogallala Formation of Pliocene age. The ridge stands 400 to 500 ft above the basin. It is bordered by a belt of badlands, 3 to 4 miles wide, eroded mainly into the Brule Clay.

The western two-thirds of the basin is underlain by Upper Cretaceous and Tertiary sedimentary rocks, with low to moderate westward dips. The Lance Formation of Late Cretaceous age and the Fort Union Formation of Paleocene age, which crop out in wide belts in a northerly direction across the basin, are composed chiefly of interbedded sandstone and shale along with some coal beds in the uppermost part of the Fort Union Forma-

tion. The plains consist primarily of tablelands on the flat-lying rocks into which deep, narrow valleys have been incised.

The Wasatch Formation of Eocene age, which crops out in the extreme western part of the basin, consists of poorly consolidated varicolored sand and clay. Erosion in areas underlain by the Wasatch Formation is minor except on steep slopes, which are restricted to a few small localized areas.

The deposits of recent alluvium in the stream valleys and the thin veneer of gravel on the high terraces make up a considerable part of the surficial geology in the basin. The valleys of most ephemeral streams in the basin have well-developed flood plains ranging from a few hundred feet to one-half mile or more in width. The unconsolidated deposits of alluvium generally reflect the mineralogic and textural characteristics of the rocks from which they were derived.

MAJOR SOURCES OF SEDIMENT

Four major types of erosion are considered to be the principal producers of sediment to the Angostura Reservoir. These are: sheet erosion, gullying, badlands (a combination of highly intensified sheet and gully erosion), and to a lesser extent, streambank cutting. The percentage contribution from each is not equal nor listed in the order of importance. Evaluation of the probable sediment contribution from each type was based on field observations and measurements of rates of reservoir sedimentation.

Sheet erosion may be defined as the removal, by surface runoff, of soil and weathered rock material in the form of a thin sheet. This runoff is not concentrated in well-defined channels. In the incipient stage, sheet erosion is difficult to evaluate with respect to sediment yield from an area.

Gullying is not generally serious in the Cheyenne River basin. Gullies and valley trenches in the Cheyenne River basin are undoubtedly a major conveyor of sediment, but their principal contribution to reservoir sedimentation is probably by transporting material from other upland sources in flume-like channels rather than by the removal of valley alluvium through lateral shifting.

Typical badlands topography is found scattered through a strip, approximately four miles wide. This strip extends across the southeastern border of the basin, which is underlain by beds of the White River Group. In contrast to the other types of erosion, the badlands type has been greatly influenced by the lithologic characteristics of the underlying bedrock. Soft clay and siltstone, comprising a large percentage of the White River beds in the badlands areas, are easily eroded after the sod cover has been broken by finger gullies and rills.

Much of the alluvial material eroded from upland areas in the basin is redeposited on the flood plains of the major tributary streams. These

deposits are exposed to erosion where channel shifting has caused under-cutting and where raw alluvial cutbanks are exposed to channel action. An examination of streambanks shows, that of the total sediment load trans-ported to the Angostura Reservoir, probably only a small fraction is derived from bank cutting. When the total exposed area of actively eroding cut-banks is compared to the areas of critical upland erosion, it is obvious that upland erosion is by far the greater sediment contributor. In the Cheyenne River basin the average percentage of actively eroding streambanks for all tributaries is only 5.3 per cent.

During this investigation, we were concerned with the disposition of fine-grained material, under 1.0 mm in diameter. We restricted the study to this size fraction because of our primary concern with the mineralogy of such material and with its disposition during stream transport. No attempt was made to determine the per cent of the total rock represented by the 1.0 mm fraction; this was due to the variable presence of pebbles and cobbles in the surface material.

Available information on sediment flow in Cheyenne River streams indicated that the maximum size particle in suspended sediment was 100 microns (U.S. Geological Survey, 1955). This size range, $< 100\mu$, includes the clay minerals, which, although varied, are easily characterized by X-ray diffraction. The combination of diagnostic mineralogy and domin-ance in stream sediment suspension makes the $< 100\mu$ size fraction an attractive target for investigation.

Rock Units

The results of the textural analyses of the $< 100\mu$ size material in rock outcrops are presented in Figs. 2 to 7. They indicate the potential contribu-tion by each rock unit to the fine-grained sediment load of the streams in the drainage basin. This analytical work was performed on all the indi-cated horizons (see appendix). Only textural data from representative parts of the weathered profile are presented here.

The depth of sampling was different from each rock unit. It varied as the apparent depth of weathering; from a shallow 21-in. weathered profile in the Pierre Shale to a 30-ft section in the Spearfish. The different sampling depths probably represent the limits of the surface available for fluvial erosion.

The Fort Union Formation is comprised chiefly of continental, deltaic deposits and is well represented in the Cheyenne River basin. Textural analyses of two samples from a 45-in. weathered profile are shown in Fig. 2. The median diameter of the material less than 1.0 mm is 130μ at the surface and is 70μ at depth. The Fort Union Formation does not represent a likely source of fine-grained sediment to the Cheyenne River.

