

Quantitative Petrographic Analysis of
Mid-Cretaceous Sandstones,
Southwestern Montana

U.S. GEOLOGICAL SURVEY BULLETIN 1830



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By T.S. DYMAN, K.B. KRYSTINIK, and K.I. TAKAHASHI

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Abstract

The Albian Blackleaf Formation and the Cenomanian to Turonian lower part of the Frontier Formation in southwestern Montana lie within or east of the fold-and-thrust belt in the Cretaceous foreland basin. Petrographic data from these strata record complex sedimentation patterns that reflect an interaction between source-area tectonism, basin subsidence, and a cyclic sequence of transgressions and regressions. Framework-grain summaries for 99 thin sections were subjected to multivariate statistical analyses to establish regional compositional trends for provenance analysis and to determine the usefulness of quantitative methods in petrographic studies.

R-mode correspondence analysis was used to determine the importance (total variance) of key framework grains. Monocrystalline quartz, plagioclase, potassium feldspar, and sandstone, limestone, and volcanic lithic grains contribute most of the variation in the framework-grain population. Q-mode cluster and correspondence analyses were used to differentiate six petrofacies. Petrofacies I through III (lower part of the Blackleaf), which are distributed throughout the study area, contain monocrystalline quartz (55–90 percent) and sedimentary lithic grains (10–50 percent). Petrofacies I through III are differentiated by variable monocrystalline quartz and sedimentary lithic grain content. Petrofacies IV through VI (upper part of the Blackleaf and lower part of the Frontier) contain less monocrystalline quartz (20–50 percent), but more feldspar, and volcanic and sedimentary lithic grains.

Information derived from quantitative analyses combined with quartz-feldspar-lithic ternary data indicate that Blackleaf and lower Frontier detritus was derived from varying source areas through time. Lower Blackleaf detritus was derived from Precambrian through Mesozoic sedimentary and metasedimentary terranes to the west, north, and east; whereas upper Blackleaf and lower Frontier detritus was derived from Precambrian through Mesozoic sedimentary, metasedimentary, and volcanic terranes to the south and west.

INTRODUCTION

Purpose

A quantitative petrographic analysis of Blackleaf and Frontier Formation sandstone samples was conducted

in order to (1) establish petrofacies units and compare them to lithofacies units for regional correlation in the northern Rocky Mountain region; (2) describe vertical and lateral variations in provenance in order to add to the sedimentary-tectonic framework for the mid-Cretaceous in the region; and (3) determine the usefulness of multivariate statistical analyses in petrographic studies. The petrographic data set was large, and because visual variations in the sample population were difficult to establish, a multivariate statistical approach was undertaken to aid the framework study.

Stratigraphy and Sedimentology

The depositional history of the Cretaceous foreland basin in southwestern Montana is represented by a sequence of interbedded marine and nonmarine clastic and carbonate rocks that reflect both Sevier- and Laramide-style tectonism along the western margin of the Cretaceous seaway. The late Albian through Turonian sequence in the Lima Peaks region and in parts of the Tendoy Mountains and Gravelly and Snowcrest Ranges (Beaverhead and Madison Counties, Mont.) (fig. 1), lies within or near the easternmost frontal thrust sheets of the southwestern Montana fold-and-thrust belt and along the margins of Late Cretaceous Laramide uplifts (fig. 2).

This mid-Cretaceous sequence in Madison and Beaverhead Counties includes the late Albian Blackleaf Formation and the Cenomanian to Turonian lower part of the Frontier Formation (fig. 3) (Dyman and others, 1985). This sequence is underlain by clastic and carbonate rocks of the Aptian to Albian(?) Kootenai Formation and the Jurassic Morrison Formation. The sequence is overlain by synorogenic conglomerate, limestone, and sandstone of the Upper Cretaceous Beaverhead Group (Nichols and others, 1985).

Cretaceous rocks in the study area are very similar to those observed at Blackleaf Creek (Cobban and others, 1976) and at the Frontier (Cobban and Reeside, 1952) type section. The Blackleaf and the lower part of the Frontier

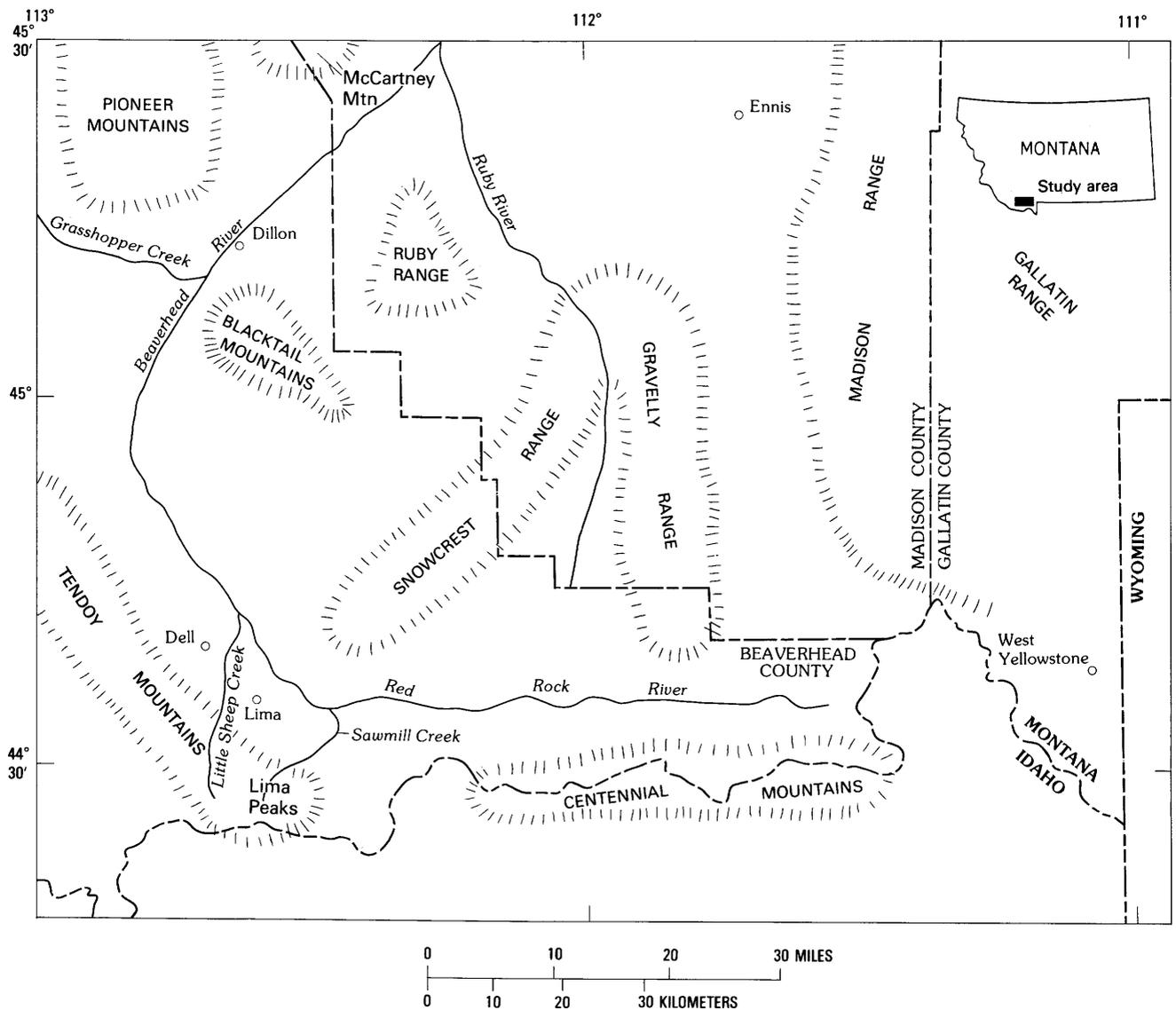


Figure 1. Index map of study area in parts of Beaverhead, Madison, and Gallatin Counties, Montana.

Formations are composed of a predominantly clastic sequence of sandstone, siltstone, mudstone, and shale with much lateral and vertical variation (fig. 4). The Blackleaf Formation varies from 425 to 600 m in thickness and is subdivided into four mappable lithofacies units, the lower three of which are equivalent to formations mapped east of the report area: lower clastic lithofacies (unit 1), lower mudstone-shale lithofacies (unit 2), upper clastic lithofacies (unit 3), and volcanoclastic lithofacies (unit 4). Formal member names are not used with the Blackleaf Formation in this report because additional work remains to be completed before lithofacies relationships with rocks beyond the report area can be fully worked out (Dyman and Nichols, in press). Formal member names that are used with the Blackleaf Formation in northwestern Montana cannot be fully mapped in Madison and Beaverhead Counties and are not used in this report (fig. 3).

Lithofacies units will be referred to by number in this report (for example, unit 1 for lower clastic lithofacies).

Unit 1 conformably overlies the upper carbonate member (gastropod limestone) of the Kootenai Formation. This basal Blackleaf unit varies from 13 m in thickness in the Gravelly Range to 87 m in thickness in the McCartney Mountain area and consists of mudstone, quartz- and chert-rich sandstone, and limestone deposited in fluvial, lacustrine, and shallow marine depositional environments. Lithofacies unit 1 is lithostratigraphically correlative with the Fall River Sandstone of south-central Montana (Rice, 1976). Unit 2 varies from 17 m in thickness in the Lima Peaks area to 70 m in thickness in the McCartney Mountain area and consists predominantly of mudstone, shale, and siltstone deposited in lagoonal to near-shore marine depositional environments. Lithofacies unit 2 is lithostratigraphically correlative with the Skull

