MONTANA STATE UNIVERSITY

Alluvial fan and fluvial interaction in a foreland basin wedge-top depozone : Upper Cretaceous Beaverhead Group, SW Montana

by Susan Leslie Dougherty

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University
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Abstract:
Intertonguing Knob Mountain and Divide conglomerate lithosomes of the Upper Cretaceous Beaverhead Group document the interaction between distinct alluvial fan and fluvial depositional environments during the evolution of the Tendoy thrust in the Knob Mountain area, southwest Montana. The sedimentology, provenance, and stratigraphic relations of conglomerate lithosomes comprising the wedge-top deposits on this frontal thrust sheet were studied to discern the role of local versus distal deformation in the thrust belt and to document the migration and interaction of two major depositional facies belts over time.

The Knob Mountain conglomerate lithosome comprises primarily limestone clasts derived from folded Pennsylvanian through Triassic strata on the hanging wall of the Tendoy thrust. Lithofacies types, bed geometry, and bed relations indicate that the poorly-sorted, massive conglomerates were deposited by clast-rich debris flows and hyperconcentrated flows in an alluvial fan environment. Conglomerates of the Divide lithosome, although dominated by well-rounded quartzite clasts, are more varied compositionally, suggesting derivation from a larger, integrated drainage basin encompassing many thrust sheets west of the area. Lithofacies analysis of the Divide conglomerate lithosome indicates the bimodally-sorted, massive, and imbricated conglomerates were deposited as gravel bars in a high-energy braided-stream environment. The Gallagher Spring conglomerate lithosome, a third, isolated lithosome also situated on the Tendoy thrust plate near the Knob Mountain area, comprises poorly-sorted, massive conglomerate beds dominated by Pennsylvanian Quadrant sandstone clasts. Although limited in exposure, an alluvial-fan depositional environment for the Gallagher Spring conglomerates is interpreted based primarily on the sorting and bed geometry of the conglomerate beds.

Conglomerate beds with both rounded quartzite and angular limestone clasts are found in the Knob Mountain and Divide conglomerate lithosomes where they intertongue. Poorly-sorted mixed-clast conglomerates were deposited as debris flows in two possible settings: 1) on the alluvial fan as quartzite-clast conglomerate was incorporated into the growing fold resulting from movement on the Tendoy thrust, or 2) immediately adjacent to the braided stream as slumped terrace deposits. Bimodally-sorted, mixed-clast conglomerates of the Divide lithosome were reworked by the braided stream as debris flows flowed directly into the stream and/or as the stream eroded the toes of prograding fans.

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	iv
LIST OF TABLES	ix
LIST OF FIGURES	x
LIST OF PLATES	xiii
ABSTRACT	xiv
INTRODUCTION	1
Purpose of Study	5
GEOLOGIC SETTING	6
Beaverhead Group Stratigraphy	6
Tectonic Setting	12
Foreland Basin Setting	15
Study Area	17
METHODS	20
Lithofacies Analysis	20
Composition	22
Paleocurrent	23
KNOB MOUNTAIN CONGLOMERATE LITHOSOME	24
Lithofacies	24
Massive, Clast-supported Conglomerate (*Gm, Gmr, Gmi*)	24
Description	24
Interpretation	27

TABLE OF CONTENTS - continued

	Page
Massive, Matrix-supported Conglomerate (*Gms, Gmsr*)	29
Description	29
Interpretation	32
Horizontally Stratified Conglomerate (*Gh*)	33
Description	33
Interpretation	33
Massive Sandstone (*Sm, Smg, Smgr*)	33
Description	33
Interpretation	35
Stratified Sandstone (*Sh, Shg, Sl, Sr_1*)	37
Description	37
Interpretation	40
Mudrock (*Fm, Fl*)	42
Description	42
Interpretation	43
Lithofacies Assemblage	43
Depositional Environment	47
Provenance	48
Composition	48
Paleocurrent Indicators	50
Source of Knob Mountain Limestone Conglomerate Lithosome	51

TABLE OF CONTENTS - continued

	Page
DIVIDE CONGLOMERATE LITHOSOME	55
Lithofacies	55
Massive, Bimodal Conglomerate (*Gmb, Gmib*)	55
Description	55
Interpretation	55
Stratified Conglomerate (*Gh, Gp*)	58
Description	58
Interpretation	60
Massive Sandstone (*Sm*)	61
Description	61
Interpretation	61
Stratified Sandstone (*Shg, Sl, Sr_2*)	61
Description	61
Interpretation	62
Lithofacies Assemblage	62
Depositional Environment	66
Provenance	67
Composition	67
Paleocurrent Indicators	68
Source of Divide Quartzite Conglomerate Lithosome	69
INTERTONGUING OF LITHOSOMES	73
Description	73
Interpretation	78

TABLE OF CONTENTS - continued

Page

Knob Mountain Mixed-Clast Conglomerates 79

Divide Mixed-Clast Conglomerates 81

GALLAGHER SPRINGS CONGLOMERATE LITHOSOME 85

Description 85

Interpretation 87

DYNAMIC STRATIGRAPHIC MODEL 88

CONCLUSIONS 96

REFERENCES CITED 98

APPENDICES 105

Appendix A: Location of measured sections 106

Appendix B: Conglomerate clast count data 108

Appendix C: Legend of lithofacies types used in measured sections 110

LIST OF TABLES

Table		Page
1.	Summary of lithofacies and flow types for Knob Mountain conglomerate lithosome	45
2.	Petrofacies of the Knob Mountain conglomerate lithosome	49
3.	Summary of lithofacies and flow types for Divide conglomerate lithosome	65
4.	Petrofacies of the Divide conglomerate lithosome	68
5.	Composition, roundness, and depositional process of the mixed-clast petrofacies	78
6.	Clast composition of conglomerates at Gallagher Spring	87
7.	Conglomerate clast count data from Knob Mountain and Gallagher Spring areas	108

LIST OF FIGURES

Figure		Page
1.	Location map of Sevier thrust belt, Laramide foreland, and the distribution of Upper Cretaceous Beaverhead Group in southwest Montana	2
2.	Simplified geologic map of Knob Mountain and Gallagher Spring study area	4
3.	Generalized stratigraphic diagram showing chronostratigraphic relations between various conglomeratic units of the Beaverhead Group in southwest Montana	7
4.	View of Lima Peaks, northeast of study area	10
5.	View from study area toward the northwest	11
6.	Simplified tectonic map of the region surrounding Lima, Montana showing major thrust faults of the Sevier thrust belt and Laramide-style Blacktail-Snowcrest uplift	13
7.	Schematic diagram of a foreland basin system	16
8.	Topographic profile of the east flank of the Thumb, Knob Mountain study area	18
9.	Massive, poorly-sorted conglomerate (*Gm*) from section A (at base), Knob Mountain conglomerate lithosome	25
10.	*Gm* bed with outsized boulder from east Thumb transect (site 9), Knob Mountain conglomerate lithosome	26
11.	Lobate *Gms* bed from measured section B_1 (67.25 m above base), Knob Mountain conglomerate lithosome	30
12.	Clast-poor *Gms* bed from the east Thumb transect (site 6), Knob Mountain conglomerate lithosome	31
13.	Stratified bed of cobbles, pebbles, and sand (*Gh*) from Irving Creek (Canyon 1), Knob Mountain limestone conglomerate lithosome	34

LIST OF FIGURES - continued

Page

14. Massive, gravelly sandstone (*Smg*), massive sandstone (*Sm*), and massive conglomerate (*Gm*) beds from east Thumb transect (site 4), Knob Mountain conglomerate lithosome 36

15. Horizontally stratified sandstone with granules (*Shg*) from east Thumb transect (site 8), Knob Mountain conglomerate lithosome 38

16. Low-angle, cross-stratified sandstone (*Sl*) from measured section B_4 (150.35 m above base), Knob Mountain conglomerate lithosome 39

17. Isolated sets of ripple cross-lamination (Sr_1) from Irving Creek, Knob Mountain conglomerate lithosome 41

18. Pre-Beaverhead strata on the hanging wall of the Tendoy thrust near Lima Peaks 52

19. Massive, bimodally-sorted conglomerate (*Gmb*) from Irving Creek (Canyon 1), Divide conglomerate lithosome 56

20. *Gmib* from measured section D (at base), Divide conglomerate lithosome 57

21. *Gp* bed from measured section D (32.5 m above base), Divide conglomerate lithosome 59

22. Coset of ripple cross-laminated sandstone (Sr_2) from Irving Creek (Canyon 1), Divide conglomerate lithosome 63

23. Orientation of major paleorivers during Late Cretaceous and early Tertiary Beaverhead Divide conglomerate, Harebell Formation and Pinyon Conglomerate deposition 71

24. Schematic cross section showing the intertonguing relation between the Knob Mountain conglomerate lithosome (north) to Divide conglomerate lithosome (south), and the presence of both mixed petrofacies 75

25. Poorly sorted, mixed-clast conglomerate of the Knob Mountain conglomerate lithosome from Irving Creek 76

26. Bi-modally-sorted, imbricated mixed-clast conglomerate of the Divide conglomerate lithosome from measured section D (46.35 m) 77

LIST OF FIGURES - continued

Page

27. Schematic diagram showing debris flows sourced by detritus from uplifted braided stream deposits mixed with detritus derived from the drainage basin 80

28. Schematic figure showing terraces comprising intertongued alluvial fan and braided stream deposits slumping to produce poorly-sorted, mixed-clast deposits 82

29. Schematic diagram showing a debris flow overrunning the toe of the alluvial fan and directly delivering detritus from the fan source area to an adjacent stream 84

30. Schematic diagram showing a stream eroding the toe of an alluvial fan resulting in the addition of fan source-area detritus to braided stream deposits 84

31. Massive, poorly-sorted conglomerate (*Gm*) in the Gallagher Spring conglomerate lithosome 86

32. Schematic diagram showing the position of the paleoriver that deposited the Frontier and Divide quartzite conglomerate lithosomes near or after Turonian time 91

33. Schematic diagram showing the interaction between the debris-flow-dominated alluvial-fan environment and shallow, gravelly braided stream environment due to the migration of the two depositional facies away from the growing hanging-wall anticline 92

34. Legend of lithofacies types used in measured stratigraphic sections 111

LIST OF PLATES

Plate

1. Geologic map of Knob Mountain study area ..... back pocket

2. Section A ..... back pocket

3. Section B_1 ..... back pocket

4. Section B_2 ..... back pocket

5. Section B_3 ..... back pocket

6. Section B_4 ..... back pocket

7. Section C ..... back pocket

8. Section D ..... back pocket

ABSTRACT

Intertonguing Knob Mountain and Divide conglomerate lithosomes of the Upper Cretaceous Beaverhead Group document the interaction between distinct alluvial fan and fluvial depositional environments during the evolution of the Tendoy thrust in the Knob Mountain area, southwest Montana. The sedimentology, provenance, and stratigraphic relations of conglomerate lithosomes comprising the wedge-top deposits on this frontal thrust sheet were studied to discern the role of local versus distal deformation in the thrust belt and to document the migration and interaction of two major depositional facies belts over time.

The Knob Mountain conglomerate lithosome comprises primarily limestone clasts derived from folded Pennsylvanian through Triassic strata on the hanging wall of the Tendoy thrust. Lithofacies types, bed geometry, and bed relations indicate that the poorly-sorted, massive conglomerates were deposited by clast-rich debris flows and hyperconcentrated flows in an alluvial fan environment. Conglomerates of the Divide lithosome, although dominated by well-rounded quartzite clasts, are more varied compositionally, suggesting derivation from a larger, integrated drainage basin encompassing many thrust sheets west of the area. Lithofacies analysis of the Divide conglomerate lithosome indicates the bimodally-sorted, massive, and imbricated conglomerates were deposited as gravel bars in a high-energy braided-stream environment. The Gallagher Spring conglomerate lithosome, a third, isolated lithosome also situated on the Tendoy thrust plate near the Knob Mountain area, comprises poorly-sorted, massive conglomerate beds dominated by Pennsylvanian Quadrant sandstone clasts. Although limited in exposure, an alluvial-fan depositional environment for the Gallagher Spring conglomerates is interpreted based primarily on the sorting and bed geometry of the conglomerate beds.