The Lance Formation is similar in texture to the Fort Union. The median diameter is 270μ at the surface and 65μ at a depth of 5 ft (see Fig. 3).
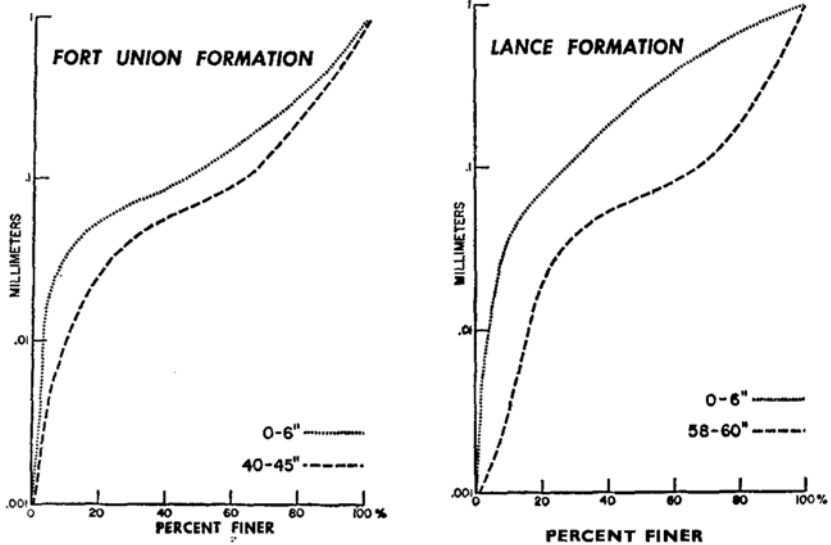
FIGURE 2.—Particle-size distribution curves for two horizons of the weathered profile in the Fort Union Formation.

FIGURE 3.—Particle-size distribution curves for two horizons of the weathered profile in the Lance Formation.

The $<20\mu$ fraction increases uniformly from 6 per cent at the surface to 20 per cent at depth. The surface horizon has less fine-grained material than that at depth, indicating the dominance of stratigraphy over weathering in the Lance profile.

The Pierre Shale crops out extensively in the eastern part of the Cheyenne basin and is a highly erodible rock formation. The erodibility has been attributed to the dominance of dispersible montmorillonitic clays in the Pierre. The two selected size distribution curves (Fig. 4) indicate the presence of significant amounts of clay-size material. The only significant difference between the surface and lowermost sample depth is confined to the $<20\mu$ fraction; there are more fines at depth than at the surface.

The Permian and Triassic Spearfish Formation is composed chiefly of red beds and forms the famed "racetrack" around the Black Hills of South Dakota. It is described as an arkosic siltstone interbedded with alabaster-like gypsum layers. The topographic expression of the Spearfish indicates many feet of outcropping rock. Accordingly, a 30-ft profile of this formation was sampled during the study. Our data indicate that the Spearfish is coarser-grained than the Pierre but shows no uniform textural gradient with depth. The per cent of $<2\mu$ material is about 20 per cent; that of the $<20\mu$ ranges from 38 to 45 per cent (see Fig. 5). There is a significant amount of silt-sized material in the Spearfish Formation.

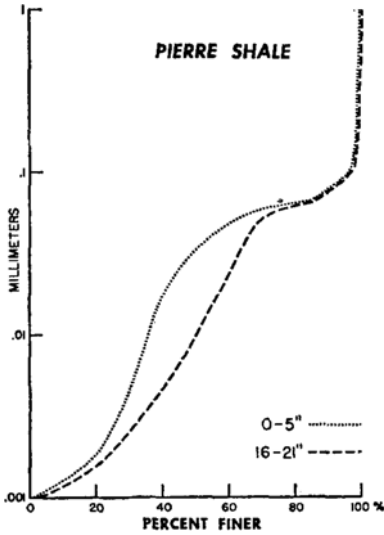The Brule and Chadron Formations of the White River Group are

FIGURE 4.—Particle-size distribution curves for two horizons of the weathered profile in the Pierre Shale.
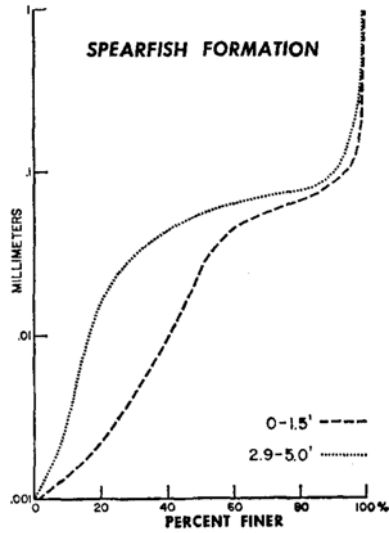
FIGURE 5.—Particle-size distribution curves for two horizons of the weathered profile in the Spearfish Formation.

composed of siltstone, claystone, sandstone, and ash beds. They represent the materials into which the Big Badlands of South Dakota have been carved. The two formations are dissimilar and are therefore discussed separately. Historically they represent major sources of sediment to streams and reservoirs.

