THE GEOLOGICAL SURVEY OF WYOMING

DANIEL N. MILLER, JR., State Geologist

Preliminary Report No. 16

Late Cretaceous and Early Tertiary Provenance and Sediment Dispersal, Hanna and Carbon Basins, Carbon County, Wyoming

By

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J. Donald Ryan
Department of Geological Sciences,
Lehigh University
Bethlehem, Pennsylvania 18015

Box 3008, University Station
Laramie, Wyoming 82071
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Acknowledgments

The problem of determining provenance for the Hanna and Carbon Basins was suggested to the author by Keith E. Chave. James M. Parks developed computer programs to assist the author in his study and Bobb Carson suggested a statistical test to verify the significance of some of the observations. Gary Glass critically reviewed the manuscript and offered many valuable suggestions. Donald Fluck performed mechanical analyses of the sandstones and prepared heavy mineral slides.

The study was supported by the National Science Foundation, Grant Number GA 1129.

ABOUT THE COVER: This is a view of the Hanna sandstone outcrops in the northwestern part of the Hanna Basin, near the north border fault.

Additional copies of this report are available for $1.50 from the Wyoming Geological Survey, P.O. Box 3008, University Station, Laramie, Wyoming 82071.

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Abstract

The Hanna and Carbon Basins in Carbon County, south-central Wyoming are subdivisions of a small but remarkably deep sediment-filled depression in the crystalline basement of the Wyoming Rockies. Deposits of Late Cretaceous, Paleocene and Eocene ages in the basins are estimated to have an aggregate thickness of 29,000 to 33,000 feet. The Medicine Bow, Ferris and Hanna Formations at the top of this sequence represent a change from marine to continental condtions.

Cross-bed orientations, maximum pebble size distribution, sand grain size distribution, feldspar frequency distribution, rock particle distribution and epidote frequency distribution suggest that the surrounding peaks did not become important source areas until the time of Ferris deposition. The source area for clastic rocks in the Medicine Bow Formation was not local. Ferris and Hanna clastics were carried into the Hanna Basin by means of three dispersal systems, two entering from the north, one from the south. The most important source area for the Hanna Basin was the Granite Mountains to the north. Clastic sediments were carried into the Carbon Basin mainly from the east flank of the Shirley Mountains and adjacent areas to the north. The Saddleback Hills anticline, separating the two basins, apparently was active during deposition of the Ferris and Hanna, forming a nearly complete sedimentation barrier between the two basins.

Introduction

Purpose

The Hanna and Carbon Basins (see Fig. 1), located in Carbon County in south-central Wyoming, are small but deep sediment-filled intermontane valleys tectonically developed during the Laramide Orogeny. The two basins are separated by the Laramide Saddleback Hills anticline. They are late subdivisions of a single sediment-filled Late Cretaceous depression in the crystalline basement.[1] The original depression underlies an area of only a little more than 12,000 square miles. It apparently contains Upper Cretaceous sedimentary rocks from 15,000 to 19,000 feet thick resting on a comparatively thin sequence of older sedimentary layers.[2] The depression extends to a depth of more than 24,000 feet below sea level.[3] For the sake of comparison, note that the Michigan Basin, one of the largest sedimentary basins on the North American Continent underlying an area of about 85,000 square miles, is shown on the Basement Map of North America as reaching a depth of something less than 13,000 feet below sea level.[4]

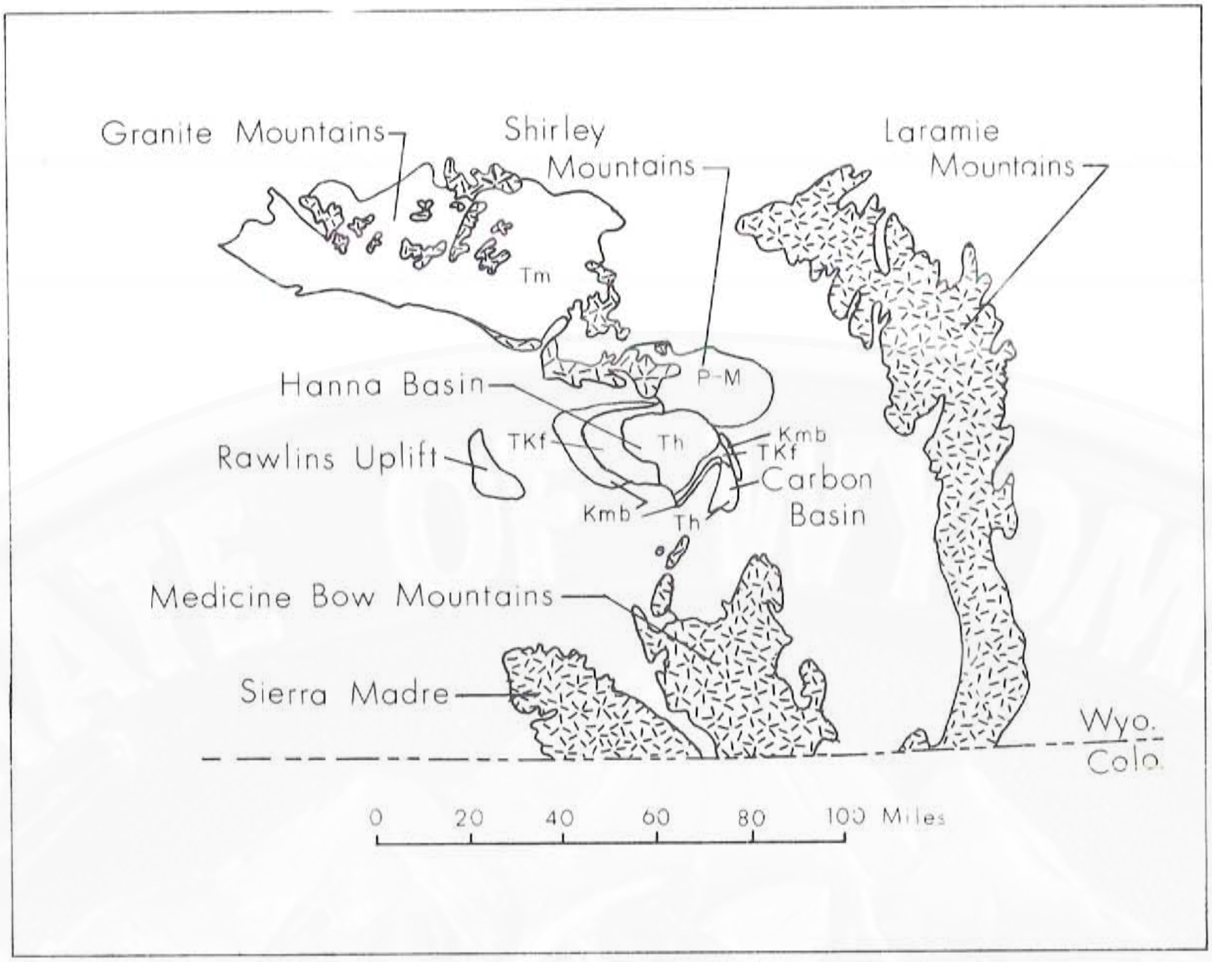

Fig. 1 — Geologic map of the Hanna and Carbon Basins showing nearby uplifts.

(Stippled area = Precambrian crystallines; P-M = Paleozoic and Mesozoic sedimentary rocks; Kmb = Medicine Bow Formation; TKf = Ferris Formation; Th = Hanna Formation; Tm = Miocene sedimentary rocks.)

Upper Cretaceous sediments in the two basins are dominantly marine clastics, almost certainly derived from erosion of highlands along the rising Mesocordilleran Arch far to the west.[5] The youngest marine formations are the Lewis Shale and the overlying Fox Hills Formation.

At the top of the Cretaceous section in the Hanna-Carbon Basins region, and grading into the Tertiary, there is a gradual transition from marine to continental deposits. The Cretaceous Medicine Bow Formation, which overlies the Fox Hills, is considered by most authors to be of continental[6] although coastal[7] origin. The younger Ferris, Hanna and North Park Formations are also clearly continental.

The continental Medicine Bow, Ferris and Hanna Formations are the subjects of this report. The three formations, estimated to have an aggregate thickness somewhere between 18,000 feet[8] and 20,000 feet,[9] were deposited just before and during "the most violent movements" of the Laramide Orogeny.[10] During the period of deposition of these three formations, the modern peaks and intermontane basins (including the modern Hanna and Carbon Basins) of the Wyoming Rockies began to appear.

