Uplift of the Bighorn Mountains, Wyoming and Montana—A Sandstone Provenance Study

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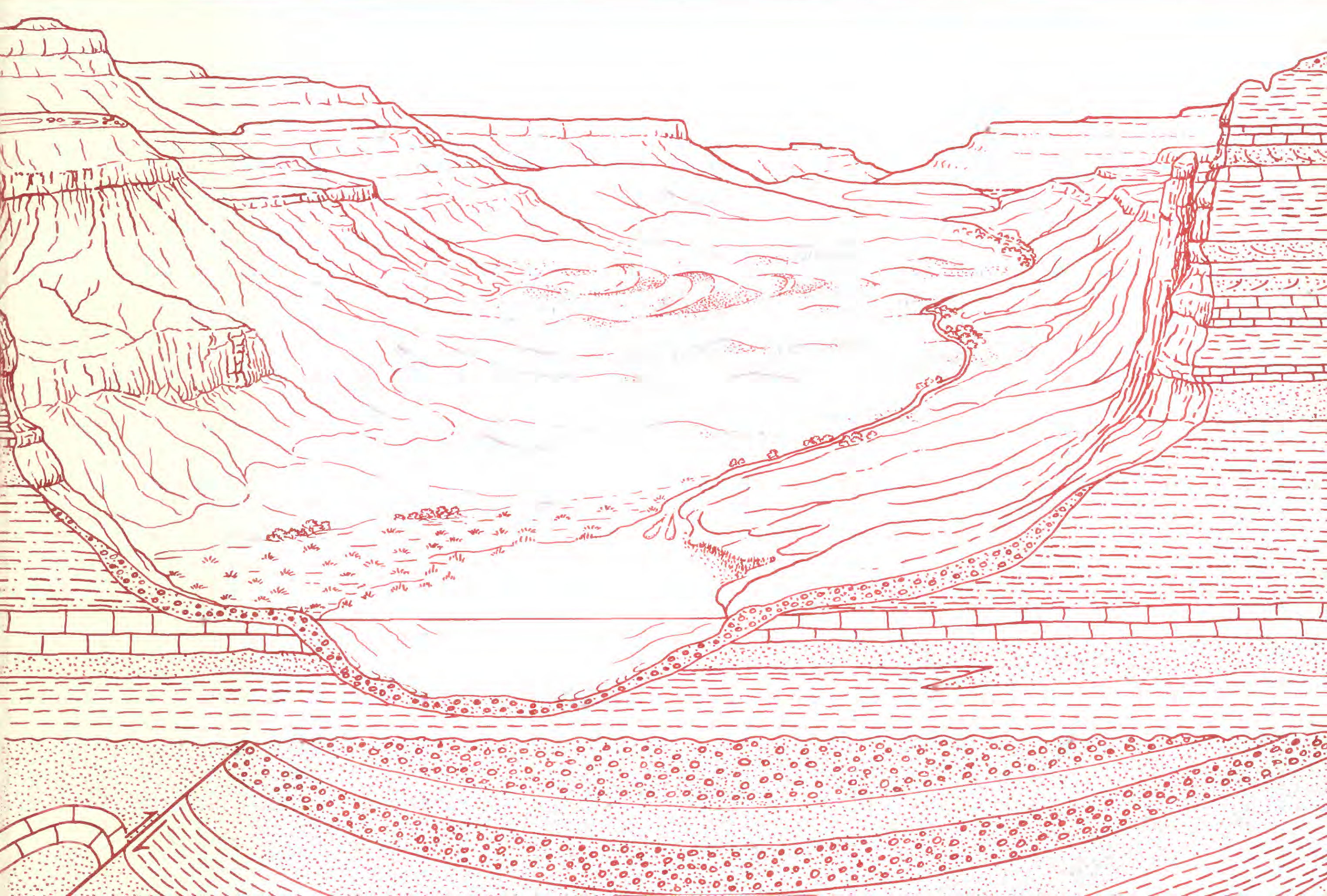

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Chapter D

Uplift of the Bighorn Mountains, Wyoming and Montana—A Sandstone Provenance Study

By C.E. WHIPKEY, V.V. CAVAROC, and R.M. FLORES

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1917

EVOLUTION OF SEDIMENTARY BASINS—POWDER RIVER BASIN

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Uplift of the Bighorn Mountains, Wyoming and Montana—A Sandstone Provenance Study

By C.E. Whipkey[1], V.V. Cavaroc[1], *and* R.M. Flores[2]

Abstract

Fluvial- and lacustrine-dominated clastic sedimentary rocks as thick as 1,800 m (6,000 ft) comprise the Paleocene Fort Union Formation and the Eocene Wasatch Formation of the western Powder River Basin in northeastern Wyoming and southeastern Montana. The systematic mineralogy of 45 samples of channel-fill sandstone from this sequence reflects the uplift and erosion of the Bighorn Mountains. Samples were collected to study vertical changes in the mineralogy of lower Tertiary sandstones adjacent to the Bighorn Mountains, lateral variations in the composition of the upper Paleocene Tongue River Member of the Fort Union Formation along the eastern front of the mountains, and variations in the composition of equivalent upper Paleocene sandstones of the central and western parts of the basin.

Vertical changes in the mineralogy of a succession of Paleocene and Eocene sandstone units adjacent to the Bighorn Mountains most likely were produced by uplift and sequential erosion of the rocks that formerly overlaid the mountains. Uplift probably began in the middle Paleocene, during deposition of the Lebo Member of the Fort Union Formation, and continued into the Eocene. Differences in the mineralogy of the sandstone units along the western edge of the Powder River Basin that correspond to differences in the rock types now exposed along the crest of the Bighorn Mountains suggest that much of the erosional degradation of the Bighorn Mountains occurred during an early Tertiary tectonic episode. Lateral changes in the suite of unstable detrital grains within the Tongue River Member are compatible with facies and paleotransport studies that indicate a substantial eastward flux of detritus of early Tertiary age from the Bighorn Mountains into the central Powder River Basin.

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[1]Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina 27695.

[2]U.S. Geological Survey, Box 25046, MS 972, Denver, Colorado 80225.

INTRODUCTION

The Powder River Basin covers about 56,000 km^2 (about 20,000 mi^2) in northeastern Wyoming and an adjacent part of Montana (fig. 1) and contains Paleocene and Eocene terrigenous detrital sedimentary rocks as much as 1,800 m (6,000 ft) thick (fig. 2). Most of the detritus accumulated during and following rapid subsidence of the basin that started in the middle Paleocene (Curry, 1971; Flores and Ethridge, 1985; Ayers, 1986). The sedimentary fill of the basin is dominated by fluvial, floodplain, and lacustrine sediments deposited in association with a generally northward flowing paleodrainage system. Blackstone (1975) and Seeland (1985) believed that the difference in elevations of the Bighorn Mountains and the adjacent Powder River Basin in the Eocene is similar to the maximum present-day relief for that region (2,800 m or 9,200 ft). This early Tertiary topography was buried beneath gently eastward sloping strata during the Oligocene and Miocene (Blackstone, 1975; Seeland, 1985). Erosion since that time has exposed the lower Tertiary strata, as well as the adjoining highlands of the Bighorn Mountains and Black Hills (King, 1977; Trimble, 1980; Swinehart and others, 1985).

The age of the beginning of uplift of the Bighorn Mountains has been debated. Along the western margin of the Powder River Basin, the Wasatch Formation of Eocene age (fig. 2) contains two thick conglomeratic members (in descending order, the Moncrief Member and Kingsbury Conglomerate Member). Cobbles and pebbles in the Wasatch are rich in feldspathic rock fragments derived from erosion of the Precambrian core of the Bighorn Mountains (Sharp, 1948; Hose, 1955; Mapel, 1959). The development of this uplift as a major source of sediment for the basin began, according to facies analysis studies, in either the late Paleocene (Flores and Ethridge, 1985) or the Eocene (Ayers, 1986). Merin and Lindholm (1986) and Ayers (1986) believed that most of the Paleocene detritus in the

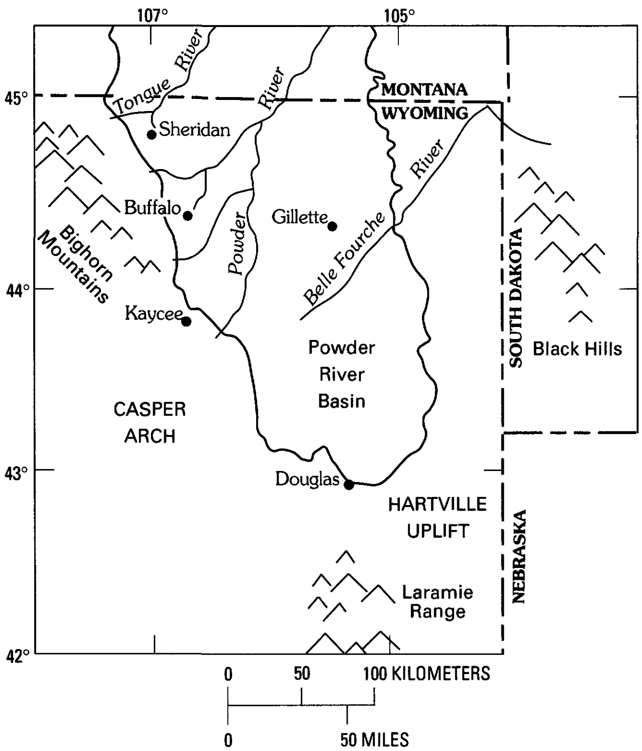

Figure 1. Powder River Basin and surrounding area, Wyoming, Montana, and South Dakota.