Our analyses of the Brule Formation indicate that the amount of fine-grained material is less than expected. The amount of clay-sized fractions is 8 per cent at the surface and only the layer from 30 to 39 in. in the 4-ft profile differs significantly from this, containing 30 per cent (see Fig. 6). Also, this layer contains about 50 per cent of material less than 20μ in size in contrast to 15 per cent in the remainder of the profile. The erodibility of the formation appears to be more dependent on mineralogy and relief than on texture.

A purple-white layer near the contact of the Brule and Chadron is significantly higher in fine material than other parts of either the Brule or Chadron (see Fig. 7). The under 2μ materials comprise 70 per cent of this layer. In the Chadron this fraction is greater than in the Brule, yet is but 20 per cent of the material less than 1.0 mm in diameter.

The inter-relationship of texture, mineralogy, and permeability to surface waters appears to be the discriminant factor in erodibility of the White River Group. This group is dominated by fine-grained material; the
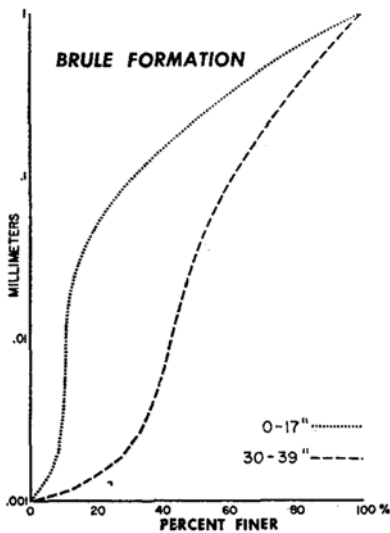
FIGURE 6.—Particle-size distribution curves for two horizons of the
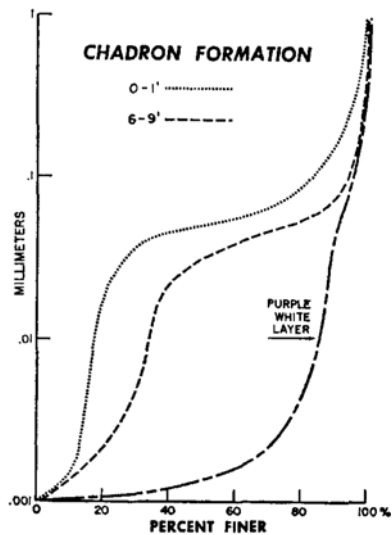weathered profile in the Brule Formation.
FIGURE 7.—Particle-size distribution curves for two horizons of the
weathered profile in the Chadron Formation and the purple-white layer.

greater percentage of clay-sized material in the purple-white layer probably
yields a comparatively impermeable surface to rainwater, similar to the
reduction in water loss produced by a bentonitic filter cake in oilfield bore-
holes.

Summary

The results of the textural analyses indicate that the Fort Union and
Lance Formations should be lesser sources of fine-grained sediment to
streams in the Cheyenne basin. The greater percentage of silt- and clay-sized
material in the Brule and Chadron Formations indicates the great potential
for sediment contribution by these formations. During a five-year period
of field investigation, the data on sediment transport in the various streams
point out quite the contrary to such expectations (Hadley and Schumm,
1961).

Table 1 presents the results of the U.S. Geological Survey study of
suspended sediment discharge in the Cheyenne River, during the period
1950-54 (U.S. Geological Survey, 1955). It indicates that Lance Creek is
the dominant source of sediment into the Cheyenne River; contributing
56 per cent while draining but 25 per cent of the basin area. Lance Creek
traverses mostly Fort Union and Lance outcrops. The contrast to Hat
Creek is striking in that this stream contributes only 9 per cent of the

Table 1.—Sediment Contributions of Streams in the Cheyenne Basin

Stream	Drainage area (sq miles)	Per cent of total area	Per cent of sus- pended sediment discharge	Principal geologic fm. traversed
Lance Creek	2090	25	56	Fort Union, Lance
Beaver Creek	1320	16	10	Pierre
Hat Creek	1044	12	9	Brule, Chadron
Others	4276	47	25	Spearfish, Wasatch
Total	8730			

suspended sediment measured near the Angostura Reservoir while draining 12 per cent of the basin area. The dominant rock units in the Hat Creek basin are the Brule and Chadron Formations. Apparently, erosion and transport of suspended sediment are not governed primarily by texture of rock outcrops, but rather by other processes in the sediment transport cycle.

PARTICLE-SIZE DISTRIBUTION

During the sampling of the suspended sediment from the various streams, two bottles were filled at each location. The material in one bottle was treated with sodium hexametaphosphate to insure good dispersion and replicable size distribution analyses. The second bottle was set aside for a chemical analysis of the native waters (Table 2). The sediment suspensions in the latter bottles displayed such rapid, clear water breaks at the surface that we re-examined the problem of size distribution in native versus dispersing water. A review of published material revealed that data on size distribution of suspended sediment have been presented in the native and in the dispersed state (U.S. Geological Survey, 1955). These results are visually presented in Fig. 8 for the sediment from the four streams.