Conglomerate beds with both rounded quartzite and angular limestone clasts are found in the Knob Mountain and Divide conglomerate lithosomes where they intertongue. Poorly-sorted mixed-clast conglomerates were deposited as debris flows in two possible settings: 1) on the alluvial fan as quartzite-clast conglomerate was incorporated into the growing fold resulting from movement on the Tendoy thrust, or 2) immediately adjacent to the braided stream as slumped terrace deposits. Bimodally-sorted, mixed-clast conglomerates of the Divide lithosome were reworked by the braided stream as debris flows flowed directly into the stream and/or as the stream eroded the toes of prograding fans.

INTRODUCTION

Alluvial drainage basins within active thrust belts can be divided into regions of erosion, sediment transport, and sediment accumulation (Damanti, 1993). Clastic sediment eroded from the thrust belt is transported to wedge-top (behind the frontal thrust) or foredeep (between frontal thrust and forebulge) depozones of the foreland basin system by integrated fluvial systems or localized alluvial fans (DeCelles and Giles, 1996). Fluvial drainage basins are large and drain multiple thrust plates; therefore, fluvial deposits document the evolution of major features in the thrust belt such as transverse structural elements (Lawton et al., 1994; Vincent and Elliott, 1997) and the growth of structural culminations (DeCelles et al., 1995). Drainage basins of alluvial fans occupy smaller portions of thrust belts; thus, alluvial fan deposits document the evolution of local structural features such as fault-bend or fault-propagation folds (Pivnik, 1990). Piggyback basins, due to their location on active thrusts (Ori and Friend, 1984), are components of the wedge-top depozone and comprise synorogenic deposits that typically record activity of the underlying thrust wedge (DeCelles and Giles, 1996).

In the Montana-Idaho portion of the Cordilleran thrust belt, the Upper Cretaceous Beaverhead Group records synorogenic deposition during Sevier and Laramide contraction (Figure 1). The Beaverhead Group is composed of conglomerate and interbedded sandstone, mudstone, and minor lacustrine limestone deposited in the wedge-top and foredeep depozones. Conglomerate clast composition generally is dominated by either limestone or quartzite clasts and is one of the main criteria for separating the Beaverhead into stratigraphic units. Previous studies of the Beaverhead Group have interpreted some limestone-clast conglomerates (e.g. Red Butte, McKnight

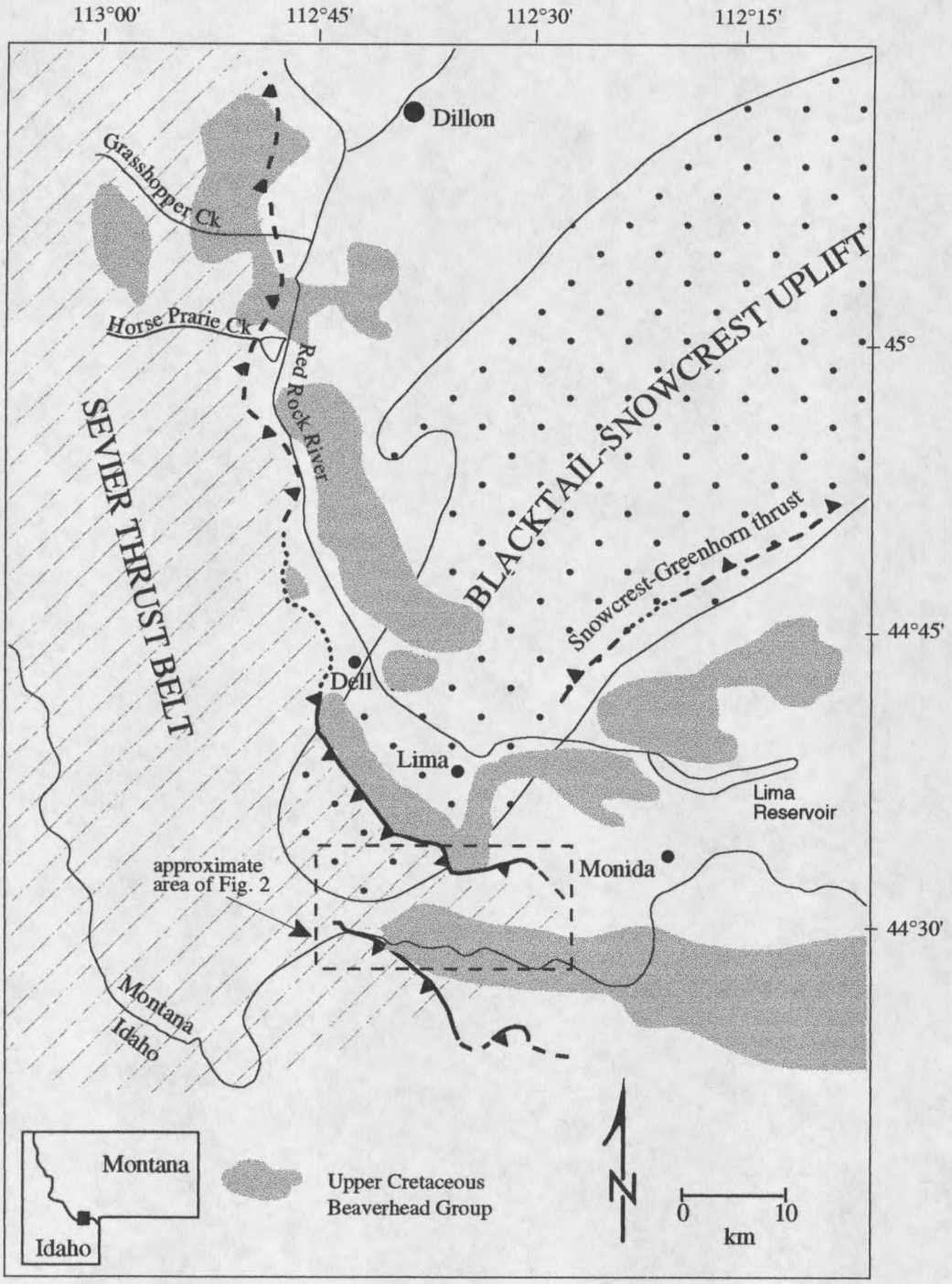


Figure 1: Location map of Sevier thrust belt, Laramide foreland (Blacktail-Snowcrest uplift), and the distribution of Upper Cretaceous Beaverhead Group in southwest Montana (after Lowell and Klepper, 1953; Haley, 1986; Perry et al., 1988)

Canyon, Grasshopper Creek) as alluvial-fan sediments derived from local uplifts (Haley, 1986; Haley and Perry, 1991; Azevedo, 1993). A braided stream environment has been proposed for the quartzite-clast conglomerates (Ryder and Scholten, 1973; Haley, 1986), although detailed sedimentologic studies are lacking due to poor outcrop exposure.

At Knob Mountain, located west of Monida, Montana on the Continental Divide along the Montana and Idaho border, Beaverhead Group conglomerate crops out on the hanging wall of the frontal thrust (Figure 2). Here, a limestone-clast conglomerate lithosome (Knob Mountain) intertongues with a quartzite-clast conglomerate lithosome (Divide), providing an excellent opportunity to ascertain the depositional environments of each lithosome and study a rare exposure of intertongued deposits which represent the marginal environment where the deposits of fluvial and alluvial fan environments interfinger. An isolated exposure of Beaverhead sandstone-clast conglomerate in the Gallagher Spring area (Figure 2) is included in this study due to its similar structural position on the hanging wall of the frontal thrust and proximity to the two major lithosomes exposed in the Knob Mountain area.

Depositional environments for the three conglomerate lithosomes were interpreted by lithofacies analysis which identifies the hydraulic and depositional processes that prevailed during deposition. Provenance studies were used to ascertain sediment dispersal patterns and the role of local versus distant sources. The migration of depositional environments, documented by change in depositional processes and clast provenance, records the growth of a local fold in this wedge-top depozone of the foreland basin.

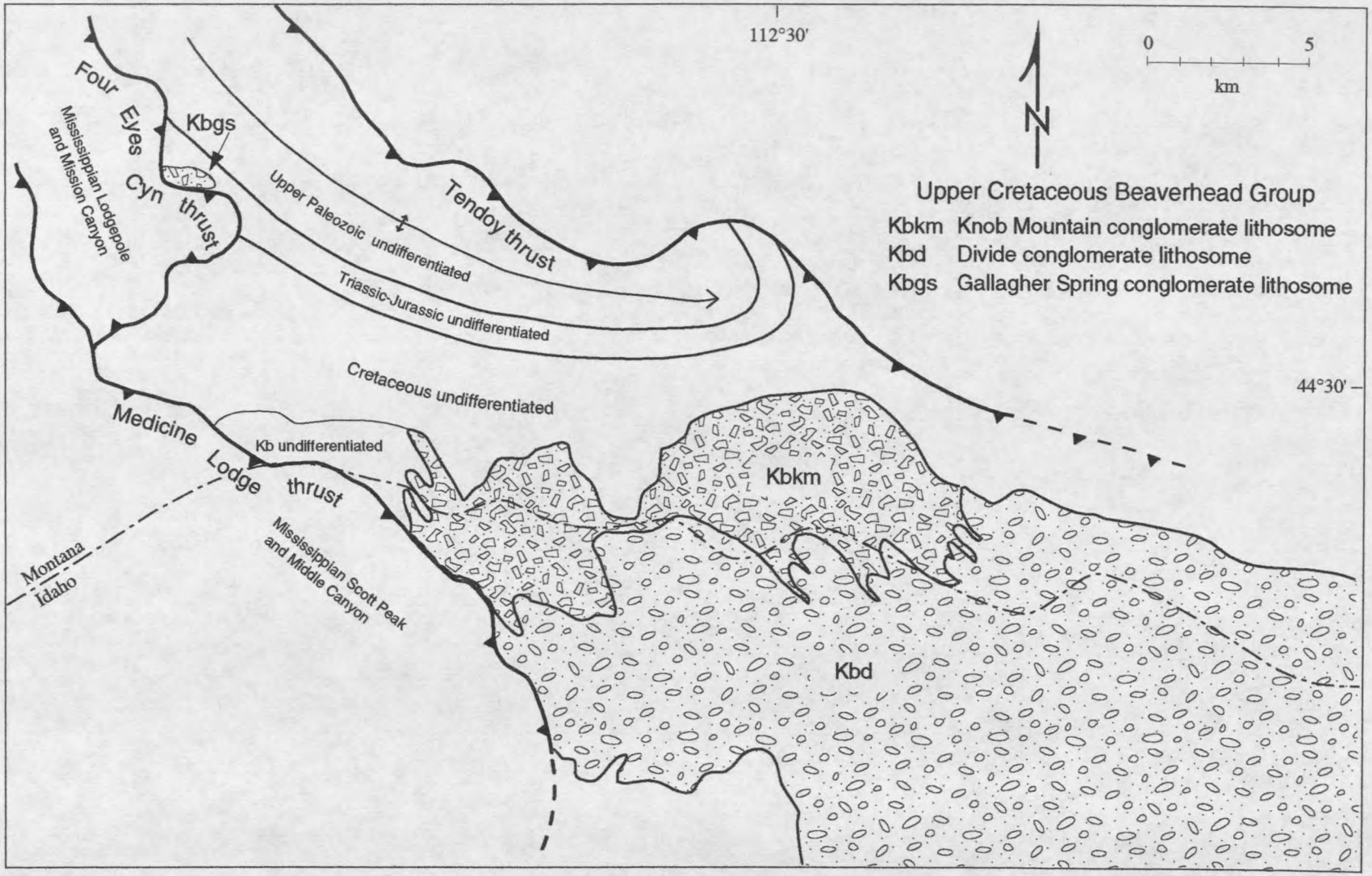


Figure 2 : Simplified geologic map of Knob Mountain and Gallagher Spring study area (after Ryder and Scholten, 1973; Haley, 1986)

Purpose of Study

The major questions addressed by this study are:

1. What are the depositional environments of the limestone-clast (Knob Mountain), quartzite-clast (Divide), and sandstone-clast (Gallagher Spring) lithosomes? What depositional processes are evident based on the physical characteristics, relations between beds, and geometry of beds of the conglomerate, sandstone, and mudstone present in the Knob Mountain area?
2. What is the provenance of the clasts in the limestone-, quartzite-, and sandstone-clast conglomerate lithosomes? Are the clasts locally derived and, if so, was sediment transport antithetic or synthetic to the overall tectonic transport direction?
3. What is the significance of the intertonguing of the limestone-clast and quartzite-clast lithosomes in the Knob Mountain area? Do the intertonguing relations between the two lithosomes record a shift or migration of depositional margins due to active tectonism?
4. Is there evidence for syndepositional, basin margin deformation recorded in alluvial fan deposits which are located in this wedge-top piggyback basin?

