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CORRELATION CHART OF LOWER AND UPPER CRETACEOUS BLACKLEAF FORMATION, LIMA PEAKS AREA TO EASTERN PIONEER MOUNTAINS, SOUTHWESTERN MONTANA

By

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Abstract

The Lower and Upper Cretaceous Blackleaf Formation in the Lima Peaks area and the eastern Pioneer Mountains of southwestern Montana was deposited at the western margin of the Western Interior seaway as a nonmarine facies of the Cordilleran foreland basin. Different names have been applied previously to these same strata even within the same area. Five measured sections show sequences of Blackleaf lithofacies that were deposited farther west than their present positions; the strata were telescoped by thrust faults of Late Cretaceous to early Tertiary age. The upper Albian and lower Cenomanian Blackleaf Formation is underlain by the Aptian to Albian(?) Kootenai Formation. At Lima Peaks, the Blackleaf is overlain by the Cenomanian to Turonian Frontier Formation; in the eastern Pioneer Mountains, overlying strata differ in lithology from the Frontier and are unnamed and undivided.

Strata of the Blackleaf Formation at Lima Peaks are subdivided into the siliciclastic Flood and overlying siliciclastic and volcaniclastic Vaughn Members, both of which also are present in the eastern Pioneer Mountains. The Taft Hill and Bootlegger Members of the Blackleaf Formation, present in their type sections near Great Falls, Mont., are not recognized by us in southwestern Montana. The Flood Member consists of a mixed clastic sequence of quartz- and chert-rich sandstone, mudstone, and siltstone, and dark-gray shale; the member ranges in thickness from a minimum of 495 ft (150 m) at the Lima Peaks section to 1,185 ft (361 m) at the Rock Creek section and 1,270 ft (387 m) at the Trapper Creek section. The Vaughn Member contains abundant porcellanitic mudstone, bentonite, lithic sandstone, and subordinate conglomerate; it varies in thickness from 880 ft (268 m) at the Lima Peaks section to 1,950 ft (594 m) at the Rock Creek section.

The Vaughn-Frontier contact at Lima Peaks is disconformable and is marked by a sharp lithologic break. The overlying Frontier Formation contains salt-and-pepper sandstone, mudstone, shale, and conglomerate. In the eastern Pioneer Mountains, the upper contact of the Vaughn is considered provisional until further field studies are completed. The provisional upper contact of the Vaughn occurs at the top of a porcellanite that consistently and directly overlies the highest maroon mudstone-siltstone bed of the upper Vaughn, and is associated with micritic limestone and dark-gray shale. Undivided Upper Cretaceous strata above this contact contain quartz-rich sandstone, quartzite conglomerate, and brown siltstone.

INTRODUCTION

At Lima Peaks in the southern part of the study area, and in the eastern Pioneer Mountains in the northern part, the Lower and Upper Cretaceous Blackleaf Formation was deposited along the western margin of the foreland basin of the Cordilleran thrust belt (fig. 1). These rocks are no longer at their original depositional sites because they were thrust eastward during Late Cretaceous to early Tertiary time. These predominantly nonmarine rocks record sedimentation events influenced by successive marine transgressions and regressions, by source area tectonism, and by volcanism. Although many names have been applied to these thick and lithically diverse strata, the rocks have not been adequately described or integrated with the regional stratigraphic framework.

The purpose of this report is to describe and correlate five measured sections of Blackleaf strata along a line from the Lima Peaks area northward to the eastern Pioneer Mountains (fig. 1). Nomenclature is reviewed, Blackleaf members are described, and contacts with overlying Cretaceous strata are tentatively established. This report is an extension of a previous report by

Tysdal and others (1989a) that presented descriptions and correlations for Blackleaf and correlative strata from the Madison Range westward to the Lima Peaks area. We acknowledge the thorough and thoughtful reviews of this manuscript by C.A. Wallace of the U.S. Geological Survey and S.A. Lewis of the Montana Bureau of Mines and Geology.

MEASURED SECTIONS

Five measured sections and their stratigraphic correlations are presented here using the SRG (Stratigraphic Report Graphic). The SRG is a stratigraphic applications computer program developed by the U.S. Geological Survey and Petroleum Information Corporation of Denver, Colo. The SRG records sedimentologic, paleontologic, lithologic, paleoecologic, and nomenclatural data for outcrop sections and cores, and displays these data in graphic form using a scale-variant format (Petroleum Information Corporation, 1984; Dyman and others, 1985). The SRG is proprietary to Petroleum Information Corporation, but it is available by contract to the U.S. Geological Survey.

The southernmost measured section, at Lima Peaks, was originally published by Dyman and others (1984), and later this section was revised and published by Tysdal and others (1989a). It is presented here because it establishes stratigraphic continuity from the Lima Peaks area northward into the eastern Pioneer Mountains. The Frying Pan Gulch and Apex sections were previously published by Dyman (1985a, b), and are supplemented here by additional data of Dyman and Tysdal. The Rock Creek and Trapper Creek sections are previously unpublished sections of Tysdal and Dyman.

The four northern sections demonstrate areal continuity of the Blackleaf Formation sufficient for use as a geologic map unit, yet record a diversity of strata. The four northern sections are spaced at intervals of about 10 mi (17 km), but the Lima Peaks section is 45 mi (75 km) south of the Frying Pan Gulch section, the southernmost of the four northern sections. No complete or nearly complete Blackleaf sections are exposed between Lima Peaks and Frying Pan Gulch because of post-Blackleaf erosion. The Lima Peaks, Apex, and Rock Creek sections are well exposed, but the middle part of the Frying Pan Gulch section is poorly exposed. The Trapper Creek section is incomplete due to structural complications. Strata at the Rock Creek section were metamorphosed by the Pioneer batholith.