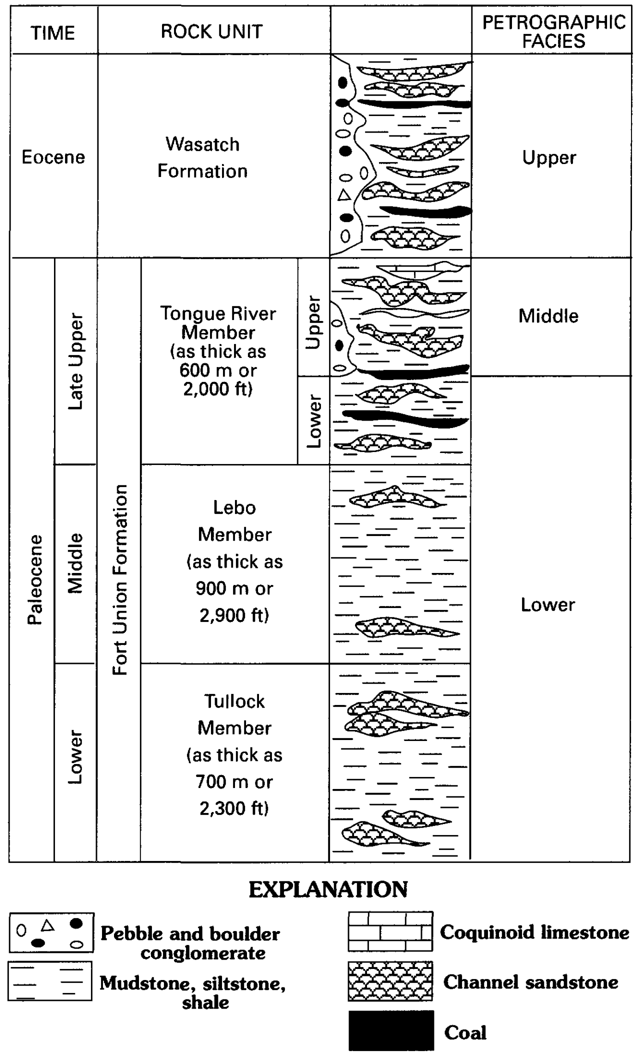

Figure 2. Lithology of lower Tertiary units, western Powder River Basin.

central part of the basin was derived from uplift of the Black Hills. This conclusion is based on the presence of lithic carbonate grains (0–11 percent) and some (0–2 percent) phyllitic rock fragments in uppermost sandstones in the Tongue River Member of the Fort Union Formation at a site east of the Powder River near the border of Wyoming and Montana.

Results of our study indicate that the Bighorn Mountains formed a significant highland during the late Paleocene (during deposition of the Tongue River Member) and likely began rising as early as the middle Paleocene (during deposition of the Lebo Member of the Fort Union). The results also demonstrate that the present-day pattern of outcrops in the Bighorn Mountains (fig. 3) was established during this early Tertiary episode of uplift and erosion.

LITHOLOGIC TYPES IN THE BLACK HILLS AND BIGHORN MOUNTAINS

Precambrian Cores

The structures that define the Powder River Basin are made up of similar rock types. In particular, both the Bighorn Mountains and the Black Hills consist of Precambrian igneous and metamorphic rocks flanked by thick sequences of upturned Paleozoic and Mesozoic strata.

The Precambrian core of the Black Hills (fig. 3) crops out in an area of approximately 2,200 km^2 (800 mi^2). It consists of metasedimentary rocks and metagabbro and minor outcrops (less than 220 km^2 or 80 mi^2) of granitic rocks. The metamorphic rocks are sillimanite to biotite in grade (Redden, 1975). The metasedimentary rocks include conglomerate, quartzite, graywacke, arkose, iron-rich strata, and dolomitic marble. Metabasalt, amphibolite, phyllite, and schist have been reported (Redden, 1975). The youngest and most extensively exposed granite is composed chiefly of quartz, albite, microcline, and muscovite; the oldest granitic rocks are commonly gneissic.

Precambrian crystalline rocks of the Bighorn Mountains crop out over a much larger area (about 4,000 km^2 or 1,500 mi^2). The southern half of the area includes Early Archean layered granitic gneiss, amphibolite, and felsic gneiss. These rocks are intercalated with metagraywacke, iron-bearing strata, quartzite, and other metasedimentary rocks. The northern half of the area consists of Middle Archean quartz diorite and quartz monzonite that have been intruded by amphibolite dikes (Love and Christiansen, 1985).

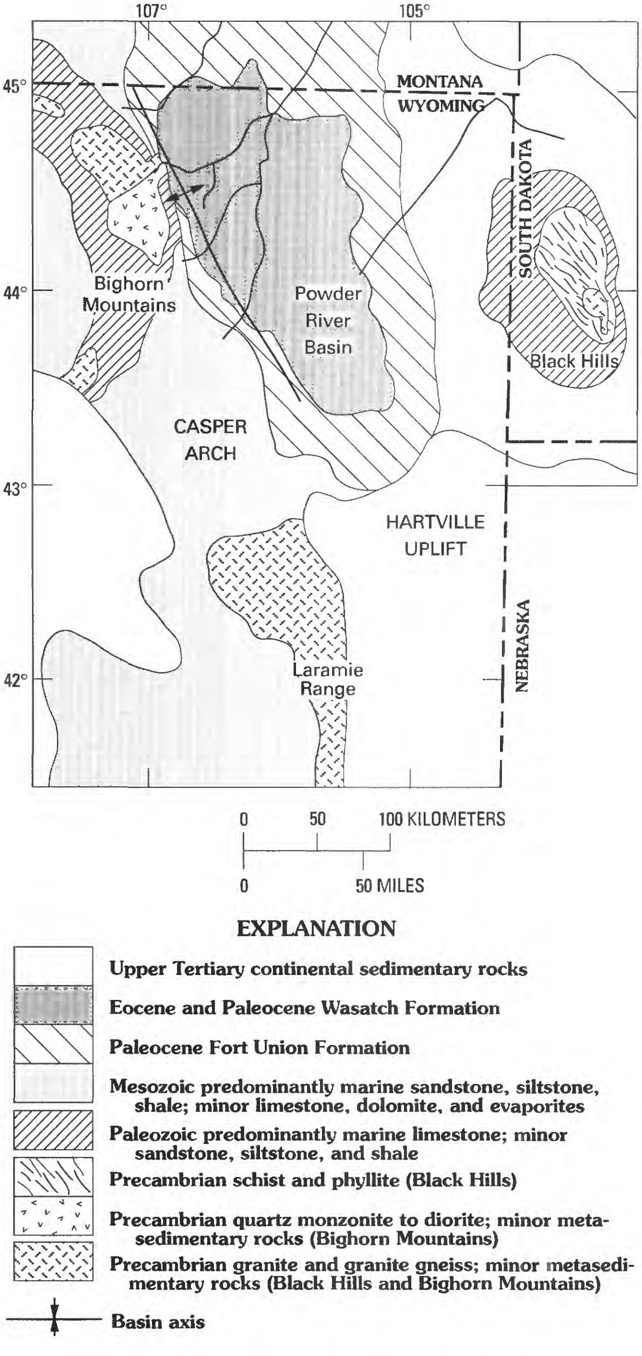

Figure 3. Generalized geology of the Powder River Basin and surrounding area. Modified from Love and Christiansen (1985) and Redden (1975).

Sedimentary Rocks of the Black Hills

The Paleozoic strata of the Black Hills are a mostly marine shelf sequence dominated by carbonate rocks but containing significant clastic beds. Cambrian and Ordovician strata consist of a few, relatively thin beds of sandstone, shale, and carbonate rocks. The Silurian and Devonian Periods for the most part are not represented in the Black Hills. A thick Mississippian sequence consists of widespread limestone, dolomite, and argillaceous dolomite. The Pahasapa Limestone (equivalent in part to the Madison Limestone), for example, is as much as 183 m (600 ft) thick. The Upper Paleozoic sequence contains a larger proportion of detrital sedimentary rocks. The Pennsylvanian and Lower Permian Minnelusa Formation, for example, consists of as much as 213 m (700 ft) of sandstone and dolomite and minor chert and shale. The remaining Permian strata consist of thinner units of carbonate rocks, silty shale, and shale that grade upward into red sandstone, siltstone, shale, and evaporite deposits of the mostly continental Upper Permian and Triassic Spearfish Formation.

Jurassic and Cretaceous formations of the Black Hills record the return of marine conditions to the region. They consist of detritus-dominated, shallow-marine strata and minor intervening continental rocks. A major clastic unit of Middle and Late Jurassic age in the Black Hills, the Sundance Formation, consists of locally glauconitic sandstone and shale. This unit thins southeastward from almost 225 m (740 ft) thick in eastern Montana to a wedge edge in central South Dakota. It is overlain by as much as 107 m (350 ft) of nonmarine, predominantly clastic beds of the Morrison Formation. Lower Cretaceous strata in the area are dominated by marine and nonmarine sandstone and mudstone, including the Lakota Formation, as much as 168 m (550 ft) thick. The Upper Cretaceous Series contains large amounts of marine shale, typified by the Pierre Shale, as much as 915 m (3,000 ft) thick. This interval also includes the coarser grained, marginal-marine Fox Hills Sandstone and the nonmarine Hell Creek Formation (Lance Formation in Wyoming), which together are more than 350 m (1,000 ft) thick.

Sedimentary Rocks of the Bighorn Mountains

Sedimentary strata of the Bighorn Mountains were deposited farther to the west of the stable craton than those of the Black Hills. Therefore, although they are similar in lithology, they tend to be both thicker and more marine. As in the Black Hills, the Paleozoic sequences are dominated by marine carbonate rocks, but they also contain extensive sandstone, siltstone, and shale. The Cambrian rocks consist of numerous fine-grained detrital beds, some arkosic sandstone and conglomerate, and a moderately thick limestone unit (50–65 m or 164–213 ft) near the top. The overlying Bighorn Dolomite (60–130 m or 197–426 ft) of Middle and Late Ordovician age contains thin sandstone and shale beds. As in the Black Hills, Silurian rocks are absent. Devonian strata are relatively thin and consist of carbonate rocks, sandstone, and shale.

The Upper Devonian and Mississippian Madison Limestone of the Bighorn Mountains is essentially the same as in the Black Hills. It is as much as 270 m (886 ft) thick and marine in origin and contains extensive limestone, dolomitic limestone, and dolomite beds, some of which are oolitic. The thick, cliff-forming, Pennsylvanian sequence includes feldspathic quartz sandstone, limestone, and shale. A thin Permian sequence of limestone, red shale, red siltstone, and evaporites is present. The Triassic is dominated by the red sandstone and shale of the Chugwater Group (as much as 275 m or 902 ft thick).

Jurassic and Cretaceous strata of the Bighorn Mountains, similar to those of the Black Hills, are composed chiefly of poorly indurated sandstones and other siliciclastic beds of continental and marine origin. Minor amounts of carbonate rocks are locally present. Jurassic rocks (as much as 230 m or 755 ft thick) include limestone, shale, and siltstone that are locally glauconitic. The Cretaceous sequence consists mainly of marine shale that commonly contains sandy intervals. The thickest of the Cretaceous formations is the Cody Shale, 800–1,075 m (2,625–3,527 ft) of shale and minor sandstone. Other thick units are the shale and sandstone-dominated Mesaverde and Lance Formations.

Provenance Implications

Similarities between outcropping rocks of the Black Hills and Bighorn Mountains (fig. 3) suggest that early Tertiary uplift and erosion of either area would have yielded detritus comprising the same four, potentially distinguishable mineral assemblages.