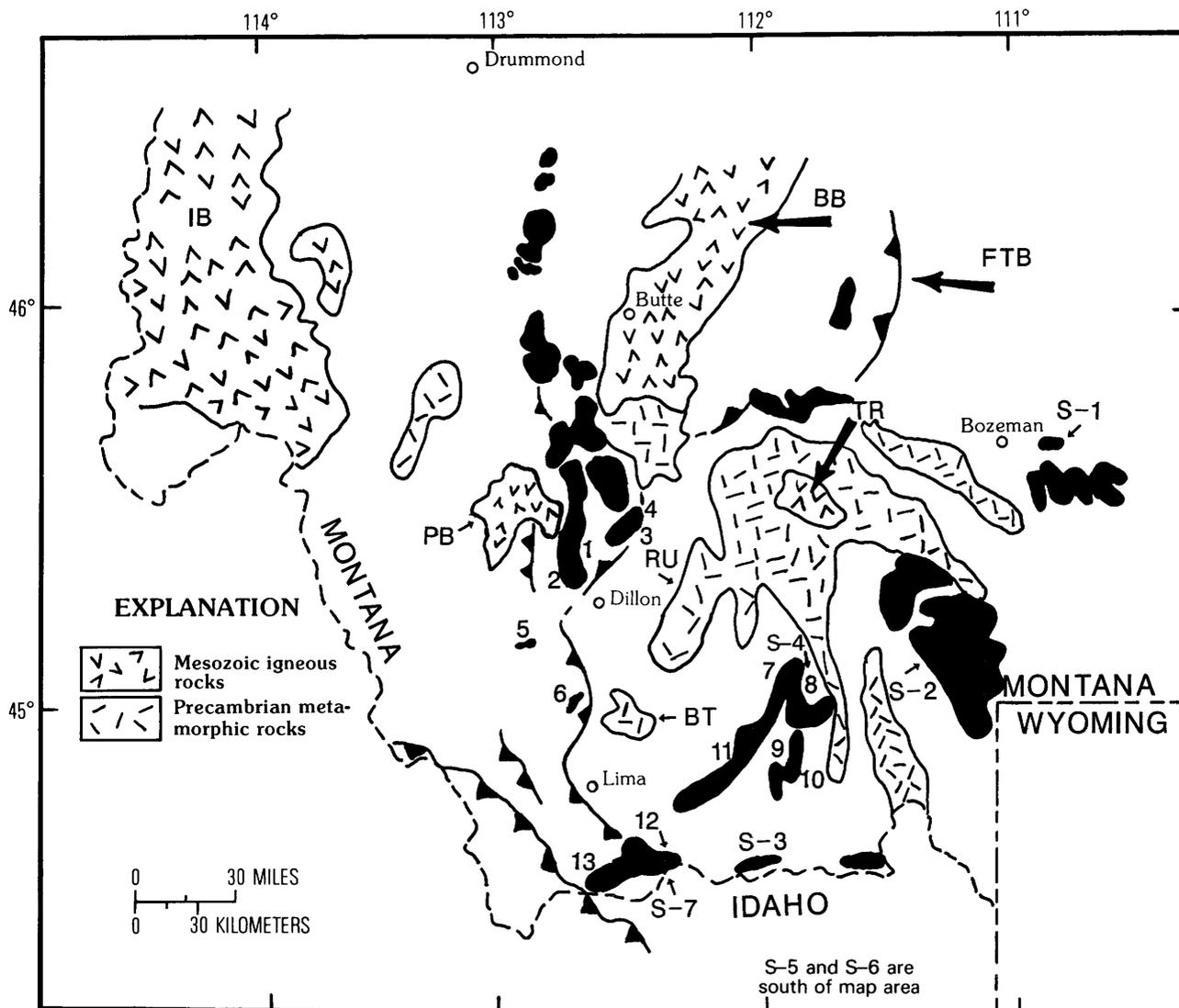


Figure 2. Generalized geologic map, southwestern Montana. BB = Boulder batholith; BT = Blacktail Range; FTB = leading edge, fold-and-thrust belt; IB = Idaho batholith; PB = Pioneer batholith; RU = Ruby Range; TR = Tobacco Root batholith; unpatterned area represents Paleozoic, Cenozoic,

non-Cretaceous Mesozoic, or upper Precambrian sedimentary rocks. Numbers represent measured section locations (Appendix). Numbers preceded by letter S represent additional sample locations. Shaded areas represent Blackleaf-Frontier outcrop distribution. Modified from Schwartz (1972).

Creek Shale of south-central Montana. Unit 3 varies from 4 m in thickness in the northern Snowcrest Range to 76 m in thickness in the Pioneer Mountains and consists of quartz-rich sandstone bodies and interbedded mudstone deposited in fluvial, deltaic, and shallow marine depositional environments. Lithofacies unit 3 is lithostratigraphically correlative with the Muddy Sandstone of south-central Montana (Rice, 1976). Unit 4 varies from 270 m in thickness in the Lima Peaks area to 360 m in thickness in the central Snowcrest Range and consists of porcellanitic mudstone, shale, and subordinate lithic sandstone deposited in fluvial, lacustrine, and shallow marine depositional environments. Lithofacies unit 4 is lithostratigraphically correlative with the Mowry Shale of south-

central Montana. The overlying lower part of the Frontier Formation (lower clastic lithofacies, unit 5) reaches a maximum thickness of at least 420 m in the Pioneer Mountains and is composed of lithic sandstone, conglomerate, and subordinate mudstone and shale deposited in fluvial to shallow marine depositional environments. An upper Frontier contact could not be established because of poor exposures and structural complications.

Study Area

The study area (fig. 2) includes (1) sections in the Pioneer Mountains, northern Snowcrest Range, and McCartney Mountain area originally measured by

		NORTHWESTERN MONTANA (GREAT FALLS)	SOUTHWESTERN MONTANA (THIS STUDY)	EASTERN IDAHO	SOUTHWESTERN MONTANA (BOZEMAN)	CENTRAL WYOMING					
UPPER CRETACEOUS	CENOMANIAN TO TURONIAN	Marias River Shale	Frontier Formation (part, unit 5)	Frontier Formation (part)	Frontier Formation (part)	Frontier Formation (part)					
LOWER CRETACEOUS	ALBIAN	Blackleaf Formation	Blackleaf Formation	Aspen Formation	Mowry Shale	Mowry Shale					
		Bootlegger Member Vaughn Member					Volcaniclastic lithofacies (unit 4)	Bear River Formation	Thermopolis Shale	Upper sandstone Middle shale Lower sandstone	Muddy Sandstone Thermopolis Shale Fall River Sandstone
		Taft Hill Member					Upper clastic lithofacies (unit 3)				
		Flood Member					Lower mudstone-shale lithofacies (unit 2)				
		Lower clastic lithofacies (unit 1)									
	APTIAN		Kootenai Formation	Kootenai Formation	Gannett Group	Kootenai Formation	Cloverly Formation				
Gastropod limestone								Smoot Shale	Draney Limestone Bechler Conglomerate Peterson Limestone Ephraim Conglomerate		

Figure 3. Stratigraphic nomenclature chart for strata of mid-Cretaceous age in western Montana, northeastern Idaho, and central Wyoming. Data from Gwinn (1960), Roberts (1972), McGookey and others (1972), Schwartz (1972), Vuke (1982), and Cobban and others (1976).

Schwartz (1972) (sections 1, 2, 3, 4, and 5); (2) sections in the central and northern Snowcrest and Gravelly Ranges (sections 7, 8, 9, and 10); and (3) sections near Lima and in the central Snowcrest and Blacktail Ranges (sections 6, 11, 12, and 13). The following additional reference sections were described and sampled in areas surrounding the study area: (1) Lincoln Mountain section, Madison Range (sample S-2; Vuke, 1982); (2) Rocky Creek section near Bozeman (sample S-1; Roberts, 1972); and (3) along the Snake River and near Alpine, in Teton County, Wyo. (samples S-5 and S-6; La Rocque and Edwards, 1954; Wanless and others, 1955; Durkee, 1980; Wallem and others, 1981). Two samples (samples S-3 and S-4) were collected in the Centennial Mountains and the northern Gravelly Range, respectively. The Appendix ("Code, lithofacies, location, and source for sections and sample localities") contains detailed locations for outcrop sections and sample localities.

The best exposed sections are those located in the Pioneer Mountains and McCartney Mountain area. Composite sections were measured where rocks are poorly exposed south of Lima and in the Snowcrest Range (Antone Peak section; Appendix).

Lithofacies descriptions, thickness variations, contacts, and sedimentology and depositional environments for all measured sections are presented separately by lithofacies unit in Dyman (1985a, b), Dyman and others (1984), and Dyman and Nichols (in press).

Data

Ninety-nine sandstone samples were cut, thin sectioned, stained for potassium feldspar, and point counted using more than 300 point counts per slide. The table of framework-grain percents and a numbered key to framework grains counted are presented in Dyman (1985c). Data were aggregated according to Dickinson and Suczek (1979).

STATISTICAL ANALYSIS OF FRAMEWORK DATA

The following statistical procedure was used in this study:

- (1) R-mode correspondence analysis was used to determine the contributing effect (percentage

of total variance) of each framework-grain variable. Based on their contributing effect, variables were either discarded from further analysis or aggregated into groups.

- (2) Q-mode cluster and correspondence analyses were used to determine sample relationships. Samples were then aggregated into groups to study stratigraphic and geographic variation.

Correspondence analysis is a form of factor analysis that combines the results of both R- and Q-mode studies and reduces variable scaling problems. Correspondence analysis reduces the problem of N-dimensional space (many variables) by projecting combinations of original variables on a new set of axes (eigenvectors) defining new hypothetical variables called factors (David and others, 1977). Variable contribution on the new axes is based on variance. Output from correspondence analysis includes (1) relative and absolute factor-variable contribution matrices that define the relative or absolute contribution of each original variable (as a percent) to each new factor (which variables are important in distinguishing all samples together); (2) a factor-score data matrix that contains factor-score loadings (which variables are important in distinguishing each sample from other samples); and (3) factor-score maps (plots) created from the factor-score matrix that graphically display sample similarity in factor space. Lines are drawn on each map to illustrate how each numbered variable contributes to differences among samples. The lines pass through a portion of factor space defined by their R-mode loadings (table 1). The lines represent the magnitude and direction to which the variables affect the sample population (David and others, 1977). The proximity of a group of sample points and variable points establishes the similarity of samples and the variable or variables that are responsible for the similarity.

Cluster analysis is a multivariate classification method by which relatively homogeneous groups are defined (Davis, 1973). In hierarchical clustering, the most similar samples are first joined and then connected to the next most similar samples until all samples are connected together in a dendrogram. Raw-data framework-grain percents for both formations were first standardized using mean deviation (Davis, 1986, p. 30) to insure that each variable was weighted equally.

The weighted pair-group Q-mode program of Davis (1973) was used in this study (Petroleum Information Corporation, 1984) with the r-correlation similarity coefficient. In the weighted pair-group cluster method, correlation matrices of samples are calculated and samples with high correlations are grouped. In subsequent steps, similarity matrices are recomputed treating clustered elements as a single element. Each new cluster member is given equal weight with the existing cluster. Thus, late

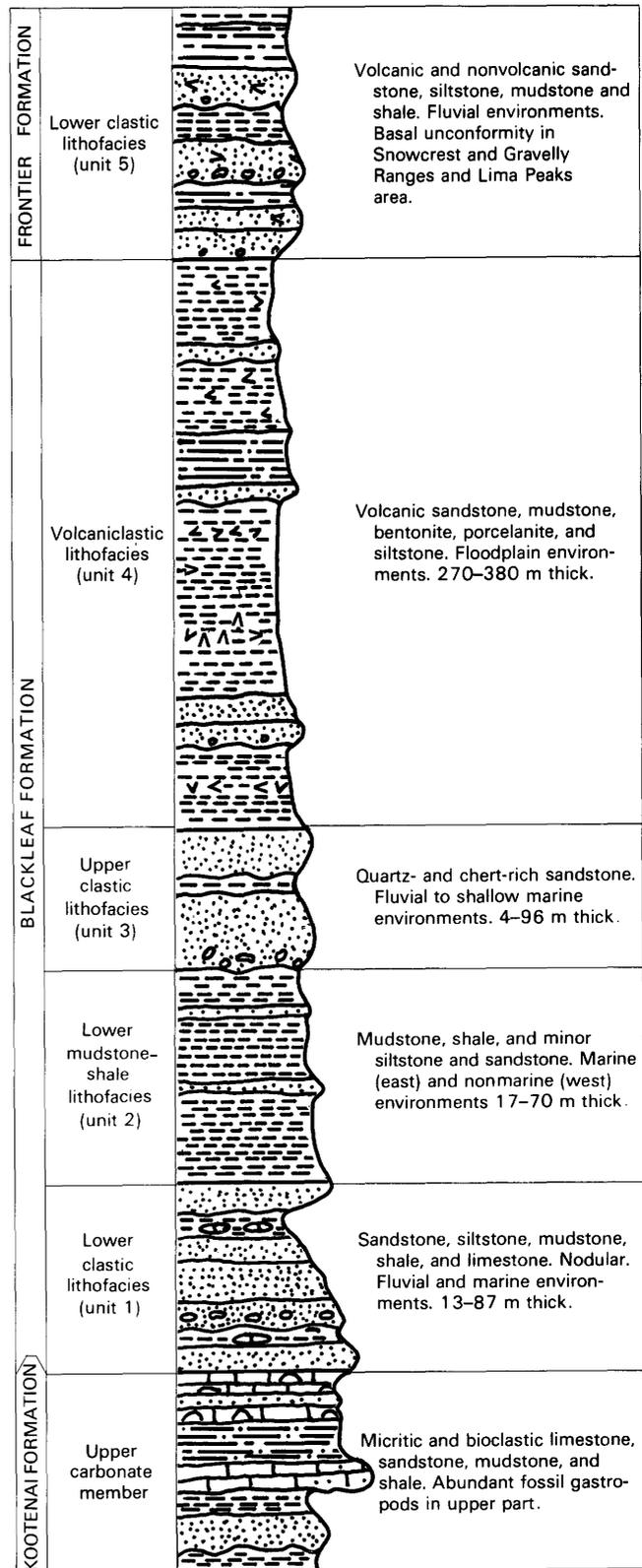


Figure 4. Composite stratigraphic description of the upper part of the Kootenai Formation, the Blackleaf Formation, and the lower part of the Frontier Formation, Beaverhead and Madison Counties, Montana. Maximum and minimum lithofacies thickness values in parentheses.