STRATIGRAPHY

Cretaceous strata exposed between the Lima Peaks area and the eastern Pioneer Mountains are assigned to the Aptian to Albian(?) Kootenai Formation and the upper Albian and lower Cenomanian Blackleaf Formation (fig. 2). At Lima Peaks, Upper Cretaceous strata above the Blackleaf Formation are assigned to the Cenomanian to Turonian Frontier Formation (Dyman and Nichols, 1988; Dyman and others, 1989), whereas strata that overlie the Blackleaf in the eastern Pioneer Mountains have not been assigned to a formation. Several different names have been used previously for strata that are here assigned to the Blackleaf and Frontier, but no consistent pattern of nomenclature had been established, in part because of the great distance between outcrops and local lithologic and facies changes. The decision by Dyman and others (1984), Dyman (1985a, b, c), and Tysdal and others (1989a) to use the names Blackleaf and Frontier for Cretaceous strata in southern Beaverhead County was made after reviewing the literature and carefully examining the area near Blackleaf Creek, Mont., the type area of the Frontier at Cumberland Gap, Wyo., and additional outcrops.

The Blackleaf Formation of the Lima Peaks area was correlated with equivalent strata in the Madison Range by Tysdal and others (1989a). The strata of these two areas represent foreland basin and shelf facies, respectively. In the measured sections of the Madison, Greenhorn, and Gravelly Ranges, Tysdal and others (1989a) assigned Blackleaf lithic equivalents to the Thermopolis Shale, Muddy Sandstone, and Mowry Shale, which were all considered to be Albian in age. Strata in the central Snowcrest Range, although poorly exposed, exhibit lithic characteristics similar to those of the Lima Peaks section. Tysdal and others (1989a, b) recognized that facies change gradually in character along the length of the Snowcrest Range, but elected to change formation names arbitrarily along the Ruby River Valley, which separates the Greenhorn and Gravelly Ranges on the east from the Snowcrest Range on the west (fig. 1). Sections correlated here all lie west of this boundary and exhibit lithic characteristics of the Blackleaf Formation.

Stratigraphic relationships and regional correlations for the Blackleaf Formation and overlying Cretaceous strata are illustrated in figure 2. Figure 3 illustrates the relative thicknesses of the Blackleaf Formation in the five measured sections, and the parts of each measured section presented on each half of the chart. In discussing stratigraphic relationships we proceed from south to north. All megafossils reported by us were identified by W.A. Cobban.

PREVIOUS WORK

Most early work in the study area left post-Kootenai strata undivided. Near Lima Peaks, strata equivalent to

the Blackleaf Formation were assigned to the Bear River or Aspen Formations (Dillon, 1947; Scholten and others, 1955; Ryder, 1968; Ryder and Ames, 1970; Wilson, 1970; Skipp and others, 1979), or to the Colorado Group (Sadler, 1980). The name Blackleaf was first used by Schwartz (1972, 1983) for equivalent strata in southwestern Montana, but he did not describe rocks in the Lima Peaks area. James (1977), Perry and others (1983), Dyman and others (1984), Dyman (1985a, b, c), Nichols and others (1985), Perry (1986), Dyman and Nichols (1988), Tysdal and others (1989a, b), and Dyman and others (1989) used the name Blackleaf for strata in the Lima Peaks area. Tysdal and others (1989a, b) subdivided the Blackleaf into formal members in Beaverhead County. Dyman and others (1984), Dyman and Nichols (1988), and Tysdal and others (1989a) used the name Frontier Formation for beds that overlie the Blackleaf in the Lima Peaks to Madison Range region. Dyman and Nichols (1988) and Tysdal and others (1989a, b) discussed mid-Cretaceous nomenclature in the Lima Peaks area and eastward in the Madison, Gravelly, Snowcrest, and Greenhorn Ranges. However, they did not include laterally equivalent strata in the eastern Pioneer Mountains in their discussion. Details of nomenclatural usage in the Lima Peaks area were presented by Tysdal and others (1989a), and are not repeated here.

A variety of names have been applied to the post-Kootenai strata in the eastern Pioneer Mountains. The rocks were assigned to the "Colorado formation" by Richards and Pardee (1925), Karlstrom (1948), and Theodosis (1956); to the Colorado Group by Lowell (1965), Sharp (1970), Peters (1971), Ruppel and others (1983), Pearson and Zen (1985), and Zen (1988); to the Blackleaf Formation by Schwartz (1972, 1983); and to the Blackleaf and Frontier Formations by Dyman (1985a, b, c) and Dyman and Nichols (1988). They were left unnamed by Meyers (1952), who subdivided the sequence into informal map units. Zen (1988) subdivided his Colorado Group into lower (Kcl) and upper (Kcu) parts in the Vipond Park 15-minute quadrangle. Sharp (1970) subdivided his Colorado Group into three informal members in the Greenstone Mountain area approximately 5 mi (8 km) northwest of our Apex section. Peters (1971) used a similar three part subdivision of the Colorado Group in the Rock Creek area. Descriptions by these authors were not detailed enough for us to correlate their units with our measured sections.

The name Frontier Formation was used by Dyman (1985a, b, c) and Dyman and Nichols (1988) for beds that directly overlie the Blackleaf at the Frying Pan Gulch and Apex sections. Their Blackleaf-Frontier boundary was determined from an overall compositional change in the rocks, including an abrupt increase in sandstone beds. They identified a similar change at Lima Peaks and in the Snowcrest and Gravelly Ranges. Age-diagnostic palynomorphs and megafossils were absent from these strata at the Apex and Frying Pan Gulch measured sections, however, and the age of rocks that overlie the Blackleaf at these localities could not be determined. Dyman and Nichols (1988) did not measure Cretaceous strata north of the Apex section. Our measured sections at Rock Creek and Trapper Creek reveal much thicker sequences than sections at Lima Peaks and in the Snowcrest Range. For these reasons, strata above our provisional upper Vaughn (equals provisional upper contact of the Blackleaf Formation) in the eastern Pioneer Mountains are here left as undivided Cretaceous. The name Frontier is not used in this report for these overlying strata. The decision to use the name Frontier in the eastern Pioneer Mountains and northward awaits further study of post-Blackleaf strata between the Apex section and Drummond, Mont.

In the eastern Pioneer Mountains, the few studies that subdivided post-Kootenai strata are discussed where appropriate in the following sections of this report.