1. The earliest uplift of either range would have been accompanied by erosion of the thick shales, sandstones, and siltstones of the Cretaceous formations. The mineralogically mature sandstones and siltstones would have yielded recycled, durable grains such as rounded monocrystalline quartz and chert, whereas erosion of the volumetrically more important marine shales would have introduced abundant clay-size detritus into the nearest basins.

2. Further uplift would have caused erosion of the Permian through Jurassic rocks. These strata would have yielded abundant recycled quartz and cherty grains from both continental and marine sandstones and siltstones. Rapid erosion of this relatively friable sequence, along with minimal transportation and quick burial, might have led to the preservation of generally unstable constituents such as glauconite. Minor amounts of carbonate fragments also could have survived transportation from the relatively unimportant outcrops of limestones and dolomites.

3. With exposure of the Paleozoic shelf sequence, large quantities of marine limestones, dolomites, and silicified carbonate rocks would have been truncated. During rapid uplift much of this material should have been mechanically eroded to form detritus dominated by recycled quartz grains but also exceptionally enriched in detrital carbonate fragments. These sediments would also have contained chert grains and possibly sparse, recycled feldspar grains derived from the mature Paleozoic arkosic sandstones.

4. Only the Precambrian rocks of the two areas would provide significantly different erosional detritus. The core area of the Bighorn Mountains is composed mostly of diorite, monzonite, and gneiss. Erosion of these rocks would have yielded abundant quartz and feldspar and some relatively large mica booklets. Smaller quantities of slate, phyllite, and schist lithic fragments would have been eroded from the periphery of the core. The core of the Black Hills, on the other hand, is especially rich in metasedimentary rocks such as quartzite, slate, phyllite, and schist. The only rocks that could have yielded sand-sized grains of feldspar in any abundance are the areally small bodies of meta-arkose and granite.

STUDY APPROACH

Sample Collection and Preparation

The three members of the Fort Union Formation and the Kingsbury Conglomerate Member and Moncrief Member of the Wasatch Formation were sampled along the western margin of the basin (fig. 3) to determine if differences in the petrography of the sandstone units can be used to accurately define the start of uplift of the Bighorn Mountains. The Tongue River Member of the Fort Union Formation was sampled at additional localities in the northern and central parts of the basin to determine if lateral changes in its mineralogy correspond to lateral changes in rocks that presently crop out along the axis of the Bighorn Mountains. All samples were obtained from fluvially dominated sandstones to minimize compositional variations related to changes in depositional environment (Davies and Ethridge, 1975). The stratigraphic and geographic positions of these samples are described in Whipkey (1988). Samples were restricted to the fine to medium sand range (1–3 phi) to minimize compositional variations related to differences in grain size (Mann and Cavaroc, 1973; Odom and others, 1976).

Thin sections of selected samples (many of which required impregnation with epoxy) were prepared. A blue epoxy impregnation aided in evaluating grain diagenesis by accentuating pore geometry. Most thin sections were stained with sodium cobaltinitrite to aid in potassium feldspar identification.

Methods of Study

The 45 samples used in this study (table 1) were selected to obtain a representative distribution from the Tertiary stratigraphic interval exposed along the eastern

Table 1. Stratigraphic and geographic locations of samples in study
[Sample areas shown by number on figures 4 and 7]

Sample number	Rock unit	Geographic location	Sample area
1	Tullock*	Southwestern part of basin	1
2-5	Lebo*	Southwestern part of basin	2
6-7	Lower part of Tongue River*	Castle Rock area	4
8-13	Lower part of Tongue River*	TA Hills area	3
14-16	Upper part of Tongue River*	Castle Rock area	4
17-26	Upper part of Tongue River*	TA Hills area	3
27-30	Wasatch Formation	Western margin of basin	4
31-36	Upper part of Tongue River*	Tongue River area	5
37-45	Upper part of Tongue River*	Powder River area	6

*Member of the Fort Union Formation.

flank of the Bighorn Mountains, as well as to maximize geographic distribution within the Tongue River Member. Only four impregnated thin sections were made from sandstones of the Wasatch; their modal grain compositions are compatible with sections prepared from disaggregated sand grains of the Wasatch. All Tongue River outcrop and core sandstones collected from east of Gillette (fig. 3) were too fine grained to be included in this study.

Apparent long axes of 50 quartz grains were measured in each thin section (Connor and Ferm, 1966) using Chayes' mechanical point-counting technique (Chayes, 1956; Griffiths, 1967). Students' t testing (0.05 level) of data from a small sample of the thin sections confirm that 50 counts are adequate to ensure precise results.

The thin sections were then point counted for modal composition by Chayes' technique using at least 100 grain counts. Matrix and cement types were also tallied. Iterative chi-square testing (0.05 level) indicates that there is no significant difference in modal grain composition (quartz, feldspar, mica, rock fragments, matrix and cement) between 75 and 100 framework grain counts for the most mineralogically complex sandstone samples. Hence, two totals are used in the analyses of modal composition: (1) total grains counted (more than 100 per thin section), and (2) total counts of grains plus matrix and cement (as many as 252 counts per thin section). These point-count data are presented in tables 2–6.

Compositional Data Testing

Chi-square testing of enumeration data was used to define broad mineralogical facies and petrographic trends that occur vertically in the Fort Union and Wasatch Formations along the western margin of the basin and laterally within the Tongue River Member. Data were converted to percentage for Students' t, analysis of variance (ANOVA), and Duncan's multiple range (DMR) tests that were used in comparisons of individual mineral constituents. Before testing, percentage compositional data were treated with the standard mathematical transformation,

$$X = \text{arcsin squareroot percent},$$

that is applied to binomially distributed data (Griffiths, 1967) or to data whose variances are likely to be proportional to their means (Ostle, 1963). Individual test formats and results are given in Whipkey (1988).

SANDSTONE MINERALOGY OF THE BASIN

Classification

The lower Tertiary sandstones (table 2) of the Powder River Basin tend to be consistently rich in quartz and contain variable amounts of detrital chert, feldspar, and rock fragments (including carbonate grains). Samples from the Tullock, Lebo, and lower part of the Tongue River commonly contain moderate amounts of chert (as much as 23 percent) and are sublitharenites of the chert-arenite variety (Folk, 1980). Sandstones of the upper part of the Tongue River also contain moderate amounts of chert (as much as 20 percent) and substantial amounts of carbonate rock fragments (as much as 23 percent). They plot near Folk's boundary between calclithite and chert-arenite. The four samples from the Wasatch Formation are rich in feldspar; individual samples contain as much as 40 percent feldspar. Due to low levels of carbonate (less than 1 percent) and cherty (4 percent) rock fragments, they plot in the subarkose to arkose range.

Grain Types

Quartz

Quartz is the dominant detrital grain in the sandstones, and monocrystalline quartz is the most common type. Extinction varies from almost straight to strongly undulatory (table 3). Common inclusions include rutile

Table 2. Modal compositions of samples

[Sample localities shown on figures 4 and 7 by sample area number (see table 1. Rk. frag., rock fragments)]

Sample	Percentage of framework grains					Percentage of total sample			
number	Quartz	Feldspar	Rk. frag.	Mica	Other	Grains	Cement	Matrix	n
					TULLOCK*				
1	75	9	16	0	0	95	0	5	106
					LEBO*				
2	74	2	22	1	1	56	43	1	180
3	65	10	24	1	0	90	1	9	114
4	78	8	13	0	1	95	2	3	105
5	83	7	10	0	0	86	0	14	116
					LOWER PART OF TONGUE RIVER*				
6	75	5	17	2	1	77	0	23	130
7	92	3	4	1	0	68	0	32	147
8	79	0	18	3	0	85	0	15	120
9	90	1	7	2	0	94	0	6	110
10	75	3	18	1	3	77	1	22	142
11	85	0	13	1	1	76	1	23	143
12	78	2	19	0	1	94	0	6	106
13	80	3	15	2	1	67	0	33	176
					UPPER PART OF TONGUE RIVER*				
14	93	4	3	0	0	71	0	29	141
15	73	0	27	0	0	76	20	4	131
16	77	5	18	0	0	72	13	14	138
17	61	2	34	0	4	71	3	25	154
18	65	4	29	0	2	93	2	5	115
19	66	3	27	1	3	73	4	23	151
20	73	1	24	0	2	84	0	16	125
21	69	4	24	0	3	85	3	13	119
22	65	2	31	0	2	84	2	13	128
23	69	1	30	0	0	97	0	3	121
24	57	4	37	0	2	76	6	18	136
25	70	1	27	0	2	86	2	11	125
26	66	2	31	1	0	86	3	11	132
					WASATCH FORMATION				
27	56	21	16	5	2	53	44	3	195
28	70	20	4	4	2	51	44	5	198
29	77	13	7	1	2	54	45	1	185
30	50	40	1	7	2	57	41	2	175
					UPPER PART OF TONGUE RIVER*				
31	56	8	35	0	1	81	9	10	124
32	58	21	16	1	4	74	11	15	136
33	54	7	34	4	1	66	17	17	152
34	72	9	18	1	0	40	57	3	252
35	57	7	33	2	0	78	18	4	127
36	57	10	31	1	1	89	2	9	112
37	56	7	35	0	2	73	1	26	138
38	68	15	14	0	4	58	38	4	189
39	60	9	29	2	0	54	42	4	188
40	62	16	22	0	1	52	47	1	198
41	50	4	41	2	3	70	21	9	149
42	63	18	15	2	1	81	3	16	129
43	67	4	10	2	17	79	9	12	135
44	44	11	42	1	2	87	5	8	118
45	72	6	20	0	2	62	36	2	179

*Member of the Fort Union Formation.