GEOLOGIC SETTING

Beaverhead Group Stratigraphy

The Upper Cretaceous-early Tertiary Beaverhead Formation was first described by Lowell and Klepper (1953) with the type section exposed at McKnight Canyon, 10 km west of Dell, Montana. Ryder and Sholten (1973) identified other Beaverhead rocks in southwest Montana using the same nomenclature. The Beaverhead Formation was later raised to group status by Nichols et al. (1985). The Beaverhead Group was deposited from Coniacian (the Monida sandstones, reinstated to the Beaverhead Group by Perry et al., 1988) through Maastrichtian time and possibly into the early Paleocene (Red Butte Conglomerate of Haley and Perry, 1991) (Figure 3). Formations currently recognized within the Beaverhead Group are the Lima Conglomerate and Red Butte Conglomerate (Nichols et al., 1985).

The Beaverhead Group comprises a complex assemblage of conglomerate and sandstone lithosomes derived from a wide-range of both foreland and thrust belt uplifts (Ryder and Sholten, 1973; Haley, 1986; Azevedo, 1993). The term *lithosome* refers to three-dimensional lithostratigraphic units described by uniform physical characteristics which are the result of particular conditions in a depositional environment (Boggs, 1987, p. 524-525). The Beaverhead Group is not completely divided into formalized units; therefore, lithosome is a useful term that refers to the various conglomerate bodies distributed in the thrust belt and foreland regions.

Previous workers subdivided Beaverhead conglomerates into lithosomes based primarily on the dominance of either quartzite or limestone clasts and the age of the

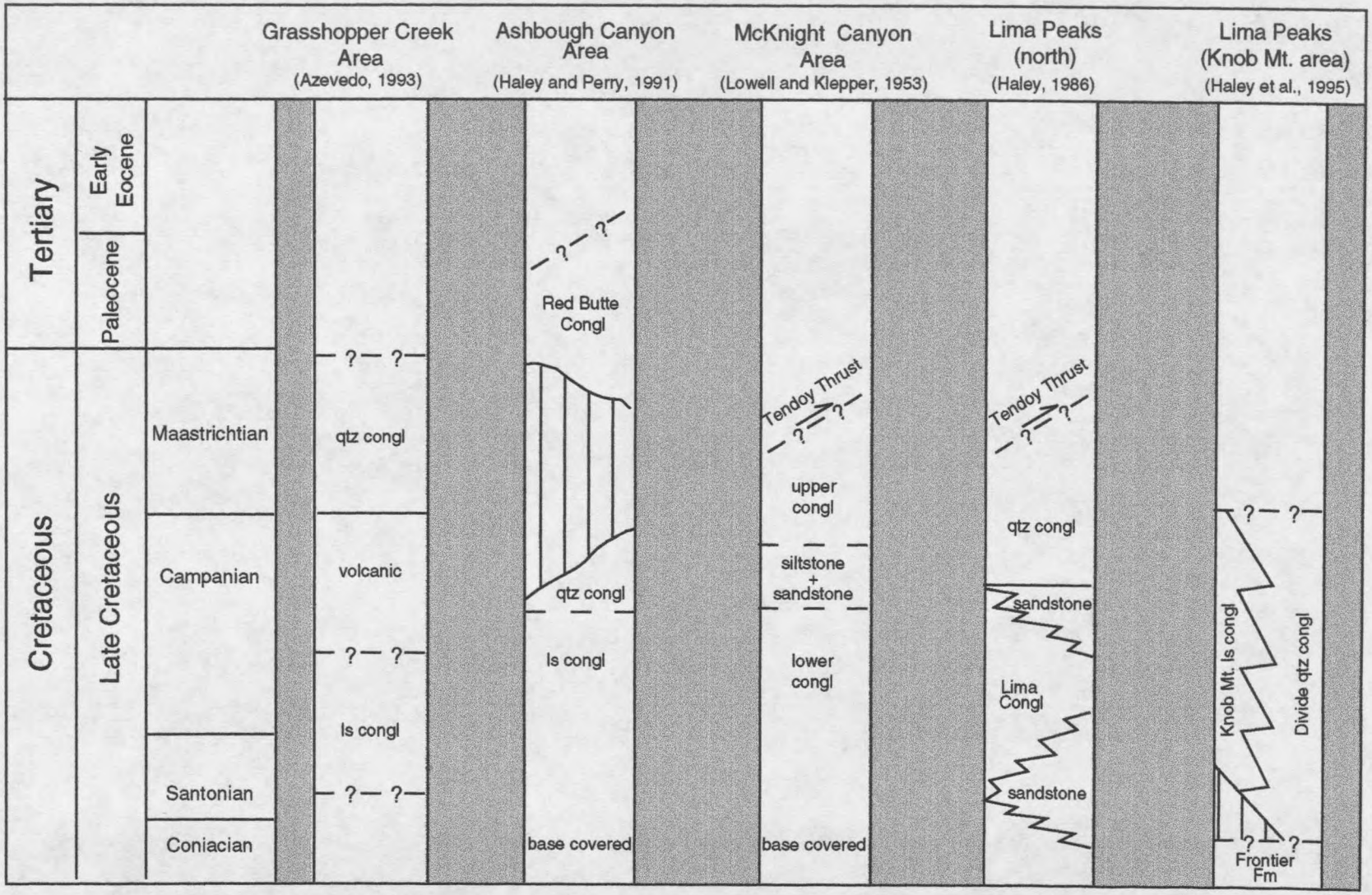


Figure 3: Generalized stratigraphic diagram showing chronostratigraphic relations between Beaverhead Group units in southwest Montana (after Schmitt et al., 1995).

limestone clasts (e.g., Ryder and Scholten, 1973). Well-rounded quartzite clasts were derived from Proterozoic, Cambrian, and possibly Ordovician sources (Lindsey, 1972; Ryder and Scholten, 1973; Haley, 1986). The source of limestone clasts varies widely from mid-Paleozoic to mid-Mesozoic rocks (Ryder and Scholten, 1973; Haley, 1986; Haley and Perry, 1991). The anomalous Red Butte conglomerates contain both quartzite and limestone clasts with an additional component of recycled Beaverhead conglomerate clasts (Haley and Perry, 1991).

Chronostratigraphic relations between the various Beaverhead units are not thoroughly understood. Lateral discontinuity of Beaverhead Group lithosomes is due in part to the derivation of most of the rock units from localized uplifts (Figure 1). For example, the Lima Conglomerate, Red Butte Conglomerate, and conglomerates at McKnight Canyon were all shed from different source areas at different times (Nichols et al., 1985). Furthermore, Beaverhead Group conglomerates are synorogenic in origin; during deposition detritus has been, in some locations, overridden and dismembered by thrusts. Subsequent Cenozoic extension has disrupted thrust belt and foreland basin strata in southwest Montana separating exposures of some conglomerate units by normal faults and graben valleys (Skipp et al., 1979; Haley, 1986). Lastly, ages of the various conglomerate units are difficult to establish because fossil evidence is scarce in these coarse-grained deposits. Reliable palynological data are rare due to a high degree of post-depositional oxidization (Nichols et al., 1985).

Two progressive unconformities have been recognized in Beaverhead Group conglomerates. These intrabasinal features document syndepositional basin-margin deformation and, in combination with provenance and lithofacies analysis, help identify source regions. One progressive unconformity is located in the Grasshopper Creek Canyon area, south of Dillon (Azevedo, 1993; Schmitt et al., 1995) (Figure 1) and documents the growth of the nearby Madigan Gulch anticline. Another progressive

unconformity has been proposed by Dyman et al. (1995) in the Knob Mountain area, although in this case the underlying Frontier Formation is included in the cumulative wedge system. The contact between the Frontier Formation and Beaverhead Group conglomerate is an angular unconformity in the northern portion of the Knob Mountain area which may gradually change southward to a conformable surface.

In the study area, the limestone-clast conglomerate, which makes up the rugged peaks of Red Conglomerate Peaks, Knob Mountain and the Thumb, is referred to as the Knob Mountain limestone conglomerate lithosome (Plate 1). It is characterized by very poorly-sorted conglomerate with rough, angular limestone clasts. The limestone-clast conglomerate is interbedded with minor quartzarenite and mudstone. The low, rolling hills in the study area are typically underlain by the Divide quartzite conglomerate lithosome, which is characterized by conglomerate with polished, well-rounded quartzite clasts in a well-sorted sand matrix (Plate 1). These poorly-cemented quartzite-clast conglomerates are interbedded with litharenite and are well-exposed only where the Knob Mountain and Divide lithosomes intertongue. The Gallagher Spring sandstone-clast conglomerate lithosome, containing angular, silica-cemented quartzarenite clasts, is exposed in small cliffs just beneath the Four Eyes Canyon thrust near Gallagher Spring (Figure 2).

Beaverhead Group rocks in the Knob Mountain area overlie the Lower Cretaceous Kootenai and Blackleaf Formations with angular discordance (Skipp, 1979; Haley, 1986; Skipp and Link, 1992) (Plate 1; Figure 4, 5). The Knob Mountain limestone conglomerate lithosome also overlies the Frontier Formation both conformably and unconformably, depending on location (Dyman et al., 1995). The Divide quartzite conglomerate lithosome conformably overlies a similar quartzite-clast conglomerate of the Frontier Formation south of the study area (Dyman et al., 1995). The Gallagher Spring conglomerate rests unconformably on lower Triassic rocks. The



Figure 4: View of Lima Peaks, northeast of study area. Ruby Range is in distant backround. The hanging-wall anticline, cored by Pennsylvanian Quadrant sandstone (exposed in unvegetated ridge of Lima Peaks), plunges toward the upper right corner of the photo; steeply dipping Permian Phosphoria through Lower Cretaceous Blackleaf strata are exposed southward (right) of Lima Peaks.



Figure 5: View from study area toward the northwest. Steeply dipping Pennsylvanian through Lower Cretaceous strata are clearly overlain by southwest-dipping Knob Mountain limestone conglomerate (in foreground) in angular discordance. Garfield Mountain is peak on right.

upper portion of the Knob Mountain, Divide, and Gallagher Spring conglomerate lithosomes in the western part of the study area has been removed by either the Medicine Lodge or Four Eyes Canyon thrust. Elsewhere, all three conglomerate lithosomes are incised by the present erosion surface.

Tectonic Setting

The Montana-Idaho thrust belt extends from the region north of the Snake River Plain in Idaho to the Lewis thrust system in northern Montana. Thin-skinned, Sevier-style structures generally trend northwest-southeast in the area of Lima, Montana (Figure 6). Local thrusts include, from west to east, the Fritz Creek, Cabin, Medicine Lodge, Four Eyes Canyon, and Tendoy, and all show east-northeast tectonic transport (Perry et al., 1988; Skipp, 1988; Sterne, 1996). Two wells drilled in 1975-76 east of the Tendoy thrust (Farmers Union 9-31 Lima and 2-33 Lima) reveal a complexly faulted subsurface anticline (the Lima anticline) interpreted by Perry and Sando (1983) to be cored by a frontal blind thrust associated with the fold and thrust belt. Thick-skinned, Laramide-style structures of the basement-involved Blacktail-Snowcrest uplift generally trend northeast-southwest, orthogonal to the trend of Sevier structures. In southwest Montana, these two styles of deformation overlapped spatially and temporally (Perry et al., 1988) (Figure 1).