Note the similarity in the curves representing the size distribution in native water. The median diameter of suspended sediment from all four streams is about 10 microns and only the sediment from Lance Creek contains coarser material than the others. Generally the samples from native water are well sorted as to size and the distribution is clustered about a single mode. This distribution is similar to that of loessial silt
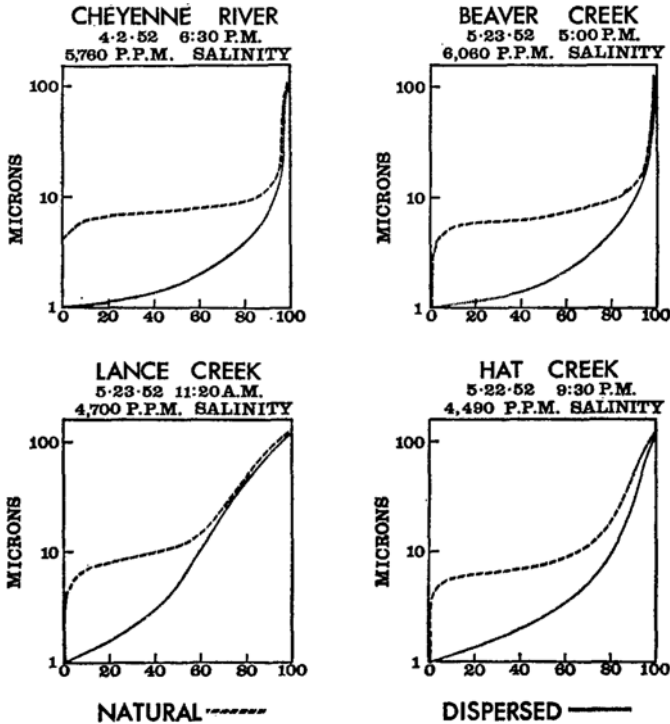
FIGURE 8.—Comparison of size–distribution curves in native water and dispersed condition for four streams in the Cheyenne River basin.

material and indicates the uniform size response of flocculated particles to stream flow energy. On the other hand, the distribution of sizes of dispersed particulate material is different among the various stream sediments. For example, that of Lance Creek is coarser than the others, including the Cheyenne River.

One may interpret this as indicating that the transport of suspended sediment in the streams of the Cheyenne River basin occurs under dispersant conditions. There is a great uniformity in the size distribution of particulate material in native water. The four curves in Fig. 8 represent conditions of low nonturbulent flow, where flocculating influences would be great. Yet, high or turbulent flow brings about mechanical dispersion and increases the number of clay-sized particles in suspension. This may account for the progressive textural winnowing in the downstream direction.

MINERALOGICAL ANALYSES

The particulate materials with diameters less than 20μ were analyzed for mineral composition by means of X-ray diffraction. Differential cation treatment was used to distinguish between vermiculite and chlorite. The first treatment of all clay-sized materials was magnesium saturation plus ethylene glycol solvation. This was followed by potassium saturation. If a mineral had a "d" spacing of 14 Å under both magnesium and potassium saturation, it was designated chlorite. If K-saturation contracted a 14 Å mineral to 10 Å, the mineral was designated vermiculite. No heat treatments were used in this procedure. The results of this examination are reported as bar graphs in Figs. 9 to 11. Each diffraction pattern was normalized or adjusted so that the mineral present in the greatest amount is represented by a complete bar. The relative abundance of other minerals is represented by bars of proportionate size. These data are presented for fine silt $(20-2\mu)$ and for clay $(<2\mu)$ size fractions.
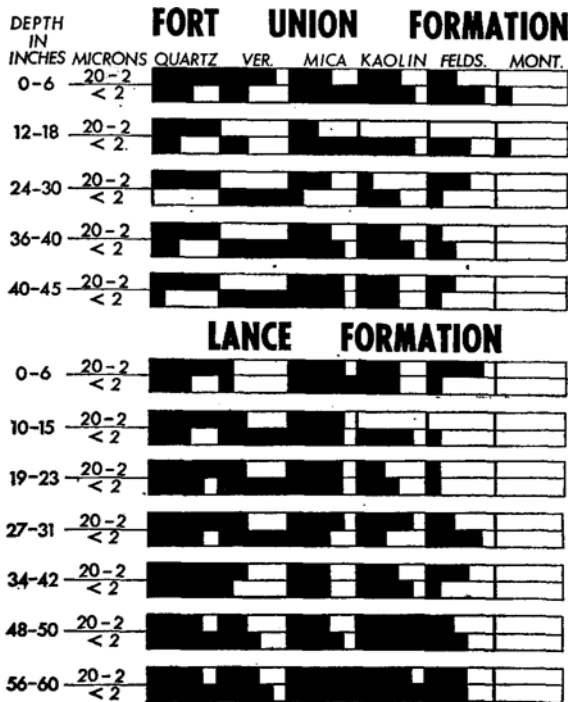

FIGURE 9.—Mineral composition of the silt and clay fraction of the weathered profile in the Fort Union and Lance Formations.