Table 3. Quartz extinction types and feldspar twin types expressed as percentage of total framework grains

[Sample localities shown on figures 4 and 7 by sample area number (see table 1). Str., straight to slightly undulose; Undl., strongly undulatory; Poly., polycrystalline grains with three or less component crystals (<3), or more than three crystalline structures (>3) in the grain]

Sample number	Quartz extinction				Feldspar twinning		
	Str.	Undl.	Poly. <3	Poly. >3	Untwinned	Gridded	Albite
			TULLOCK*				
1	42	27	5	2	9	1	0
			LEBO*				
2	59	13	3	0	2	0	0
3	5	62	0	0	9	0	1
4	49	23	2	4	8	0	0
5	57	21	4	1	6	1	0
			LOWER PART OF TONGUE RIVER*				
6	42	19	6	8	5	0	0
7	68	22	1	1	3	0	0
8	67	9	2	3	0	0	0
9	86	6	1	0	1	0	0
10	51	23	3	6	3	0	0
11	68	19	3	3	0	0	0
12	50	20	4	4	2	0	0
13	76	11	3	4	3	0	0
			UPPER PART OF TONGUE RIVER*				
14	73	18	2	0	3	1	0
15	52	19	2	0	0	0	0
16	56	18	2	1	5	0	0
17	52	13	1	1	2	0	0
18	58	10	0	1	4	0	0
19	53	14	3	3	2	0	1
20	73	--	4	--	1	0	0
21	44	23	3	0	4	0	0
22	55	14	0	1	2	0	0
23	63	9	5	4	0	1	0
24	46	9	1	3	3	1	0
25	61	12	2	1	1	0	0
26	58	14	2	1	1	1	0
			WASATCH FORMATION				
27	38	15	1	4	20	1	1
28	45	17	4	5	19	0	1
29	57	12	4	4	12	1	0
30	33	12	3	2	35	1	4
			UPPER PART OF TONGUE RIVER*				
31	26	14	5	11	8	0	0
32	36	18	4	0	18	1	2
33	23	15	2	14	6	1	0
34	37	21	6	9	8	1	0
35	36	8	0	13	6	1	0
36	25	14	6	12	10	0	0
37	48	4	1	4	4	1	2
38	55	12	4	4	9	5	2
39	39	16	4	2	4	2	3
40	45	13	2	3	14	0	2
41	36	7	2	8	4	0	0
42	46	15	0	5	14	0	5
43	58	6	2	6	3	1	0
44	34	3	3	5	9	0	3
45	62	9	8	2	5	0	2

*Member of the Fort Union Formation.

Table 4. Rock-fragment types expressed as percentage of total framework grains
[Sample localities shown on figures 4 and 7 by sample area number (see table 1)]

Sample number	Granitie rock fragments	Metamorphic rock fragments	Sedimentary rock fragments			Glauconite present?
			Silt/shale	Carbonate	Chert	
TULLOCK*						
1	2	1	1	0	12	No
LEBO*						
2	0	1	1	0	20	Yes
3	0	0	2	0	23	Yes
4	0	0	0	0	13	No
5	0	0	2	0	8	Yes
LOWER PART OF TONGUE RIVER*						
6	0	2	2	0	13	Yes
7	0	0	0	0	4	No
8	0	0	0	0	18	No
9	0	0	0	0	7	No
10	0	2	1	0	17	No
11	0	0	0	0	14	Yes
12	0	0	0	0	19	Yes
13	0	1	4	0	13	Yes
UPPER PART OF TONGUE RIVER*						
14	1	0	0	2	0	Yes
15	0	0	0	18	9	Yes
16	0	0	0	15	3	Yes
17	0	0	0	17	20	Yes
18	0	0	0	16	15	Yes
19	0	1	1	16	12	Yes
20	0	0	0	18	7	Yes
21	0	7	0	14	3	Yes
22	0	0	6	23	4	Yes
23	0	0	5	15	15	Yes
24	0	0	2	13	23	Yes
25	0	1	0	22	6	Yes
26	0	0	0	21	14	Yes
WASATCH FORMATION						
27	0	0	2	0	12	No
28	2	0	2	0	2	No
29	0	0	1	2	3	Yes
30	1	0	0	0	0	Yes
UPPER PART OF TONGUE RIVER*						
31	3	4	3	9	16	No
32	0	1	0	8	7	No
33	1	3	7	12	11	Yes
34	1	5	2	0	10	No
35	2	7	5	5	14	Yes
36	0	6	6	8	11	No
37	1	0	7	7	20	Yes
38	2	0	1	4	8	No
39	0	0	3	4	22	No
40	0	1	4	5	12	No
41	0	0	6	26	11	Yes
42	0	4	2	0	10	Yes
43	0	2	3	1	5	No
44	0	0	12	14	17	No
45	1	0	2	6	13	No

*Member of the Fort Union Formation.

Table 5. Grain counts of chert types (inclusions)

[Sample localities shown on figures 4 and 7 by sample area number (see table 1)]

Sample number	Normal (incl. free)	Carbonate inclusions	Quartz blebs	Chalcedony	Cloudy	Clay	Aligned mica	Detrital grains	Total
				TULLOCK*					
1	3	0	4	0	0	2	0	3	12
				LEBO*					
2	6	0	9	3	0	0	1	1	20
3	6	1	5	2	4	0	5	0	23
4	3	0	5	2	0	0	0	3	13
5	4	0	1	1	0	1	1	0	8
				LOWER PART OF TONGUE RIVER*					
6	4	2	2	0	2	3	0	0	13
7	2	0	1	1	0	0	0	0	4
8	5	0	3	0	0	5	5	0	18
9	4	0	3	0	0	0	0	0	7
10	8	0	7	0	0	2	0	0	17
11	2	1	2	0	6	3	0	0	14
12	5	0	5	0	0	0	0	0	10
13	6	0	1	0	0	3	3	0	13
				UPPER PART OF TONGUE RIVER*					
14	0	0	0	0	0	0	0	0	0
15	3	0	1	1	0	0	0	0	5
16	2	0	0	0	0	0	0	0	2
17	2	1	6	0	0	3	8	0	20
18	7	0	5	1	1	0	1	0	15
19	5	0	3	0	1	0	3	0	12
20	5	1	1	0	0	0	0	0	7
21	3	0	0	0	0	0	0	0	3
22	1	0	2	0	1	0	4	1	9
23	6	1	4	2	0	0	0	2	15
24	1	1	2	0	0	2	0	0	6
25	0	1	3	1	1	0	0	0	6
26	2	1	3	1	4	0	3	0	14
				WASATCH FORMATION					
27	3	0	4	0	4	1	0	0	12
28	1	0	0	0	0	0	0	1	2
29	2	0	0	0	1	0	0	0	3
30	0	0	0	0	0	0	0	0	0
				UPPER PART OF TONGUE RIVER*					
31	2	1	1	0	11	0	1	0	16
32	4	0	0	0	2	0	0	1	7
33	3	0	2	0	5	1	0	0	11
34	2	0	0	0	0	6	1	1	10
35	1	0	3	0	4	2	4	0	14
36	5	0	2	0	3	0	0	0	11
37	4	1	2	1	8	1	0	3	20
38	4	0	1	0	1	2	0	0	8
39	10	1	6	2	0	3	0	0	22
40	3	1	3	0	3	1	0	1	12
41	3	0	2	0	0	3	1	2	11
42	4	0	4	0	0	1	1	0	10
43	2	0	2	0	0	1	0	0	5
44	6	0	6	0	2	2	1	0	17
45	2	3	4	0	1	3	0	0	13

*Member of the Fort Union Formation.

Table 6. Quartz-grain apparent long axes (phi scale) and rounding (Powers' scale)
[Sample localities shown on figures 4 and 7 by sample area number (see table 1). n, is number of quartz grains measured]

Sample number	Quartz apparent long axes			Quartz rounding	
	n	Mean (ϕ)	Sorting	n	Power's
		TULLOCK*			
1	50	1.93	0.45	50	3.5
		LEBO*			
2	50	2.57	0.44	50	3.7
3	50	2.40	0.55	50	3.7
4	50	2.26	0.60	50	3.9
5	50	2.43	0.49	50	3.6
		LOWER PART OF TONGUE RIVER*			
6	50	2.31	0.60	50	3.4
7	50	2.84	0.58	50	3.8
8	50	2.99	0.45	50	3.5
9	50	2.91	0.43	50	3.4
10	50	3.16	0.49	50	3.3
11	50	2.86	0.60	50	3.3
12	50	2.30	0.61	50	3.5
13	50	2.42	0.61	50	3.4
		UPPER PART OF TONGUE RIVER*			
14	50	2.72	0.55	50	3.9
15	50	2.29	0.68	50	4.5
16	50	2.32	0.66	50	4.2
17	50	3.09	0.41	50	3.1
18	50	2.02	0.73	50	3.4
19	50	2.79	0.62	50	3.3
20	50	1.55	0.42	50	3.9
21	50	3.16	0.60	50	3.3
22	50	3.06	0.54	50	3.4
23	50	1.08	0.46	50	4.1
24	50	2.33	0.74	50	3.9
25	50	2.35	0.78	50	3.7
26	50	2.38	0.71	50	3.5
		WASATCH FORMATION			
27	50	2.26	0.62	50	3.7
28	50	2.57	0.62	50	3.1
29	50	1.64	0.74	50	3.8
30	50	1.87	0.56	50	3.4
		UPPER PART OF TONGUE RIVER*			
31	50	2.44	0.39	50	2.8
32	50	2.71	0.40	50	2.7
33	50	2.30	0.40	50	2.8
34	50	2.69	0.46	50	2.7
35	50	2.31	0.51	50	2.6
36	50	2.27	0.50	50	2.8
37	50	2.33	0.44	50	2.7
38	50	1.94	0.49	50	2.8
39	50	2.03	0.73	50	2.7
40	50	2.17	0.52	50	2.9
41	50	2.57	0.57	50	2.9
42	50	2.08	0.37	50	2.7
43	50	2.82	0.68	50	3.1
44	50	2.64	0.51	50	3.0
45	50	2.30	0.48	50	2.8

*Member of the Fort Union Formation.

needles, mica flakes, tourmaline, zircon, and various minor opaque minerals. Less common are inclusions of vermicular chlorite.

Semicomposite grains (Folk, 1980) are not common. Other varieties of polycrystalline quartz were divided into two categories: those containing three or fewer crystals (that is, not in optical alignment) and those containing more than three crystals. Included in the latter group is schistose "stretched" polycrystalline quartz, which commonly contains aligned mica crystals and (or) crenulate subgrain boundaries. Polycrystalline quartz composed of three or fewer crystals is probably derived from granitic or high-rank metamorphic source terranes (Basu and others, 1975).

Feldspar

Untwinned feldspar, generally orthoclase, is the most common type of feldspar (table 3). Albite and carlsbad-albite feldspar twins were identified simply as plagioclase. Gridiron (tartan) twinned feldspars were assumed to be microcline. Perthitic grains are relatively rare. Alteration due to sericitization and replacement by calcium carbonate is common, especially in samples of the upper part of the Tongue River and the Wasatch. If identifiable, a partially replaced grain was counted as the original grain. A few feldspar overgrowths were observed.

Granitic Rock Fragments

Granitic rock fragments (GRF's) (table 4) were distinguished by the presence of relatively large interlocked crystals of quartz and feldspar, with or without mafic minerals or mica. These are the products of either granitic or gneissic source terranes. Few were noted, probably in part because of the fine grain size of the sandstones.

Metamorphic Rock Fragments and Mica

Common phyllosilicate minerals include muscovite and biotite booklets, which are present in almost all samples, and chlorite, which is much less common. Schistose and phyllitic metamorphic rock fragments (MRF's) (table 4) were identified by the parallel orientation and relatively large size of their constituent mica crystals. Slate fragments are very fine grained and difficult to distinguish from intraformational shale grains (relict "clay balls"). These were therefore combined into a single category (low-grade MRF's) unless other evidence, such as included detrital quartz silt, was observed.