KOOTENAI FORMATION

The Kootenai Formation is described briefly in this report because it underlies all of our measured sections, and contact relationships with the overlying Blackleaf Formation require description of the upper part of the Kootenai. The uppermost part of the Kootenai in the study area contains gastropod-rich carbonate strata informally called the "gastropod limestone," which marks the top of the formation throughout most of southwestern Montana and is used as a marker unit in this report. In the Lima Peaks and Apex measured sections, discontinuous beds of nongastropod-bearing limestone occur directly above the contact in the lowermost Blackleaf Formation and are interbedded with lithologies typical of the lower Blackleaf, to which they are assigned (Dyman and Nichols, 1988; Tysdal and others, 1989a). C.A. Wallace has placed equivalent limestone beds within the Kootenai Formation in the Drummond, Mont., area, which is about 50 mi (80 km) northwest of Butte (fig. 1) (C.A. Wallace, written commun., 1989).

A palynomorph assemblage including the species *Appendicisporites jansonii* was collected from the "gastropod limestone" in the uppermost part of the Kootenai Formation at the Lima Peaks section and supports an age of Berriasian to late Albian (Dyman and Nichols, 1988). The Kootenai is considered Aptian

in age by most workers (Suttner, 1969; James, 1977; Vuke, 1984; Schwartz, 1972, 1983). Palynomorphs were not recovered from samples of the uppermost Kootenai at the base of the four measured sections in the eastern Pioneer Mountains.

BLACKLEAF FORMATION

Cobban and others (1959) named four members of the Blackleaf Formation in northwestern Montana, from bottom to top: Flood, Taft Hill, Vaughn, and Bootlegger (fig. 2). Gwinn (1965) subdivided the Blackleaf into the Flood, Taft Hill, and Dunkleberg Members near Drummond in westernmost central Montana. Wallace and others (1986), following extensive mapping in the Drummond area, did not use the name Dunkleberg based on lithologic data. The Flood name was used in the Lima Peaks area of southwestern Montana by Perry and others (1983) and Tysdal and others (1989a); Schwartz (1972, 1983), Dyman and others (1984), Dyman (1985a, b, c), Dyman and others (1988), and Dyman and Nichols (1988) used informal names for lithic units of the Blackleaf Formation. We use the Flood name in the eastern Pioneer Mountains, but recognize that lithologies of this member in the eastern Pioneer Mountains differ somewhat from those at Lima Peaks and at the type section near Flood Siding near Great Falls in Cascade County, Mont. (fig. 1). We follow our previous work (Tysdal and others, 1989a, b) and use the name Vaughn for the upper member of the Blackleaf in the Lima Peaks area and we also use Vaughn in the eastern Pioneer Mountains. We generally recognize Schwartz's (1972, 1983) informal intervals of the Blackleaf Formation (designated by him as intervals A through D); however, precise correlation with Schwartz's intervals is difficult because Schwartz did not publish his measured sections. Lithologic descriptions presented in Schwartz (1972) establish that the upper part of the Vaughn Member of the Blackleaf Formation (his interval D) in the eastern Pioneer Mountains includes strata that we tentatively consider to be younger than the Blackleaf.

General correlation of the Blackleaf Formation in southwestern Montana with the formation in the Drummond area and on Blackleaf Creek near Great Falls was established previously (Schwartz, 1972, 1983; James, 1977; Perry and others, 1983; Perry, 1986; Dyman and Nichols, 1988), but detailed correlation of members through the use of published measured sections has not been undertaken previously. Members of the Blackleaf defined in the measured sections presented here also have been identified in sections that we have measured farther north near Jerry Creek in the southwesternmost part of an unnamed mountain range north of the Pioneer Mountains (fig. 1), but these sections are not yet published. Lewis (1989) described and mapped similar strata in the eastern part of the Dickie Peak 7.5-minute quadrangle, a few miles northwest of Jerry Creek; she assigned lower Blackleaf strata to the Flood Member, and overlying rocks to the Vaughn Member. Although the strata she mapped are metamorphosed, we have examined these strata and are in general agreement with her interpretations. We do not recognize lithologies of the Taft Hill or Bootlegger Members of the Blackleaf Formation in the eastern Pioneer Mountains, nor did Tysdal and others (1989a) recognize these members farther east in southwestern Montana.

The Blackleaf Formation ranges from a minimum thickness of 1,375 ft (420 m) at the Lima Peaks section in southern Beaverhead County to a maximum of 3,135 ft (955 m) at the Rock Creek section in northern Beaverhead County (fig. 3).

Flood Member of the Blackleaf Formation

The Flood Member of the Blackleaf Formation in the eastern Pioneer Mountains and Lima Peaks area is composed of three informal lithologic units that Dyman and Nichols (1988) designated as lower clastic, middle mudstone-shale, and upper clastic. These units show extensive lithic and thickness variations throughout the region, and reflect several different depositional environments. These units are not regional map units, but illustrate lithic variations and can be used for stratigraphic correlation. The units appear to be conformable, and sandstones within them form topographic breaks that may be mapped locally. The Flood Member ranges in thickness from a minimum of 495 ft (150 m) at the Lima Peaks section to 1,185 ft (361 m) at the Rock Creek section and 1,270 ft (387 m) at the Trapper Creek section (fig. 3).

The lower clastic unit forms the base of the Flood Member at each of the five sections of this report and consists of gray to green and red calcareous mudstone and siltstone, and fine- to medium-grained quartz- and chert-rich sandstone. Minor micritic and nodular limestone, limestone conglomerate, and dark-gray shale form thin and lenticular interbeds. The unit contains mudstone zones with abundant limestone nodules. Sandstones are quartz rich at the Lima Peaks measured section but are lithic rich with abundant limestone detritus in the eastern Pioneer Mountains sections At the Frying Pan Gulch measured section, a sandstone channel sequence forms the major part of the lower unit. The sandstone sequence is poorly defined at the Apex section. The lower clastic unit is about 250 ft (76 m) thick at the Rock Creek section and about 285 ft (86

m) at the Apex section. The lower clastic unit is the lithic equivalent of the Fall River Sandstone in eastern Wyoming and eastern Montana, and of the lower sandstone member of the Thermopolis Shale in the Gravelly, Greenhorn, and Madison Ranges of southwestern Montana.