Table 1. Absolute variable-factor contribution matrix (first 4 factors) and cumulative percent contribution for 13 original framework-grain variables
[Data in percent. See Dyman (1985c) for detailed variable description]

VARIABLE	FACTOR			
	1	2	3	4
1. Monocrystalline quartz.....	13.2	16.9	9.0	3.0
2. Polycrystalline quartz.....	0.4	1.0	1.5	0.1
3. Foliated polycrystalline quartz..	0.1	0.4	0.0	0.5
4. Chert.....	1.0	11.5	6.2	0.7
5. Plagioclase.....	54.9	0.5	3.1	5.3
6. Potassium feldspar.....	6.7	1.1	14.2	60.1
7. Limestone.....	2.0	1.6	62.5	16.7
8. Mudstone.....	0.1	0.2	1.9	4.8
9. Sandstone.....	0.4	55.4	0.1	3.9
10. Volcanics.....	18.5	1.1	0.1	2.2
11. Plutonics.....	0.1	0.0	0.2	0.3
12. Metamorphics.....	0.1	0.1	0.9	0.6
13. Mica.....	2.5	0.1	0.1	0.7
Cumulative percent contribution..	28	47	58	64

cluster arrivals carry more weight than do earlier arrivals. Other clustering procedures and similarity coefficients yielded similar groupings.

R-Mode Analysis

Table 1 represents the absolute factor-variable contribution matrix for the 13 framework-grain types. Together, the first four factors contribute 64 percent to the variation in the total sample of framework grains. The most important variables and the percentage of variability that they contribute are (1) for factor 1, plagioclase (55 percent) and volcanic fragments (19 percent); (2) for factor 2, monocrystalline quartz (19 percent) and sandstone fragments (55 percent); (3) for factor 3, limestone fragments (63 percent); and (4) for factor 4, potassium feldspar (60 percent). Polycrystalline quartz (foliated and nonfoliated), mudstone grains, mica, metamorphic and plutonic grains contribute less to the total variation in the sample. Chert exhibits intermediate discriminating ability.

Q-Mode Analysis

Six well-defined petrofacies (with three additional subfacies) were identified using Q-mode cluster analysis. Petrofacies are here defined from petrographic data, whereas the Blackleaf-Frontier lithofacies are defined solely from outcrop studies. Figure 5 illustrates the weighted pair-group dendrogram and the identified petrofacies for 99 Blackleaf-Frontier sandstone samples using all 13 original variables. Table 2 summarizes the characteristics of each petrofacies.

Petrofacies I

Petrofacies I is divided into two petrofacies subgroups. Petrofacies I-A is rich in quartz with abundant quartz overgrowths. Calcite cement and mudstone and chert grains are rare (fig. 6). Petrofacies I-A is found predominantly in lithofacies unit 1 in the Gravelly and Snowcrest Ranges, in the Lima Peaks area, and at the Rocky Creek section near Bozeman. Petrofacies I-B contains less quartz but more chert and mudstone grains

Table 2. Petrofacies summary, Blackleaf and lower part of Frontier Formations, Beaverhead and Madison Counties, Montana [Refer to Dyman (1985c) for locality identification]

Petrofacies/ rock name	Mineralogy/cements/ comments	Lithofacies unit distribution	Aerial distribution/ measured sections
I-A Quartz- arenite.	Quartz: \bar{x} =90%; quartz over- growths abundant; lithic grains rare, but chert and mudstone grains most abundant.	All from unit 1, except one unit 3 sample.	Monument Hill, Warm Springs Creek, Rocky Creek, Cottonwood Iron Creek, Little Sheep Creek, Frying Pan Gulch (unit 3 sample), Antone Peak.
I-B Sedlith- arenite.	Quartz: \bar{x} =63%; chert: \bar{x} =10%; mostly mudstone lithic grains (\bar{x} =12%), and rare sandstone, limestone, and volcanic grains; cement rare to abundant.	Units 1, 2, and 3 present; two unit 4 samples (LP-56 and MH-2). Unit 4 samples from nonvolcanic lower part.	Equally represented throughout study area.
II-A Sedlith- arenite.	Quartz: \bar{x} =55%; chert: \bar{x} =16%; mostly mudstone lithic grains (\bar{x} =24%); volcanic grains rare or absent.	Predominantly from units 1 and 3; Two unit 5 samples (AP-184 and RR-63) are more than 50 m above base of Frontier Formation.	Snake River, Warm Springs Creek, Cottonwood Iron Creek, Lima Peaks, Antone Peak, Apex, Monument Hill.
II-B Sedlith- arenite.	Quartz: \bar{x} =43%; chert: \bar{x} =25%; mostly mudstone lithic grains (\bar{x} =13%); limestone grains rare (\bar{x} =5%); volcanic and sandstone grains less than 5%; calcite cement varies from 9 to 45%; samples RR-38 and LM-5 (on edge of cluster) have no calcite.	Predominantly from units 1 and 3 but some unit 4 and 5 samples present.	Equally represented throughout study area.
III Sedlith- arenite.	Quartz: \bar{x} =47%; chert; \bar{x} =17%; predominantly limestone lithic grains (\bar{x} =19%); mudstone grains subordinate; volcanic grains rare; calcite cement.	Units 1 and 3	Equally represented throughout study area.
IV Sedlith- arenite.	Quartz: \bar{x} =38% (much variation); chert: less than 17%; sedimentary grains variable (less than 20%); volcanic grains subordinate; variable cement.	All lithofacies units represented.	Predominantly in western part of study area.
V-A Sedlith- arenite.	Quartz: \bar{x} =45%; abundant volcanic and sedimentary grains; plagioclase and potassium feldspar abundant; difficult to differentiate from petrofacies VI; variable cement.	Units 4 and 5	Western part of study area.
V-B Sedlith- arenite.	Quartz: \bar{x} =50%; as much as 50% sandstone and siltstone lithic grains; volcanic lithic grains rare; arbitrarily placed with petrofacies V-A (only 3 samples); variable cement.	Units 4 and 5	Western part of study area.
VI Litharenite	Quartz: \bar{x} =20%; abundant volcanic and sedimentary grains; abundant plagioclase and potassium feldspar; mica rare to abundant; variable cement.	Units 4 and 5	Represented throughout study area, but most abundant in western part.



Figure 5. Weighted pair-group average Q-mode dendrogram of framework-grain constituents for Blackleaf Formation and lower part of the Frontier Formation samples. See table 2 for petrofacies description.

and calcite cement than petrofacies I-A (fig. 6). Petrofacies I-B is found predominantly in lithofacies units

1 and 3 throughout the study area. The increase in calcite cement may be in part due to alteration of limestone grains. Two lithofacies unit 4 samples present within petrofacies I were collected from the nonvolcanic lower part of lithofacies unit 4 in the Gravelly Range and Lima Peaks area.

Quartz in petrofacies I has straight to undulose extinction and straight to slightly curved grain contacts, and locally contains abundant dust vacuoles and overgrowths. Quartz may contain abundant rutile and zircon inclusions and may be stress fractured. Feldspar and volcanic grains are rare or absent in petrofacies I. Grains in petrofacies I are rounded to subangular and well sorted.

Petrofacies II

Petrofacies II is divided into two petrofacies subgroups. Petrofacies II-A contains abundant quartz with subordinate mudstone and chert grains. Other lithologic components and calcite cement are rare or absent. Re-worked quartz overgrowths are present in some samples. Polycrystalline quartz (foliated and nonfoliated) is locally abundant (fig. 7). Petrofacies II-B contains less quartz and more chert and calcite cement than petrofacies II-A. The relationship between petrofacies II-A and II-B is transitional, and many intermediate forms exist. A few lower Frontier sandstone samples (for example, sample RR-38, Ruby River section) are similar to petrofacies III samples and contain as much as 10 percent volcanic grains. Petrofacies II sandstone is found in all lithofacies units (table 2), but is most abundant in units 1 and 2. Petrofacies II-A however contains only sandstone from lithofacies units 1 and 3. Some nonvolcanic sandstone incorporated in lithofacies units 4 and 5 commonly occurs in petrofacies II, but there appears to be no geographic control over petrofacies II distribution.

Petrofacies II quartz has straight to slightly undulose extinction and as much as 20 percent strongly undulose extinction in some samples. Contacts between quartz grains are straight to slightly curved. Dust vacuoles, rutile, vermicular chlorite(?), zircon, and pyrite inclusions are common. Rare volcanic grains contain lathlike plagioclase or are microcrystalline and contain potassium feldspar. Mudstone grains are brown to black; they may be variably calcareous and grade compositionally into micritic limestone and chert. Chert grains locally contain inclusions. Some petrofacies II samples contain variably rounded grains and are poorly sorted, which suggests a mixed source.

Petrofacies III

Petrofacies III is characterized by abundant quartz and micritic limestone grains and subordinate sandstone and mudstone grains (table 2, fig. 8). Igneous and metamorphic grains are rare or absent. Only one sample

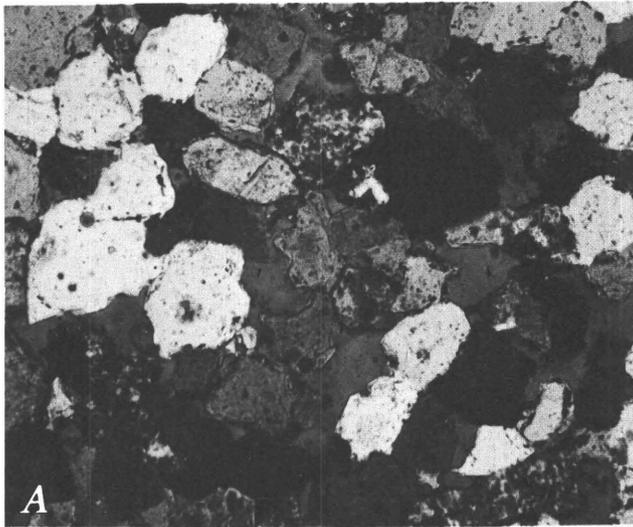


Figure 6. Petrofacies I sandstone. *A*, Lithofacies unit 1 (sample MH-13), Monument Hill section, Gravelly Range. Quartz-arenite. (3 mm across.) *B*, Lithofacies unit 1 (sample WS-7), Warm Springs Creek section, Gravelly Range. G = glauconite grain, M = metamorphic grain. (1.5 mm across.)