Sedimentary Rock Fragments

A wide variety of chert and siliceous grains forms a major category of sedimentary rock fragments (SRF's). The grains were grouped into eight basic types, based partly on the presence and nature of mineral inclusions (table 5): (1) clean, inclusion-free chert; (2) chert containing calcium carbonate fragments, which probably are remnants of the replacement of limestone or dolomite; (3) chert containing small "blebs" of megaquartz that probably is recrystallized chert because of its clarity, irregular shape, and gradational boundaries with the surrounding microcrystalline quartz; (4) grains composed partly or totally of chalcedony; (5) siliceous rock fragments ("cloudy chert") that contain dispersed, very fine grained clay or mud; chert containing significant coarse clay or fine-grained mica in (6) random or preferred (7) orientation; and (8) chert containing detrital grains (silt-size quartz or mica).

Detrital calcium carbonate grains are a major SRF type (table 4). Both micritic and sparry calcite are common. The latter was commonly recognized by its aggregate nature or rhombic habit.

Some shale fragments were distinguished from slate by the inclusion of silt-size detrital quartz. Siltstone, although fine grained, commonly was distinguished from metaquartzite by the presence of intergranular clayey matrix material within the rock fragment. These SRF's are also designated on table 4.

Glauconite

Detrital glauconite is a common trace constituent (table 4) and was identified by its pelletlike shape, aggregate nature, and green absorption color, which masks birefringence. Some glauconite is surrounded by a reddish rim of oxidized iron that has been leached from the grain. Although generally found as a discrete grain, in a very few samples several glauconite pellets were within single detrital calcite grains.

Glauconite is thought to form only in marine environments (Folk, 1980). Although not a durable mineral, it is reported to survive limited sedimentary transport and has thus been found in nonmarine sedimentary rocks (Galliher, 1935; Pettijohn and others, 1972; Selley, 1978). Survival during prolonged transportation is not likely, however, because of its unstable nature, and its presence in a freshwater deposit is a reliable indicator of short, rapid transport and quick burial.

Cementation and Diagenesis

Calcium carbonate in the form of calcite is the most common cementing agent. It makes up more than 40 percent by volume of each of the Wasatch samples but generally less than 6 percent of the Paleocene rocks along the western margin of the basin (samples 1–30, table 2). Calcite cement probably formed as a result of recrystallization of detrital calcium carbonate grains or as a result of their dissolution and subsequent calcite precipitation. Evidence to support these possibilities includes the large size of many cement-filled pores, which indicates that their volume was once occupied by grains. Partly recrystallized (or dissolved) detrital carbonate was found embedded within the cement of some samples.

Partial replacement of feldspar and, to a much lesser extent, quartz by calcite cement is fairly common, especially in the Wasatch samples, which are very rich in both feldspar grains and carbonate cement. In some samples, ghosts of twinned former plagioclase grains indicate that replacement was almost complete.

Some samples contain small amounts of silica or feldspar as overgrowths, and authigenic clay was noted in very few samples; however, these materials are very minor cementing agents. No evidence of fine-clay matrix grading to larger clay or mica crystals was found.

VERTICAL CHANGES IN PETROGRAPHIC FACIES OF LOWER TERTIARY SANDSTONES

Sample Localities

Samples from the Paleocene Fort Union and the Eocene Wasatch Formations were collected at outcrops along the western margin of the basin (fig. 4) in an attempt to document the time of Tertiary uplift of the Bighorn Mountains. Sample localities were selected as close as possible to the uplift in order to minimize the possibility of contamination of the samples with detritus from other sources and to ensure the least possible modification of the mineralogy of the samples due to the effects of paleotransport.

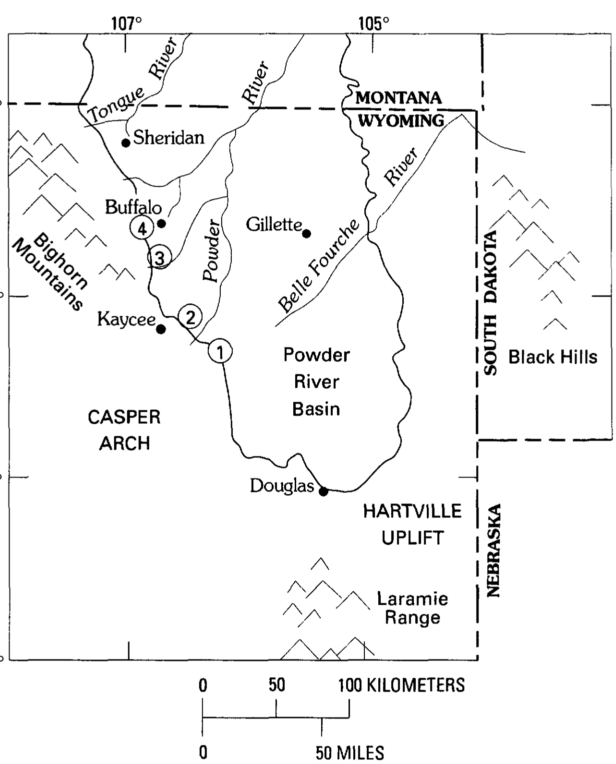

Figure 4. Sample areas used to determine vertical variation in mineralogy in the western Powder River Basin. Areas 1 and 2 are referred to in text as southwestern basin, area 3 as TA Hills area, and area 4 as Castle Rock area. Sample numbers for areas given in table 1.

The Tullock Member of the Fort Union Formation is the lowermost Tertiary unit of the Powder River Basin, and some studies suggest that the basin did not exist during deposition of this unit (see, for example, Curry, 1971). Because paleocurrent directions in the Tullock are controversial (see, for examples, Flores and Ethridge, 1985; Ayers, 1986), only one crossbedded channel sandstone (area 1, fig. 4) was collected from this interval as a check for consistency with the younger sandstones.

Samples of the Lebo Member (middle Paleocene) were collected from four localities in areas 1 and 2 (fig. 4). The Lebo is a mudstone-dominated lacustrine unit along the western margin of the basin but contains some coarse to pebbly, crossbedded, channelized sandstone.

Unlike the Tullock and Lebo, the upper Paleocene Tongue River Member is rather extensively exposed. Samples of the lower part of the Tongue River were collected at several localities in the southwestern part of the basin (areas 1 and 2, fig. 4), as well as from pebbly channel sandstones of the TA Hills (area 3). An upper, conglomeratic facies of the member (Weaver and Flores, 1985) also was sampled (area 4, fig. 4).

Samples from sandy parts of the Kingsbury Conglomerate Member and the Moncrief Member of the Eocene Wasatch Formation were also collected along the western margin of the basin near Castle Rock (area 4, fig. 4). Pebbles and cobbles in the Kingsbury, a distal fan deposit, are composed predominantly of chert and carbonate but also contain rare granitic fragments (Hose, 1955). The Moncrief, a proximal fan deposit, contains mainly coarse sandstone and granitic and gneissic cobbles and boulders.

Petrographic Facies

Three stratigraphically sequential petrographic facies are apparent on the ternary diagram of figure 5. The diagram contains the poles Q (quartz and chert), F (feldspar and granitic rock fragments), and L (lithic fragments, including carbonate grains). Quartz (including polycrystalline quartz) and chert were placed at the same pole (Q) because of their stability during transport and because of their possible significance concerning source terrane. Feldspar and granitic rock fragments (GRF's) were placed at a second pole (F) because of their utility as possible indicators of intrusive igneous or higher grade metamorphic source terranes. Very few GRF's are actually present, so their inclusion at the F pole has a negligible effect on the ternary plots. Unstable lithic fragments (L) include metamorphic rock fragments (MRF's) and sedimentary rock fragments (SRF's). Although detrital carbonate grains are commonly excluded from ternary plots because of their instability and the possible ambiguity as to their source, they were included

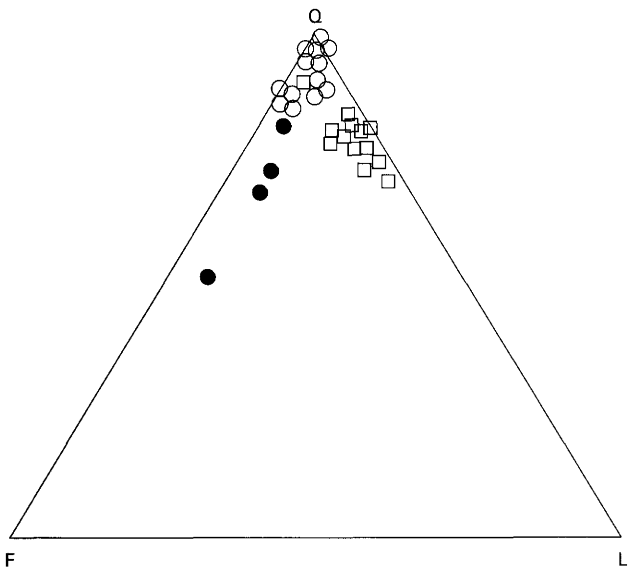

Figure 5. Ternary diagram showing the composition of sandstones along the western margin of the Powder River Basin. Petrographic facies (described in text): solid circle indicates upper facies; open square indicates middle facies; open circle indicates lower facies. Q indicates quartz plus chert; F indicates feldspar plus granitic rock fragments; L indicates lithic fragments.

as lithic fragments because (1) they are very common in some samples, and (2) limestone and dolomite beds comprise much of the Paleozoic sequence in nearby potential source areas.

One petrographic facies forms a cluster very near the quartz (Q) pole. It includes the Tullock and Lebo Members and the lower part of the Tongue River Member. Samples from the upper part of the Tongue River form a middle facies, which, as a whole, plots more toward the lithic fragments (L) pole. Samples of the Wasatch Formation comprise a third facies marked by abundant feldspar and relatively low rock-fragment content. Chi-square testing (0.05 level) confirms that significant mineralogical differences exist between the three facies, primarily due to the higher amounts of feldspar in the upper facies and carbonate fragments in the middle facies.

Textures

The samples were selected in the field to be relatively uniform in grain size (table 6). Most samples were in the fine sand range (2–3 phi), although a few are in the medium sand range (1–2 phi). Based on 50 measurements per thin section of quartz apparent long axes, mean values for the three petrographic facies are lower, 2.56 phi (s=0.35 phi); middle, 2.40 phi (s=0.60 phi); and upper, 2.08 phi (s=0.41). No major differences were observed in quartz grain roundness between the three petrographic facies. Average numerical values (Power's scale, *in* Folk, 1980) based on 50 observations per thin section are lower, 3.5; middle, 3.7; and upper, 3.5. Thus, most grains are in Power's subrounded range. The sandstones contain substantial amounts of matrix material (as much as 33 percent) and thus are texturally immature. This type of textural inversion (Folk, 1980) can be caused by relatively short transport of recycled sedimentary strata.