The middle unit of the Flood Member, which is gradational with the lower clastic unit, contains abundant mudstone and shale with subordinate siltstone and quartz-rich sandstone. At the Lima Peaks and Frying Pan Gulch measured sections, dark-gray shale is the dominant lithology, whereas at the Apex and Rock Creek measured sections, mudstone is dominant. At the Trapper Creek measured section, dark-gray shales are abundant, but are interbedded with sandstones. Sandstones are interbedded with mudstone and shale at each of the measured sections. The middle unit varies in thickness from a minimum of 100 ft (30 m) at Apex to about 150 ft (46 m) at Lima Peaks and about 350 ft (107 m) at Rock Creek. The middle unit has been identified in the subsurface east of Lima where 46 ft (14 m) of dark-gray shale is recognized (Perry, 1986). The mudstone-shale unit is equivalent to the middle shale of the Thermopolis Shale to the east in the Gravelly, Greenhorn, and Madison Ranges and in areas farther east in southern Montana, and is equivalent to the Thermopolis Shale as used in Wyoming.

The upper clastic unit, which is conformable with the underlying middle unit, forms the uppermost lithic unit of the Flood Member. It contains quartz- and chert-rich sandstone and subordinate mudstone, siltstone, shale, and conglomerate. At the Lima Peaks measured section it is poorly exposed and may be discontinuous, but is composed of one chert-rich sandstone bed. In the eastern Pioneer Mountains sections, the unit thickens to the north where it is about 190 ft (58 m) thick at Apex, about 600 ft (183 m) thick at Rock Creek, and about 650 ft (198 m) thick at Trapper Creek. At Apex two distinct thick-bedded sandstone units are present and are separated by as much as 10 ft (3 m) of brown siltstone. Significant thickening north of the Apex section reflects a facies change. Ongoing field studies by Dyman and Tysdal may establish facies relationships between this thickened upper Flood sequence and the Taft Hill Member recognized farther to the north in the type area and near Drummond. The upper clastic unit forms a distinctive ridge in the eastern Pioneer Mountains, and the top of the unit is marked by a topographic break in slope. The upper clastic unit is the lithic equivalent of the Muddy Sandstone to the east in the Gravelly, Greenhorn, and Madison Ranges, and farther east in Montana and Wyoming, and of the Taft Hill Member near Great Falls, Mont.

Meyers (1952) placed strata here assigned to the Flood Member in his informal map unit Ku_1, which also included nonvolcanic strata in the lower part of the Vaughn as we define it. The Flood Member is part of Zen's (1988) lower part (Kcl) of the Colorado Group. Sharp (1970) placed these strata in his member 1, although identification of his upper boundary is difficult because the upper sandstone of the Flood Member is not evident from his description. Peters (1971) also placed these strata in his member 1, although based on written descriptions, Peters' upper boundary may be different from that of Sharp (1970).

Few identifiable megafossils were found in the Flood Member at the five measured sections. A single specimen of *Anomia* (identified by W.A. Cobban, *in* Meyers, 1952) was found at the base of the upper clastic unit of the Flood Member by Meyers (1952) (his map unit Ku_1) approximately 0.3 mi (0.2 km) north of our Frying Pan Gulch measured section. We collected megafossils from the same interval, but *Brachiodontes* sp. was the only identifiable specimen. *Brachiodontes* is not age diagnostic but occurs in brackish-water environments (W.A. Cobban, written commun., 1988). Palynomorphs were not recovered from samples of the Flood Member.

Vaughn Member of the Blackleaf Formation

The name Vaughn Member was first applied to strata in southwestern Montana by Tysdal and others (1989a, b), and presented with specific measured sections for the Madison, Greenhorn, and Snowcrest Ranges, and for the Lima Peaks area (Tysdal and others, 1989a). In this report we define the lower limit of the Vaughn Member in the eastern Pioneer Mountains and define a mappable contact that tentatively is considered to be the top of the member and the formation. However, the certainty of this definition of the upper limit must await examination of additional strata, and thus is considered provisional. Strata above the mappable contact in the eastern Pioneer Mountains are best exposed in the vicinity of the Rock Creek measured section, where they are conformable and have some similarities with strata below the contact.

The Vaughn Member marks the first significant influx of volcanic detritus during deposition of the Blackleaf Formation. Rock types include mudstone, tuff, porcellanitic tuff, porcellanitic mudstone, siltstone, volcaniclastic sandstone, conglomerate, and limestone. Locally, chert-pebble conglomerate is present in the basal parts of several sandstone units. At least one conglomerate unit at the Rock Creek section contains limestone clasts. Conglomerate zones are lenticular but may be several tens of meters in length. Mudstone and siltstone are the dominant lithologies and are generally

olive green to gray and often calcareous. Bentonite is abundant at the Lima Peaks section and exhibits well-developed "popcorn texture" on exposed slopes. Lithophysae as much as 0.1 in. (0.03 cm) in diameter occur in tuffaceous and porcellanitic beds in the eastern Pioneer Mountains sections.

There is a marked lithologic change in the Vaughn from the Lima Peaks to the eastern Pioneer Mountains measured sections. In the Lima Peaks section, bentonitic mudstones are most abundant, exhibiting pastel-colored shades of red, green, and gray. The Pioneer Mountains sections do not exhibit the pastel colors, and bentonitic mudstones are rare. Porcellanitic mudstones and porcellanitic tuffs are abundant and generally exhibit dull shades of green, brown, and gray in the eastern Pioneer Mountains sections. Some mudstones, particularly in the lower Vaughn at Rock Creek, exhibit porcellanitic textures, but are nonvolcanic in origin and resulted from thermal alteration associated with the Pioneer batholith. Brown siltstone is abundant in the middle and upper Vaughn in the eastern Pioneer Mountains sections.