Rock Units

The mineral composition reported here is best discussed in terms of relative amount in the sampled profile. Thus, in the weathered profile of the Fort Union Formation, Fig. 9, quartz is a major constituent of the silt fraction at all depths. In the clay, quartz varies from moderate to zero in amount. Vermiculite is present in the silt fraction only in the surface layer, whereas its occurrence in the clay increases markedly with depth. The mica content of both size fractions is most abundant both at the surface and at depth, being least in the middle layers. Kaolin occurs in moderate amounts in both sizes and at all depths, save for its absence in the silt of the 12–18-in. layer. Feldspar is present in moderate amounts in both sizes at the surface and decreases in amount thereafter with depth. Montmorillonite occurs only in the clay fraction of the two uppermost layers.

The mineral composition of the weathered profile of the Lance Formation differs slightly from the Fort Union. Quartz is a major constituent of silt and clay fractions throughout the profile. Vermiculite occurs as the principal mineral in the clay fraction of the 10–31-in. layers but is minor in both sizes throughout the rest of the profile. Kaolin occurs strongly at depth in both sizes but moderately elsewhere. Feldspar is in weak to moderate amounts in both silt and clay. Montmorillonite is absent (see Fig. 9).

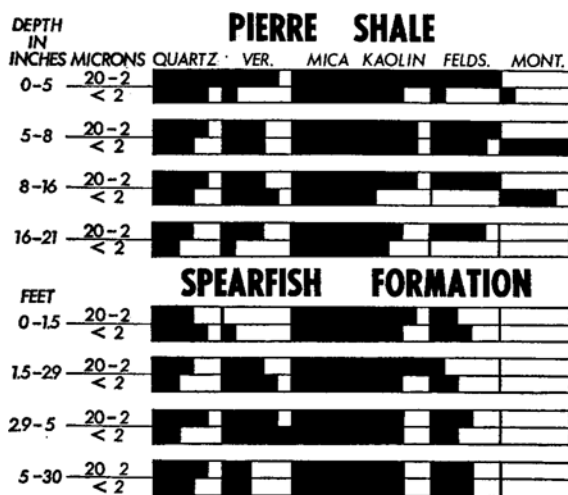The weathered profile of the Pierre Shale is dominated by mica in both

FIGURE 10.—Mineral composition of the silt and clay fraction of the weathered profile in the Pierre Shale and Spearfish Formation.

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size classes. Montmorillonite occurs only in the clay fraction of the upper 16 in. (see Fig. 10). Quartz dominates both sizes at the surface but decreases with depth. Vermiculite occurs throughout in fairly strong amounts in the silt fraction but varies from weak to moderate to weak in the clay. Kaolin content of the silt fraction is dominant at the surface and decreases thereafter; its content in the clay fraction is moderate in the upper layers and weak in the lower. The feldspar content of the silt fraction is prominent throughout the 21-in. profile, but that of the clay fraction is weak, except for the 5–8-in. layer.

The Spearfish profile represents a 30-ft outcrop face and its mineral composition is marked by the dominance of mica in both silt and clay throughout the 30 ft (see Fig. 10). Montmorillonite is absent and kaolin is moderately present in both sizes throughout the profile. Quartz is present in both silt and clay fractions in moderate amounts throughout the 30 ft. Vermiculite and feldspar are present in weak to moderate amounts in both size classes.

The Brule and Chadron Formations are discussed together. The mineral composition of the purple-white layer, separating the Brule from the underlying Chadron, is most striking. Here, mineral composition is segregated by size. Quartz and feldspar are found only in the silt fraction whereas montmorillonite occurs only in the clay (see Fig. 11). Vermiculite and kaolin are absent from this layer. Mica occurs in moderate amounts in the silt and clay of this layer.

In the Brule and Chadron, quartz is generally restricted to the silt fraction. It is present in the clay fraction of the 0–17-in. layer in the Brule
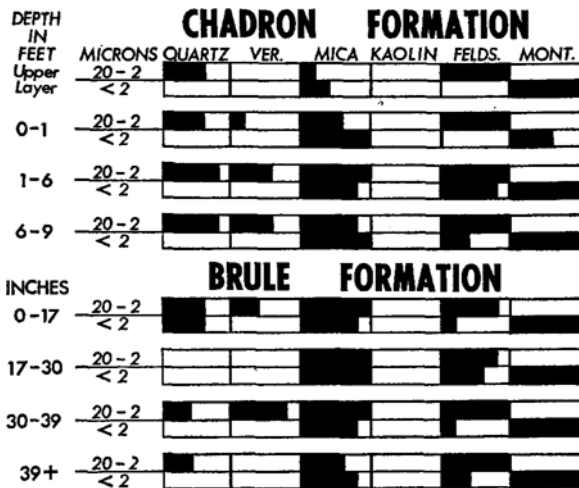

FIGURE 11.—Mineral composition of the silt and clay fraction of the weathered profile in the Chadron and Brule Formations.

and not in the 17–30-in. zone. Vermiculite is restricted to the silt size in the Chadron and is similarly restricted, where present, in the Brule. Mica is uniformly strong in both size fractions of the two formations. Kaolin does not occur in the two formations. Feldspar is stronger in the silt than in the clay fraction of both Brule and Chadron. Montmorillonite dominates the clay fraction of all samples.