This study was undertaken 1) to determine when the Hanna and Carbon Basins appeared as closed or semi-closed basins, 2) to determine whether the two basins were joined or separated during depositions of the three formations studied, 3) to locate as precisely as possible the source areas of the clastic sediments filling the two basins, 4) to try to establish the relative times of uplift of the highlands surrounding the basins and 5) to investigate in general the process of intermontane basin-filling which accompanied the Laramide Orogeny in this region.

Method of Study

This study focused primarily on sandstones (including the conglomeratic sandstones) in the Medicine Bow, Ferris and Hanna Formations.

Directional Structures

Sandstone outcrops were examined for sedimentary structures, especially those "directional" structures which can be used to determine direction of sediment transport. The directional structures were chiefly cross-beds.

The attitudes of cross-beds (or other directional features) and normal beds were measured at a large number of localities using a Brunton compass. Wherever possible, ten cross-bed attitudes were measured at each locality, each measurement being taken in a different cross-bed set. In a very few cases, fewer than ten measurements could be taken; nevertheless, in such instances, those measurements which could be taken were recorded and used for the calculation of a mean at each locality of measurement.

At localities where normal beds had a dip of five degrees or more, cross-bed readings were adjusted to their presumed original attitude by rotation on an axis parallel to the strike of normal beds through an angle equal to the dip of the normal beds[11]. This was accomplished using a computer program designed by J.M. Parks (1970).

The mean dip azimuth (assumed to be equivalent to the direction of sediment transport) at each locality was determined using vector summation methods described by Reiche (1938) and by Curray (1956). This also was accomplished using a computer program designed by Parks (1974).

In order to minimize random local variations, moving averages of cross-bed dip azimuth means were calculated on a grid using a spacing of three miles between points. The method employed is described by Pelletier (1958, p. 1035). Using this method, an average value is obtained for each point on the grid by a trigonometrical summation of all of the locality averages within the four quadrangles for which the grid point is a common corner.

Petrographic Measurements

Thin sections of Ferris and Hanna sandstones were examined and point counts were made to classify the rock and to determine the frequency percentage of each of the major components of each specimen examined. Generally, only three major components were present: quartz, rock fragments and feldspar. Since only this small number of components were present, a point count of 200 grains per slide was considered sufficiently accurate for purposes of this study.

Heavy mineral fractions in the 3Ø to 2Ø size grade were separated and heavy mineral frequencies in sandstones from each formation were determined. Generally, there were not more than five or six species recognized on a single slide. Point counts were continued until at least 200 transparent grains were included. In a few cases, there were not enough transparent grains on a slide to reach this number; in such instances, the entire population of the slide was counted.

Mineral or rock component frequencies were plotted on a map, and for those which showed potentially significant trends, moving averages were calculated, plotted and contoured.

Mean grain sizes of a large number of sandstone samples were determined using standard sieve analysis techniques. Additionally, the longest diameter of the largest pebble found at each of the stations where conglomerates were found was recorded. Median sand grain sizes and maximum pebble diameters were plotted and moving averages of these values were calculated and contoured.

Topography and Structure

The Hanna and Carbon Basins are bounded on nearly all sides by Laramide uplifts (Fig. 1).

The largest, immediately adjacent mass of uplifted material is on the north side of the basin. Here, the Freezeout Mountains, the Shirley Mountains and peaks of the Granite Mountains (both part of the Sweetwater Arch) form a series of elevated highlands whose long axis is generally parallel to the long axis of the Hanna-Carbon Basin complex. The high granite peaks in the southeastern edge of the Granite Mountains group are called the Ferris and Seminoe Mountains. Granite is also exposed on the west side of the Shirley Mountains. Between the Seminoe Mountains and the Shirley Mountains, there is a narrow pass which opens to the north onto a broad plateau largely underlain by sedimentary rocks of Miocene age. A number of monadnocks of Precambrian crystalline rocks project above the Miocene plain. This is the major part of the area shown on Figure 1 as the Granite Mountains.

Apparently, the monadnocks are remnants of a once high and massive mountain range, at least 90 miles long and 30 miles wide, which rose during early Tertiary time (during the Eocene according to Love, 1970, p. C1). During later Cenozoic (Miocene) time, the range largely collapsed along a system of block faults, leaving only the Ferris, Seminoe, Shirley and Freezeout Mountains and the large number of small monadnocks projecting along the basin-filled plain. The long axis of the Granite Mountains is parallel to the long axis of the Hanna Basin.

What seems to be a high-angle reverse fault of extremely large displacement separates the Hanna Basin from the ranges to the north. Movement on the fault was partly post-Hanna, but certainly also partly pre-Hanna and pre-Ferris.[12] Knight (1961) also suggests that the fault might date back to pre-Medicine Bow times.

The west edge of the Hanna Basin is formed by the Rawlins Uplift in which an extremely limited area of Precambrian crystalline rocks also is exposed.

The basins are bounded on the south by the north-south trending Sierra Madre and the Medicine Bow Mountains. Elk Mountain, the most northerly peak in the Medicine Bow Mountains, is a north-south trending, elongate, crystalline-cored ridge just south of the two basins. The Saddleback Hills, formed by a Laramide anticline which separates the two basins, appears to be a northerly extension of Elk Mountain.

Minor Laramide folds, which do not expose crystalline rocks, bound the Hanna Basin on its southwest edge and separate the Carbon Basin from the Laramie Basin to the east.

Stratigraphic Nomenclature

The names of the four post-Lewis continental Upper Cretaceous and Tertiary formations which occur in the Hanna and Carbon Basins (including the three considered in this report) originally were proposed by Bowen (1918):

"Bowen subdivided the post-Lewis succession into the Medicine Bow, Ferris, Hanna, and North Park Formations. He described the Medicine Bow as consisting of 6,200 + or — feet of shales, sandstones and thin beds of coal which contain fresh and brackish water invertebrates, land plants and fragmentary bones of Lance age. The Ferris, as described by Bowen, consists of 6,500 + or — feet maximum of shales, sandstones, coal seams and pockets, lenses and thin beds of conglomerate distributed through a zone 1,000 feet thick at the base of the formation. The formation contains fresh-water invertebrates and land plants of Fort Union age and, in the basal portion, fragmentary remains of vertebrates including a few specimens identified as Triceratops. *The Ferris rests conformably on the Medicine Bow - - - -. He described the Hanna as consisting of some 7,000 feet of shales, sandstones, coal seams and conglomerates composed of local material, notably granite, Mowry shale and Cloverly conglomerate. According to Bowen, the Hanna rests unconformably upon the Ferris."*[13]

Later, Dorf (1938) placed the lower 500 feet of the Medicine Bow Formation as described by Bowen in the Fox Hills Formation. The sandstones in the Fox Hills Formation as described by Dorf are burrowed and, as such, appear to represent nearshore marine deposition. (A few of the cross-bed measurements described in the present report for the Medicine Bow Formation may have been taken from Dorf's Fox Hills Formation.) Dorf also suggested a revision in the age of the Hanna Formation.

The geologic ages of late Cretaceous and early Tertiary formations in the Hanna and Carbon Basins of Wyoming according to Dorf (1938) are shown in Table 1.

AGE	FORMATION	THICKNESS
Miocene	North Park Fm.	0–400 ft.
	Unconformity	
Eocene	Hanna Fm.	7000 ft.
	Unconformity	
Paleocene	Ferris Fm.	6500 ft.
Upper Cretaceous	Medicine Bow Fm.	3600-5800 ft.

Table 1 — Formations studied in this report.

Gross Lithologies

Excellent lithologic descriptions of the Medicine Bow, Ferris and Hanna, and a large number of columnar sections can be found in Dobbin et al, 1929. These descriptions and a few observations by the author are summarized below.

Medicine Bow Formation

The Medicine Bow Formation crops out in discontinuous belts which nearly surround the outcrop areas of the Ferris and Hanna Formations (see Fig. 1). Exposures are generally poor except near the mouth of the Medicine Bow River.

The Medicine Bow Formation consists of dark-gray and carbonaceous shales, beds of coal and lenticular sandstones. The coal beds occur in the lower 1,500 feet of the formation. Knight (1961) reports an exposure on the east flank of the Medicine Bow Mountains containing a thin conglomeratic lense.