The Vaughn Member ranges in thickness from a minimum of 880 ft at Lima Peaks to a maximum of 1,950 ft (594 m) (using the provisional contact) at Rock Creek. The member is 1,410 ft (430 m) thick at the Frying Pan Gulch section and 1,915 ft (584 m) thick at the Apex section (fig. 3); these thicknesses differ slightly from those in Dyman and Nichols (1988), who used a somewhat different definition for the top of the Vaughn Member (their volcaniclastic lithofacies). The significantly greater thickness northward from the Lima Peaks measured section to the sections in the eastern Pioneer Mountains (fig. 3) results from an increase in the amount of sandstone and conglomerate. Such lateral thickness changes are typical for fluvial deposition during active tectonism. We have mapped the Cretaceous strata between the Rock Creek and Apex sections to be certain that thickness changes are stratigraphic and not the result of structural telescoping. The true Vaughn thickness at Trapper Creek cannot be determined because of structural complications.

The base of the Vaughn Member at the Lima Peaks measured section lies at the base of an olive-green nonvolcanic mudstone unit directly above gray sandstone of the upper sandstone unit of the Flood Member. The contact is easy to define because it forms a distinctive break in slope. In the eastern Pioneer Mountains sections, the base of the Vaughn is lithologically similar to that at Lima Peaks, but nonvolcanic mudstone is predominantly brown rather than olive green. The lower mudstone varies in thickness from section to section, but is overlain everywhere by porcellanitic mudstones and siltstones of the Vaughn.

The upper contact of the Vaughn Member changes in character northward. In the Lima Peaks area, pastel-colored bentonitic and porcellanitic rocks of the Vaughn Member are overlain disconformably by salt-and-pepper sandstone, conglomerate, gray shale, and mudstone of the Frontier Formation. At Lima Peaks, Dyman (1985a, b) and Dyman and Nichols (1988) placed the upper contact of the Vaughn at the base of the first sandstone, conglomerate, or dark-gray shale bed above the pastel-colored bentonitic mudstones.

In the eastern Pioneer Mountains, the provisional upper contact is conformable but represents a change in lithologies. Conglomerates and sandstones similar to those at the base of the Frontier Formation at Lima Peaks occur in the uppermost part of a porcellanite-bearing sequence, as well as higher in the section. The Vaughn exhibits a wide range of lithologies and thicknesses in northwestern and central-western Montana where the unit has been mapped, but the abundant volcanic and volcaniclastic components, particularly porcellanites, throughout that region provide a unifying characteristic. This characteristic led Tysdal and others (1989b) to use the name Vaughn in southwestern Montana. Porcellanitic rocks are abundant in the Vaughn Member of the Blackleaf Formation throughout the area of the measured sections. At the Lima Peaks measured section, porcellanitic mudstones are rare in the overlying lower part of the Frontier Formation. At the Frying Pan Gulch measured section in the eastern Pioneer Mountains, the uppermost porcellanite occurs 1,410 ft (430 m) above the base of the Vaughn Member. At the Apex measured section, the uppermost significant porcellanite (minimum thickness 10 ft (3 m)) is overlain by a sequence of brown siltstones and interbedded salt-and-pepper sandstones. At the Rock Creek measured section and northward, where post-Vaughn Cretaceous strata are extensive, porcellanites significantly decrease in abundance and the contact is clearly gradational. Hence, we chose the provisional top of the Vaughn Member (thus the Blackleaf Formation) as that which meets the volcanic/volcaniclastic criterion and is easily mappable. The contact criteria are set forth in the following paragraph.

The association of distinctive lithologies are recognized in the uppermost part of the Vaughn Member. Rocks of the uppermost part of the Vaughn Member include an interval of maroon mudstone and siltstone, gray freshwater limestone or locally very calcareous mudstone and siltstone, dark-gray shale, and bright-green porcellanite. The top of the member is tentatively chosen as the top of the porcellanite that consistently and directly overlies the highest maroon mudstone. This porcellanite unit is interbedded with micritic limestone beds. We have found the maroon beds and

associated limestone, dark-gray shale, and porcellanite to occur for more than 45 mi (75 km) along the east flank of the Pioneer Mountains from just north of the Frying Pan Gulch measured section to the unnamed mountain range to the north of the Pioneer Mountains (fig. 1). S.E. Lewis (Montana Bureau of Mines and Geology, oral commun., 1989) recognized several distinctive porcellanite beds above the maroon mudstone unit in the Dickie Peak 7.5-minute quadrangle in the unnamed range north of the Pioneer Mountains.

Maroon siltstone and mudstone beds are commonly calcareous, commonly contain small (less than 0.5 in. (1.3 cm) in diameter) calcareous nodules, and are mottled gray green from bioturbation by burrowing organisms. The maroon color often cuts across bedding planes. Maroon beds in the uppermost part of the member range in thickness from less than 20 ft (6 m) approximately 0.5 mi (0.8 km) north of the Frying Pan Gulch section to 75 ft (23 m) at the Apex measured section. They occur as low as 500 ft (152 m) below the top of the Vaughn at the Rock Creek measured section, where eight individual maroon beds were identified, but only the uppermost maroon beds are associated with limestone and bright-green porcellanite. The maroon beds were not identified at the Frying Pan Gulch measured section, but they crop out 0.5 mi (0.8 km) north where maroon beds are stratigraphically equivalent to the uppermost Vaughn porcellanite and are very tuffaceous.

Porcellanite near the top of the Vaughn is commonly bright green, whereas porcellanite in the lower Vaughn is light green, gray, or white. The zone of bright-green porcellanite reaches a maximum thickness of more than 50 ft (15 m) at the Rock Creek section. The limestone beds at the top of the Vaughn Member are light to dark gray, silty, nodular, and concretionary. Concretions reach a maximum of 1.5 ft (0.5 m) in diameter.

Strata here called Vaughn were called volcaniclastic lithofacies unit by Dyman and Nichols (1988). Their criteria for definition of the top of the Blackleaf differ from ours, however, so some strata that we include in the Vaughn were placed in the overlying unit by Dyman and Nichols (1988). Dyman and Nichols (1988) placed the contact of the overlying unit at the base of the first thick sandstone or conglomerate bed above the base of the porcellanitic strata. At the Frying Pan Gulch section they placed the contact at the base of a distinctive conglomerate bed approximately 100 ft (30 m) below the top of the Vaughn. This criterion was abandoned by us because conglomerate beds occur discontinuously throughout the Vaughn in the eastern Pioneer Mountains.