Suspended Sediment

Stream flow in the Cheyenne River usually occurs in response to thunder-storms in the spring and summer months. Therefore, stream gauging is effectual only during the rainy season. This accounts for the wide separation in reported times of sampling of streams. The four streams, the hydrology of which is discussed in this report, were included in a study program from 1950 to 1954 in which both authors participated. In May 1962 we returned to the study area and were rewarded by significant amounts of rainfall and runoff.

The four streams, Cheyenne River, Lance, Beaver, and Hat Creeks were sampled at reference, accessible gauging points shortly after the start of gentle rainfall. A heavy downpour followed immediately, and only two streams were then accessible for sampling of the high flow. We regret the incompleteness of the data on high versus low flow (available for only Hat Creek and the Cheyenne River) but believe that the available data indicate the significance of this variable in any hydrologic study.

The suspended sediment in the streams is very fine and indicates the need for a change in previously used textural classes. The samples of suspended sediment were treated with a dispersing agent, sodium hexa-metaphorphate, and were grouped by the following diameters in microns: 1, 1 to 2 and greater than 2. We recognize that the size distributions of dispersed samples do not offer a true representation of the travelling diameters of these particles, but it does permit a comparison under replicable conditions, i.e. there are less confounding variables in the data.

Figure 12 is a bar graph of the mineral composition of the suspended sediment from the four streams. There are two striking features in the graph; namely (1) the absence of vermiculite from all stream sediment and (2) a contrast between the composition of Cheyenne River sediment at low and at high flow.

The surprising prominence of vermiculate in the weathered profiles is contrasted with its absence from the suspended sediments of all streams in the Cheyenne River basin. One may speculate that this "degraded" mica was reconstituted or converted to ten angstroms mica by the addition of potassium ions to the exchange complex at a point between the outcrop and the stream, or one may associate the absence of vermiculite with the great increase in montmorillonite content in the stream sediment. If we
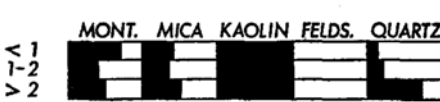
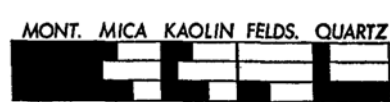# MINERAL COMPOSITION OF SUSPENDED SEDIMENT
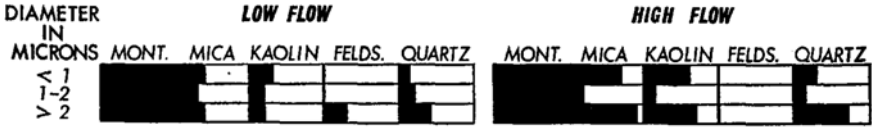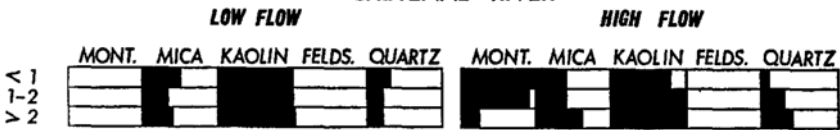
HAT CREEK

FIGURE 12.—Mineral composition of suspended sediment transported by streams in the Cheyenne River basin with some comparisons for high flow versus low flow.

regard montmorillonite and vermiculite as size end members in a family of swelling clays, one may then postulate that vermiculite has been comminuted to montmorillonite during erosional processes. This hypothesis is based only on the data at hand and may be completely obviated by a large, infrequent storm with a recurrence interval of fifty years wherein all available material are nonselectively transported from outcrop to stream.

A review of the graph shows that the suspended sediment is composed mainly of montmorillonite and kaolin. However, montmorillonite is absent from all size fractions in the Cheyenne River low flow but is prominent in the finer size fractions of the Cheyenne River at high flow. Although minerals other than kaolin and montmorillonite were prominent in the weathered profiles of rock outcrops, only these two remain to dominate the suspended sediment of the streams. The major contribution of Lance Creek to the sediment flow in the Cheyenne River may be observed in the similarity in kaolin percentages in both streams. As stated before, montmorillonite dominates the composition of all samples, except that of the Cheyenne River at low flow. It is important to note the appearance of montmorillonite in all three size fractions in that this probably indicates the resistance of the particulate material in this sediment to standard dispersing procedures.

Otherwise the montmorillonite would be restricted to the finer size fraction, i.e. under one micron. Although feldspar is fairly prominent in the weathered profiles, it shows up in trace amounts in the over-two-micron fraction in Beaver Creek and Hat Creek at low flow. Quartz was present in greater amounts in the tributary streams than in the Cheyenne River. This mineral, like feldspar, is prominent in the weathered profiles but is scarce in the suspended sediment. Mica is a prominent constituent of all seven weathered profiles, yet is moderately represented in the suspended sediment of the various streams. The hypothesis that vermiculite absence may be due to its conversion to reconstituted micas is weakened by the modest composition of micas in the suspended sediment of the streams.