Skipp (1988) proposes that the Cabin and Medicine Lodge allochthons have been transported approximately 40 km to the northeast with the Cabin thrust overriding the Medicine Lodge thrust during later stages of emplacement. Other workers (Perry et al., 1988; Sterne, 1996) treat the Fritz Creek, Cabin, Medicine Lodge, and Four Eyes Canyon thrusts together as a thrust system, with significantly greater cumulative transport (perhaps up to 218 km) relative to the Tendoy. The Tendoy thrust carries

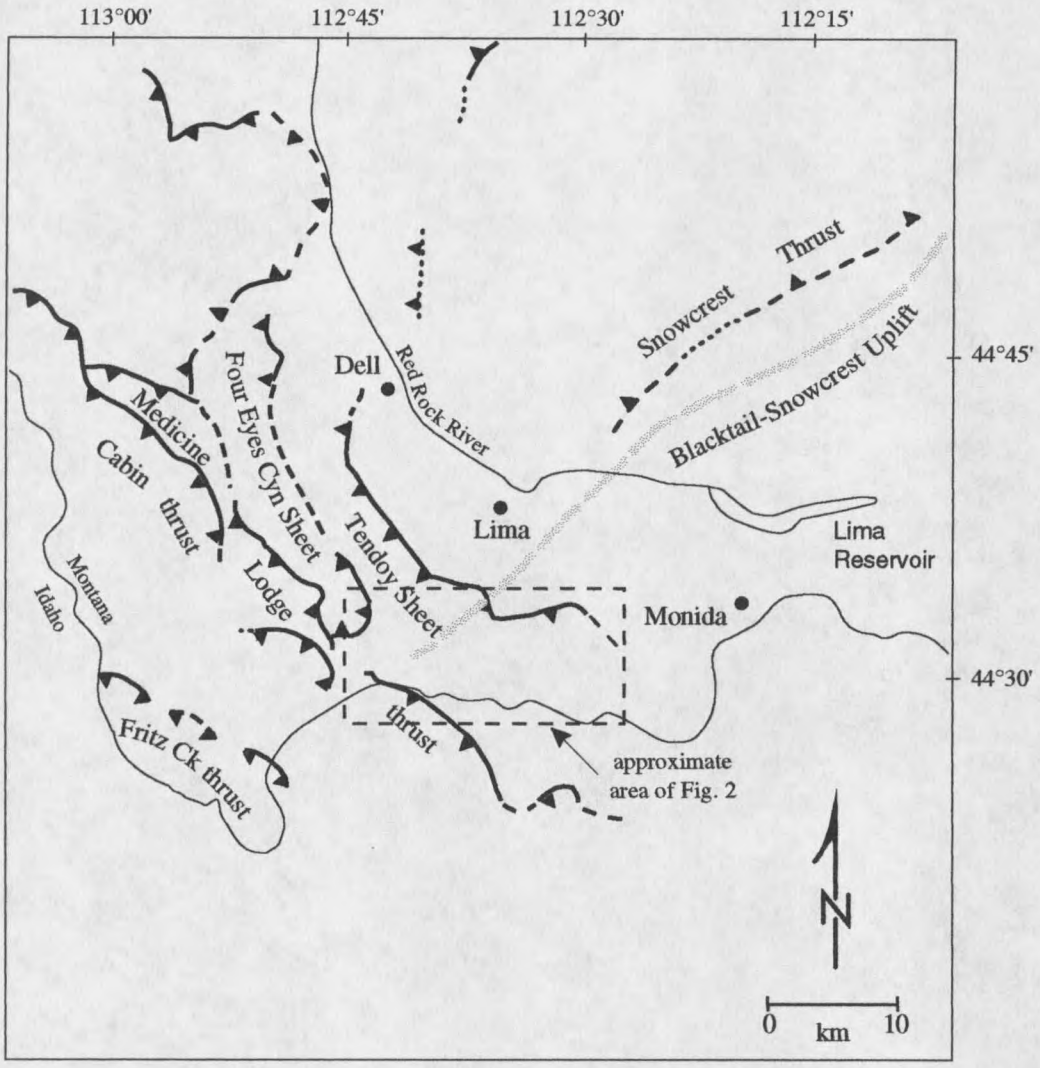


Figure 6: Simplified tectonic map of the region surrounding Lima, Montana showing major thurst faults of the Sevier thrust belt (Fritz Creek Cabin, Medicine Lodge, Four Eyes Canyon, Tendoy thrusts) and Laramide-style Blacktail-Snowcrest uplift (after Perry et al., 1988).

rocks of Cretaceous to Pennsylvanian age over Late Cretaceous rocks. Stratigraphic offset of 5 km was proposed by Skipp (1988) for the Tendoy thrust, and 8-10 km of shortening is proposed for the Lima anticline and associated Lima thrust (Perry et al., 1983).

Foreland structures associated with Laramide-style deformation in the Lima area are part of the Blacktail-Snowcrest uplift (Perry et al., 1988) (Figure 6). The Snowcrest-Greenhorn thrust system places Archean gneiss over Paleozoic limestone (Perry et al., 1988) and is projected to extend beneath the thrust belt to the southwest (Kulik and Perry, 1988). In the Lima region, thrust-belt structures cross-cut foreland structures. For example, the Lima conglomerate, derived from the Blacktail-Snowcrest uplift and dated as mid-Campanian, is overridden by the Tendoy thrust near the Lima Peaks area (Wilson, 1970; Haley and Perry, 1991). Both Skipp (1988) and Perry et al. (1988) interpret changes in strike of Sevier thrusts and general disruption of thrust sheets west of the Tendoy thrust as further evidence of the influence of foreland deformation on thrust-belt structures.

Since the mid-Tertiary, this segment of the Montana-Idaho thrust-belt region has undergone multiple episodes of extension (Janecke, 1994). The prominent northwest-southeast trending Red Rock normal fault dissects the Red Butte Formation in the Lima area (Haley and Perry, 1991). Several normal faults cut the Beaverhead rocks in the Knob Mountain area; major faults in the study area have northwest trends parallel to the thrust belt and minor normal faults trend northeast-southwest (Skipp et al., 1979).

The Knob Mountain limestone, Divide quartzite, and Gallagher Spring sandstone conglomerate lithosomes structurally are on the hanging wall of the Tendoy thrust and, therefore, lie within the orogenic wedge of the thrust belt. The Knob Mountain and Gallagher Spring conglomerate lithosomes were deposited on the flanks

of a prominent, steep-limbed, southeast-plunging anticline (and associated small, upright, and overturned folds) involving Pennsylvanian Quadrant sandstone through Cretaceous Blackleaf shale (Figure 2, 4, 5). As mentioned previously, the Knob Mountain and Divide conglomerate lithosomes are overridden by the Medicine Lodge thrust, and the Gallagher spring conglomerate lithosome is cut by the Four Eyes Canyon thrust.

Foreland Basin Setting

Sedimentation related to thrust-belt deformation occurs in four depozones within a foreland basin system: wedge-top, foredeep, forebulge, or back-bulge (Figure 7) (DeCelles and Giles, 1996). Wedge-top depozones overlie the frontal part of the orogenic wedge and are characterized by coarse-grained sediment, numerous local and regional unconformities, and syndepositional deformation. The foredeep depozone, a rapidly subsiding region in front of the orogenic wedge, accumulates sediment derived primarily from the thrust belt via transverse and longitudinal fluvial systems. Because thrust belts typically migrate toward the foreland, the four depozones will also migrate. The type of depozone is determined by its position at the time of deposition rather than by its location after possible subsequent migration. This convention is necessary if these synorogenic deposits are to be useful in interpreting the evolution of deformation as well as the subsidence history of the thrust belt (DeCelles and Giles, 1996).

Beaverhead Group conglomerates in this study, due to their coarse-grained character and structural position on the hangingwall of the frontal thrust (Tendoy thrust), were deposited in either the wedge-top depozone or a complex, foredeep depozone partitioned by Laramide-style deformation. Provenance and sedimentologic

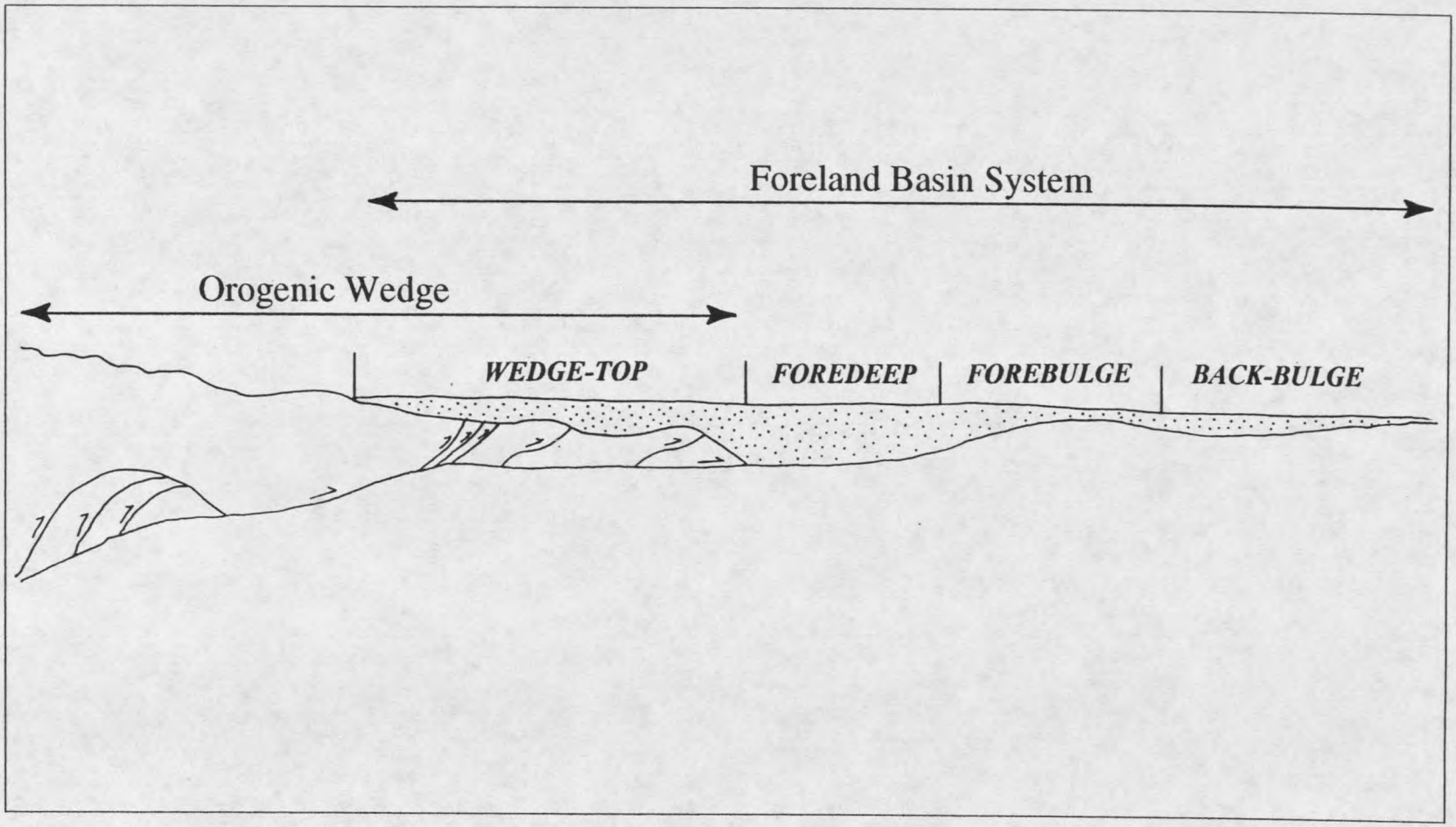


Figure 7: Schematic diagram of a foreland basin system comprising wedge-top, foredeep, forebulge, and back-bulge depozones. Note the orogenic wedge of the thrust belt overlaps the wedge-top depozone of the foreland basin system (after DeCelles and Giles, 1996).

evidence presented in this report suggest the depositional setting for the three conglomerate lithosomes was on the Tendoy thrust sheet and, therefore, within the orogenic wedge.

Study Area

The study area is located in the Sawmill Creek drainage basin in Beaverhead County, Montana and the Bull Pen tributary to the Irving Creek drainage basin in Clark County, Idaho (Plate 1). Seven measured stratigraphic columns were constructed in the study area (Appendix A; Plates 2-8). Six measured sections are in the Knob Mountain limestone conglomerate lithosome (Sections A, B_1, B_2, B_3, B_4, and C), and one section is at Irving Creek (Section D) where the two conglomerate lithosomes interfinger. Measurement of a section in the Divide conglomerate lithosome was not feasible due to the general poor exposure of the Divide where it does not intertongue with the Knob Mountain lithosome.