Our Vaughn Member includes the upper part of Meyers' (1952) map unit Ku_2 and all of map unit Ku_3, although contact relations with these units are difficult to interpret from his discussion. Zen (1988) included strata that we refer to as Vaughn Member as his upper part of the Colorado Group (Kcu). He also mapped individual conglomerate beds (Kcc) within his upper member. Based on geologic mapping, we infer that some strata of Zen's upper member are actually part of a younger, and poorly understood depositional cycle. Zen's upper member is lithologically and stratigraphically different from the Vaughn and is separated from it by a prominent fault (Zen, 1988; unpublished field data of Tysdal and Dyman, 1988). Palynomorphs from these upper strata were dated by D.J. Nichols (*in* Zen, 1988) as mid-Campanian to Maastrichtian. Sharp's (1970) member 2 is part of our Vaughn Member, based on his description of abundant porcellanite; his member 3 may represent overlying undivided Cretaceous strata of this report but this conclusion is difficult to establish based on his descriptions. In the Rock Creek area, Peters' (1971) three members are slightly different from those described in Sharp (1970) in part because of the geographic differences in map areas—the stratigraphic section at Rock Creek is much thicker than that at Greenstone Mountain approximately 10 mi (3 m) south. Peters' (1971) member 1 includes the lower part of our Vaughn Member, whereas his member 2 includes the upper part of our Vaughn Member (including the maroon beds near the top). His member 3 includes strata correlative to our overlying undivided Cretaceous strata.

No age-diagnostic megafossils were found in the Vaughn Member. The freshwater clam *Plesiellipti*? sp. and gastropod fragments (identifications by W.A. Cobban, written commun., 1983) were collected from a limestone bed in the uppermost part of the Vaughn at the Apex measured section. Two palynomorph assemblages indicate a mid-Cretaceous age for the Vaughn at the Lima Peaks section (Dyman and Nichols, 1988). Several specimens of the seed fern *Tempskya* were found at the Lima Peaks section; it is common in both Albian and Cenomanian strata in the Rocky Mountain region (Read and Ash, 1961). The Vaughn Member is correlative with the Vaughn Member and the upper part of the Mowry Shale to the east in the Gravelly, Greenhorn, and Madison Ranges (Tysdal and others, 1989b).

FRONTIER FORMATION AND UNNAMED POST-VAUGHN CRETACEOUS STRATA

Strata directly overlying the Blackleaf Formation differ markedly from one measured section to the next

in southwestern Montana. More than 7,000 ft (2,134 m) of Cenomanian to Turonian strata may occur south of Lima Peaks (Dyman and others, 1989), and were assigned to the Frontier Formation. Approximately 3,000 ft (914 m) of Frontier strata crop out in a structurally thinned section in the Greenhorn Range to the east (Tysdal and others, 1990).

The lower part of the Frontier near Lima Peaks is composed of salt-and-pepper, lithic-rich sandstone, conglomerate, bentonitic mudstone, siltstone, and shale. Based on an analysis of palynologic data and sedimentary structures, we infer that these strata were deposited predominantly in fluvial to shallow-marine environments. Sandstones are chert rich and generally calcareous; they are massive to crossbedded and form discontinuous channel-like bodies. Lowermost Frontier strata consist of about 30 ft (9 m) of dark-gray nonvolcanic shale of Cenomanian age that occurs directly above the volcaniclastic Vaughn Member. These basal beds are succeeded upward by sandstone and conglomerate. These lower Frontier sandstone and conglomerate beds are laterally discontinuous in the Lima Peaks area.

The name Frontier is not used by us in the eastern Pioneer Mountains because of lithologic differences between this post-Vaughn sequence and the Frontier Formation at the Lima Peaks measured section, sections in the Greenhorn and Snowcrest Ranges, and the type area in Wyoming. In addition, post-Vaughn strata in the Great Falls, Mont., area show a marked marine influence that produced rocks of different character from those that we have observed in post-Vaughn strata of the eastern Pioneer Mountains. Hence, names used in those areas also are not used in the eastern Pioneer Mountains.

No relative or absolute ages, either from fossils or radiometric methods, that may aid interpretation of lateral changes in facies have been obtained for strata in this sequence directly above the upper contact of the Vaughn in the eastern Pioneer Mountains. Even within the eastern Pioneer Mountains, a lithologic contrast occurs in beds directly overlying the Blackleaf. At the Frying Pan Gulch section, strata directly overlying the uppermost porcellanitic mudstone of the Vaughn include chert-rich sandstone, conglomeratic sandstone, conglomerate, olive-green and dark-gray mudstone, dark-gray to brown siltstone, and limestone. Conglomerate clasts include quartzite and dark-gray chert; conglomerate forms discontinuous bodies encased in mudstones. Mudstones and siltstones form approximately 80 percent of the sequence. At the Apex and Rock Creek measured sections, the lowermost part of the overlying unnamed Cretaceous sequence is metamorphosed and composed predominantly of brown siltstone and minor chert-rich sandstone; dark-gray mudstone and siltstone occur locally. Meyers (1952) referred to these Upper Cretaceous strata as his map unit Ku_4, and locally recognized more than 4,000 ft (1,219 m) of this sequence. We cannot precisely determine how Meyers' unit Ku_4 relates to our unnamed Cretaceous sequence because of his brief and general descriptions of strata. We measured 2,400 ft (732 m) of these strata at the Rock Creek section, where the upper part of the measured section is truncated by a fault. Dyman (1985b) measured 1,371 ft (418 m) of these strata at Apex although he incorrectly referred to them as Frontier Formation.