Mineralogy

Plots of percentage composition of individual mineral constituents (fig. 6) expand and illuminate trends shown in the ternary diagram. The lower (quartzose) facies is represented by samples 1–13. Note in particular the lack of carbonate grains. The increase in rock fragments in the middle facies (samples 14-26) is due mainly to an abrupt and large increase in detrital carbonate grains (calcite and dolomite). The upper facies (samples 27–30) is marked by a substantial increase in feldspar and mica. Cherty fragments and, to a much greater extent, carbonate fragments decrease in this facies. Carbonate cement is very prominent in the upper facies.

Quartz

Total quartz in the lower petrographic facies is almost 80 percent (s=7.2 percent) of framework grains but only 69.5 percent (s=8.8 percent) in the middle facies. Total quartz (63 percent, s=12.4 percent) is also low in the upper (Wasatch Formation) facies. ANOVA-DMR tests (0.05 level) of transformed data indicate that total quartz decreases significantly between the lower and upper facies. Polycrystalline quartz (including metamorphic quartz) accounts for 6.4 and 4.4 percent of total quartz in the lower and middle facies, respectively, and 10.3 percent in the upper facies (significant in ANOVA-DMR tests, 0.05 level).

The decrease in total quartz above the lower petrographic facies reflects the increase in carbonate rock fragments in the middle and upper facies and feldspar in the upper facies. The moderate increase in polycrystalline quartz in the upper facies may be attributed either to shorter transport distances (these Wasatch Formation samples are from alluvial fans) or to deeper erosion levels in the igneous-metamorphic core of the Bighorn Mountains.

Carbonate Rock Fragments

The detrital carbonate content of the lower quartz-rich petrographic facies is almost zero. The upward decrease in quartz in the middle facies (upper part of the Tongue River Member) is accompanied by an increase in detrital carbonate (calcite and (or) dolomite) to more than 15 percent (s=2.9 percent) of framework grains. Detrital

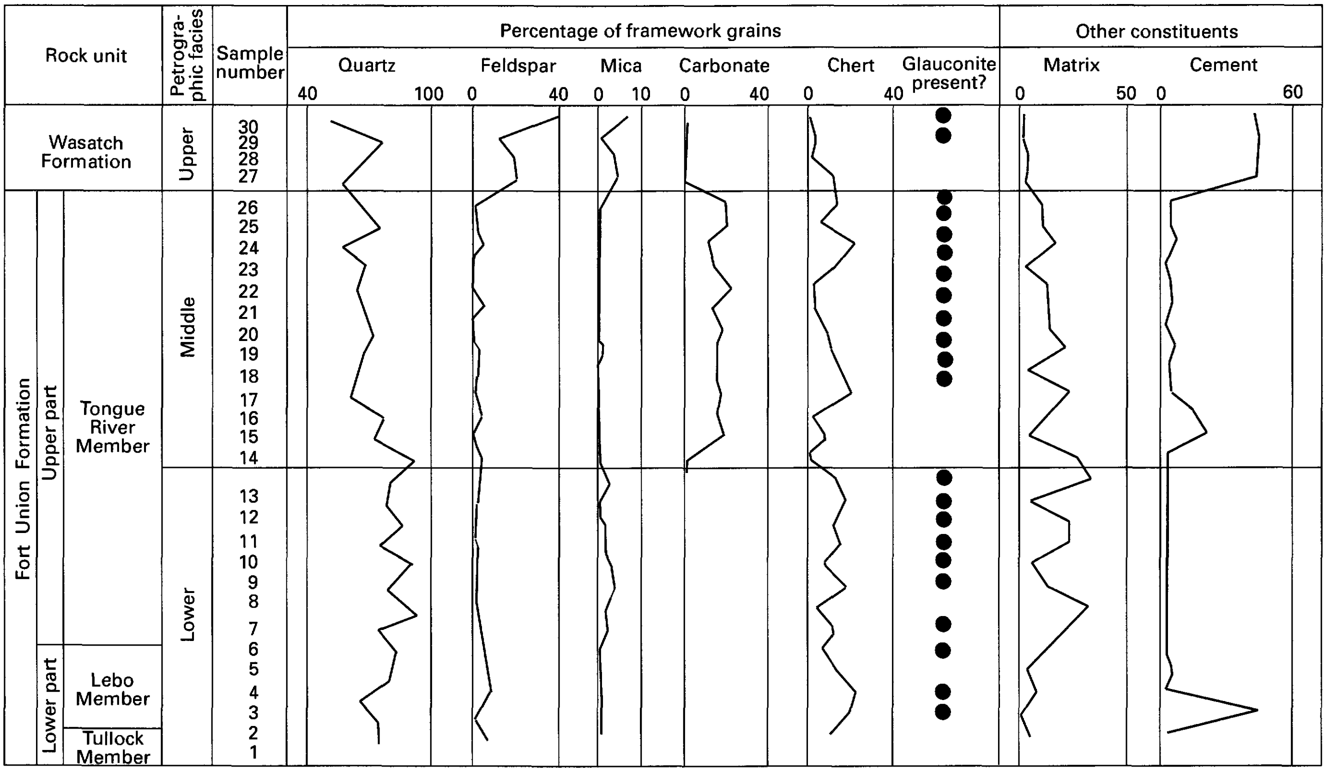

Figure 6. Point-count data for sandstones from the western margin of the Powder River Basin. Clastic grains are given as percentages of total framework grains; matrix and cement are given as percentages of the total volume of the sample. The presence of detrital glauconite (always less than 1 percent) is indicated. Point-count values are given in tables 2–6.

carbonate content then drops to a very low level (less than 1 percent) in the upper facies. ANOVA-DMR tests (0.05 level) confirm that detrital carbonate is significantly more abundant in the middle facies than in either the lower or upper facies.

The most likely source of the large quantities of carbonate fragments in the middle facies is the extensive Paleozoic limestone and dolomite beds of the Bighorn Mountains. The drastic decrease in detrital carbonate in the upper facies may be related to the greatly increased abundance of calcite cement.

Cherty Fragments

Chert makes up about 13.5 percent of framework grains in the lower petrographic facies, 9.5 percent in the middle facies, and only about 4 percent in the upper facies. ANOVA-DMR tests detect significant differences (0.05 level) only between the lower and upper facies. Cherty fragments are very diverse in these facies (table 5). Normal microcrystalline chert is most common, but chalcedony and grains containing various inclusions are also present. Too few chert grains were tabulated in point counts for statistical tests between the different varieties. Subjectively, the data do suggest that samples of the Tullock and Lebo contain slightly more chalcedony than those of the overlying Tongue River and Wasatch. Chert grains of the middle facies more commonly have carbonate inclusions than those of the other facies.

Feldspar

Untwinned feldspar (generally orthoclase, 91 percent of total feldspar) is most common, but smaller amounts of grid-twinned (microcline, 5 percent) and albite-twinned (plagioclase, 4 percent) feldspar also are present. A few perthitic grains were noted. No systematic vertical changes in feldspar types were observed.

Feldspar is a very minor component in the Paleocene sandstones, only about 3 percent of framework grains in the lower and middle facies; however, it makes up more than 23 percent of grains in the upper facies (significant on ANOVA-DMR, 0.05 level). In rocks of the upper facies, feldspar has been diagenetically replaced by calcite cement, and thus these percentages may be lower than the original feldspar content.

The increase in feldspar in the upper facies is probably associated with erosion of the Precambrian core of the uplift. This inference is supported by the previously noted concurrent increase in polycrystalline quartz. The relatively low quantities of feldspar in the lower and middle facies may have been derived from recycled Paleozoic and Mesozoic arkosic sandstones.

Mica

Muscovite, as well-developed booklets, is the most common mica; biotite and chlorite are less common. Mica content is less than 1 percent in the lower and middle facies (a few samples contain as much as 3 percent) and only 4 percent in the upper facies. The increase in well-developed mica booklets in the upper facies (significant on ANOVA-DMR tests, 0.05 level) agrees with the preceding evidence for Eocene exposure of the Precambrian granitic and gneissic core of the Bighorn Mountains.

Other Rock Fragments

Rock fragments other than chert and carbonate are not abundant in these rocks. Rocks of the upper facies contain a few (1–2 percent) granitic fragments, and one sample of the Tullock contains 2 percent granitic fragments.

Sedimentary rock fragments, as well as high-grade (schistose) and low-grade (phyllitic and slate) metamorphic rock fragments, are present in small amounts (generally less than 2 percent) throughout the interval. These amounts are well within the range of phyllite rock fragments reported by Merin and Lindholm (1986) from the basin center.

Glauconite

Glauconite is present in all samples of the Tongue River and Wasatch, although always in volumes of less than 1 percent of the grains. It most probably was derived from the nearby, friable, glauconite-bearing Mesozoic strata of the eastern Bighorn Mountains. Although difficult to characterize quantitatively because of the small amounts, glauconite probably is much more common in the middle petrographic facies than in either of the others.

Discussion and Interpretation

The three vertically sequential sandstone petrographic facies along the western margin of the Powder River Basin are characteristic of progressive uplift and erosion of a basement-cored structure; however, they are mineralogically very similar. The same basic grain types are present in all facies, and differences are in relative proportion rather than kind. This compositional similarity strongly suggests that the Fort Union and Wasatch sedimentary rocks have, at least in part, a common provenance. Because the conglomerates of the Wasatch Formation (Kingsbury Conglomerate Member and Moncrief Member) are well established as alluvial fan deposits shed from the eastern front of the Bighorn Mountains (Sharp, 1948; Mapel, 1959), the similarity argues that the provenance of the Tongue River also is the Bighorn Mountains (Whipkey and others, 1987). Such a conclusion is bolstered by the proximity of Tongue River outcrops to the uplift margin, by sedimentary structures indicating eastward paleotransport in the TA Hills (Weaver and Flores, 1985), by the ubiquitous presence of nondurable glauconite grains, and by the pebbly to conglomeratic character of many sandstones of the upper part of the Fort Union Formation.