(sample MM2-3) from the McCartney Mountain II section contains more mudstone than limestone grains (Dyman, 1985c). The presence of this sample in petrofacies III may be a result of the clustering procedure. Micritic limestone transitionally grades into sparry calcite cement but, in all cases, it is more abundant than the cement. Petrofacies III is found throughout the study area but is only present in lithofacies units 1 and 3. This petrofacies is especially abundant at the Apex section in the Pioneer Mountains, where limestone is also abundant in the upper part of the Kootenai and lower part of the Blackleaf Formations.

Mudstone grains are red brown to black and are variably calcareous. Sandstone grains are rounded to

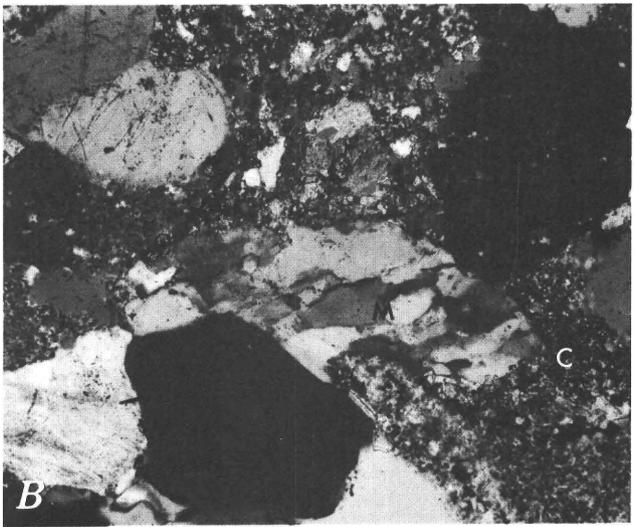
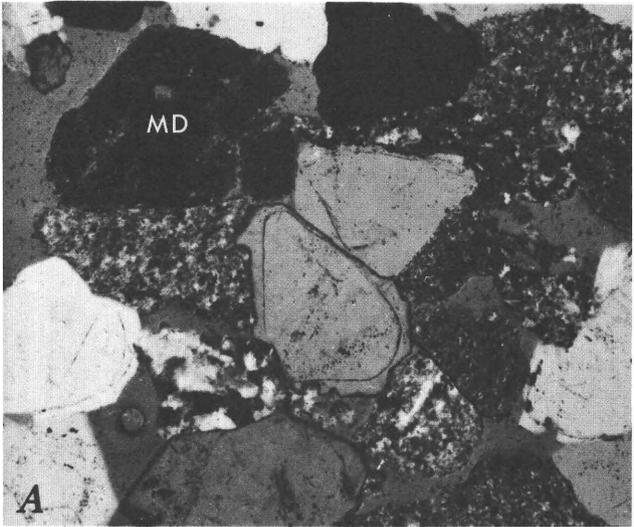


Figure 7. Petrofacies II sandstone, lithofacies unit 3. *A*, Warm Springs Creek section (sample WS-109), Gravelly Range. MD = mudstone. *B*, McCartney Mountain I section (sample MM-36). C = limestone grain altering to calcite, M = metamorphic quartz grain. (Both 3.0 mm across.)

subrounded and are commonly cemented with chert. Petrofacies III quartz grains are similar to those of petrofacies I and II, but more subangular grains are present. Hornblende and zircon are present in minor amounts in most petrofacies III samples.

Petrofacies IV

Petrofacies IV through VI are poorly defined and more heterogeneous than petrofacies I through III. Again, the presence of some samples in certain cluster groups may be due to the particular clustering method used (fig. 9). Petrofacies IV contains (1) variable quartz, chert, and sedimentary grains and (2) more mica and

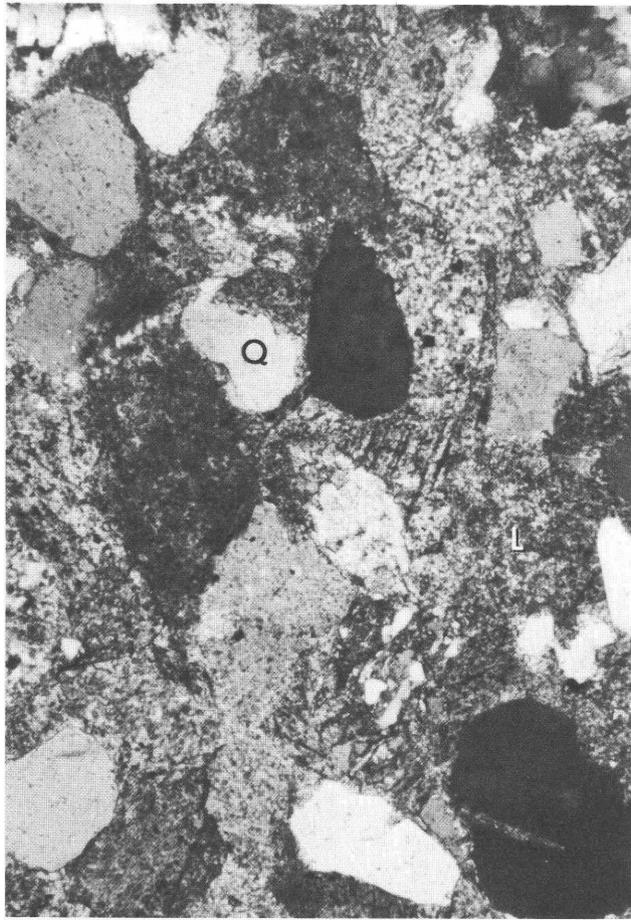


Figure 8. Petrofacies III sandstone, lithofacies unit 1. Apex section (sample AP-60), Pioneer Mountains. Quartz (Q) and limestone (L) rich. (2.0 mm across.)



Figure 9. Petrofacies IV sandstone. Frontier Formation, conglomerate (sample SH-1) from Shine Hill, approximately 1 km south of Lima Peaks section, south of Sawmill Creek. (4.0 mm across.)

volcanic grains than petrofacies I through III. Petrofacies IV is distributed throughout all five lithofacies units, predominantly in the western part of the study area (table 2). The sediments were probably derived from a heterogeneous source. Quartz occurs as rounded to subangular grains with straight or undulose extinction, or as foliated metamorphic(?), bipyramidal volcanic, and sedimentary quartz grains with abundant overgrowths. Petrofacies IV quartz grains may contain abundant dust vacuoles and a variety of inclusions including zircon, hornblende, rutile, and mica(?). Micritic limestone and sandstone grains and chert are typically more abundant than mudstone grains (fig. 9), but mudstone grains are locally abundant and include (1) dark-brown silty siliceous, (2) gray calcareous, and (3) red-brown opaque forms.

Petrofacies V

Petrofacies V is also heterogeneous but contains more volcanic, feldspar, and quartz grains (mean = 50

percent quartz) than petrofacies IV (table 2). Petrofacies V-A contains either (1) an anomalously high sandstone-mudstone grain content (sample FP-19, Frying Pan Gulch section, fig. 10); or (2) high sandstone, mudstone, and feldspar grain content (sample LP-79, Lima Peaks section). More than 90 percent of petrofacies V samples are found in lithofacies units 4 and 5. Seventy-five percent of these samples are from the western side of the study area, but this may be in part due to sampling bias. Petrofacies V-B commonly contains abundant plagioclase or potassium feldspar.

Petrofacies VI

Petrofacies VI is the most heterogeneous group and occurs exclusively in lithofacies units 4 and 5, predominantly in the Lima Peaks area, and in the Snowcrest and Gravelly Ranges (table 2). Petrofacies VI sandstone contains abundant plagioclase and potassium feldspar and volcanic grains, and this sandstone is variably micaceous

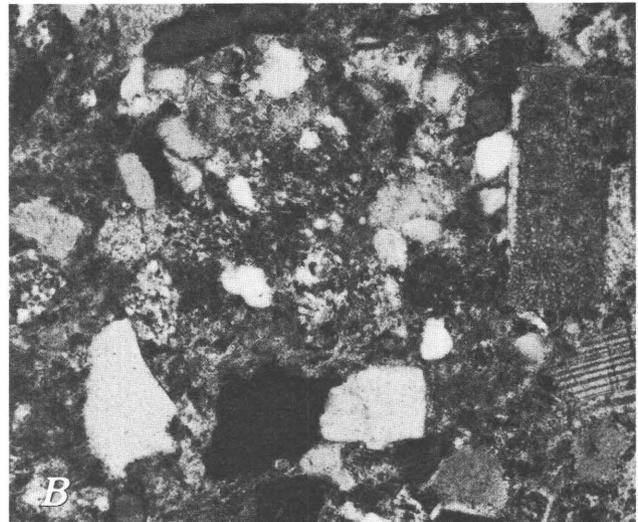
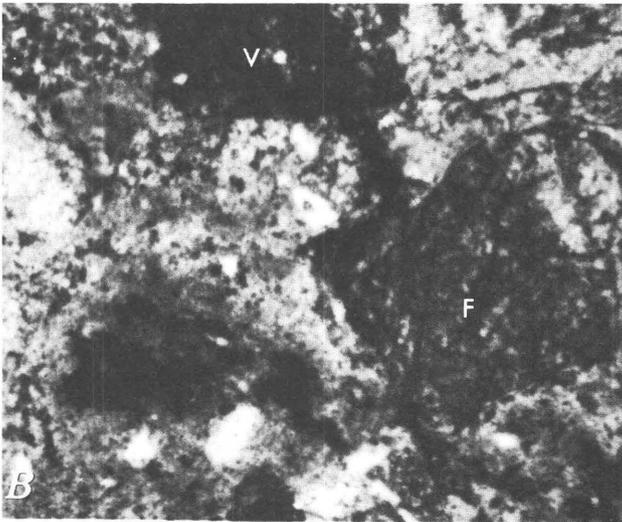
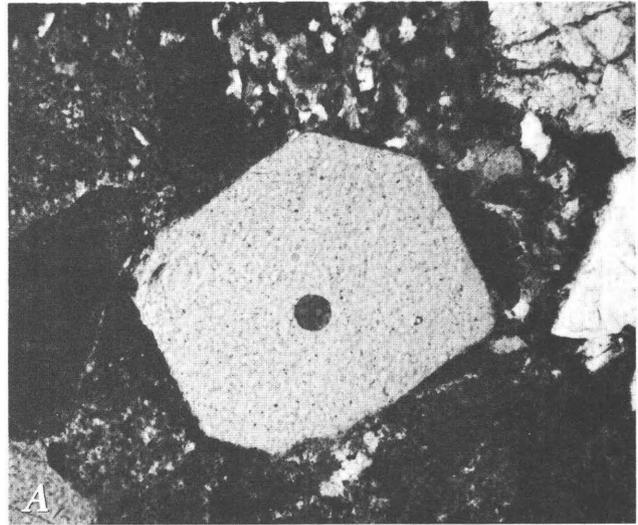
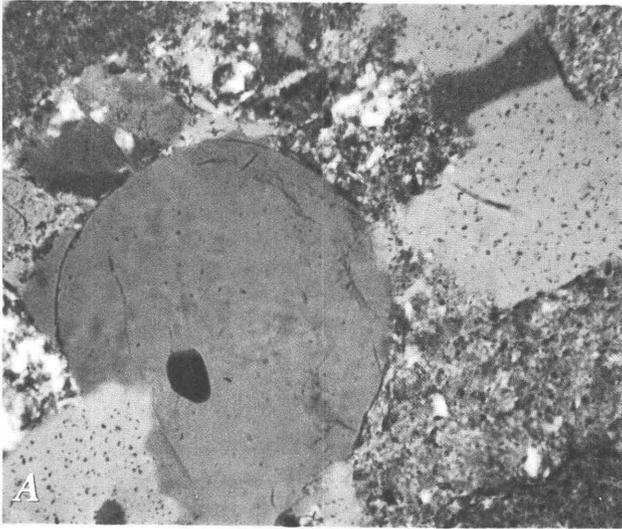


Figure 10. Petrofacies V sandstone. *A*, Lithofacies unit 5 (sample FP-19), Frying Pan Gulch section, Pioneer Mountains. (3.0 mm across.) *B*, Lithofacies unit 4 (sample LP-79), Lima Peaks section. F = potassium feldspar grain, V = volcanic grain. (6.0 mm across.)