Medicine Bow sandstones are brown, tan, gray, or light-buff, fine- to coarse-grained, laminated to thickly bedded. Many have a "salt and pepper" appearance because they are composed of a mixture of quartz and both light- and dark-colored rock fragments. The sandstones in the lower part of the section more commonly are fine-grained and thinly bedded or laminated. These form relatively thin, often poorly exposed ledges. The more coarse-grained and more thickly bedded sandstones are more common in the upper part of the section. These form imposing ledges some of which are several tens of feet thick. Cross-beds (see later section) are common; ripple marks, parting lineations and oriented plant stems are rarely present, usually in the fine-grained more thinly bedded sandstones.

In 1970, Gill et al noted that fossil collections from the Medicine Bow Formation include fresh- and brackish-water invertebrates, cerotopsian dinosaur remains and plants. More recently, Fox (1972) identified Foraminifera-bearing shales interbedded with brackish- and fresh-water bivalves and fresh-water snails in the basal portion of the Medicine Bow. Invertebrate fossils above these lower brackish water units consist of fresh-water bivalves and snails.

The Medicine Bow has been interpreted as representing a coastal marsh, mudflat and coal swamp environment cross-cut by meandering streams and tidal channels.[14]

Ferris Formation

The Ferris Formation crops out in a fairly broad crescent-shaped belt between the outcrop areas of the Medicine Bow and the Hanna along the west side of the Hanna Basin and in a narrow belt along the east side of the Basin at the base of the Saddleback Hills (see Fig. 1). This latter belt curls eastward around the nose of the Saddleback Hills anticline into the northern tip of the Carbon Basin.

"The lower 300 feet of the Ferris Formation consists of dark shale and coarse, friable massive buff to yellow sandstone containing small scattered pebbles and irregular thin beds of conglomerate. Overlying this lithologic unit is one about 800 feet thick, made up largely of conglomerate, which occurs as pockets, lenses and thin beds irregularly distributed throughout the sandstone that constitutes the remainder of the unit. The remaining 5,400 feet of the formation consists of gray, brown and yellow sandstones interstratified with numerous thick beds of coal."[15]

These sandstones, like those of the Medicine Bow (and Hanna), also generally are composed of a mixture of quartz and light- and dark-colored rock fragments which imparts a "salt and pepper" appearance. They are usually cross-bedded and broadly lenticular, wedging out laterally. Basal contacts where observed are sharp and, at a few localities, the bottom few inches of the sandstone were observed to contain reworked shale fragments from underlying beds. No lateral contacts were observed.

Fossils in the Ferris consist of leaves, charophytes, fresh-water gastropods, bivalves, ostracods and vertebrate remains.[16]

The Ferris Formation is entirely continental. The sandstones must represent fluviatile deposition and probably each successively higher sandstone body in the stratigraphic sequence formed in response to an episode of tectonic uplift in the source area. In contrast, the coal deposits represent periods of relative tectonic stability.

Hanna Formation

The Hanna Formation occupies the central parts of the Hanna and Carbon Basins (see Fig. 1) and rests unconformably on the Ferris Formation. One small outlier is located about one-half mile east of the main outcrop area in the Carbon Basin (see Fig. 7).

The formation consists of conglomerates, sandstones, shale and coal. Hanna sandstones range from coarse-grained, thickly bedded types forming bold ledges and cliffs to fine-grained, thinly bedded types usually poorly exposed. The coarse-grained types are buff to grayish white and usually have a "salt and pepper" appearance. Many are conglomeratic, especially along the northwestern edge of the Hanna Basin. The conglomeratic sandstones grade into massive conglomerates.

Hanna sandstones are also broadly lenticular. Cross-beds are common in nearly every outcrop. Basal contacts are sharp and some sandstones contain reworked shale fragments from underlying beds in the bottom few inches. At several localities, the author observed truncation of underlying beds at the basal contact. No lateral contacts were observed.

Sandstone outcrops are most abundant in the northwestern, central and southwestern portions of the Hanna Basin, and in the northern and central portions of the Carbon Basin. Conglomerates occur along the northern edges of both basins and along the southern edge of the Hanna Basin.

Fossils in the Hanna include plant remains, fresh-water gastropods, bivalves and ostracods, and fragmentary vertebrate remains[17].

The Hanna Formation appears to represent a continental environment of deposition entirely similar to that of the Ferris. The sandstones are fluviatile and, like those in the Ferris, probably formed in response to tectonic movements in the source areas. Coal layers represent periods of comparative tectonic stability.

Cross-Beds

General

Cross-beds are common in some sandstone outcrops of the Medicine Bow Formation and in most sandstone outcrops of the Ferris Formation. They are present in almost all sandstone outcrops of the Hanna Formation. Most cross-beds observed in all three formations are tangential[18]; planar cross-beds[19] are less abundant but also common (Fig. 2). In many places, sets of tangential cross-beds[19] and sets of planar cross-beds are observed in the same outcrop.

Thickness of cross-bed sets vary both within formations and from one formation to another.

Cross-bed sets in the Medicine Bow Formation are generally thinner than those in the Ferris and Hanna. Micro-cross-beds in sets two to three centimeters thick are extremely common especially in the more thinly bedded, finer-grained sandstones. These often form rib and furrow structure[20] on bedding planes. Sets from 15 to 20 cm. thick to as much as 30 cm. thick are found in the more massive sandstones in the Medicine Bow.

Cross-bed sets in the Ferris and Hanna Formations commonly are 15 cm. to 30 cm. thick, but some are much thicker. At one Ferris outcrop, sets about one and one-half meters thick were observed; at one Hanna outcrop, a cross-bed set about three meters thick was observed. Micro-cross-beds and rib and furrow structure are also observed in some of the finer-grained, more thinly-bedded sandstones in both the Ferris and Hanna.

The lower surfaces of cross-bed sets in the Ferris and Hanna Formations generally appear to be very gently rolling to nearly planar, where viewed in a profile parallel to the dip azimuth (Fig. 3). These same surfaces viewed in a profile perpendicular to the dip azimuth, in many places at least, undulate in a pattern which suggests deposition of the cross-bedded sand in an intricate network of interlacing shallow channels separated by low ridges of sand (Fig. 4). Underlying cross-beds are truncated by this undulating surface. This type of structure suggests deposition of sand in braided streams.

Fig. 2 — Large scale planar cross-beds in the Hanna Formation.

Cross-Bed Orientations

Medicine Bow Formation

The orientation of 253 cross-bed sets at 27 stations in the Medicine Bow was measured and analyzed 1) by calculating mean dip azimuths for each station and plotting these on a map and 2) by constructing a composite circular histogram showing frequency percentages of all cross-bed dip azimuths plotted in 30-degree segments (see Fig. 5). Moving averages of dip azimuth means were not calculated and plotted for this formation because the distribution was so erratic as to make moving averages meaningless.

No consistent trend of dip-azimuth orientations can be observed in the belt along the west edge of the Hanna Basin. In fact, the only consistency seems to be inconsistency. For example, stations separated by only one-quarter of a mile may show nearly opposite dip azimuth means. Twenty of the sample stations were located in this belt.

Measurements were taken at only seven stations east of the town of Hanna, but dip azimuth means at each of these stations were generally eastward. The mean of the dip azimuths taken at these seven stations is 87 degrees, or nearly due east.

Figure 5 is a composite circular histogram constructed using all dip azimuth orientations measured in the Medicine Bow. The distribution is polymodal. Concentrations in each of the twelve 30-degree segments range from 6 percent to 12 percent and 12 percent of maxima appear in four of the segments. Concentrations in the eastern half of the diagram are a little higher than in the western half, probably largely because of the influence of the seven stations east of Hanna. It would appear that except in this eastern area, there is no preferred orientation.

These data support Davidson's (1966) suggestions that the Medicine Bow represents a coastal or paralic environment of deposition cut by meandering streams and tidal channels. Polymodal paleocurrent distributions are characteristic both of coastal sands and sands deposited in meandering streams[21]. In either case, the environment is characterized by extreme variability of current direction.

In a similar study of cross-bed orientations in sandstones of the Upper Cretaceous Mesaverde Group in this region, the author found a similar polymodal distribution of dip azimuths. Almost all authors consider the Mesaverde also to represent coastal depositional conditions.

This distribution offers no suggestion of the existence of local source areas.

Ferris Formation

The orientation of 292 cross-bed sets at 33 stations in the Ferris Formation was measured and analyzed (see Fig. 6).