Field observations also included a transect over part of the northeast flank of the Thumb (Plate 1, Figure 8) beginning in the Frontier Formation to the north and continuing south through the Beaverhead limestone- and quartzite-clast conglomerate lithosomes. Along this transect, subcrops of quartzite-clast conglomerate are mantled by aprons of loose cobbles. At Irving Creek, well-exposed conglomerate beds in a canyon northeast of measured section D were also described; these conglomerates lie within the Knob Mountain and Divide conglomerate lithosome intertonguing zone. Additionally, an isolated occurrence of sandstone-clast conglomerate is located near Gallagher Spring, approximately 16 km northwest of Red Conglomerate Peaks (Figure 2). Although the outcrop is not continuous with the limestone-clast conglomerate lithosome in the Knob Mountain area, the Gallagher Spring conglomerate also rests on

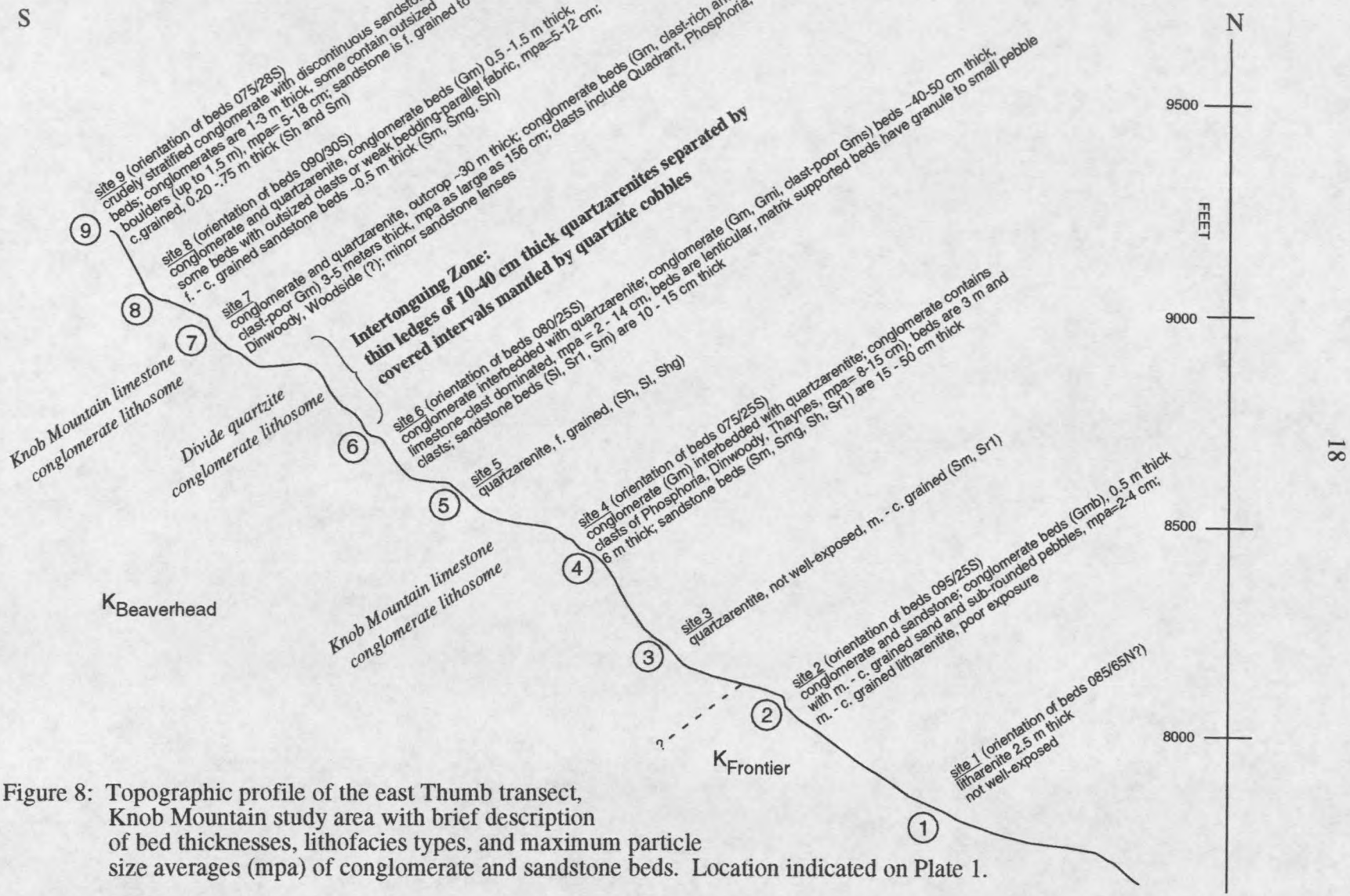


Figure 8: Topographic profile of the east Thumb transect, Knob Mountain study area with brief description of bed thicknesses, lithofacies types, and maximum particle size averages (mpa) of conglomerate and sandstone beds. Location indicated on Plate 1.

the Tendoy thrust hanging wall. Provenance and lithofacies analysis of this limited exposure was included in this study because the depositional history of the Gallagher Spring conglomerate may be related to conglomerate deposition in the main study area.

METHODS

Lithofacies Analysis

Lithofacies types were defined on the basis of grain size, sorting, types of sedimentary structures, and the internal arrangement of grains. Lithofacies codes used in this report are similar to the lithofacies terminology used by Miall (1978), although the code scheme here is modified slightly to accommodate the wide variety of conglomerate in the study area. Beds were categorized by three major grain size classes: gravel (conglomerate), sand (sandstone), or mud (mudrock). Physical characteristics of conglomerate beds were further described by sorting (poorly-sorted or bimodal), internal fabric (massive or stratified), amount of matrix (clast-supported or matrix-supported), and arrangement of framework clasts (disordered or preferentially arranged). Framework clasts were defined as gravel larger than 1 cm. Sandstone and mudrock were classified based on the presence or absence of sedimentary structures such as horizontal or inclined stratification. The first letter of the lithofacies codes in this study denotes grain size (*G* for gravel, *S* for sand, and *F* for fine-grained (mudrock)); the remainder of the code indicates other physical characteristics discussed above (e.g. *Gmib* is used to describe a massive, imbricated conglomerate with bimodal sorting).

Lithofacies analysis included observations of the lateral and vertical relations of differing lithofacies types as well as bed geometry. In some cases, the interpretation of flow process was based on the nature of the lower and upper bounding surfaces

(erosional, gradational, abrupt) in addition to the vertical arrangement of lithofacies types.

Sediment transport mechanisms (e.g. traction transport, suspension), hydrodynamics of transport fluids (e.g. turbulent flow, laminar flow), sediment support mechanisms (e.g. dispersive pressure, buoyancy, matrix support), and depositional processes (selective versus *en masse*) were inferred from the lithofacies types, lithofacies relations, and bed geometry. Interpretation of flow types was based primarily on degree of sorting, but was also supported by the presence or absence of stratification and abundance of mud matrix in the conglomerate beds. Costa (1988) defines three types of flows based on sediment concentration: water floods (1-40% by weight), hyperconcentrated flows (40-70% by weight), or debris flows (70-90% by weight). Sediment concentration fundamentally affects the shear strength of a flow, and the resultant rheologic behavior influences how sediment is deposited (Costa, 1988). Although sediment concentration at the time of deposition cannot be determined for rocks deposited in the Late Cretaceous, the sedimentologic evidence cited above were used to infer the type of flow based on the criteria described by Costa (1988). Basic terms for depositional flow types interpreted in this study are: fluid-gravity, hyperconcentrated, and sediment-gravity.

The assemblage of lithofacies were then considered in the interpretation of the depositional environment for each lithosome. Lithofacies assemblages represent the range of depositional processes operating in a depositional system and help to identify variations within some systems (e.g. shallow gravel-bed braided streams from gravel-sand meandering streams) (Miall, 1996, p. 198-245). Lithofacies analysis also facilitates discernment of depositional environments which can be confused because their deposits are grossly similar (e.g. braided streams and alluvial fans) (Blair and McPherson, 1994b). In this study, hydraulic processes and the resultant sedimentary

deposits in modern alluvial fans and fluvial settings are compared to those recognized in the conglomerates, sandstones, and mudstones of the three lithosomes.

Lithofacies types present in the lithosomes were recorded in the seven stratigraphic sections (Plates 2-8) and east Thumb transect (Figure 8), and were included in additional field observations at Irving Creek and Gallagher Spring. Selection of measured section locations was governed mainly by exposure, and, therefore, the Knob Mountain limestone conglomerate lithosome was described more extensively. All stratigraphic sections were measured with a Jacob staff and Brunton compass. Sections were divided into 1.25 meter intervals, and bed thickness was estimated for beds less than this increment. In addition to lithofacies type, rock descriptions included general clast composition, texture, and maximum particle size averages. Maximum particle size average was obtained by measuring the approximate intermediate length of the five largest clasts in each bed. The maximum particle size average is listed for each bed in the measured sections and indicated in the graphic column.

Composition

Conglomerate clast composition was determined by clast counts at each measured section, the east Thumb transect, Irving Creek, and Gallagher Spring locations. For the measured sections, clast counts were performed near the base, top, and, for sections A and B_4, the middle of the section. Normally, two hundred clasts were counted in an outward spiral pattern; clasts smaller than 1 cm were considered as part of the matrix and not counted. Clast lithology was identified using basic rock terms (e.g. sandstone, limestone, limestone with chert), and formations were noted only if distinctive formation characteristics were observed.

The composition of sandstone interbeds was determined primarily by examining hand samples in the field. Thin sections were made of several sandstone samples to verify composition and to identify lithic fragments. These Beaverhead Group sandstones were classified using the terminology of Folk (1980, p. 127).

Paleocurrents

The sole paleocurrent indicator measurable in the field was clast imbrication. Imbrication is only well-developed in the Divide conglomerate lithosome; therefore, measurements were limited to the Irving Creek area. Imbrication was measured at five locations at Irving Creek by estimating the dip direction of the a-b plane of oblate or platey clasts at the outcrop; three-dimensional measurements of the dip direction were available at only two of these locations. The orientations of ten imbricated cobbles from conglomerate beds in Canyon 1 were plotted on a stereonet and rotated to compensate for structural tilting.

KNOB MOUNTAIN CONGLOMERATE LITHOSOME

Lithofacies

Massive, Clast-supported Conglomerate (*Gm, Gmr, Gmi*)

Description. Massive, poorly-sorted, and unstratified conglomerate (*Gm*) is the most abundant lithofacies type present in the study area. *Gm* conglomerate is clast-supported and framework clasts are disordered (Figure 9). Occasionally, framework clasts are arranged horizontally or parallel to the lower bounding surface; however, not all clasts are preferentially oriented so this fabric is sometimes only expressed weakly and difficult to see. *Gm* beds can contain rare, outsized boulders (Figure 10), or have outsized boulders concentrated at the top of the bed. Some *Gm* beds are crudely stratified with cobbles and pebbles; these beds typically have gradational contacts with other massive conglomerate beds. Coarse-tail reverse grading (*Gmr*) is also present but not abundant. Conglomerate beds with a weakly developed imbricate fabric of framework clasts are also rare (*Gmi*).

Grain size of the matrix ranges from clay to granule, and framework clasts range in size from pebble to boulders as large as 2.5 m; matrix is not readily distinguished from framework clasts. Therefore, *Gm*, *Gmr*, and *Gmi* beds are very poorly-sort. Although these conglomerates are clast-supported, they are not matrix-poor or densely packed. Maximum particle size average of framework clasts ranges from 3 to 99 cm , and clasts are angular to sub-rounded.

Upper and lower bounding surfaces for each of these lithofacies often appears gradational with underlying and overlying beds, although this may be in part due to the



Figure 9: Massive, poorly-sorted conglomerate (*Gm*) from section A (at base), Knob Mountain conglomerate lithosome. Framework clasts are angular to subrounded and are not arranged to show any internal fabric (they are disordered). Both matrix and framework clasts are poorly-sorted; maximum particle size average is 8 cm (pencil is 14 cm long).



Figure 10: *Gm* bed with outsized boulder from east Thumb transect (site 9), Knob Mountain conglomerate lithosome. Outsized sandstone boulder to left of hammer is 110 cm in diameter; maximum particle size average of conglomerate is 18 cm (hammer is 40 cm long).

very poorly-sorted character of the conglomerates and subtle differences in clast orientation. Contacts may be abrupt yet not visually discernible at the outcrop. *Gm, Gmr,* and *Gmi* beds occasionally contain 3 to 10 cm-thick lenses of either fine-grained sandstone or thin mudstone stringers. Beds are rarely laterally continuous for more than 10 m and are sheet-like, wedge-shaped, lobate, or lens-shaped. Beds range in thickness from 10 cm to nearly 16 m.