Figure 11. Petrofacies VI sandstone, Lima Peaks section. *A*, Lithofacies unit 5 (sample LP-133). *B*, Lithofacies unit 4 (sample LP-92), plagioclase and matrix rich. (Both 6.0 mm across.)

(fig. 11). Quartz and sedimentary grains are subordinate. Many petrofacies V and VI samples are difficult or impossible to differentiate visually.

Factor-Score Maps and Petrofacies Analysis

The relative importance of each grain type in differentiating between sandstone samples cannot be graphically presented using cluster dendrograms. Correspondence-analysis factor-score maps were therefore generated in order to (1) corroborate the petrofacies division identified by cluster analysis (can the 6 petrofacies defined using cluster analysis be recognized?), (2) observe sample distribution in factor space (how are the samples

compositionally related and what can be said about provenance?), and (3) identify variable influence for factor-score groupings (how does each variable affect each sample?). Figures 12–14 represent factor-score maps for the first four factors using only the six most important variables: monocrystalline quartz, plagioclase, potassium feldspar, and limestone, sandstone, and volcanic grains. Factor-score maps that included unimportant variables (polycrystalline quartz, mudstone, mica, and metamorphic and plutonic grains) provided similar results.

Figure 12 is the factor-score map for factors 1 and 2. Forty-seven percent of the sample population variance is represented by the first two factors (table 1). The cluster of points in the lower left represents petrofacies I through III, which are found predominantly in lithofacies units 1

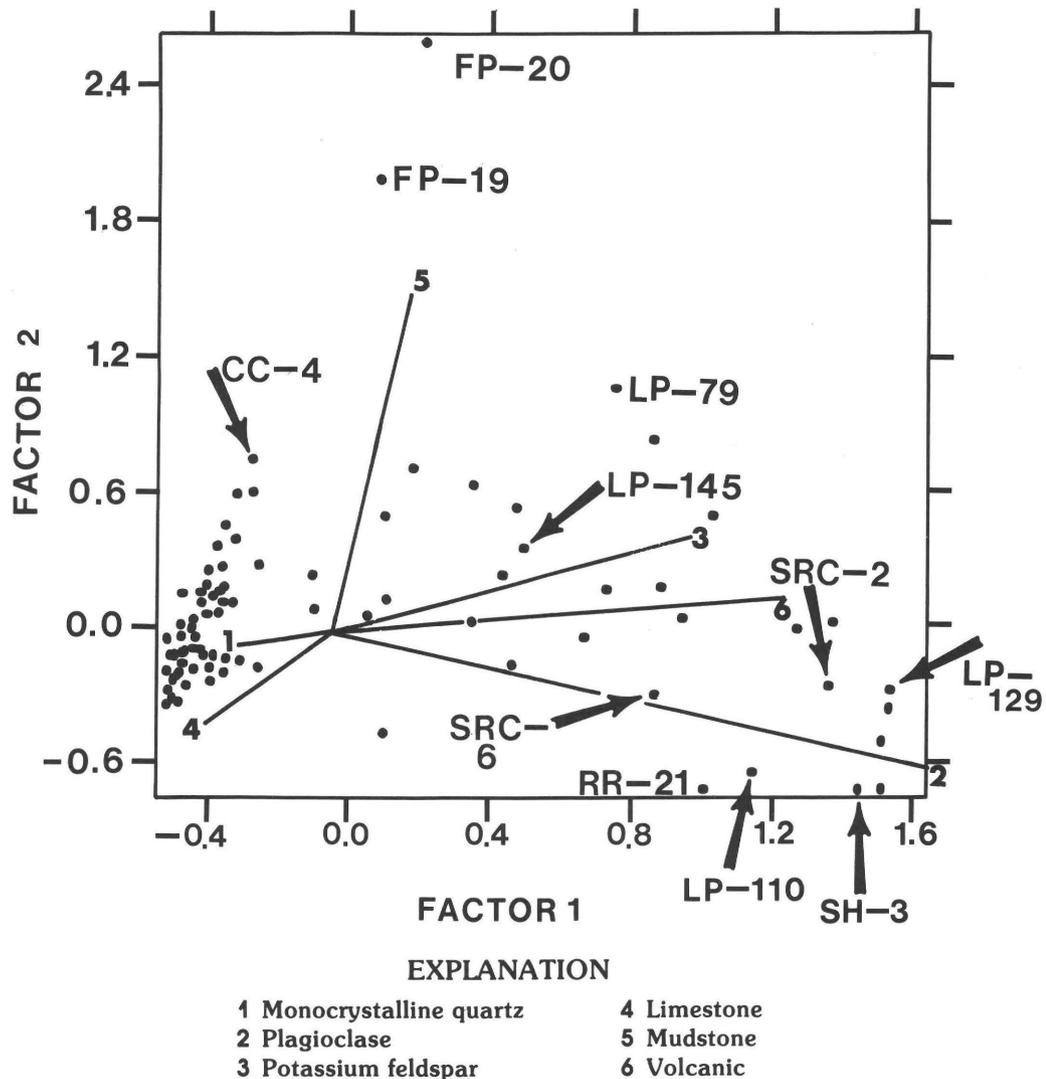


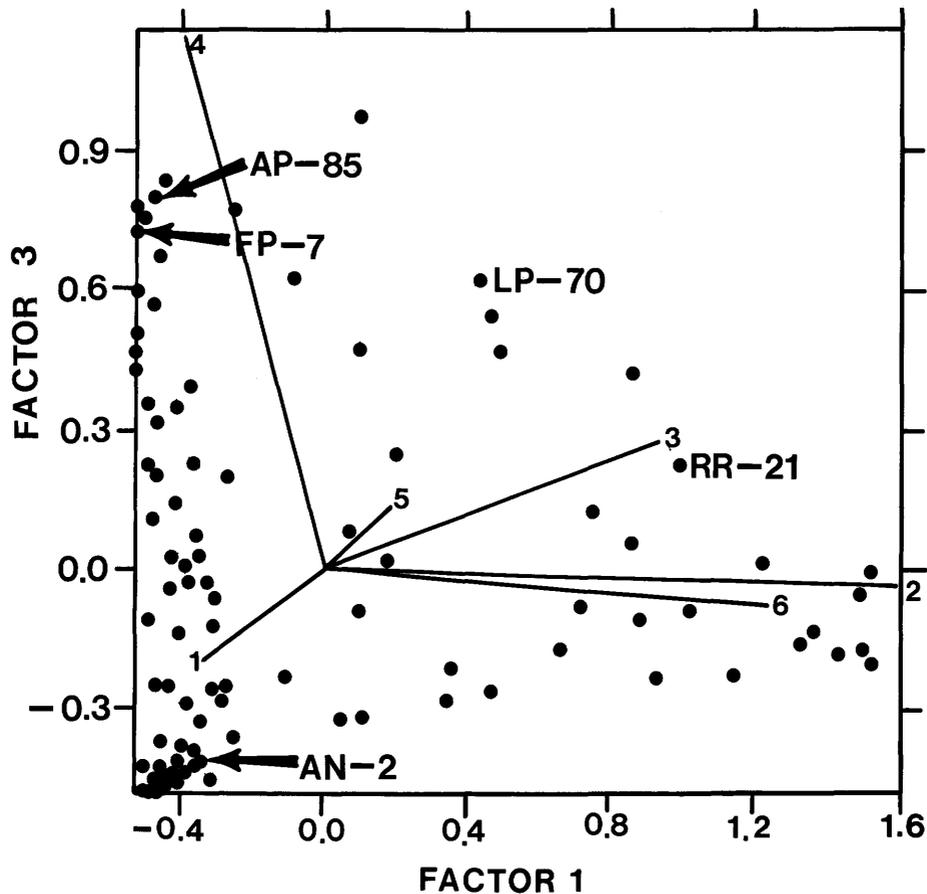
Figure 12. Correspondence-analysis factor-score map for factors 1 and 2 (framework data). This map excludes redundant variables as determined from R-mode analysis. Refer to Dyman (1985c) and Appendix for sample identification and location data. Variable numbers represent variable contribution in factor space (lines on map). See also table 2.

through 3. The scattered array of points to the right and top of the figure are from lithofacies units 4 and 5. Samples FP-19 and FP-20 at the top of the diagram represent anomalously high percents of sandstone grains in the lower Frontier at Frying Pan Gulch in the Pioneer Mountains (high factor 2 scores). Sample distribution in the scattered data set on the right is determined mostly by plagioclase, potassium feldspar, and volcanic grains. The occurrence of samples near the right center of the figure (for example, sample LP-79) is determined by the abundance of potassium feldspar (variable 3). Samples on the far right contain much plagioclase (variable 2) and volcanic grains (variable 6). The distribution of these points is gradational; no tight cluster groupings exist.

Figure 13 is the factor-score map for factors 1 and 3. An additional 11 percent of the sample population

variance is represented by factor 3 (table 1). Samples on the left with negative factor 1 scores and highly variable factor 3 scores represent samples from lithofacies units 1 and 3 with significant variations in limestone grain content. Sandstones range from those that contain less monocrystalline quartz and more limestone grains (samples AP-85 and FP-7 in the Pioneer Mountains) to petrofacies I-A samples that contain predominantly monocrystalline quartz (sample AN-2 in the Snowcrest Range). Again, many compositionally intermediate forms exist. The scattered array of samples to the right again represents petrofacies IV through VI from the upper volcanic-rich lithofacies.