The composite circular histogram for all

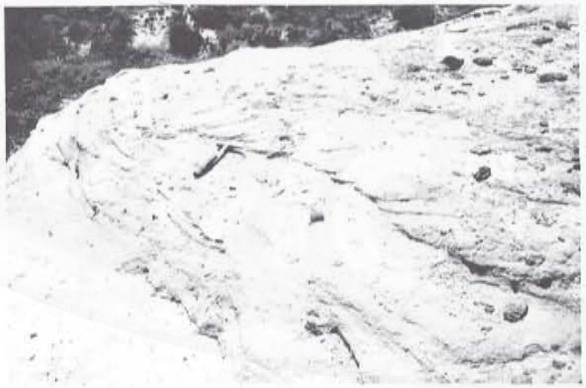

Fig. 3 — Cross-beds in a Hanna Formation sandstone viewed in a profile parallel to the dip azimuth.

(Sand transport is from right to left.)

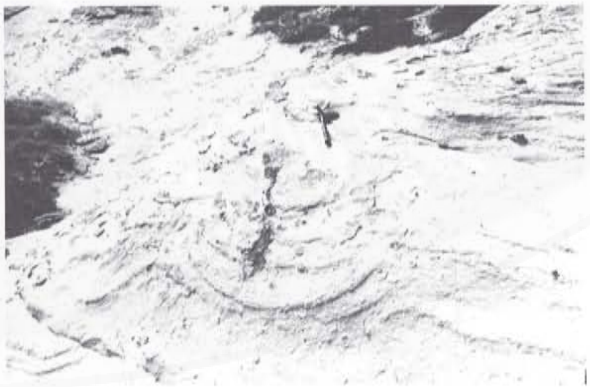

Fig. 4 — Cross-bed sets in a Hanna Formation sandstone viewed in a profile perpendicular to the dip azimuth.

(This photo was taken in a profile immediately adjacent to that of Figure 3 and at right angles to it. Sand transport is toward the viewer.)

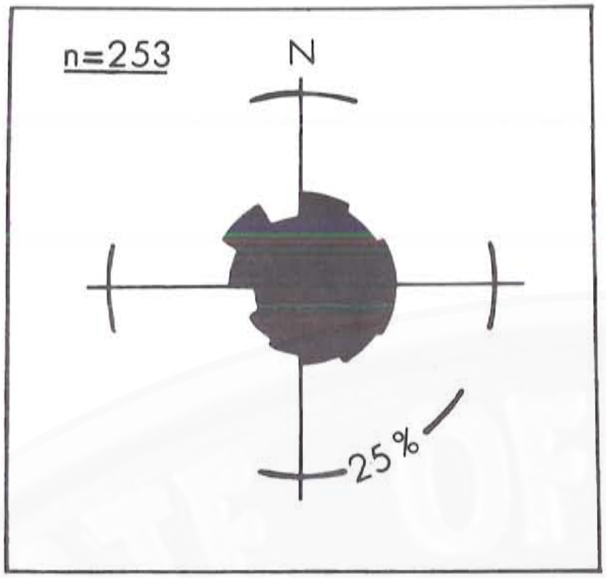

Fig. 5 — Orientations of cross-bedding dip azimuths in Medicine Bow sandstones.

(Histogram shows frequency percent of cross-bedding dip azimuths plotted in 30° classes; n = number of readings.)

cross-bed azimuths measured in the Ferris Formation is unimodal and indicates a regional easterly drainage pattern. This type of distribution is characteristic of ancient fluviatile environments.[22] However, there is considerable spread in the eastern (particularly in the northeastern) portion of the diagram. The reason for this is illustrated by the map showing moving averages plotted on a three mile grid. This map shows paleodistributary systems draining into the Hanna Basin 1) from the southwest carrying sediments nearly to the northern edge of the Basin and 2) from the north extending for at least a short distance southward into the Basin. Where the two systems meet, they combined to form a drainage pattern to the east.

Apparently, there were two major source areas for Ferris sands in the Hanna Basin. The southwest source area would seem to be the Medicine Bow Mountains-Sierra Madre complex, with sediment transport possibly coming out of the area now occupied by the Over-

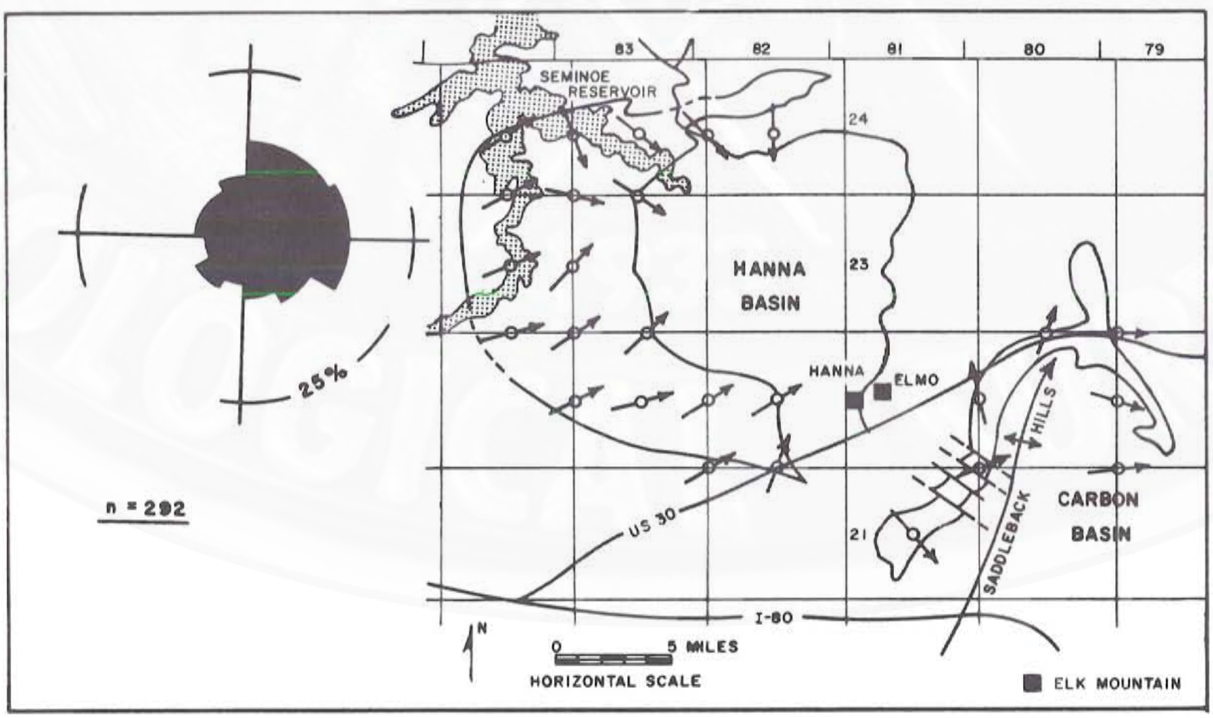

Fig. 6 — Orientations of cross-bedding dip azimuths in Ferris sandstones.

(Histogram shows frequency percent of cross-bedding dip azimuths plotted in 30° classes. Arrows are moving averages of cross-bedding dip azimuth vector means based on data from four immediately adjacent quadrangles.)