Interpretation. Due to the unsorted matrix and framework clasts, generally disorganized fabric, and large grain size, these conglomerate units are interpreted as sediment-gravity flow and hyperconcentrated flow deposits. Laterally discontinuous *Gm* units possessing disordered internal fabric may have been deposited by clast-rich, non-cohesive debris flows (Shultz, 1984; Costa, 1988; Blair and McPherson, 1994a). Although the clay content in the matrix is lower than that typically found in matrix-supported conglomerates, only a few percent of clay is needed to prevent the escape of pore fluids, reduce internal friction (Shultz, 1984; Blair and McPherson, 1994a), and enable the mass to flow as a non-Newtonian fluid. *Gm* could also be deposited by high-density floods (hyperconcentrated flood flows) as described by Smith (1986). The dense concentration of clasts may be due to settling during rapid sedimentation in a hyperconcentrated flow with dampened turbulence (Shultz, 1984; Pierson and Costa, 1985). Lack of grading indicates dispersive pressures were not significant (Bagnold, 1954), and lack of well-developed imbrication indicates turbulence was not the only sediment-support mechanism present (Smith, 1986; Costa, 1988; Miall, 1996, p. 101).

Alternatively, *Gm* beds could have been originally deposited with more matrix which was subsequently winnowed out by secondary or post-depositional processes (Sharp and Nobles, 1953; Costa, 1988; Blair and McPherson, 1992, 1994a) producing matrix-free gravel mantle as is common on alluvial fan surfaces (Blair and McPherson,

1994a). Secondary processes that remove fine material from debris flow deposits include runoff associated with the catastrophic flow that deposited the debris flow, reworking of old debris deposits by overland flow not directly related to that which deposited the debris flow, or removal of fine material by wind (Blair and McPherson, 1992). The laterally discontinuous and lobate shape of poorly-sorted, clast-supported conglomerate beds suggest they were originally deposited as cohesive or viscous debris flows which commonly had their matrix removed by subsequent fluid-gravity flow.

Gm beds that contain randomly distributed outsized boulders may be the deposits of debris flows that incorporate talus from the base of steep mountain fronts (Beaty, 1989). In east-central California, large ($\geq$ 10 m) boulders on alluvial fans distributed 1.5 km or more from the canyon mouth are hypothesized to have been shaken loose from jointed bedrock by large magnitude earthquakes and subsequently transported by viscous debris flows down the surface of the fan (Beaty, 1989). *Gm* beds with outsized boulders in the Knob Mountain conglomerate are neither matrix-supported nor clay matrix-rich. Nonetheless, because only a minor amount of clay is necessary to produce a viscous, cohesive flow, it is likely that these units are debris flow deposits. Conversely, it is possible that much of the clay fraction was removed by secondary surficial processes from what was originally a clay-rich deposit.

Deposition by a viscous debris flow can also be inferred for *Gm* beds which have large boulders distributed along the top. Outsized clasts were either supported by matrix strength in a cohesive debris flow (Fisher, 1971; Costa, 1988) or perhaps supported by the buoyancy of a dense matrix (Johnson, 1970, p. 461-490).

Gm beds which also exhibit a weak, bedding-parallel fabric were deposited by the same processes describe above; however the internal fabric suggests laminar flow was prevalent at the time of deposition (Sharp and Noble, 1953; Lindsay, 1968; Fisher,

1971). The horizontal fabric may also be due to clasts jostling in a less viscous debris flow (Lindsay, 1968).

Reverse grading in *Gmr* is a result of dispersive pressures in flows with very high sediment concentrations (Bagnold, 1954; Johnson, 1970, p. 461-463; Fisher, 1971; Costa, 1988). If particle concentrations are high, flow is facilitated by grain-to-grain collisions which disperse grains away from a rigid boundary (base of flow) (Bagnold, 1954, Johnson, 1970, p. 461-163). Large particles tend to drift away from zones of high shear or toward the top of the flow. Therefore, deposits which exhibit reverse grading were deposited by clast-rich, non-cohesive debris flows where grain-to-grain interaction was a significant grain-support mechanism (Johnson, 1970, p. 461-463; Smith, 1986; Boggs, 1987, p. 58-59; Miall, 1996, p. 105).

Imbrication in *Gmi* conglomerates is probably not due to turbulent flow because it is not well-developed (Smith, 1986; Costa, 1988; Miall, 1996, p. 101). Weak imbrication can result from dampened turbulence in hyperconcentrated flows (Smith, 1986; Costa, 1988). Imbrication may also result from a shingling or close-packing effect at the edge of a debris flow where large clasts are concentrated along the flow margins (Sharp and Nobles, 1953; Blair, 1987).

Massive, Matrix-supported Conglomerate (*Gms, Gmsr*)

Description: Matrix-supported conglomerates (*Gms*) are generally massive, poorly-sorted, and contain angular to sub-rounded clasts which are disordered (Figure 11). Matrix is dominantly silt and clay size particles, and framework clasts range from 1 cm to 2.5 m in size. Some *Gms* beds have a fine-grained sand-rich matrix, while others are extremely clast-poor with smaller granules and pebbles "floating" in a mud matrix (Figure 12). Matrix-supported conglomerates with reverse grading (*Gmsr*) are also present. *Gms* and *Gmsr* are not as abundant as the clast-supported conglomerate (*Gm)*



Figure 11: Lobate *Gms* bed from measured section B_1 (67.25 m), Knob Mountain conglomerate lithosome (field book approximately 20 cm long).



Figure 12: Clast-poor *Gms* bed from the east Thumb transect (site 6), Knob Mountain conglomerate lithosome (hammer is 40 cm long).

and usually occur as isolated lobate beds surrounded by other conglomerate lithofacies. One rare case of lateral continuity of a *Gms* bed exits in the east Thumb area where the bed extends laterally for approximately 13 m.

Interpretation. *Gms* and *Gmsr* are the deposits of clast-rich to clast-poor debris flows. Clearly, deposition of particles was not selective; no sorting or settling of large clasts occurred, and sediment was deposited *en masse*. Eyewitness accounts document the ability of clay-rich debris flows to support large boulders on their tops (Sharp and Nobles, 1953; Johnson, 1970, p. 439; Fisher, 1971; Webb et al., 1988). Large clasts are supported by cohesion and buoyancy in the dense, clay matrix (Johnson, 1970, p. 439; Harvey, 1984; Shultz, 1984; Pierson and Scott, 1985; Blair and McPherson, 1994a, b). Where beds exhibit reverse grading, high sediment concentrations promote dispersive pressures which distribute larger particles toward the top of the bed (Bagnold, 1954). Therefore, *Gmsr* and clast-rich *Gms* beds are interpreted to have been deposited by sediment-gravity debris flows.

Clast-poor *Gms* beds are interpreted to be debris flow deposits by Blair and McPherson (1994b). The absence of boulders and cobbles may be due to a lack of available coarse material. Clast-poor *Gms* beds may also be the deposits of hyperconcentrated flow. During hyperconcentrated flow, cobbles and boulders may settle out as flow velocity drops (Costa, 1988). Clast-poor, mud rich deposits result because even though sediment concentrations are high enough to slow particle fall velocities, shear strength of flow is low enough to allow selective deposition of large clasts as flow competence drops.

Horizontally Stratified Conglomerate (*Gh*)

Description. Horizontally stratified conglomerate is composed of alternating layers of cobbles and coarse-grained or pebbly sand (*Gh*) (Figure 13). Beds are generally more laterally continuous and tabular than other conglomerate lithofacies and are 0.5 to 1.5 m thick. Bounding surfaces are sharp but, in most cases, do not appear to be erosional. These stratified beds are associated with horizontally stratified sandstone (*Sh*), gravelly, massive sandstone (*Smg*), and massive, clast-supported conglomerate (*Gm*).

Interpretation. *Gh* was deposited by hyperconcentrated flow. In super-critical, hyperconcentrated flow, sand particles are held in suspension by turbulence and gravel deposition occurs during antidune washouts. Blair (1987, 1996a) describes the deposition of gravel and sand couplets during catastrophic flooding in unconfined channels (sheetflood deposits). Based on lahar deposits from Mount St. Helens, Pierson and Scott (1985) hypothesize that flows can be partitioned into a head which is dominated by hyperconcentrated, turbulent flow and a tail which is a debris-flow slurry. The non-erosional contact between the "head" deposits and the "tail" deposits indicates that the two flow conditions are transitional within the same mass-flow event. At the front of the flow, gravel falls out of suspension rapidly and travels as bedload. The debris flow slurry deposits are subsequently laid down. Where *Gh* beds are in gradational contact with other *Gm*-type beds, the stratified bed may be a result a hyperconcentrated flow preceding a sediment-gravity flow.

Massive Sandstone (*Sm, Smg, Smgr*)

Description. Massive, ungraded sandstone (*Sm*) varies from fine-grained to coarse-grained sand. No traction structures, such as horizontal stratification or cross-

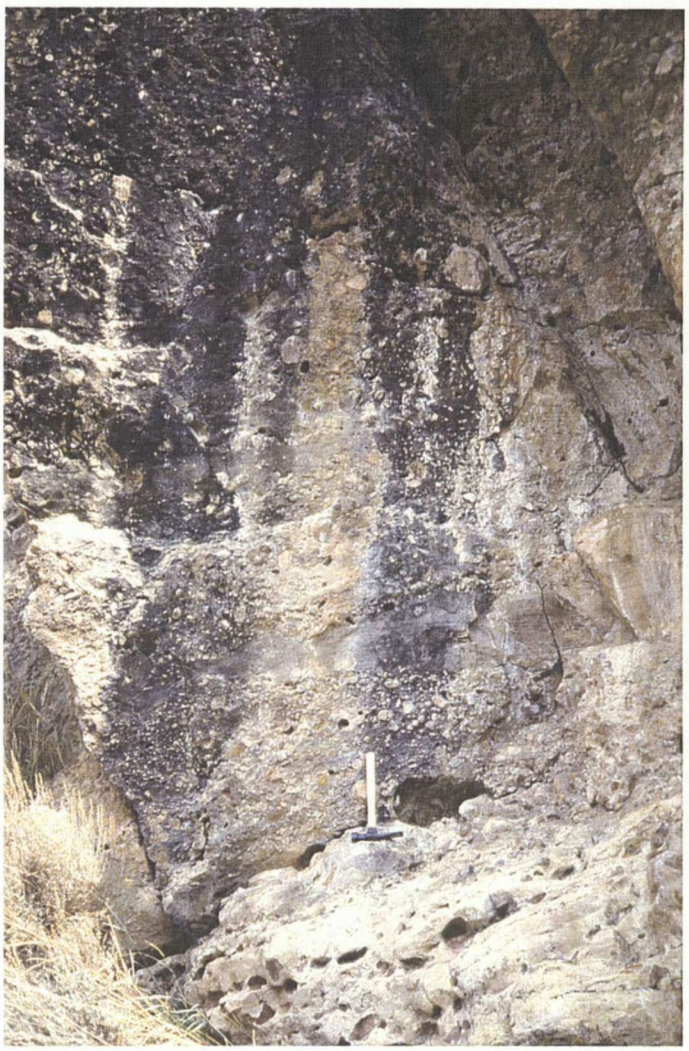


Figure 13: Stratified bed of cobbles, pebbles, and sand (*Gh*) from Irving Creek (Canyon 1), Knob Mountain limestone conglomerate lithosome (hammer is 40 cm long).

stratification, exist. Massive sandstone beds in this study have two general shapes: small, less than 50 cm thick lenses contained within *Gm* conglomerate beds and 0.5 to 1.5 m thick sheets which are laterally continuous over 10 to 15 meters. *Sm* beds are generally associated with *Gm* beds and only rarely associated with low-angle cross-stratified sand beds (*Sl*) or matrix-supported beds (*Gms*). Bounding surfaces are abrupt due to marked grain size differences with overlying and underlying beds, but erosional surfaces are difficult to discern. Some of the massive sandstone beds at Irving Creek exhibit burrow traces, and this feature may be present in other locations.

Only two massive, gravelly sandstone beds (*Smg*) (Figure 14) are described in the stratigraphic columns (B_2 and B_4) and both are less than half a meter thick. At B_2 (35.5 m above base), a *Gm* bed underlies *Smg* and is overlain by a *Gm* bed with abrupt contacts. At B_4 (173 m above base), the *Smg* bed contains two outsized boulders, and the overlying bed is *Gm* (base is covered).