Lower Petrographic Facies

The lowest petrographic episode consists of accumulation of large amounts of rounded, monocrystalline, probably recycled quartz in sandstones of both the Lebo and the lower part of the Tongue River Members of the Fort Union Formation. This mineralogy is consistent with the sample from the Tullock Member of the Fort Union. The channel sandstones contain subordinate chert grains, and many contain trace amounts of detrital glauconite, a mineral that is unstable during freshwater transport. This characteristic mineralogy strongly indicates proximity to a source of friable clastic sedimentary strata, some of which contain appreciable amounts of glauconite. Local chert-pebble conglomeratic lenses in channelized sandstones of both the Lebo and the lower part of the Tongue River indicate that fairly competent, high-gradient drainage systems existed adjacent to the present Bighorn Mountains in both middle and late Paleocene time.

These observations all point to the start of uplift and erosion of the Bighorn Mountains by at least middle Paleocene time. The body of friable Mesozoic strata that formerly overlaid the mountains is the probable source of much of the sediment associated with sandstones of the lower petrographic facies. Sandy Cretaceous strata (Lance Formation) may have been stripped to provide sands to the Tullock depositional sites, whereas thick, younger Cretaceous shales provided a local source for the voluminous lacustrine mudstones of the Lebo Member. Younger quartz-dominated channel sandstones of the lower part of the Tongue River Member reflect erosion of the more sandstone dominated lower Mesozoic rocks in the mountains. The abundant cherty pebbles in the conglomeratic channels of the Tongue River, as well as the large amounts of chert in the sand fraction of those rocks, are difficult to explain at this time. Erosion of one of the locally chert rich areas of the Lower Cretaceous Cloverly Formation is a one explanation. Another is deep tributary dissection along the front of the uplift that may locally have exposed more deeply buried cherty rocks of the Paleozoic marine sequence. Such deeply entrenched tributaries characterize the present-day eastern slope of the Bighorn Mountains.

Middle Petrographic Facies

A marked increase in carbonate rock fragments (calcite and dolomite) is the distinctive feature of the middle petrographic facies (upper part of the Tongue River

Member). Quartz, although less common, retains the rounded, monocrystalline character of the lower facies. Chert continues to be a relatively constant subordinate grain type. Fragments of carbonate in some chert grains suggest that the chert represents replacement of limestone or dolomite in the source rock area. Glauconite is also a ubiquitous trace mineral that, at times, is present within carbonate grains.

Paleocurrent measurements of channel sandstones in the TA Hills (area 3, fig. 4) indicate an eastward-flowing drainage network (Weaver and Flores, 1985). The coarseness of these sandstones suggests that the stream gradient was relatively high. The high stream gradient and the relatively high detrital carbonate content indicate that by the time of deposition of the upper part of the Tongue River continued uplift of the Bighorn Mountains had exposed the carbonate-rich Paleozoic sequence to extensive erosion. Concurrent erosion of previously exposed clastic-rich Mesozoic strata continued to supply quartz, glauconite, and finer grained detritus into these fluvial systems.

Upper Petrographic Facies

Feldspar is a major framework grain type in the sandstones of the upper petrographic facies (Wasatch Formation), and mica booklets are a common minor component. Detrital carbonate and chert grains, which are abundant in the middle facies, are relatively unimportant. The sudden decrease in carbonate grains may be explained in part by dissolution and subsequent recrystallization to form the abundant carbonate cement in the Wasatch Formation. Rounded, monocrystalline quartz is the major quartz type, but polycrystalline varieties are proportionally more abundant than in the other two facies. As in the other facies, detrital glauconite is a distinctive trace mineral.

This change in mineralogy, particularly the increases in amounts of feldspar and mica, strongly suggests renewed uplift and widespread exposure of the intrusive igneous and high-grade metamorphic core of the Bighorn Mountains during deposition of the Wasatch Formation. This renewed uplift may reflect major thrusting reported by Grow and others (1988) along the mountain front northwest of Buffalo (fig. 1) that juxtaposed Precambrian igneous gneiss atop the Fort Union Formation.

LATERAL VARIATION WITHIN THE TONGUE RIVER MEMBER

Sample Localities

Rocks now exposed along the crest of the Bighorn Mountains in Wyoming (fig. 3) are Paleozoic carbonate rocks in the south and Precambrian crystalline rocks in the north. Samples were collected from outcrops of the Tongue River Member within three general areas along the Bighorn Mountains (areas 3, 4, and 5 of fig. 7) in order to determine if a corresponding mineralogical change could be detected. These samples were restricted to the upper, detrital-carbonate-enriched-sandstone part of the Tongue River in the TA Hills (area 3) and the Castle Rock vicinity (area 4). Channel-fill sandstones of the Tongue River (area 5), showing north to northeast paleotransport directions (Toth, 1982), were sampled from both the middle and upper parts of the Tongue River Member. Preliminary paleobotanical correlations suggest that the base of the carbonate-bearing sandstones is correlative between areas 3 and 4 but is older northward, toward area 5.

Additional sandstone samples were collected from the valley of the Powder River (area 6, fig. 7) to determine whether the mineralogy of Tongue River channel fills in the center of the basin is compatible with eastward transport from the Bighorn uplift. Here, paleotransport of channel sandstones ranges from northeast to southeast (Canavello, 1980; Lynn, 1980).

Sandstone Mineralogy Groupings

Sandstone samples from the TA Hills and Castle Rock areas (areas 3 and 4), which were obtained from the

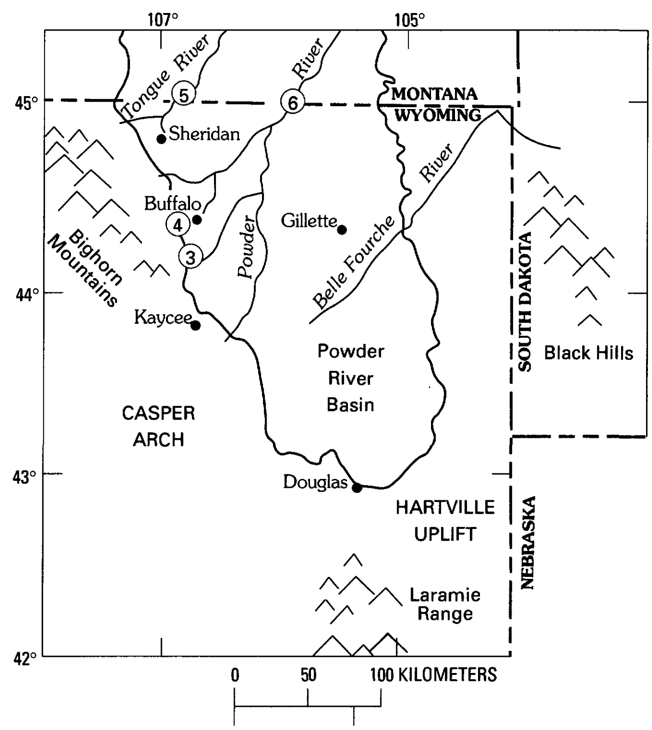

Figure 7. Sample areas used to determine lateral variation in mineralogy of the Tongue River Member of the Fort Union Formation in the Powder River Basin. Sample numbers for areas are given in table 1.

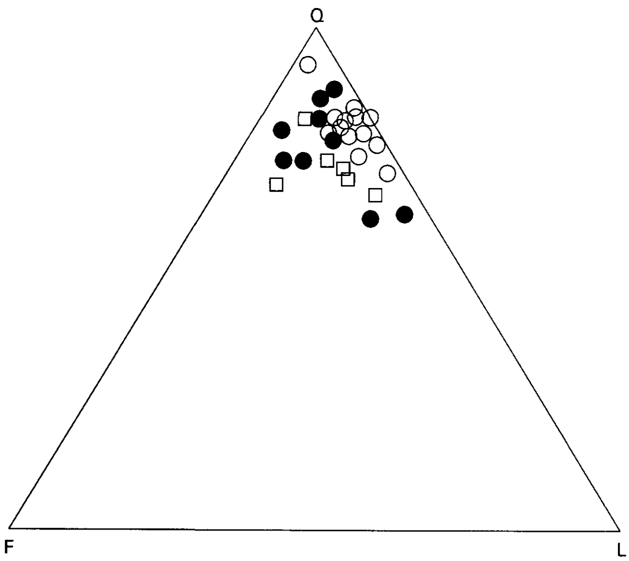

Figure 8. Ternary diagram showing the composition of sandstones from the Tongue River Member of the Fort Union Formation in the Powder River Basin. Areas: open circle indicates west-central areas; solid circle indicates Powder River valley of the northern areas; solid square indicates Tongue River valley of the northern areas. Q indicates quartz plus chert; F indicates feldspar plus granitic rock fragments; L indicates lithic fragments.

carbonate-enriched middle petrographic facies (upper part of Tongue River Member) described earlier, plot very near to the Q-L line on the ternary diagram (fig. 8). The remaining samples, from the Tongue River and Powder River valleys (areas 5 and 6), form a statistically distinct (chi-square, 0.05 level) dispersed group of sandstones. Although these samples contain carbonate grains, they are also markedly enriched in feldspar grains.

No difference can be detected using either figure 8 or chi-square tests between the modal mineralogy of sandstones of the Tongue River and Powder River valleys or between that of the TA Hills and Castle Rock areas. Data from these areas are therefore pooled into "northern areas" and "west-central areas," respectively, in much of the following discussion.

Textures

Mean grain size (table 6) is uniformly in the fine sand range (2–3 phi). Mean grain size for samples from the Tongue River and Powder River drainages (northern areas) is 2.45 phi (s=0.20 phi) and 2.32 phi (s=0.30 phi), respectively; whereas, that for samples from the TA Hills and Castle Rock areas (west-central areas) are 2.53 phi (s=0.6 phi) and 2.50 phi (s=0.26 phi).

Rounding of grains is markedly different in the west-central areas and the northern areas. Quartz grains from the northern areas are subangular (average rho=2.8 and 2.7 for the Tongue River and Powder River drainages, respectively, on Power's scale), whereas those from the west-central areas are more commonly subrounded (average rho=3.5 and 4.0 for the TA Hills and Castle Rock areas, respectively).

Mineralogy

General trends noted on the ternary diagram are shown in more detail in the plot of major mineral constituents (fig. 9). Sandstones from the Powder River and Tongue River drainages (samples 31–45) of the northern areas are considerably enriched in feldspar and moderately rich in mica booklets and rock fragments (other than chert and carbonate). On the other hand, sandstones from the TA Hills (samples 17–26) and Castle Rock (samples 14–16) of the west-central areas contain more carbonate rock fragments and quartz.

Quartz

The mean quartz content of carbonate-bearing facies of the west-central areas is 69.5 percent (s=8.8 percent); polycrystalline quartz accounts for 5.6 percent of this total (table 4). The quartz content in the northern areas is significantly less (t-test, 0.05 level), 59.7 percent (s=7.8 percent) of framework grains. Polycrystalline quartz, however, is distinctly more abundant (ANOVA-DMR, 0.05 level) in the northern areas, where it is 16.3 percent (s=8.6 percent) of the total quartz. The proportion of polycrystalline quartz within the northern areas decreases significantly eastward (ANOVA-DMR, 0.05 level) between the Tongue River (23.4 percent of quartz; s=9.1 percent) and the Powder River drainages (11.6 percent of total quartz; s=4.1 percent).