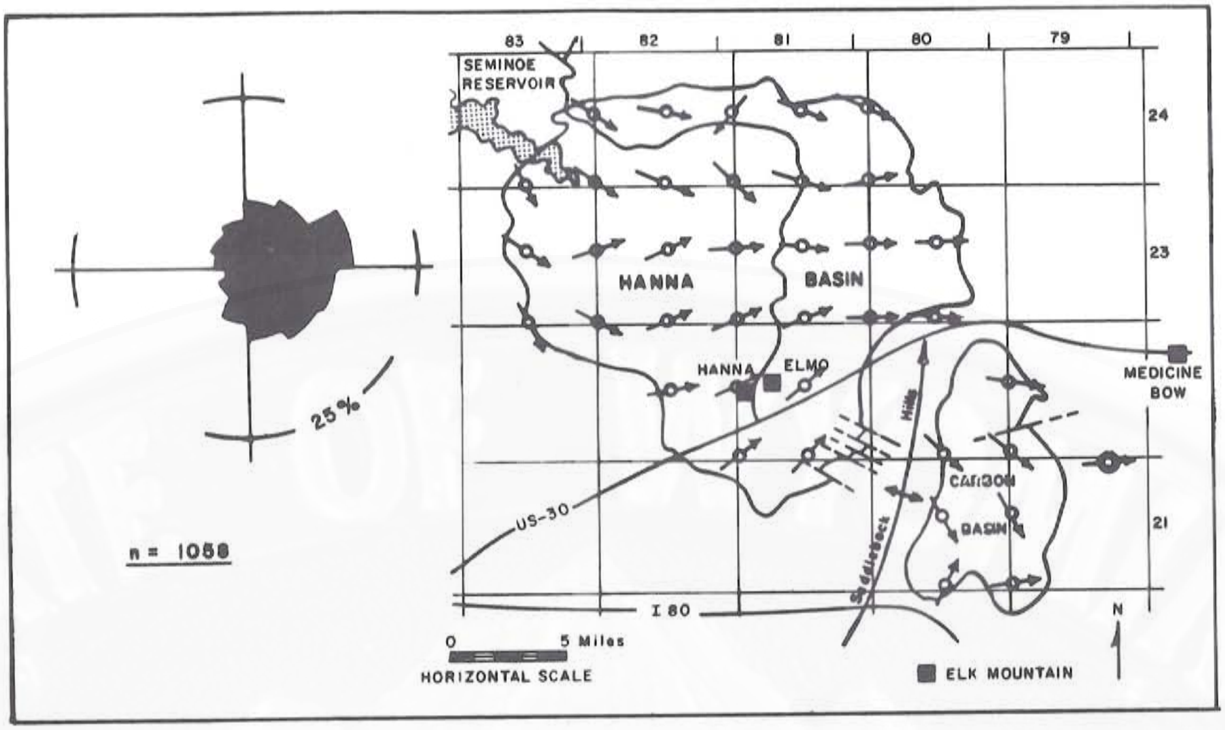

Fig. 7 — Orientations of cross-bedding dip azimuths in Hanna sandstones.

(Histogram shows frequency percent of cross-bedding dip azimuths plotted in 30° classes. Arrows are moving averages of cross-bedding dip azimuth vector means based on data from four immediately adjacent quadrangles.)

land Flats. A second source to the north would be the Granite Mountains and the Freezeout Mountains.

Ferris paleocurrents in the southeastern part of the Hanna Basin along the edge of the Saddleback Hills were toward the northeast, then to the east across the nose of the anticline into the Carbon Basin. Clearly, the Ferris drainage pattern in this region was diverted by at least a partial barrier following the axis of the Saddleback Hills. Apparently, the north-plunging Saddleback Hills anticline had begun its rise during Ferris time, permitting transport of sand from the Hanna Basin to the Carbon Basin only on a minor scale around its nose.

Cross-bed dip azimuths in the Carbon Basin are not very definitive with regard to source area. The outcrop belt is very small. The azimuths indicate sand transport out of the basin toward the Laramie Basin to the east.

Hanna Formation

Orientations of 1,058 cross-bed measurements at 110 stations were analyzed (see Fig. 7). The distribution as illustrated in the composite circular histogram is strongly unimodal with the major concentration in the segment from 60 degrees to 90 degrees. Again, there is considerable spread in the eastern half of the histogram. As in the case of the Ferris Formation, sand moved into the Hanna Basin from the north and from the southwest. Then the two systems joined and moved to the east. However, the system moving into the basin from the north apparently was the more important system during Hanna time. The pattern of moving averages for the Hanna Formation shows that the system moving into the basin from the north was effective a great deal further to the south than during Ferris time. This is particularly evident in the area along the west edge of the outcrop belt. As in Ferris time, there were two major source areas for Hanna clastics in the Hanna Basin, the Medicine Bow-Sierra Madre peaks to the south and the Granite Mountains and Freezeout Mountains to the north.

The orientation of cross-bed dip azimuths along the eastern edge of the Hanna Basin indicates that the Saddleback Hills anticline continued as a barrier or partial barrier between the Hanna and Carbon Basins. Moving averages of the dip azimuths indicate that in this area, paleocurrents were blocked and diverted toward the north. Although the Hanna Formation outcrop areas in the two basins are not now physically connected, the cross-bed dip azimuth distribution suggests that there was at least minor transport of clastic sediments from the Hanna Basin into the Carbon Basin around the nose of the Saddleback Hills anticline. As will be shown in later sections, such transport probably accounts for an extremely small proportion of Hanna Formation clastics in the Carbon Basin.

Within the Carbon Basin, cross-bed orientations suggest sand moving into the basin both from the north and possibly also from the south with the northern source clearly dominant. Sand transport out of the Carbon Basin was to the east toward the Laramie Basin.

Petrographic Measurements

Sandstones

General

Thin sections of specimens taken from ten localities in the Medicine Bow Formation, ten localities in the Ferris Formation and 34 localities in the Hanna Formation were studied and point-counted.

Three components make up the framework; quartz (usually the most abundant component), rock fragments and feldspar (except for two Hanna specimens, always the least abundant).

All three major components occur as subangular to subrounded grains and, except for some differences in relative abundance, their characteristics do not change from one formation to another. The rock fragments consist of polycrystalline quartz (chert and/or quartzite), generally heavily altered fine-grained pelitic material, and carbonate rock. Chert and pelitic material are usually most abundant but in some specimens in all three formations, there are more carbonate grains present. Carbonate grains and carbonate cement are more plentiful in the Medicine Bow Formation than in the Ferris and Hanna. Polycrystalline quartz appears to be more abundant in Ferris and Hanna sandstones cropping out along the southwest edge of the Hanna Basin.

The mean frequency percentages of each of the three framework components in thin sections studied are shown for each formation in Table 2. Quartz values do not appear to change significantly from one formation to another. However, there is a progressive increase in the size of the feldspar mean from the Medicine Bow through the Ferris to the Hanna and a corresponding (though not so well marked) decrease in the size of the rock fragment mean. The significance of these differences was verified using "two sample students' t-tests"[23] comparing values for Medicine Bow sandstones with those of Hanna sandstones. The difference in feldspar means at a 95 percent confidence level

$$(t_{\text{calculated}} = 6.32 \;\; t_{(.05,\, 42\ \text{d.f.})} = 1.68),$$

is clearly significant; the difference in rock fragment means at a 95 percent confidence level

$$(t_{\text{calculated}} = 2.09 \;\; t_{(.05-\, 42\ \text{d.f.})} = 1.68)$$

while not so well defined still is significant. Similarly, the difference in feldspar means for Medicine Bow sandstones and Ferris sandstones at a 95 percent confidence level

$$(t_{\text{calculated}} = 2.10 \;\; t_{(.05,\, 18\ \text{d.f.})} = 1.73)$$

also appears to be significant. Feldspar frequencies in a few thin sections of sandstones from the marine Upper Cretaceous Lewis Shale were about the same as those of the Medicine Bow. It would thus appear that new nearby sources of feldspar did not begin to appear until deposition of Ferris clastics. These new feldspar sources become even more important during deposition of the Hanna. Apparently, by Ferris time (but not before), erosion of nearby newly produced Laramide uplands had exposed Precambrian crystalline rocks in certain of the source areas.

Matrix material is generally absent in sand-

FORMATION	QUARTZ	FELDSPAR	ROCK FRAGMENTS
HANNA FM. (34)	56.4	10.5	33.1
FERRIS FM (10)	52.8	6.8	40.3
MEDICINE BOW FM. (10)	52.9	1.9	45.1

Table 2 – Frequency percentages of framework components in Medicine Bow, Ferris and Hanna sandstones.

(The number of thin sections point counted for each formation is shown in parentheses.)

stones of all three formations and never exceeds five percent. These sandstones, therefore, are "clean sands" or arenites[24] and most are lithic arenites. Some of the Ferris and Hanna sandstones in the northwest part of the Hanna Basin are arkosic arenites (see next section).

Feldspar Frequency Distribution

Feldspar frequencies noted in the ten thin sections of Ferris sandstones and in the 34 thin sections of Hanna sandstones previously described were plotted on a map at the localities where the samples were taken. Moving averages were calculated for the Hanna samples, plotted, and contoured (Fig. 8). The contour diagram shows concentrations greater than 25 percent in the northwestern part of the Hanna Basin in the region south of the gap separating the Seminoe Mountains from the Shirley Mountains to the east. Concentrations gradually decrease southeastward into the central part of the basin. This pattern clearly suggests that the quantitatively most important source area for the Hanna Formation in the Hanna Basin was the Granite Mountains to the northwest. The area now occupied by the gap would appear to be the locus of a major dispersal system opening into the Hanna Basin. The contour pattern also suggests a second smaller dispersal system entering the Hanna Basin from the north at a point between the gap and the Saddleback Hills, probably originating in the Freezeout Mountains. A third dispersal system, also relatively small, carried feldspar-bearing sands into the Hanna Basin from the Medicine Bow-Sierra Madre uplifts to the south through the region now occupied by the Overland Flats.