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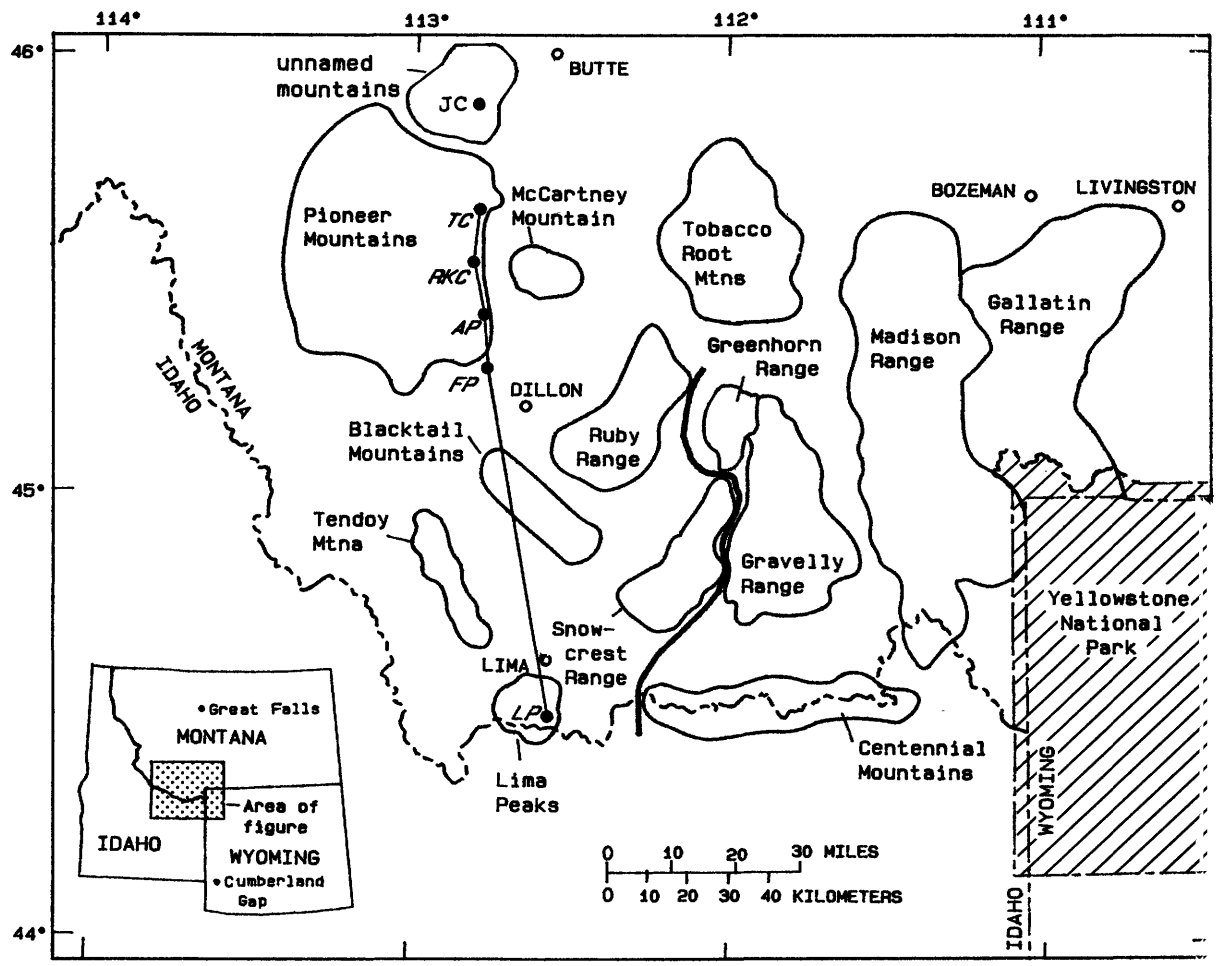

Figure 1.—Index map of southwestern Montana showing mountain ranges, locations of measured sections, and line (heavy) marking geographic position of change in nomenclature between Blackleaf Formation (west) and its lithic equivalents (east). Abbreviations for measured sections are as follows: *LP*, Lima Peaks; *FP*, Frying Pan Gulch; *AP*, Apex; *RKC*, Rock Creek; *TC*, Trapper Creek; JC, Jerry Creek. Section JC not shown on chart.