Massive, reverse-graded sandstone (*Smgr*) is also only present in two locations, both in section B_4. One sandstone bed is associated with massive conglomerates (*Gm* and *Gms*) (165.25 m above base); the other is associated with horizontally stratified and low-angle, cross-stratified sandstone beds (*Sh* and Sr_1) (217 m above base).

Interpretation. Tabular bodies of sand with no internal fabric or stratification could be unconfined sheetflood deposits (Blair, 1987, 1994a) deposited by hyperconcentrated flow with high sediment concentrations. Turbulent flow may have been present at the time of deposition but was likely dampened, hindering development of cross-strata (Costa, 1988).

Lenticular *Sm* bodies could be derived from sand-rich, cohesionless, sediment-gravity debris flows (Boggs, 1987, p. 144; Blair and McPherson, 1994a; Miall, 1996, p. 123), although these flows are not well-described by workers interpreting deposits of



Figure 14: Massive, gravelly sandstone (*Smg*), massive sandstone (*Sm*), and massive conglomerate (*Gm*) beds from east Thumb transect (site 4), Knob Mountain conglomerate lithosome (hammer is 40 cm long).

either modern or ancient depositional settings. Most sediment-gravity flows are poorly-sorted due to *en masse* deposition; the fairly well-sorted grain size distribution of *Sm* is not in accordance with the flow type, but could be explained by lack of both coarser and finer material in the source area. While this scenario seems unlikely, the Pennsylvanian Quadrant Formation (a well-sorted quartzarenite) is considered to be one of the source rocks for the Knob Mountain lithosome. Possibly the Quadrant Formation supplied sand-size material in large enough quantities to generate clast-poor debris flows. Therefore, these massive sandstones may have been deposited by a sand-rich, clast-poor debris flow.

Due to the massive character and poor sorting of *Smg* beds, hyperconcentrated flow and/or sedimentary-gravity flow are inferred to be responsible for their deposition. High sediment concentrations, dampened to no turbulence, and rapid sedimentation will yield massive beds similar to the *Sm* lithofacies described above. *Smgr* indicates significant dispersive pressures which can be effective in hyperconcentrated flows, but are most often associated with higher sediment concentrations (Smith, 1986; Costa, 1988).

Stratified Sandstone (*Sh, Shg, Sl, Sr_1*)

Description. Horizontally stratified, fine-grained to coarse-grained sandstones (*Sh*) and stratified beds with granule to small pebble layers (*Shg*) (Figure 15) are fairly common in the Knob Mountain conglomerate lithosome and range in thickness from 0.10 to 1 meter. *Sh* is often associated with low-angle cross-stratified sand beds (*Sl*) or laminated mudstones (*Fl*). *Shg* beds are found with massive, poorly-sorted conglomerates or massive sandstones (*Gm* and *Sm*).

Sl is a sandstone with low-angle (<10°) cross-stratification (Figure 16). Grain size is typically medium- to coarse-grained sand, and, in some cases, includes granules.



Figure 15: Horizontally stratified sandstone with granules (*Shg*) from east Thumb transect (site 8), Knob Mountain conglomerate lithosome (lens cap is 4 cm).

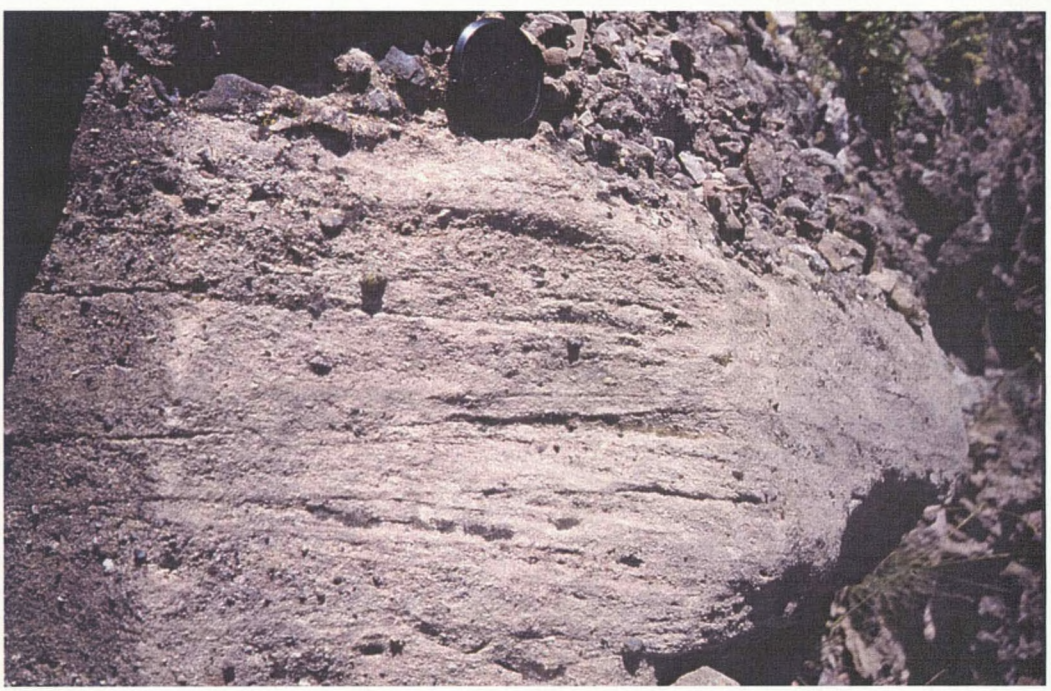


Figure 16: Low-angle, cross-stratified sandstone (*Sl*) from measured section B_4 (150.35 m above base), Knob Mountain conglomerate lithosome (lens cap is 4 cm).

Bed thicknesses are approximately 0.5 meters or less; *Sl* beds are typically associated with horizontally stratified sandstone (*Sh*), massive sandstone (*Sm*), and massive, clast-supported conglomerate (*Gm*).

Ripple cross-laminated sandstone with isolated sets of cross laminae Sr_1 are minor sandstones that extend no more than a meter laterally (Figure 17). Beds are typically less than 30 cm thick and consist of fine-or medium-grained sand with granules. Sr_1 is found with massive gravelly sandstones (*Smg*), massive clast-supported conglomerates (*Gm*), and, in the east Thumb transect, Sr_1 overlies a clast-poor, matrix-supported conglomerate (*Gms*).

Interpretation. *Sh* and *Shg* were deposited either by upper-flow regime, fluid-gravity flow or hyperconcentrated flow. During fluid-gravity flow, horizontal stratification forms under upper-flow regime, plane-bed conditions, especially where stratified with pebbles (*Shg*) (Harms and Fahnestock, 1965; Smith, 1986; Miall, 1996, p. 120). Nemec and Steel (1984) describe similar sand and gravel stratified beds and interpret them as "intersurge" deposits, especially where the upper bounding surface is sharp but non-erosive. These intersurge deposits are from "heavily sediment-laden stream flow following the debris flow," and may be part of the partitioned mass-flows of Pierson and Scott (1985) discuss in the interpretation of the *Gh* lithofacies. Therefore, *Sh* and *Shg* beds which are sheet-like with non-erosive bounding surfaces are probably hyperconcentrated flow deposits with rapid deposition dominant over erosion (Smith, 1986), or the deposits of upper-flow regime fluid-gravity flow.

Beds of *Sl* are deposited by upper flow regime, fluid-gravity flows which form standing wave or antidune bedforms (Harms and Fahnestock, 1965; Harms et al., 1982). Antidunes form in shallow water less than one foot deep under high flow velocities; strong turbulent currents tend to destroy antidunes and, therefore, preservation is rare



Figure 17: Isolated sets of ripple cross-lamination (Sr_1) from Irving Creek (Canyon 1), interpreted to be formed due to scour around obstacles. Conglomerate bed at base of photo is in the Divide conglomerate lithosome. Beds above are in the Knob Mountain conglomerate lithosome: horizontally stratified sandstone (*Sh*), massive conglomerate (*Gm*), horizontally stratified with granules (*Shg*), and ripple cross-laminated sandstone (Sr_1) (field book is approximately 20 cm long).

(Harms and Fahnestock, 1965). Rust (1978) and Miall (1996, p. 120) suggest that this type of cross-stratification can form by deposition of sand sheets under plane-bed conditions in scour hollows and, therefore, low-angle cross-stratification does not represent a bedform. Miall (1996, p. 120-121) recommends that when *Sl* is associated with horizontal stratified sandstones (*Sh*), that upper plane bed conditions can be inferred. Antidune formation and destruction can also occur during hyperconcentrated flow; Pierson and Scott (1985) recorded sediment concentrations of 22 to 67% (by weight) during a 1982 catastrophic lahar-runout flow in the Toutle River channel near Mount St. Helens and observed antidune bed conditions. A flow with this sediment concentration is a hyperconcentrated flow as defined by Costa (1988).

Sr_1 beds that occur as single cross-laminated sets in an otherwise massive or horizontal stratified sandstone could be U-shaped current crescents indicative of scour around of obstacles (Karcz, 1968). Scoured areas can be irregularly shaped particularly around large, boulder-size objects (Karcz, 1968). Harms et al. (1982) describe these features as "isolated, trough-like scours," and Picard and High (1973, p. 77-78) label them "longitudinal ripples."

Mudrocks (*Fm, Fl*)

Description. Massive red siltstones and mudstones lacking internal stratification (*Fm*) are the most common fine-grained lithofacies type in the study area. *Fm* is probably underrepresented in the stratigraphic columns due to lack of induration of the rock type resulting in poor outcrop exposure. Some *Fm* beds display rootlet traces. *Fm* is rarely more than about 15 cm thick; it is more commonly found as mud drapes within thick *Gm* deposits where contacts are sharp but wavy. Where beds are not draped over cobbles and boulders, *Fm* deposits are usually exposed at the base of an outcrop with the lower bounding surface covered and a sharp upper bounding surface.

Commonly, these thicker, sheet-like *Fm* beds are associated with *Gm* beds. In the Irving Creek measured section, *Fm* layers alternate with thin *Sm* layers.

Laminated siltstones and mudshales (*Fl*) are commonly about 10 to 15 cm thick and often associated with *Gm* beds possessing weak, bedding-parallel fabric. In stratigraphic section B_3 (65.35 m above base), a 10 cm thick bed is underlain by a fine-grained, massive sandstone and overlain by a very coarse-grained, horizontally stratified sandstone with sharp, horizontal bounding surfaces. *Fl* is not as common as *Fm*, but also is probably more prevalent than the outcrops show.

Interpretation. Fine particles settling out of suspension during waning flow is the simplest interpretation of the depositional process for *Fm* (Harms and Fahnestock, 1965). Lack of internal stratification or fabric negates deposition by traction currents, and abundance of silt and clay suggests very weak flow conditions. Thin layers or drapes may be deposited in standing pools of water (Miall, 1996, p. 125). Deposition by clast-poor mudflows (probably hyperconcentrated flows) with no turbulent eddies is another possible depositional process (Harvey, 1984; Shultz, 1984; Blair and McPherson, 1994b), as is discussed in the interpretation of clast-poor *Gms* beds above.

Deposition of *Fl* occurred by suspension settling with weak traction currents (Harms and Fahnestock, 1965; Miall, 1996, p. 123). Under these conditions, flow velocities are too low to generate ripples, and suspension settling is not inhibited greatly by fluid-gravity flow (Harms and Fahnestock, 1965).

Lithofacies Assemblages

Nearly all of the Knob Mountain conglomerate beds are poorly-sorted, massive, and clast-supported (lithofacies type *Gm*) (Table 1). Reverse-grading (*Gmr*) or weak imbrication (*Gmi*) is present but relatively rare. In addition to clast-supported

conglomerates, matrix-supported conglomerates (*Gms*) are only present in this lithosome. Some matrix-supported conglomerate beds are very clast-poor and only contain small, isolated pebbles in a very fine-grained silt and clay matrix. Other matrix-supported conglomerates contain a higher percentage of larger cobbles and boulders and, therefore, have a stronger resemblance to the clast-supported conglomerates. With one exception, conglomerate beds cannot be traced laterally beyond about 10 m; contacts between beds of slightly different grain size are often indistinct because the conglomerates are so poorly sorted.