Figure 14 is the factor-score map for factors 1 and 4. An additional 6 percent of the sample population variance is represented by factor 4 (table 1). Clearly



EXPLANATION

- | | |
|--------------------------|-------------|
| 1 Monocrystalline quartz | 4 Limestone |
| 2 Plagioclase | 5 Mudstone |
| 3 Potassium feldspar | 6 Volcanic |

Figure 13. Correspondence-analysis factor-score map for factors 1 and 3 (framework data). This map excludes redundant variables as determined from R-mode analysis. Refer to Dyman (1985c) and Appendix for sample identification and location data. Variable numbers represent variable contribution in factor space (lines on map). See also table 2.

defined groups include (1) Lima Peaks Frontier Formation potassium feldspar-rich (variable 3) outliers (samples LP-56, LP-59, and LP-70 in petrofacies V); (2) petrofacies I through III samples from the lower Blackleaf Formation; and (3) the scattered array of points on the right from the upper part of the Blackleaf and lower part of the Frontier Formations. Sample distribution patterns from additional combinations of factors 2, 3, and 4 (not illustrated) show the same relationships presented here.

The six petrofacies that were previously defined using cluster analysis can be recognized using the correspondence analysis method. The spatial distribution of sandstone samples based on the influence of each grain type is best illustrated using the correspondence-analysis factor-score maps.

DISCUSSION

QFL Plots

QFL (quartz-feldspar-lithic) and QmFLt (monocrystalline quartz-feldspar-total lithic) plots (Dickinson and others, 1983) were prepared separately to verify and support the quantitative studies. These plots do not differentiate sandstones based on many variables but do support the results of the quantitative analyses. Results of these analyses are presented in figures 15 and 16. Sample numbers annotated on these figures are stratigraphically identified in Dyman (1985c).

The QFL and QmFLt plots indicate that lower Blackleaf sandstones (petrofacies I through III) were derived from recycled-orogen (thrust belt) terranes, whereas

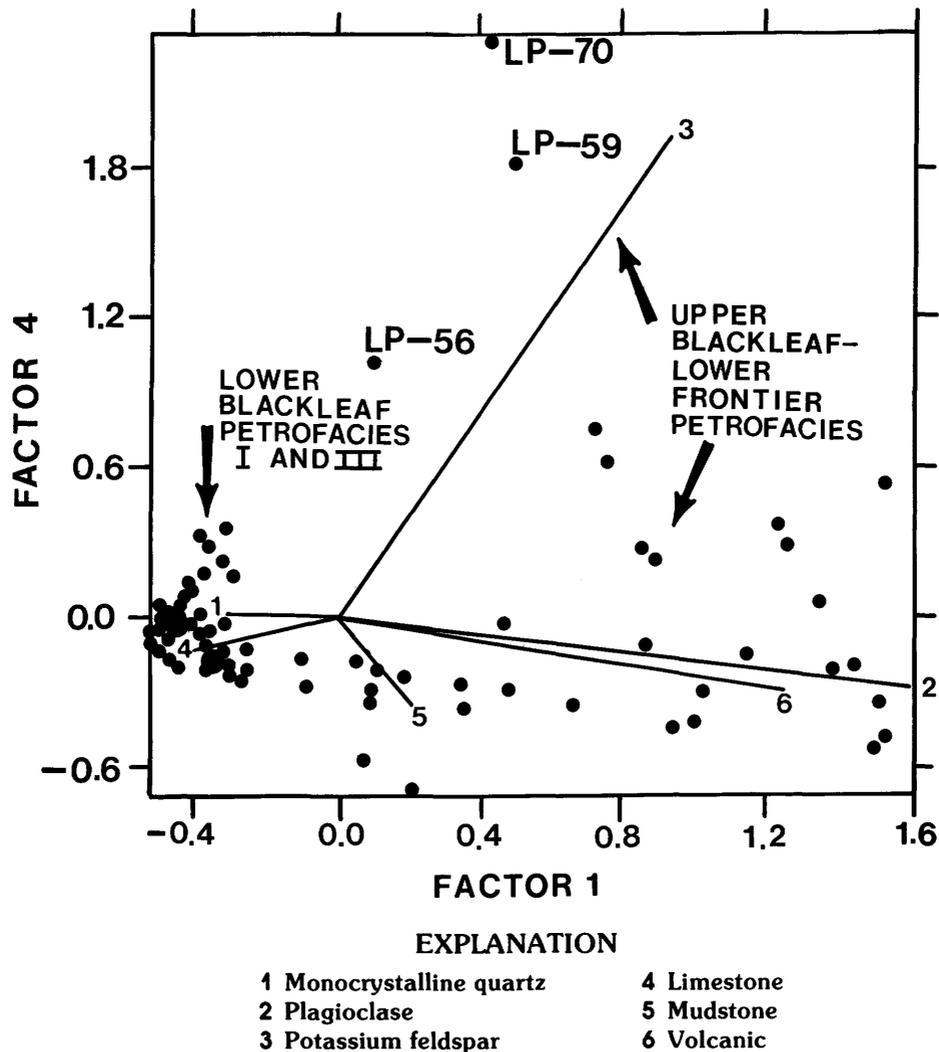


Figure 14. Correspondence-analysis factor-score map for factors 1 and 4 (framework data). This map excludes redundant variables as determined from R-mode analysis. Refer to Dyman (1985c) and Appendix for sample identification and location data. Variable numbers represent variable contribution in factor space (lines on map). See also table 2.

most upper Blackleaf and lower Frontier sandstones (petrofacies IV through VI) were derived in part from volcanic sources, which included dissected-arc and, to a lesser degree, transitional-arc terranes (fig. 15). The small population of very quartz rich lithofacies unit 1 samples (petrofacies I-A), primarily from the eastern and southern part of the study area, were derived from the craton-interior portion of the continental-block provenance (recycled cratonic detritus). Samples from Rocky Creek (Bozeman Pass; Dyman, 1985b) and Snake River (near Alpine, Wyo.) fall within this very quartz rich group. Lower unit 1 sandstones are locally more quartzose (petrofacies I-A) than upper unit 1 or unit 3 sandstones (petrofacies I-B, II, and III). In the eastern part of the study area, an upward trend exists from lower unit 1 quartzose provenance to upper lithofacies unit 1 and units 2 and 3 transitional- and lithic-recycled provenance.

Lower Blackleaf sandstones in the western part of the study area are compositionally more heterogeneous than lower Blackleaf sandstones in the eastern part of the study area. Unit 3 sandstones were derived exclusively from recycled-orogen terranes.

Upper Blackleaf and lower Frontier sandstones are very heterogeneous, but samples from the southern and eastern parts of the study area were more consistently derived from volcanic arc terranes (for example, sample LP-121, fig. 15). Samples from the lower part of unit 4, particularly from the Pioneer Mountains and McCartney Mountain area, contain little feldspar (note petrofacies subdivision in figure 5 and table 2). Lower sandstones of the Frontier Formation are very heterogeneous, with provenance varying from (1) more transitional and lithic recycled in the Pioneer Mountains to (2) more arc derived in the Lima Peaks area and Snowcrest

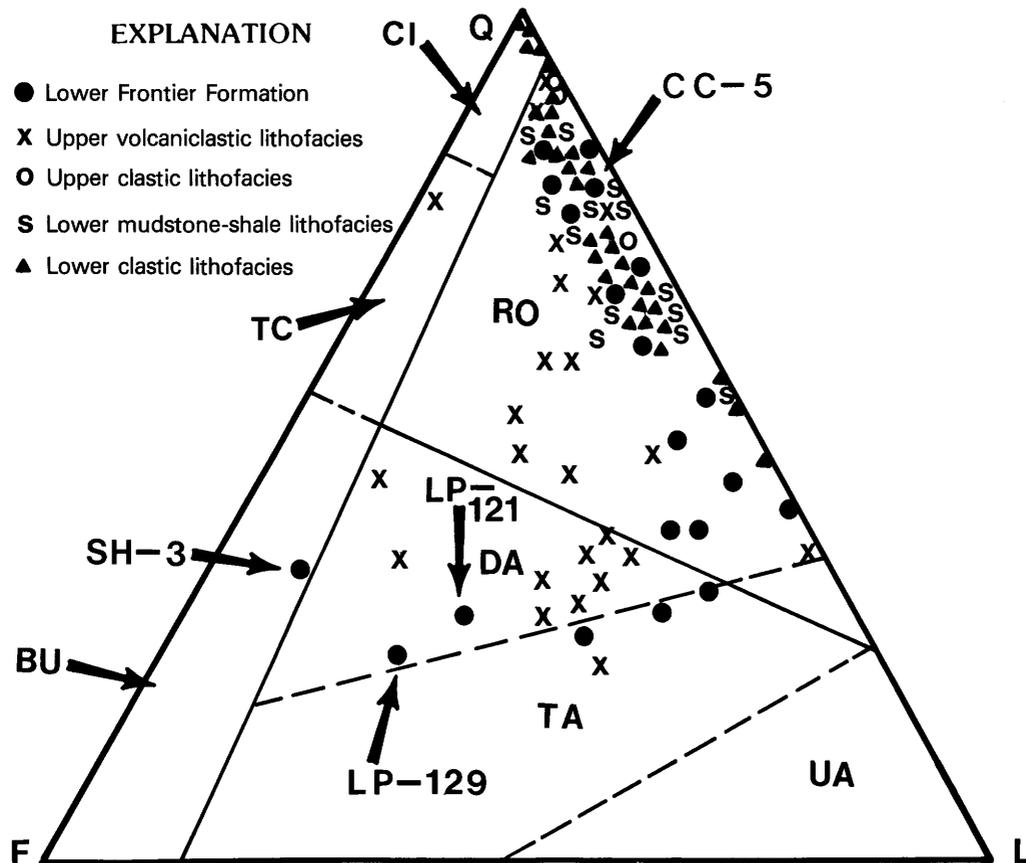


Figure 15. QFL (quartz-feldspar-lithic) plot of Blackleaf and lower Frontier sandstone samples based on Dickinson and others (1983) provenance boundaries. See Dyman (1985c) and Appendix for sample number identification. BU = basement uplift, CI = continental interior, DA = dissected arc, F = total feldspar grains, L = total lithic grains, Q = total quartz grains, RO = recycled orogen, TA = transitional arc, TC = transitional continental, UA = undissected arc.

Range. The two lithic-rich samples from the Frontier Formation at Fryng Pan Gulch (samples FP-19 and FP-20) represent a more local influx of sandstone detritus (petrofacies V-A). Samples from the Frontier Formation in the Lima Peaks area (particularly sample SH-3) comprise components whose origin was close to the basement-uplift portion (Archean terranes) of continental-block provenance (petrofacies V and VI). Samples become lithic and feldspar rich upward from the lower part of the Blackleaf Formation through the lower part of the Frontier Formation in the Lima Peaks area and the Snowcrest Range.

Petrofacies-provenance relationships can best be analyzed by comparing the factor-score maps (figs. 12-14) with the QFL compositional plots (figs. 15, 16). The factor-score maps illustrate variable-sample relationships not readily seen on the compositional plots. For example, the direct relationship between monocrystalline quartz and limestone grains (fig. 12) in differentiating between quartzose and transitional recycled-orogen provenance, particularly in the western part of the study area (fig. 15), is best observed using both displays.

Paleocurrent Data

Vector means and composite rose diagrams for paleocurrent data from Blackleaf and Frontier lithofacies are presented in figure 17. More than 500 paleocurrent readings were collected from directional structures, which included trough cross-stratification, imbricated pebbles, parting lineations, and sole marks. Data from lower Blackleaf lithofacies units 1 and 3 are variable but suggest predominantly north-to-south, east-to-west, and southwest-to-northeast paleocurrent directions. Lower Frontier lithofacies unit 5 data suggest predominantly south-to-north paleocurrent directions. Blackleaf lithofacies units 2 and 4, however, contain few paleocurrent indicators, and the sparse data for these units were not aggregated for presentation here.