The pattern of feldspar frequency distributions in the Carbon Basin is less revealing

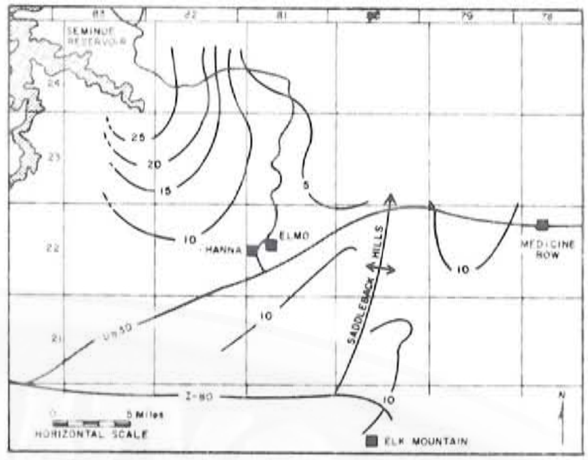

Fig. 8 – Numerical frequency percentage distribution of feldspar grains in thin sections of Hanna sandstones.

(Contours based on moving averages.)

because of the relatively slight variations within the basin. Feldspar frequency is slightly lower in the central part of the basin and slightly higher to the north and south. Two sources are suggested, one to the north and one to the south. With the exception of this pattern, and with the possible exception of cross-bed dip azimuth distributions in Hanna Formation sandstones in the Carbon Basin (see Fig. 7), all other data collected in the course of this study indicate a single northern source for the bulk of Hanna Formation sands supplied to the Carbon Basin.

There is no suggestion from the feldspar frequency distribution that sediments were transported from the Hanna Basin into the Carbon Basin.

There were too few thin sections of Ferris sandstones available to construct a diagram. However, the feldspar frequency distribution appears to be similar to that observed in Hanna sandstones. The feldspar frequency in a sandstone specimen collected in the northwestern part of the Hanna Basin was 25.5 percent; only one other frequency higher than six percent was recorded, that in a sandstone collected at the northern tip of the Carbon Basin (12.4 percent).

Rock Fragment Frequency Distribution

Rock fragment frequencies in the 34 thin sections of Hanna sandstones were plotted on a map and moving averages were then calculated, plotted, and contoured (Fig. 9).

Within the Hanna Basin, there is a marked and systematic areal change in rock fragment frequencies similar to the pattern of change in feldspar frequencies, but in an opposite sense. Rock fragment frequencies increase toward the southern end of the basin and decrease toward the gap separating the Seminoe Mountains and the Shirley Mountains at the north edge of the basin. Evidently, the increase to the north in feldspar frequency is at the expense of rock fragment frequency, clearly indicating an important granitic source area to the north. Again, the contour pattern suggests a major distributary system entering the Hanna Basin with its locus at the site of the gap, and a second system, probably of lesser importance, slightly to the east.

Rock fragment frequencies in the Carbon Basin systematically increase to the north. The contour pattern suggests a northern source largely located to the east or northeast of the Shirley Mountains. There is no indication of a connection between the Hanna Basin and the Carbon Basin. The source rocks for Ferris and Hanna clastics in the Carbon Basin were largely sedimentary rock types.

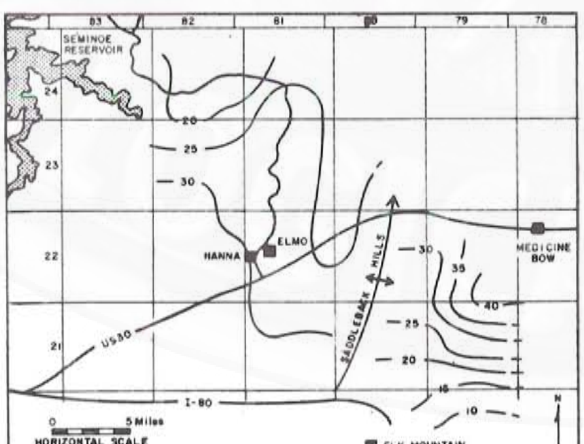

Fig. 9 — Numerical frequency percentage distribution of rock fragments in thin sections of Hanna sandstones.

(Contours based on moving averages.)

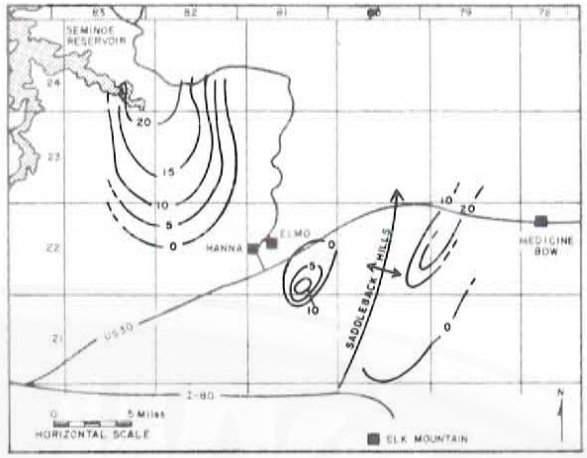

Fig. 10 — Numerical frequency percentage distribution of epidote grains in thin sections of Hanna sandstones.

(Contours based on moving averages.)

Epidote Frequency Distribution

The frequency distributions of heavy minerals in 12 Medicine Bow sandstone specimens, 15 Ferris sandstone specimens and 37 Hanna sandstone specimens were determined and studied as possible paleocurrent direction indicators using the techniques previously described.

Twenty-two species of transparent minerals and several varieties of opaque grains were identified. The areal frequency distributions of the opaques (as a single class) and five of the most abundant transparent minerals (garnet, epidote, micas, tourmaline, zircon) were studied, but the areal frequency distribution of only one mineral, epidote, proved to be valuable as a paleocurrent direction indicator.

Variations in the areal distribution of epidote in Hanna sandstones were determined by plotting frequency distributions of epidote at sample sites on a map, then calculating, plotting and contouring moving averages (Fig. 10). The contour diagram indicates a supply of epidote carried into the Hanna Basin from the Granite Mountain area to the northwest and a supply carried into the Carbon Basin from the north or northeast. An isolated area of epidote-bearing sandstones also occurs in the east-central part of the Hanna Basin close to the Saddleback Hills. The entire pattern again suggests a barrier between the Hanna and Carbon Basins along the axis of the Saddleback Hills.

Epidote frequency distributions in Medicine Bow and Ferris sandstones appear to be random.

Median Grain Size Distribution

Nineteen sandstone specimens from the Medicine Bow Formation, 17 from the Ferris, and 48 from the Hanna were disaggregated and sieved, and median grain sizes (Md Ø) were determined. The range in median values is considerable, from a smallest Md Ø (one specimen in the Medicine Bow) of 3.9 to a largest Md Ø (one specimen in the Hanna) of 0.3.

Median grain sizes of sandstones increase from the Medicine Bow to the Hanna. The median Md Ø for Medicine Bow sandstones is 2.54 Ø (ranging from 3.9 Ø to 1.25 Ø), for Ferris sandstones it is 2.06 Ø (ranging from 2.7 Ø to 1.5 Ø), and for Hanna sandstones it is 1.72 (ranging from 3.3 Ø to 0.3 Ø). Apparently, the sandstones generally become progressively coarser-grained from Medicine Bow time to Hanna time. The significance of the change in median Md Ø values from the Medicine Bow to the Hanna was verified using a two sample t-test at a 95 percent confidence level

$$(t_{calculated} = 4.59 \;\; t_{(.05,\, 65\ d.f.)} = 1.67).$$

This change suggests an increasing rate of erosion, probably related to increasing gradient between the source areas and the Hanna and Carbon Basins.

The median Md Ø of 16 samples taken in the Carbon Basin (1.67) was lower (indicating larger grain size) than the median Md Ø for 32 samples taken in the Hanna Basin (1.74). This difference does not appear to be at all significant

$$(t_{calculated} = 0.35 \;\; t_{(.05,\, 46\ d.f.)} = 1.68).$$

However, the fact that there is no systematic decrease in grain size from the Hanna Basin to the Carbon Basin suggests that detrital sediments deposited in the Carbon Basin did not move into the basin entirely by way of the Hanna Basin; i.e., each basin had separate sources.

Median grain sizes for each sample were plotted on a map at sample site locations, moving averages were calculated, plotted, and contoured (Fig. 11). The contour pattern again suggests two sources for Hanna Basin detrital sediments, a dominant source from the northwest (the Granite Mountains) and a less important source from the southwest (Medicine Bow-Sierra Madre complex via the Overland Flats route). A separate northern source is indicated for the Carbon Basin.