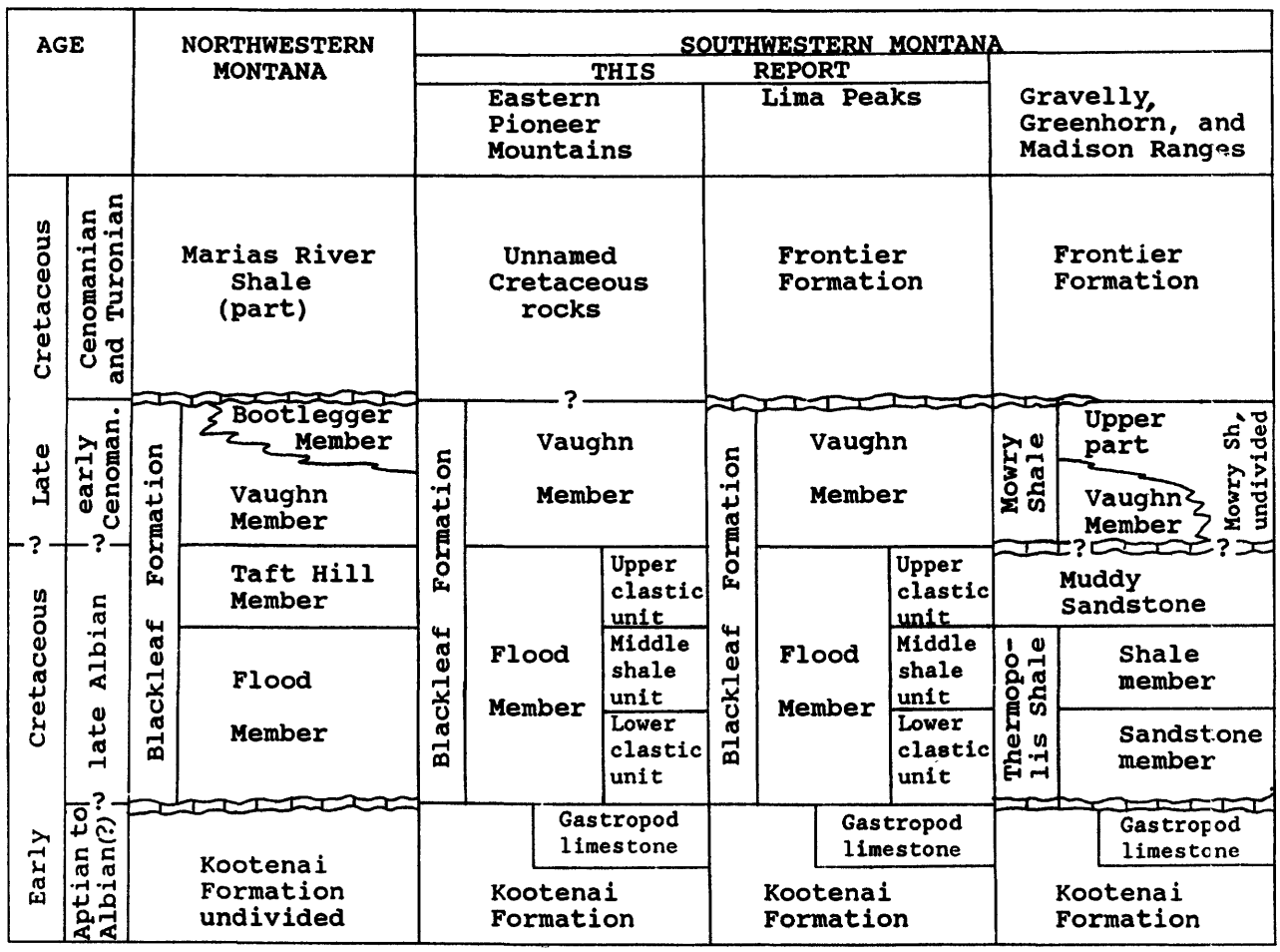

Figure 2.—Correlation chart of Lower and Upper Cretaceous rocks in western Montana. Wavy line used to designate unconformity; vertical lined pattern designates hiatus. Recent work by Cobban and Kennedy (1989, p. 9) indicates that upper part of Mowry Shale may be early Cenomanian in age.

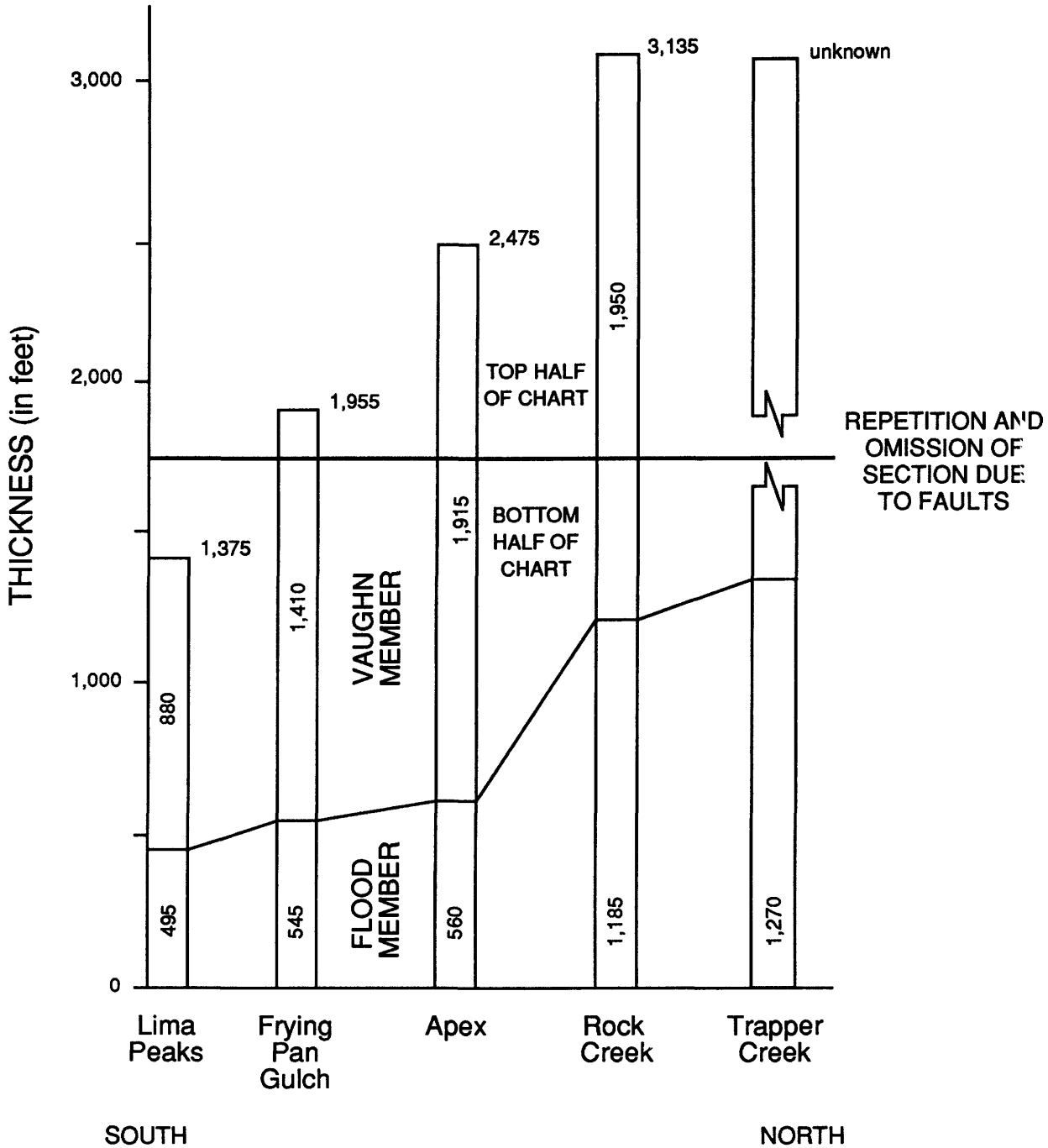

Figure 3.—Diagram showing (1) relative thicknesses of Blackleaf Formation in measured sections of this study and (2) parts of each measured section presented on each half of chart. 1 ft = 0.3048 m.