Lower Part of Blackleaf Formation and Tectonic Quiescence

Paleocurrent and compositional data suggest that Albian Age sandstones from lithofacies units 1 and 3 were

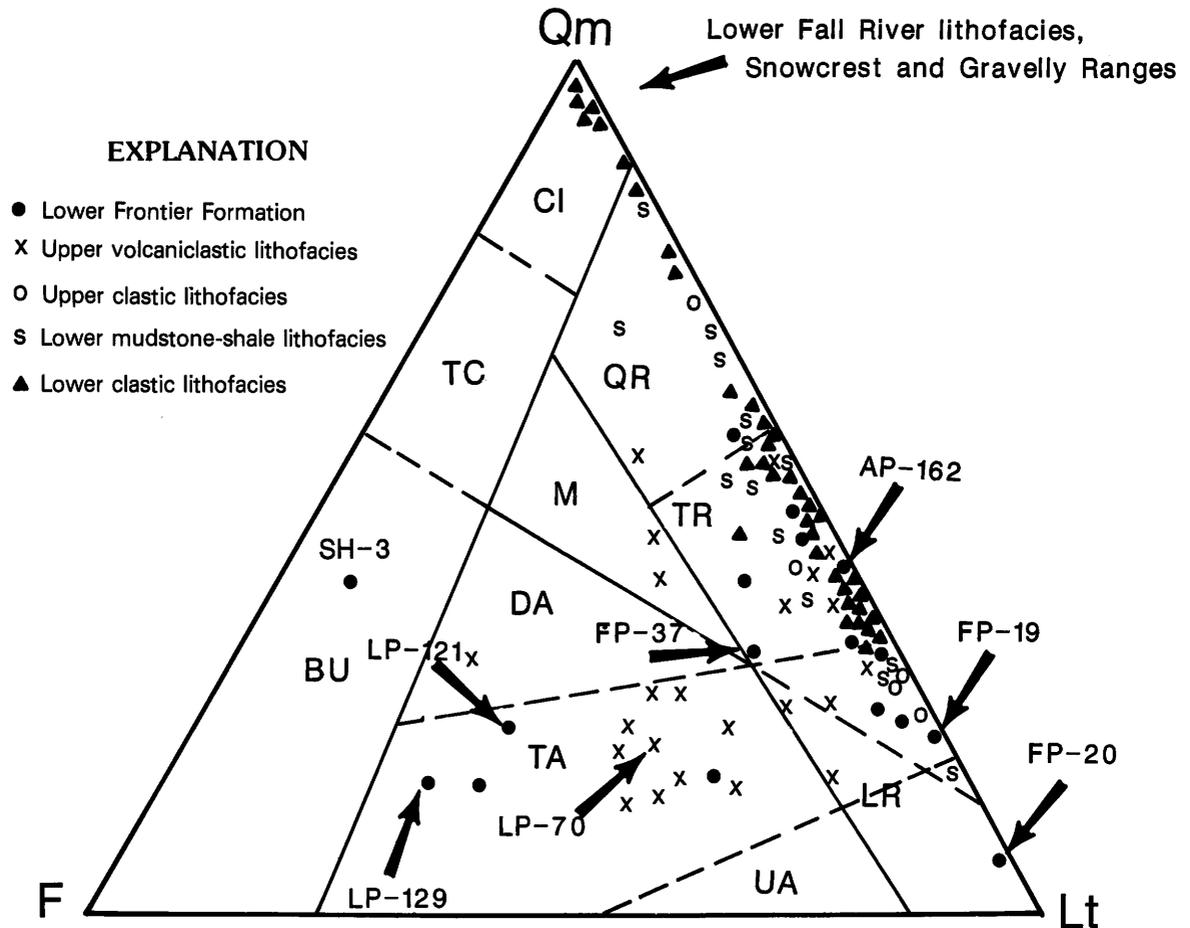


Figure 16. QmFLt (monocrystalline quartz-feldspar-total lithic) plot of Blackleaf and lower Frontier sandstone samples based on Dickinson and others (1983) provenance boundaries. See Dyman (1985c) and Appendix for sample number identification. BU = basement uplift, CI = continental interior, DA = dissected arc, F = total feldspar grains, LR = lithic recycled orogen, Lt = total lithic grains, M = mixed, Qm = monocrystalline quartz grains, QR = quartz recycled orogen, TA = transitional arc, TC = transitional continental, TR = transitional recycled orogen, UA = undissected arc.

derived predominantly from sedimentary and low-grade metamorphic source terranes to the north, west, and east (fig. 18). A westward increase in limestone detritus favors a western source for unit 1. By Albian time, the Cordilleran orogenic belt had migrated eastward into central Idaho, and southwestern Montana was a subsiding foreland basin (Kauffman, 1977; Schwartz, 1983). Sands in the uppermost Kootenai were derived from Paleozoic sources in central Idaho and lower Paleozoic sources in eastern Oregon and western Idaho (Suttner, 1969; James, 1977). The absence of volcanic, plutonic, and high-grade metamorphic detritus in sandstone from lithofacies units 1 and 3 in this study area suggests that batholith volcanism and unroofing had not yet begun. Schwartz (1972, 1983) suggested an increase in provenance complexity beginning with Blackleaf sedimentation, but noted that unroofing of major batholiths (for example, Idaho batholith) did not take place during Albian time.

Unit 1 sandstone is relatively homogeneous throughout the study area. This lower Blackleaf homogeneity reflects relative tectonic quiescence similar to conditions existing during deposition of the upper part of the Kootenai Formation. Unit 3 sandstone is rich in chert, which suggests that the detritus was derived from Mississippian through Permian sedimentary rock sources. The most obvious sources for sedimentary chert include equivalents of the Phosphoria, Madison, Wood River, and Quadrant Formations in the Paleozoic miogeoclinal belt to the west (Suttner, 1969). Crinoid columnals were noted in unit 3 chert grains. An increase in sandstone and mudstone grains relative to limestone grains upward from lithofacies unit 1 to lithofacies unit 3 reflects a source area change that may be related to sequential unroofing in the thrust belt of dominantly limestone terranes at first and of siliciclastic terranes later.

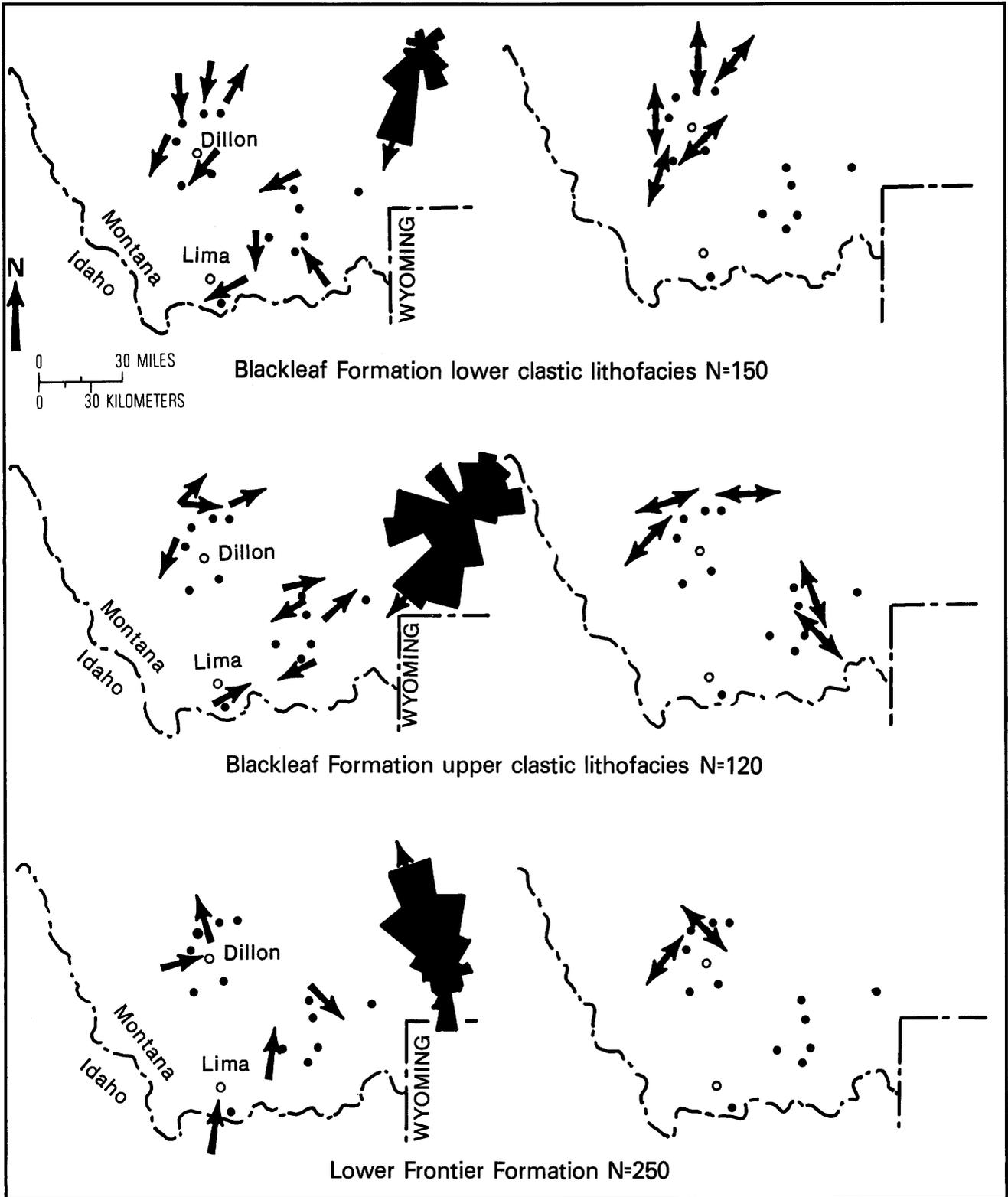


Figure 17. Paleocurrent data summary, Blackleaf and lower part of Frontier Formations, Beaverhead and Madison Counties, Montana. Circles show locations of sample sites. Single-barbed arrows represent vector means for trough cross-bed and

imbricated pebble axes. Double-barbed arrows represent vector means from parting lineations and sole structures. N = number of structures measured. Vector means calculated according to Potter and Pettijohn (1977).