DISCUSSION OF RESULTS

Pulsations in Sediment Transport

The relations found to exist between topographic characteristics, character of weathered material, and rates of sediment movement in small basins (Hadley and Schumm, 1961) cannot be applied directly to larger drainage basins. A decrease in sediment yield per unit area with increasing size of drainage area may be due to one of the following: (1) Absorption of flow in the channel beds of ephemeral streams causing deposition of sediment load. (2) Greater diversification of topography in larger drainage basins providing sites for deposition of eroded material from steep upland slopes. (3) Development of bottomlands in larger drainage basins, thus providing situations for deposition on flood plains and valley floors.

Deposits of sediment which have accumulated on flood plains and in channels in many tributaries of the Cheyenne River represent sediment from upland sources that has been intercepted en route to the master stream. Many of these aggradational features are unstable and are removed and transported downstream in a short span of years; others have become well stabilized by vegetation and continue to weather in place before removal.

The cycle of transportation, as reflected in the Cheyenne River basin, occurs in a series of pulsations and the transported material must undergo weathering and diagenesis between movements. Therefore, the problem of comparing mineralogy of weathered rock material in upland areas with the mineralogy of suspended sediment in the flow of the Cheyenne River is complicated by these intermediate processes.

The interruptions or pulsations in the transport cycle of sediment are intimately related to the development of hill slopes. In an earlier study of erosional processes on hill slopes (Hadley and Rolfe, 1955) in the Cheyenne River basin, it was demonstrated that a mineralogical winnowing occurs in slope erosion by seepage steps. Therefore, a study of weathered material on upland slopes must be done with some knowledge of the processes that

form the slope. Downslope migration of soil material is a fundamental part of slope formation. Surficial material is continually moved downslope as the seepage step erodes upslope. In this manner young soil profiles in a semi-arid climate may acquire the characteristics of a more mature soil.

In order to understand the problem of weathering and transport of sediment within a basin it is necessary to begin with the processes of slope development on the smallest upland units. The continuous reworking of materials in its downslope migration separated by periods of deposition and weathering alters the mineralogical assemblages and the particle-size distribution. Climate will affect the relative speed of these processes but the processes themselves are probably similar from place to place.

Summary and Discussion

The outcropping formations and major streams in the Cheyenne River drainage area of eastern Wyoming were studied with respect to texture, mineralogy, and quality of water. The objectives were (1) to determine the sediment contributions of tributaries to the master stream, (2) determine the sediment contribution of the outcropping geologic formations and (3) investigate fully that part of the sedimentation sequence that includes weathering–erosion–fluviatile transport.

The investigation produced several interesting results. Briefly, they are as follows:

(1) There is a change in the mineralogical composition of the silt and clay fractions of the transported material as it passes from upland slopes to stream channels.

(2) There is also a change in textural composition of the material finer than 1.0 mm as it moves from upland slope to stream channel. The weathered material is sorted en route to stream channels; the texture is finer and there are fewer kinds of minerals when it reaches the stream channel.

(3) There are vermiculitic or degraded micas in outcropping formation but there are none in the stream. This phenomenon may be due to re-potassication or reconstitution of degraded micas between outcrop and stream or to alteration of vermiculites to montmorillonites.

(4) The texture or particle size distribution of the suspended sediment is different in the natural state from that of the dispersed, laboratory state. The median diameter of suspended particles is larger in native waters than under dispersed conditions.

(5) Streams may be distinguished, one from the other, on the basis of the chemical composition of their waters, even within a relatively small watershed.

(6) The mineralogy of the suspended sediment and the chemistry of the water in stream are different for low and high flows. Therefore, the time of sampling is critical in studies of fluviatile transport of sediment.

(7) Geomorphologic processes in the semi-arid climate of east-central Wyoming occur at an erratic rate. The movement of sediment material on upland slopes and in stream channels takes place in pulses. In other studies by the authors (Hadley and Rolfe, 1955) it was shown that the process of slope retreat also takes place in a pulsating, steplike pattern.

QUALITY OF WATER IN VARIOUS STREAMS

The waters of the four streams were analyzed for dissolved constituents and the results are reported in Table 2.

TABLE 2.—CHEMICAL ANALYSES OF STREAM WATERS* IN MEQ PER LITER

	pH	Na	Ca	Mg	HCO$_3$	SO$_4$	Cl
Beaver Creek	6.2	8.7	4.54	2.3	0.74	10.8	4.0
Lace Creek	6.8	1.9	3.7	2.3	2.8	4.9	0.2
Hat Creek (low flow)	7.1	20.77	10.88		4.0	27.14	0.51
Hat Creek (high flow)	7.3	17.16	10.4		3.7	23.3	0.56
Cheyenne River (low flow)	7.2	17.18	17.16	5.58	2.75	32.86	4.31
Cheyenne River (high flow)	7.0	13.79	9.03	2.21	3.93	18.51	2.59

*Samples taken on May 17, 18, 1962.