The lower total quartz content in the northern areas reflects the higher proportion of feldspar, mica, and micaceous rock fragments. The concurrent proportional increase in the percentage of polycrystalline quartz indicates that much of the detritus was derived from first-cycle erosion of nearby granitic or high-grade metamorphic terranes. The basinward decrease in polycrystalline quartz content (Powder River valley) suggests longer transport distances, consistent with reported eastward paleocurrent indicators.

Feldspar

Untwinned varieties of feldspar (generally orthoclase) make up 80 percent of the total feldspar. Grid-twinned (microcline; 8.5 percent) and albite-twinned (plagioclase; 11.6 percent) feldspar and perthite are less common (table 4). Feldspar grains in rocks of the Tongue River Member of the northern areas have been replaced by carbonate cement, as discussed earlier in the discussion of

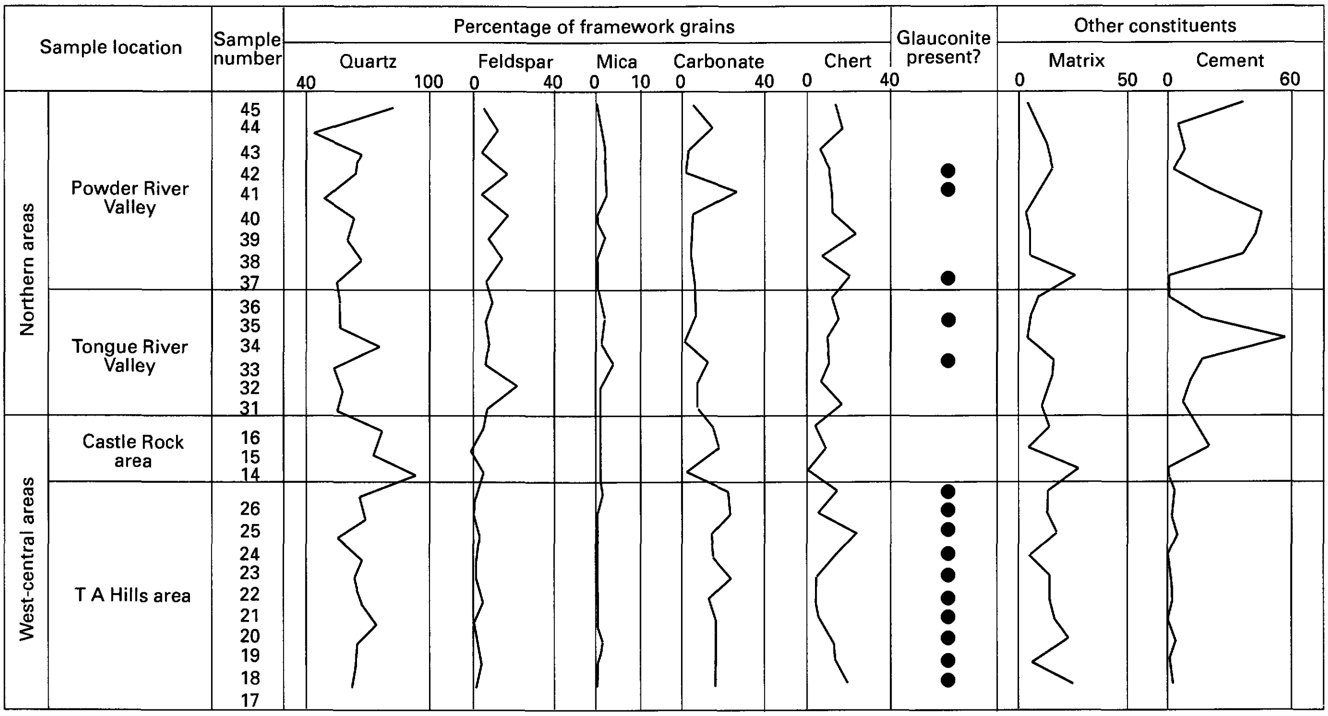

Figure 9. Point-count data for the Tongue River Member of the Fort Union Formation, Powder River Basin. Clastic grains are expressed as percentages of total framework grains; matrix and cement are represented as percentages of the total volume of the sample. The presence of glauconite (always less than 1 percent) is indicated. Point-count values are given in tables 2–6.

samples of the upper petrographic facies. Partly consumed grains are common, and some of the grains may be totally replaced. Therefore, the content of feldspar actually determined for the northern areas probably represents a minimum value.

Feldspar content increases markedly northward. Feldspar makes up about 2 percent of framework grains in sandstones of the west-central areas, detectably (t-test, 0.05 level) less than an average of 10.1 percent in the northern areas (an individual thin section contains as much as 21 percent). No basinward differences could be detected (t-test, 0.05 level) between the two areas of the northern areas.

Feldspar distribution in the upper sandstones of the Tongue River probably is closely related to rock types now exposed in the Bighorn Mountains. Granitic and high-grade metamorphic rocks crop out in the northern part of the uplift in Wyoming (fig. 3), whereas Paleozoic rocks cap the southern part. The TA Hills sample area is approximately east of the present-day surface contact of these two rock types. One fault block lying to the west of the Castle Rock sample area does expose Precambrian basement, but much of the movement along its underlying fault(s) postdates the early Tertiary.

Mica

Mica booklets are a minor component of Tongue River Member rocks. They make up less than 1 percent of the framework grains in the west-central areas and slightly more than 1 percent in the northern areas. The most common types of mica are muscovite, biotite, and chlorite. The small amounts of mica are compatible with the lack of major outcrops of schistose rocks in the northern Bighorn Mountains.

Cherty Fragments

No major variations in total chert content were noted between the sampled areas, although the amount of chert varies considerably from sample to sample (table 5). Mean content of cherty rock fragments is 10.1 percent (s=7.1 percent) in the west-central areas and 12.5 percent (s=4.7 percent) in the northern areas.

Carbonate Rock Fragments

Carbonate clasts are significantly (t-test, 0.05 level) less common (less than 7 percent) in the northern areas than in the west-central areas, perhaps in part because of dissolution of carbonate grains to form the carbonate cement common (fig. 9) in sandstones of the northern areas. In great part, however, the lesser amounts of carbonate grains probably reflect the smaller outcrop areas of carbonate rock types in the northern area of the uplift during uncovering of the Precambrian crystalline rocks. A more rapid rate of erosion in the northern Bighorn Mountains may also explain the presence of carbonate fragments stratigraphically lower in the north than along the west-central basin margin.

Other Rock Fragments

Rock fragments other than carbonate and chert are more abundant in the northern areas (more than 8 percent) than in the west-central areas (about 2 percent). These consist primarily of high-grade (schistose) and low-grade (phyllitic and slaty) metamorphic rock fragments and some shale fragments and a few granitic rock fragments. Similar to the variation in carbonate content, this difference in abundance probably mirrors the exposed rocks of the adjacent uplift.

Within the northern areas, rock fragment content detectably decreases eastward (t-test, 0.05 level) from the Tongue River valley (about 10 percent) to the Powder River valley (about 5 percent). Similar to the equivalent eastward decrease in polycrystalline quartz, this decrease may be caused by progressive destruction with increased transport distance (Davies and Ethridge, 1975).

Glauconite

Glauconite is present in trace amounts in all of the samples from the west-central areas but in only 6 of 15 samples from the northern areas. This difference can be explained by the proximity of the basin-margin sandstones to probable Mesozoic-age source rocks.

Discussion and Interpretation

Changes in sandstone mineralogy within the carbonate-bearing facies of the Tongue River Member of the west-central areas closely parallel differences in potential source rocks now exposed along the crest of the Bighorn Mountains. In the south, only the Bighorn Mountains Phanerozoic cover rocks were eroded and transported into the west-central areas. In the north, the greater amounts of feldspar, metamorphic rock fragments, and polycrystalline quartz suggest that detritus from exposed intrusive and high-grade metamorphic rocks was being deposited in the northern part of the basin.

Westward-flowing paleotransport for the Tongue River Member (for example, Ayers, 1986) is unlikely to have introduced basement-derived feldspathic detritus into the northern part of the basin because there are few outcrops of coarsely crystalline intrusive or metamorphic potential source rocks in the Black Hills. The reported generally northeastward paleotransport directions (Canavello, 1980; Lynn, 1980; Toth, 1982) for the interval are consistent with the easterly decline in mechanically less durable grain types such as metamorphic rock fragments and polycrystalline quartz. Similarly, the apparent paucity of sandstones as coarse as fine to medium grained east of Gillette can be explained by such a paleogeographic model.

SUMMARY AND CONCLUSIONS

Early Tertiary deposition within the Powder River Basin in Wyoming was strongly dependent upon an episode of tectonic uplift of the Bighorn Mountains that extended from at least middle Paleocene into Eocene time. Grain types derived from the erosion of this uplift indicate that the northerly change from exposed Paleozoic strata to Precambrian core along the present-day crest of the Bighorn Mountains developed during this early Tertiary tectonic episode.

Subsidence along the western margin of the basin was in progress by the middle Paleocene and led to the formation of the extensive Lebo lake. Mud-dominated sediments of the lake probably reflect early transfer of large volumes of uplifted Cretaceous shale from the mountains into the western flank of the basin. Pebbly sand channel fills in lacustrine mudstones of the Lebo Member along the western margin of the basin attest to substantial local relief associated with deeply entrenched drainage tributaries.

By late Paleocene time, the subsidence rate for the basin was more closely matched by the rate of detrital influx, and sandy fluvial systems of the Tongue River Member prograded eastward into the central part of the basin. Paleozoic marine sequences exposed in the southern mountains provided carbonate-rich sands to the fluvial systems of the upper part of the Tongue River along the west-central basin margin. Uplift and erosion probably was greater in the northern Bighorn Mountains. Stratigraphically equivalent channels in the adjacent northern basin area transported feldspar grains, coarse mica, metamorphic rock fragments, and complex quartz types in sands derived from the Precambrian core of the uplift.

Renewed uplift of the Bighorn Mountains during the Eocene (Grow and others, 1988) led to deposition of the conglomerates of the Kingsbury Conglomerate Member and Moncrief Member of the Wasatch Formation along the eastern flank of the mountains (Seeland, 1985). Feldspathic sandstones of the Wasatch Formation, deposited by a network of eastward-flowing fluvial systems, characterize Eocene rocks across most of the western half of the Powder River Basin.

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Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

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