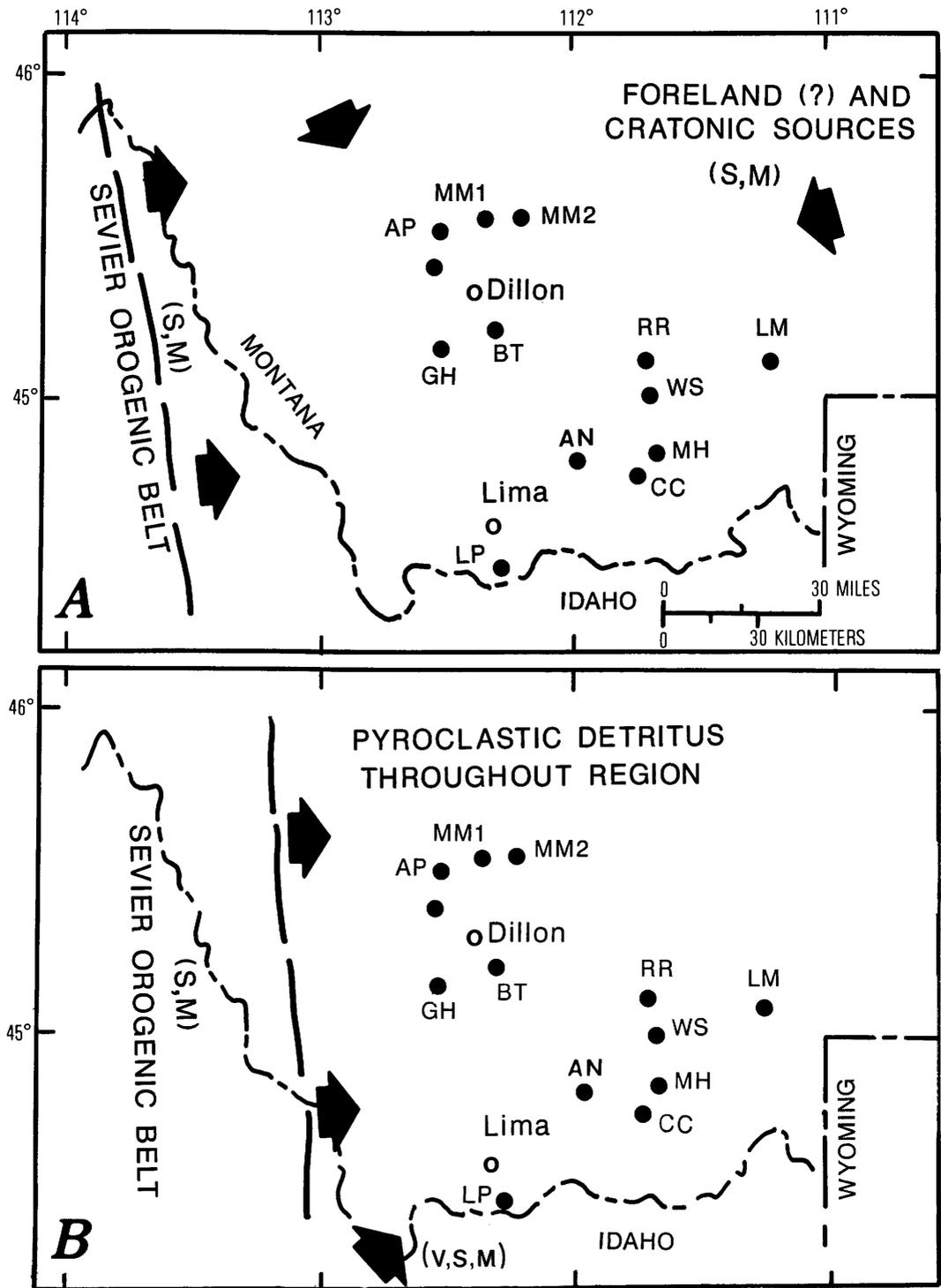


Figure 18. Generalized paleogeographic map of study area. *A*, Lower part of Blackleaf Formation (lithofacies 1 through 3). *B*, Upper part of Blackleaf and lower part of Frontier Formations (lithofacies 4 and 5). M = metasedimentary rock sources, S = sedimentary rock sources, V = volcanic rock sources. Not palinspastically reconstructed. Probable source areas (arrows) determined by paleocurrent and compositional data. See Appendix for measured section identifications and locations.

Upper Part of Blackleaf and Lower Part of Frontier Formations and Mid-Cretaceous Tectonism

Late Albian volcanism in the area is represented by Blackleaf Formation lithofacies unit 4 mudstone and sandstone. Detritus was derived mainly from sedimentary, volcanic, and low-grade metamorphic source terranes. Pyroclastic detritus may have originated directly from volcanic centers such as those related to the Idaho batholith or from erosion of older pyroclastic deposits. Abundant plagioclase grains in sandstones with rare epiclastic volcanic grains may represent reworking of pyroclastic rocks.

Frontier Formation unit 5 sandstones were derived predominantly from sedimentary, metasedimentary, and volcanic terranes to the south and west (fig. 18). Sandstones in the Pioneer Mountains contain less plagioclase and potassium feldspar and volcanic grains than do sandstones in the Lima Peaks area and Snowcrest Range (Dyman, 1985c). Frontier sandstones at the Apex and Frying Pan Gulch sections are rich in sedimentary lithic grains, which suggests that the sedimentary detritus was derived from sources in the thrust belt to the west and south. Abundant volcanic detritus in the Lima Peaks area and Snowcrest Range probably originated in volcanic centers associated with development of the Idaho batholith to the west.

SUMMARY

Quantitative techniques, such as correspondence and cluster analyses, are very useful in understanding variation and objectively establishing petrofacies in large, highly variable sample populations such as the one used in this study.

Results from R-mode correspondence analysis indicate that the relative proportions of monocrystalline quartz, plagioclase, potassium feldspar, and volcanic, limestone, and sandstone grains best characterize the Blackleaf and Frontier Formations.

Results from cluster analysis and Q-mode correspondence analysis indicate that lower Blackleaf (lithofacies units 1, 2, and 3) sandstones are relatively homogeneous and rich in monocrystalline quartz, chert, and sedimentary grains (petrofacies I through III). These sandstones exhibit some stratigraphic and geographic variation based primarily on the distribution of sedimentary grains. Lower Blackleaf sandstones can be subdivided into (1) an eastern quartzarenite province and (2) a northwestern litharenite province. Upper Blackleaf and lower Frontier sandstones (lithofacies units 4 and 5) are heterogeneous and variably rich in feldspar and volcanic and sedimentary grains (petrofacies IV through VI).

Composition of upper Blackleaf and lower Frontier sandstones varies stratigraphically and geographically, but sandstones are most compositionally mature in the Pioneer Mountains and McCartney Mountain area.

Blackleaf and Frontier lithic constituents are heterogeneous and represent the erosion of structurally complex sedimentary, volcanic, and metasedimentary source areas that lay predominantly to the north, west, and south. The upward increase in lithic complexity and volcanic content may be due partly to increased volcanism and partly to increased erosion of a complex Sevier-style orogen to the west of the study area.

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CODE, LITHOFACIES, LOCATION, AND SOURCE
FOR SECTIONS AND SAMPLE LOCALITIES

CODE, LITHOFACIES, LOCATION, AND SOURCE
FOR SECTIONS AND SAMPLE LOCALITIES

- | | |
|---|---|
| 1. AP: Apex section. Lithofacies units 1-5 present. SE ½ sec. 7 and S ½ sec. 6, T. 5 S., R. 8 W., Twin Adams Mountain Quadrangle, Beaverhead County, Montana. Dyman (1985b). | 11. AN: Antone Peak section. Lithofacies units 1-5 present. and NW ¼ sec. 22 and SW ¼ sec. 11, T. 12 S., R. 5 W., SRC: Antone Peak Quadrangle, Beaverhead County, Montana. Dyman (1985b). |
| 2. FP: Frying Pan Gulch section. Lithofacies units 1-5 present. Sec. 30, T. 6 S., R. 9 W., Bond Quadrangle, Beaverhead County, Montana. Dyman (1985b). | 12. LP: Lima Peaks section. Lithofacies units 1-5 present. Secs. 13, 14, and 18, T. 15 S., R. 8 W., Lima Peaks Quadrangle, Beaverhead County, Montana. Dyman and others (1984). |
| 3. MM1: McCartney Mountain I section. Lithofacies units 1-4 present. E ½ secs. 21 and 28 and S ½ sec. 16, T. 4 S., R. 8 W., Block Mountain Quadrangle, Madison County, Montana. Dyman (1985b). | 13. LS: Little Sheep Creek sample locality. Lithofacies units 1-4 present. N ½ sec. 26, T. 15 S., R. 9 W., Gallagher Gulch Quadrangle, Beaverhead County, Montana. T.S. Dyman (unpublished data, 1984). |
| 4. MM2: McCartney Mountain II section. Lithofacies units 1-3 present. NE ¼ sec. 35, T. 4 S., R. 8 W., Block Mountain Quadrangle, Madison County, Montana. Dyman (1985b). | S-1 RC: Rocky Creek Canyon sample locality. Lithofacies units 1-5 present. SW ¼ sec. 20, T. 2 S., R. 7 E., northern side of Interstate 90, Gallatin County, Montana. Roberts (1972, p. C61). |
| 5. GC: Grasshopper Creek section. Lithofacies unit 1 present. SE ¼ sec. 26, T. 8 S., R. 10 W., Dalys Quadrangle, Beaverhead County, Montana. Dyman (1985b). | S-2 LM: Lincoln Mountain sample locality. Lithofacies units 1-5 present. Sec. 7, T. 9 S., R. 4 E., along southern flank of Lincoln Mountain, Gallatin County, Montana. Hall (1961). |
| 6. BT: Blacktail Creek section. Lithofacies unit 1 present. NE ¼ sec. 15, T. 9 S., R. 9 W., west of Cramp-ton Ranch, Gallagher Mountain Quadrangle, Beaverhead County, Montana. Dyman (1985b). | S-3 CR: Centennial Mountains sample locality. Lithofacies unit 5 present. W ½ sec. 30, T. 14 S., R. 37 E., western side of Price-Peet road, Corral Creek Quadrangle, Beaverhead County, Montana. T.S. Dyman (unpublished data, 1985). |
| 7. RR: Ruby River section. Lithofacies units 1-5 present. SE ¼ sec. 18, T. 9 S., R. 3 W., Home Park Ranch Quadrangle, Madison County, Montana. Dyman (1985b). | S-4 WS: Warm Springs sample locality. Lithofacies 1-3 present. SE ¼ sec. 21, T. 9 S., R. 3 W., near junction of Warm Springs road and Ruby road, Varney Quadrangle, Madison County, Montana. T.S. Dyman (unpublished data, 1984). |
| 8. WS: Warm Springs Creek section. Lithofacies units 1-5 present. E ½ sec. 15 and NE ¼ sec. 22, T. 9 S., R. 3 W., Varney Quadrangle, Madison County, Montana. Dyman (1985b). | S-5 SR: Snake River sample locality. Lithofacies units 1-3 present. Sec. 4, T. 37 N., R. 117 W. (unsurveyed), northern side of U.S. Highway 89 east of Wolf Creek, Lincoln County, Wyoming. Durkee (1980). |
| 9. CC: Cottonwood Iron Creek section. Lithofacies units 1-3 present. N ½ sec. 25, T. 10 S., R. 3 W., Monument Ridge Quadrangle, Madison County, Montana. Dyman (1985b). | S-6 WC: Willow Creek sample locality. Lithofacies units 1-5 present. Secs. 6 and 7, T. 38 N., R. 116 W., western side of Willow Creek, Teton County, Wyoming. Wanless and others (1955). |
| 10. MH: Monument Hill section. Lithofacies units 1-5 present. Unsurveyed area west of Gravelly Range Road along southwestern flank of Monument Hill, Monument Ridge Quadrangle, Madison County, Montana. Dyman (1985b). | S-7 SH: Shine Hill sample locality. Lithofacies 5 present. E ½ sec. 17, T. 15 S., R. 7 W., Snowline Quadrangle, Beaverhead County, Montana. T.S. Dyman (unpublished data, 1984). |