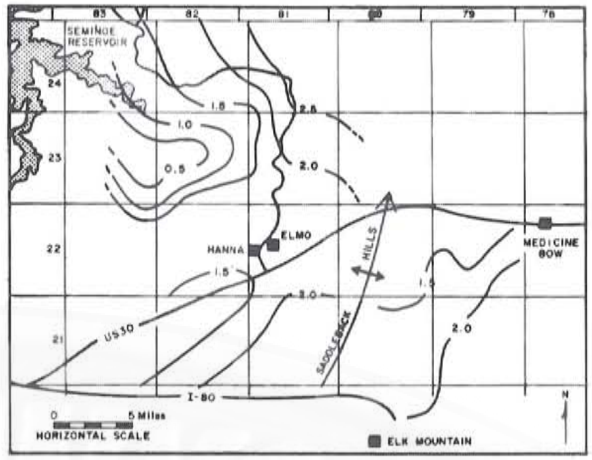

Fig. 11 — Median grain size distribution (in phi units) in Hanna sandstones.

(Contours based on moving averages.)

Conglomerates

General

Conglomerates and conglomeratic sandstones are common in the Ferris and Hanna Formations along the northern and southern edges of the Hanna Basin and in the northern part of the Carbon Basin. A thin conglomeratic lens on the east flank of the Medicine Bow Mountains at Corner Mountain, southeast of the Hanna and Carbon Basins, has been tentatively assigned to the Medicine Bow Formation by Knight (1961); other than this, no occurrences of conglomerate in the Medicine Bow have been reported.

The occurrence and composition of pebbles in conglomerates in the Ferris and Hanna Formations in the northern part of the Hanna Basin has been described by Knight (1961). There is a progressive increase in abundance and in size of the pebbles from the base of the Ferris to a stratigraphic level about 2,000 feet above the Lewis-Medicine Bow con- level to the top of the section, the pebbles decrease in size. The first pebbles to appear in the Ferris consist of chert, quartzite, and Mowry shale. Granite pebbles appear "5,640 feet above the Lower-Medicine Bow contact."[25] Thereafter, these are the most abundant type in both the Ferris and Hanna Formations. The present author has also identified chert, vein quartz, quartzite, sandstone, phyllite and amphibolite pebbles.

Knight (1961) suggests that the distribution of conglomerates in the Ferris and Hanna Formations along the northern edge of the Hanna Basin indicates an alluvial fan extending into the basin carrying sediments from the rising

Sweetwater Arch (i.e., the Granite Mountains). The data collected in this study are entirely consistent with this hypothesis.

The composition of pebbles in Ferris and Hanna conglomerates in the northern part of the Carbon Basin and in the southern part of the Hanna Basin is similar to that of conglomerates in the northern part of the Hanna Basin. However, in all three areas, sedimentary rock pebbles (especially chert) are more abundant than granite pebbles. Quartzite pebbles are more common in the southern part of the Hanna Basin than in the northern parts of the two basins.

The conglomerate lens in the Medicine Bow Formation at Corner Mountain along the edge of the Medicine Bow Mountains is said to contain "pebbles of the resistant rock types common to the older rocks down to and including Precambrian granites."[26] If this truly is a Medicine Bow conglomerate, its presence is an indication that erosion had stripped off younger rocks exposing the Precambrian granites somewhere nearby in the Medicine Bow uplift by Medicine Bow time. However, this must have been an extremely local condition; the paleocurrent pattern in the Hanna and Carbon Basins was not affected.

Apparently granite was not exposed in the Granite Mountains until well into Ferris time and the most rapid rate of erosion and sedimentation was not reached until Hanna time. Love (1970, p. C1), from a study of the Granite Mountains, reached the conclusion that "the most violent movements of the Laramide Orogeny in central Wyoming came during earliest Eocene time." The vertical distribution of granite pebbles in Ferris and Hanna conglomerates in the Hanna Basin would support this conclusion.

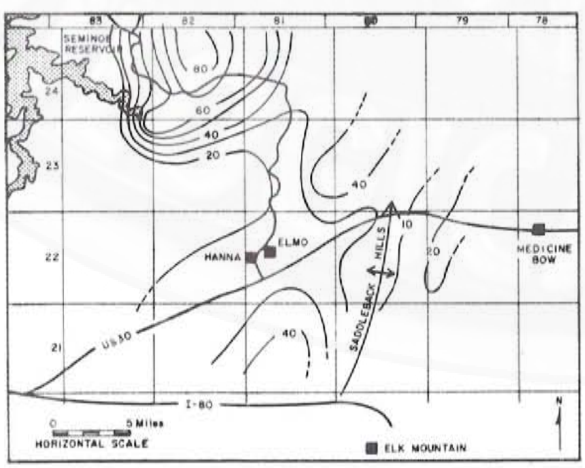

Fig. 12 — Distribution of maximum pebble sizes (in mm.) in Hanna sandstones.

(Contours based on moving averages.)

Maximum Pebble Size

Many workers have used the decrease in pebble size as an indicator of the down-current direction of sedimentary transport.[27] At each locality visited where conglomerates or conglomeratic sandstones occur in the Ferris and Hanna Formations, the author searched for the largest pebble he could find in the outcrop and measured its diameter. Forty-seven such measurements were made at Hanna localities, nine at Ferris localities. Moving averages of these maximum pebble diameters in the Hanna Formation were calculated, plotted, and contoured (Fig. 12). The distribution of maximum pebble sizes measured in Ferris conglomerates was compared to that of the Hanna Formation, but moving averages were not calculated.

The contours in Figure 12 indicate three Hanna dispersal systems in the Hanna Basin and one in the Carbon Basin. The largest and most impressive of the three systems draining into the Hanna Basin again is from the northwest, suggesting the Granite Mountains as a source. A second system of lesser importance shown by the 40 mm contour line in the northeastern part of the Hanna Basin came in from the north—the source area probably was the Freezeout Mountains. A third system carried sediments into the basin from the southwest draining the Medicine Bow-Sierra Madre Range Complex via the Overland Flats region.

This diagram also suggests that the Hanna and Carbon Basins were almost totally separated by a barrier following the axis of the Saddleback Hills. The principal source of pebbles in Hanna conglomerates in the Carbon Basin was located to the northeast.

Maximum pebble size distribution in the Ferris Formation appears to be similar.

Conclusions

The development of the Hanna and Carbon Basins as Rocky Mountain intermontane basins began in very late Cretaceous time after deposition of the Medicine Bow Formation and during the early stages of Ferris deposition. The two basins appeared as by-products of the Laramide Orogeny which reached its climax in early Eocene time during deposition of the Hanna Formation. From the beginning of their appearance as intermontane basins, the two were separate basins separated by the Saddleback Hills anticline (an extension of the Medicine Bow Uplift) and were connected only by a narrow corridor across the plunging nose of the anticline.

Medicine Bow sediments in both basins appear to represent deposition in a coastal or paralic environment as suggested by Davidson (1966), Winn (1971), and others. Among the parameters measured in this study, none showed any indication of the existence of nearby local highland source areas. The regional distribution of cross-bed azimuths in sandstones is polymodal, a characteristic of sands deposited in coastal areas and/or by meandering streams. Rock component frequency distributions also do not suggest the presence of local sources. Conglomerates do not occur in the Medicine Bow Formation within the two basins, and the sandstones, in general, are finer-grained than those in the Ferris and Hanna Formations.

The appearance of new local highland source areas is signaled by the sudden appearance of conglomerates (largely containing sedimentary rock pebbles) at the base of the Ferris in the northern part of the outcrop area. Granite pebbles which appear higher in the Ferris Formation, and are even more abundant in the Hanna Formation, show that erosion had exposed the Precambrian basement in the Granite Mountains and in the Shirley Mountains by Paleocene and Eocene times.

All parameters measured in this study suggest three source areas for Ferris and Hanna clastic sediments in the Hanna Basin, the Granite Mountains to include the Shirley Mountains and the Freezeout Mountains to the north, and the Sierra Madre-Medicine Bow Complex to the south. During Ferris time, judging from the distribution of moving averages of cross-bed dip azimuths in Ferris sandstones (Fig. 6), the southern Sierra Madre-Medicine Bow Complex was quantitatively most important. These suggest that distributary streams from the south moved sands into the basin to positions well north of the center line of the basin. However, all data (including the distribution of moving averages of cross-bed dip azimuths) show that during Hanna time, the most important source area was the Granite Mountains. The Freezeout Mountains continued as a less important source, and the Sierra Madre-Medicine Bow Complex was reduced to a relatively minor source.