Inspection of these data indicates two outstanding facts. The first is the absence of magnesium from Hat Creek determinations and the second is the difference in effect of flow conditions on water composition of Hat and Cheyenne streams. Relative flow volume has little apparent effect on Hat Creek composition but has produced a noticeable change in that of the Cheyenne River.

The textural and mineralogical analyses of suspended sediment from the streams did not record any striking criterion for differentiation of streams. The chemical composition of the stream waters appeared sufficiently different to warrant further review of the data. Accordingly, B. F. Whitney of the Tulsa Research Center, Sinclair Research, Inc., statistically analyzed the results.

The composition of the streams was first compared by a method in which the absolute values of the differences between specific components in any two streams were summed. This total was then divided by the

sum of all components for the two streams being considered. The formula for this computation is:

Compare

$$\dfrac{\displaystyle\sum_{i=1}^{6} (A_i - B_i)}{\displaystyle\sum_{i=1}^{6} (A_i + B_i)}$$

where A_i is the ith component of stream A
and B_i is the ith component of stream B.

Quality of Water in Various Streams

As an example of this computation, the Beaver Creek and Lance Creek data are compared using the table below:

i	1	2	3	4	5	6	
Ion	Na	Ca	Mg	HCO$_3$	SO$_4$	Cl	Total
$(A_i - B_i)$	6.80	0.84	0.00	2.06	5.90	3.80	19.4
$(A_i + B_i)$	10.60	8.24	4.60	3.54	15.70	4.20	46.88

The ratio of the two totals produces a compare value of 0.415 for Beaver versus Lance Creek.

The compare values were computed for all fifteen possible comparisons, as shown in Table 3.

TABLE 3.—Compare Values

Beaver Creek					
0.415	Lance Creek				
0.464	0.659	Hat Creek (low flow)			
0.412	0.633	0.070	Hat Creek (high flow)		
0.440	0.671	0.183	0.197	Cheyenne River (low flow)	
0.270	0.523	0.192	0.133	0.247	Cheyenne River (high flow)

The table provides a means of comparing paired stream compositions. The greater values indicate greater deviations from a mean and therefore

greater differences between the paired streams. For example, note the value for the comparison between Lance Creek and Hat Creek (low flow), i.e. 0.659. This means that for every part involved in this comparative analysis, 0.659 parts are in deviation from the average of the two streams, Lance and Hat (low flow). The data indicate that Hat Creek is most like the Cheyenne River, regardless of flow volumes in either stream. Lance Creek is most dissimilar of all the streams, including the Cheyenne.

The preceding table (Table 3) does not account for the probable effects of salt concentration or dilution in the various streams. Therefore, the data were recalculated in terms of percentage. Table 4 presents the component percentages for each stream water.

The data in Table 4 indicate that the two Hat Creek samples are more similar than the two from the Cheyenne River. Apparently, higher flow volumes merely dilute the dissolved components and do not change the relative proportions.

TABLE 4.—PERCENTAGE COMPOSITION OF STREAM WATERS

	Total meq	% Na	% Ca	% Mg	% HCO$_3$	%SO$_4$	% Cl
Beaver Creek	31.08	27.99	14.61	7.40	2.38	34.75	12.87
Lance Creek	15.8	12.03	23.42	14.56	17.72	31.01	1.27
Hat Creek (low flow)	63.3	32.81	17.19	0	6.32	42.88	0.81
Hat Creek (high flow)	55.12	31.13	18.86	0	6.71	42.27	1.02
Cheyenne River (low flow)	79.84	21.52	21.49	6.99	3.44	41.16	5.40
Cheyenne River (high flow)	50.06	27.55	18.04	4.41	7.85	36.98	5.17

For further examination of constituent percentages, compare values were computed from the preceding data and are presented in Table 5. These compare values, adjusted to a percentage basis, are lower than those in Table 3. Note the great similarity among the Cheyenne River (low and high flow), Hat Creek (low and high flow) and Beaver Creek. Only Lance Creek is consistently dissimilar from the others. Note also that high flow conditions in Cheyenne River reduce the compare values for all paired streams except Lance Creek.

Several conclusions may be derived from this brief statistical review of the chemical analyses of Cheyenne stream waters: (1) the tributaries are more like the parent stream in high flow than at low flow; (2) the

TABLE 5.—COMPARE VALUES FOR PERCENTAGE.

Beaver Creek					
0.313	Lance Creek				
0.195	0.327	Hat Creek (low flow)			
0.192	0.304	0.023	Hat Creek (high flow)		
0.144	0.238	0.159	0.140	Cheyenne River (low flow)	
0.111	0.254	0.112	0.097	0.104	Cheyenne River (high flow)

unique composition of Lance Creek waters suggests that it may be quantitatively distinguished from the others; (3) the Cheyenne River is more saline than any of its tributaries, implying either a loss of water or a contribution of water significantly different in composition from tributaries, Cheyenne, or both; (4) the seeming dissimilarities among the streams are largely due to relative concentrations of dissolved salts; and (5) the combined use of percentage values and the compare calculations permit differentiations of stream waters.

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