Ultimately, once the surrounding ranges had achieved their highest elevations (by Eocene time) the Granite Mountains, because of their imposing size and proximity to the Hanna Basin, and their orientation with respect to the Hanna Basin, had to be the most important source area, quantitatively, for Hanna Basin clastic sediments. Since the Sierra Madre-Medicine Bow Complex appears to have been somewhat more important during Ferris time, it may have reached maturity earlier than the Granite Mountains.

All three fluviatile distributary systems which, from time to time, carried large volumes of sand and mud into the Hanna Basin, built up alluvial fans. The largest of these, first recognized by Knight (1961), is the fan extending into the basin from the now largely collapsed Granite Mountains to the northwest. The fans met, coalesced and formed broad, bajada-like bodies of clastics which, alternating with layers of peat (later changed to coal), filled the basin.

Ferris and Hanna clastics in the Carbon Basin were derived almost entirely from a dominantly sedimentary terrain to the north and northeast.

This area of supply probably included the eastern edge of the Shirley Mountains and the Como Bluffs area and may have extended as far to the northeast as the northern part of the Laramie Mountains. The orientations of cross-bed dip azimuths in the Carbon Basin and the feldspar frequency distributions within the Basin suggest the possibility of a minor southern source. However, this does not appear to be consistent with patterns of sediment dispersal indicated by other data collected in this study.

Almost all data suggest that the Hanna and Carbon Basins essentially were two separate basins during Ferris and Hanna time. The outcrop belt of the Ferris Formation is continuous from one basin to the other (but not the outcrop belt of the Hanna). Moving averages of cross-bed dip azimuths (see Figs. 6 and 7) indicate that there probably was a narrow connection between the two basins across the nose of the anticline during deposition of sands in both formations. However, feldspar, rock fragment and epidote frequency distributions as well as textural data all indicate separate sources. At best, only a very small proportion of the clastic sediments in the Carbon Basin could have arrived by way of transport from the Hanna Basin.

The relatively small folds which presently exist along the southwest edge of the Hanna Basin and along the east edge of the Carbon Basin apparently exercised no influence on Medicine Bow, Ferris or Hanna sediment dispersal patterns. Therefore, these folds must be post-Hanna in age.

Footnotes

1. Krumbein and Nagel, 1953.
2. Dobbin et al, 1929, p. 10.
3. Knight, 1961, p. 156.
4. Flawn, et al, 1967.
5. Speiker, 1946; Krumbein and Nagel, 1953; King, 1959; others.
6. Dobbin and Reeside, 1929; Knight, 1961.
7. Davidson, 1966.
8. Dobbin, et al, 1929.
9. Knight, 1961.
10. Love, 1970, p. C1.
11 Potter and Pettijohn, 1963.
12. Knight, 1961.
13. Knight, 1961, p. 155.
14. Davidson, 1966.
15. Dobbin, et al, 1929, p. 24.
16. Dobbin, et al, 1929; Glass, 1976.
17. Dobbin, et al, 1929; Glass, 1976.
18. Pettijohn and Potter, 1964, p. 347.
19. Pettijohn and Potter, 1964, p. 328.
20. Stokes, 1953, p. 17-21.
21. Selley, 1968.
22. Selley, 1968.
23. Snedecor and Cochran, 1967, p. 60.
24. Pettijohn, Potter and Siever, 1973, p. 155.
25. Knight, 1961, p. 159.
26. Knight, 1961, p. 163.
27. Pelletier, 1958.

References

American Association of Petroleum Geologists, 1972, Geological highway map of the Northern Rocky Mountain Region: Map No. 5, United States Geological Highway Map Series, Scale 1 inch = approximately 30 miles.

Bowen, C.F., 1918, Stratigraphy of the Hanna Basin, Wyoming *in* Shorter contributions to general geology: U.S. Geological Survey Professional Paper 108, p. 227-235.

Curray, J.R., 1956, Analysis of two dimensional orientation data: Journal of Geology, v. 64, p. 117-131.

Davidson, P.S., 1966, The stratigraphy of the Upper Cretaceous Lewis Formation, Albany and Carbon Counties, Wyoming: Master of Arts Thesis, University of Wyoming, 207 p.

Dobbin, C.E., Bowen, C.F., and Hoots, H.W., 1929, Geology and coal resources of the Hanna and Carbon Basins, Carbon County, Wyoming: U.S. Geological Survey Bulletin 804, 88p.

Dobbin, C.E. and Reeside, J.B., 1929, The contact of the Fox Hills and Lance Formations: U.S. Geological Survey Professional Paper 158, p. 9-25.

Dorf, Erling, 1938, Upper Cretaceous floras of the Rocky Mountain region: Carnegie Institute of Washington Publication #508, p. 1-168.

Flawn, P.T. et al, 1967, Basement map of North America: American Association of Petroleum Geologists and the United States Geological Survey.

Fox, J.E., 1972, Invertebrate fossils and environments of the Fox Hills and Medicine Bow Formations (Late Cretaceous) in south-central Wyoming: Ph.D. Dissertation, University of Wyoming, Laramie, 136 p.

Gill, J.R., Merewether, E.A., and Cobban, W.A., 1970, Stratigraphy and nomenclature of some Upper Cretaceous and lower Tertiary rocks in south-central Wyoming: U.S. Geological Survey Professional Paper 667, 53 p.

Glass, G.B., 1972, Mining in the Hanna Coal Field: The Geological Survey of Wyoming, Laramie, Wyoming, 45 p.

_____, 1976, Eocene and Paleocene fossils from the Hanna Basin, southcentral Wyoming: unpublished report on file at Geological Survey of Wyoming, 27 p.

King, P.B., 1959, The evolution of North America: Princeton University Press, Princeton, New Jersey, 190 p.

Knight, S.H., 1961, The Late Cretaceous-Tertiary history of the northern portion of the Hanna Basin, Carbon County, Wyoming: Wyoming Geological Association Guidebook, 16th Annual Field Conference, p. 155-164.

Krumbein, W.C. and Nagel, F.G., 1953, Regional stratigraphic analysis of "Upper Cretaceous" rocks of Rocky Mountain region: American Association of Petroleum Geologists Bulletin, v. 37, no. 5, p. 940-960.

Love, J.D., Weitz, J.L., and Hose, R.K., 1955, Geologic map of Wyoming: U.S. Geological Survey, Scale 1:500,000.

Love, J.D., 1970, Cenozoic geology of the Granite Mountains area, central Wyoming: U.S. Geological Survey Professional Paper 495C, 154 p.

Parks, J.M., 1970, Computerized trigonometric method for rotation of structurally tilted sedimentary directional features: Geological Society of America Bulletin, v. 81, p. 537-540.

_____, 1974, Paleocurrent analysis of sedimentary crossbed data with graphic output using three integrated computer programs: Journal International Association for Math Geologists, v. 6, no. 4, p. 353-362.

Pelletier, B.R., 1958, Pocono paleocurrents in Pennsylvania and Maryland: Geological Society of America Bulletin, v. 69, p. 1033-1064.

Pettijohn, F.J., and Potter, P.E., 1964, Atlas and glossary of primary sedimentary structures: Springer-Verlag, New York, 370 p.

Pettijohn, F.J., Potter, P.E., Sievers, R., 1973, Sand and sandstone: Springer-Verlag, New York, 618 p.

Potter, P.E. and Pettijohn, F.J., 1963, Paleocurrents and basin analysis, Academic Press, Inc., New York, 296 p.

Reiche, P., 1938, An analysis of cross-lamination in the Coconino sandstone: Journal of Geology, v. 46, p. 905-932.

Selley, R.C., 1968, A classification of paleocurrent models: Journal of Geology, v. 76, no. 1, p. 99-110.

Snedecor, G.W. and Cochran, W.G., 1967, Statistical methods: Iowa State University Press, 5th edition, 593 p.

Spieker, E.M., 1946, Late Mesozoic and early Cenozoic history of central Utah: U.S. Geological Survey Professional Paper 205, p. 117-161.

Stokes, W.L., 1953, Primary sedimentary trend indicators as applied to ore finding in the Carrizo Mountains, Arizona and New Mexico: U.S. Atomic Energy Commission, RME-3043, 48 p.

Winn, R.D., 1971, Relationship of paleocurrent indicators to sandstone body types in the Fox Hills and Medicine Bow Formations, Hanna and Laramie Basins, Wyoming: unpublished report on file at Lehigh University, Bethlehem, Pennsylvania, 24 p.