Thin beds of massive sandstone (*Sm*) are relatively continuous compared to conglomerate beds. These sandstone stringers are especially prevalent in the upper part of Red Conglomerate Peaks, Knob Mountain, and the Thumb, although conglomerates with large, outsized boulders are also present. In the lower part of the section (described in the measured sections), sandstone beds are more lenticular in shape, and occur as lenses within conglomerate beds. Gravelly sandstones are also massive, showing reverse grading only rarely. Well-defined sedimentary structures such as ripple cross-lamination or cross-bedding are not present in the sandstones interbedded with the conglomerates. The only sedimentary structures observed are isolated sets of ripples (Sr_1) interpreted to be formed by scouring around large obstacles. Fine-grained mudrocks are commonly thin bedded and found as drapes within conglomerate beds.

Flow types indicated by the lithofacies assemblage are either hyperconcentrated flow or debris flow (Table 1). Flow was usually laminar or only locally turbulent and sediment concentrations were evidently high. Outsized boulders in clast-supported, massive conglomerate suggests transportation by cohesive debris flows. In particular, the matrix-supported conglomerate beds are clear indicators of non-selective deposition as opposed to selective deposition by fluid-gravity flows with varying flow velocities.

Table 1: Summary of lithofacies types and flow types for Knob Mountain conglomerate lithosome

Code	Rock Description	Sedimentary Structures	Type of Flow	Flow Characteristics
Gm	clay to boulders clast-supported poorly-sorted angular to sub-angular clasts	massive weak bedding-parallel orientation of clasts may be present	hyperconcentrated flow sediment gravity flow	sheet flood clast-rich debris flow, laminar flow, buoyancy support, (cohesive or non-cohesive)
Gmr	clay to boulders clast-supported poorly-sorted angular to sub-angular clasts	massive reverse grading	sediment gravity flow	clast-rich, non-cohesive debris flows, laminar flow, buoyancy support, significant dispersive pressure
Gmi	clay to boulders clast-supported poorly-sorted angular to sub-angular clasts	massive weak imbricate fabric	hyperconcentrated flow sediment gravity flow	dampened turbulence, relatively high sediment concentration clast-rich debris flow, imbrication developing by shingling at edges of flow
Gms	clay to boulders matrix-supported poorly-sorted angular to sub-angular clasts	massive	hyperconcentrated flow sediment gravity flow	laminar to turbulent flow, low yield strength, fall velocities slowed, applies to clast-poor deposits clast-rich or clast-poor, cohesive debris flow, substantial plastic yield strength
Gmsr	clay to boulders matrix-supported poorly-sorted angular to sub-angular clasts	massive reverse grading	sediment gravity flow	clast-rich or clast-poor, cohesive debris flow, significant buoyancy support and dispersive pressures, deposition by cohesive freezing
Sm	sand	massive	fluid gravity flow hyperconcentrated flow sediment gravity flow	flow characteristics unknown; deposit extensively bioturbated turbulent or dampened turbulent flow, high sediment concentration clast-poor, non-cohesive debris flow
Smg	sand with gravel	massive	hyperconcentrated flow sediment gravity flow	high sediment concentrations, dampened turbulence clast-poor debris flow, sand-rich and clay poor matrix, low yield strength, buoyancy support
Smgr	sand with gravel	massive reverse grading	hyperconcentrated flow or sediment gravity flow	high sediment concentrations, dampened turbulence, significant dispersive pressure

Table 1(continued):

Sh, *Shg*	sand, some beds contain gravel	horizontally stratified	fluid gravity flow hyperconcentrated flow	transition from subcritical to supercritical flow, plane bed or low standing wave transport, no large-scale turbulence laminar flow or dampened turbulence
Sl	sand	low-angle cross stratification	fluid gravity flow	upper-flow regime, standing waves, antidune migration
Sr_1	sand	ripple cross-laminated	fluid gravity flow	turbulent, subcritical, lower flow regime
Fm	silt and clay	massive	fluid gravity flow sediment gravity flow	waning flow, suspended sediment fall-out mudflows, viscous flow with no turbulent eddies
Fl	silt and clay	horizontally laminated	fluid gravity flow	waning flow, suspended sediment fall-out with weak traction currents

Depositional Environment

The limestone-clast conglomerates and associated sandstones and mudstones were deposited in an alluvial fan environment. Alluvial fans are constructed primarily by catastrophic sediment-gravity flows, hyperconcentrated flows, and upper-flow regime, fluid-gravity flows (Blair and McPherson, 1994a). All of these flow types are indicated by the poorly-sorted conglomerates (clast-supported and matrix-supported) and stratified sandstones (horizontal and low-angle) that constitute the limestone conglomerate lithosome. In particular, clast-rich, matrix-supported conglomerates are deposits of viscous debris flows which resulted from deposition *en masse* by flows characterized by high sediment concentrations and matrix strength. The laterally discontinuous and sometimes lobate shape of abundant conglomerate beds suggests various debris flow lobes and levee deposits constructed a major portion of the fans.

The lack of lower-flow regime sedimentary structures in the sandstones and mudstones and absence of cross-bedded conglomerate also supports an alluvial fan interpretation; the conditions that produce these features rarely exist on alluvial fans. Due to small catchment areas drained by high-order streams, alluvial fans are prone to catastrophic, sediment-laden flooding on steep slopes (1.5° to 25°) (Blair and McPherson, 1994b). These conditions induce sediment-gravity flows and deposition *en masse*. Development of lower-flow regime bedforms and selective deposition of coarse material in large gravel bars are not common processes in alluvial fan environments because of steep slopes of the fan surfaces and shallow, unconfined flow (Blair and McPherson, 1994a, b).

The Knob Mountain alluvial fans were primarily constructed by debris flow deposits (Type I fan) rather than sheetflood deposits (Type II fan) (Blair and

McPherson 1994b), implying clay-rich source rocks were present in the catchment areas. The prevalence of debris flows also suggests drainage basins were small and unable to store deposits of sediment-gravity flows such as rock falls, colluvial slides, and debris flows. Quartzarenite beds are possibly sheetflood deposits (upper-flow regime fluid-gravity flows) described by Blair and McPherson (1994b), or they may be deposits of hyperconcentrated or debris flows which transported friable rubble from eroded outcrops of Quadrant Formation. The debris-flow-dominated fan of Blair and McPherson (1994b) is not characterized by sheetflood deposits. However, the presence of the Quadrant with several other argillaceous stratigraphic units (discussed in the next section) in the source area may account for interbeds of debris flow deposits with minor sheetflood deposits.

Significant reworking of abundant debris-flow deposits by secondary flow is inferred due to the paucity of matrix-supported conglomerates in the Knob Mountain conglomerate lithosome. The presence of gravel lags with outsized boulders also suggests that secondary, fluid-gravity flows winnowed finer material, leaving large boulders behind.

Provenance

Composition

The Knob Mountain conglomerate lithosome comprises two petrofacies. The major petrofacies is dominated by limestone clasts (Table 2; Appendix B) with lesser amounts of chert, sandstone, and siltstone clasts. Clasts are angular and rough in texture. All of the conglomerate beds exposed in the Sawmill Creek drainage basin, including the beds that make up the Thumb, Knob Mountain, and Red Conglomerate Peaks, are of this dominant type of petrofacies. Where the Knob Mountain

conglomerate lithosome interfingers with the Divide conglomerate lithosome, a few beds of limestone-clast conglomerate also contain rare, rounded quartzite clasts.

Table 2: Petrofacies of the Knob Mountain conglomerate lithosome

petrofacies	limestone	sandstone	chert	quartzite	igneous	angular	rounded
limestone	78%	8%	14%	-	-	100%	-
mixed	29%	14%	5%	49%	4%	30%	70%

The second petrofacies is a mixture containing mostly quartzite in combination with limestone, fine-grained sandstone and siltstone clasts; 70% of the clasts are rounded and very smooth. Although dominated by quartzite clasts, this petrofacies is included in the Knob Mountain conglomerate lithosome because these beds are very poorly-sorted. The mixed-clast petrofacies also crops out where the Knob Mountain and Divide conglomerate lithosomes intertongue, and it is clear that the mixed-clast petrofacies is a mixture of material derived from both lithosomes. Therefore, only the provenance of the major petrofacies (limestone petrofacies) is discussed in this chapter. In a later chapter, the mixed-clast petrofacies of the Knob Mountain conglomerate is discussed with mixed conglomerates of the Divide conglomerate in the context of the intertonguing relations between the two lithosomes.

Clasts in the Knob Mountain conglomerate lithosome are predominately limestone and limestone with brown-black chert; the remaining clasts are fine-grained sandstone, siltstone, and chert (Appendix B). Limestone clasts, where large enough to identify, were derived from the Permian Phosphoria/Park City, and Triassic Dinwoody and Thaynes Formations. Chert clasts are commonly brown and brown-black and are found as small, pebble-size fragments or as rare boulder-size clasts (e.g., Section B_4, 206 m). Quartzarenite clasts, probably from the Pennsylvanian Quadrant Formation, are rare in the Knob Mountain area. However, a few large (60 - 130 cm) boulders in a

matrix-supported conglomerate on the east flank of the Thumb (site 7), and other scattered occurrences in the Knob Mountain section (Section C, 46 m) and one of the Red Conglomerate Peak sections (B_4, 207.5 m) attest to the presence of the Quadrant Formation in the source area. Permian Phosphoria Formation clasts are buff, tan, or light orange, silty limestones with chert nodules; however, some beds in the Triassic Thaynes Formation have a similar lithology and positive discrimination is difficult. Clasts from the Grandeur Tongue of the Permian Park City Formation, laterally equivalent with the Phosphoria, are identified by the presence of large crinoid columns (up to 2 cm in diameter) and productid brachiopod fossils (Sadler, 1980). Triassic Dinwoody Formation clasts are identified by a chocolate-brown weathering color, fine-grained texture, pelecypod fragments, and lack of a fetid odor (Sadler, 1980). Pentacrinus and other abundant crinoid debris in the Triassic Thaynes Formation (Scholten, 1955; Sadler, 1980) are relatively easy to identify in clasts.

Sandstones interbedded with the Knob Mountain limestone-clast conglomerate are white quartzarenites with minor carbonate lithic fragments. Petrographic analysis shows these sands to consist of primarily monocrystalline quartz grains with reworked quartz overgrowths (95%) and extremely diagenetically altered micrite fragments (5%). Grains are cemented with sparry calcite.

Paleocurrent Indicators.

Cross-bedding is rare in sandstone units of the Knob Mountain lithosome and, therefore, is not a reliable paleocurrent indicator. Imbrication is also rare and weakly developed in conglomerate units, precluding any meaningful paleocurrent determinations.

Source of Knob Mountain Limestone Conglomerate Lithosome

Detritus of the Knob Mountain conglomerate lithosome was derived from source rocks exposed on the Tendoy plate. The best available evidence to support a Tendoy source area is the clast composition which strongly resembles the strata immediately to the north in the Lima Peaks area (Figure 2). Within 5-10 km from the conglomerate exposures, Pennsylvanian Quadrant through Cretaceous Blackleaf Formations are exposed in a southeast plunging fold in the hanging wall of the Tendoy thrust. All of the rock types in the limestone-clast conglomerate (limestone, fossiliferous limestone, limestone with chert, silty limestone, siltstone, and quartzarenite) are represented in the fold on the hanging wall of the Tendoy thrust (Figure 18). Ample argillaceous formations are also present in the Tendoy thrust hanging wall which could supply clay for the clast-rich and clast-poor debris flows which dominate the Knob Mountain conglomerate lithosome.

Additional support for a Tendoy thrust plate source is the presence of quartzarenite interbeds in the limestone conglomerate lithosome. Massive sandstone beds (*Sm*) containing reworked quartz grains with quartz overgrowths indicate sandstone source rocks were subjected to erosion during deposition of the Knob Mountain lithosome. Approximately 730 m of Quadrant Formation, which is cemented with either silica or calcite, is exposed in Garfield Peak and Lima Peaks (Sadler, 1980). It is possible that where the Quadrant was cemented with silica, large, resistant clasts remained intact and are now preserved in conglomerate. Where the Quadrant was cemented with calcite, the formation may have disaggregated more readily, with the resultant sand detritus preserved as quartzarenite. A similar interpretation for the presence of quartzarenite beds and lack of Quadrant Formation clasts in Beaverhead Group rocks was made by Wilson (1970) in the Lima area, Corner (1992) in the

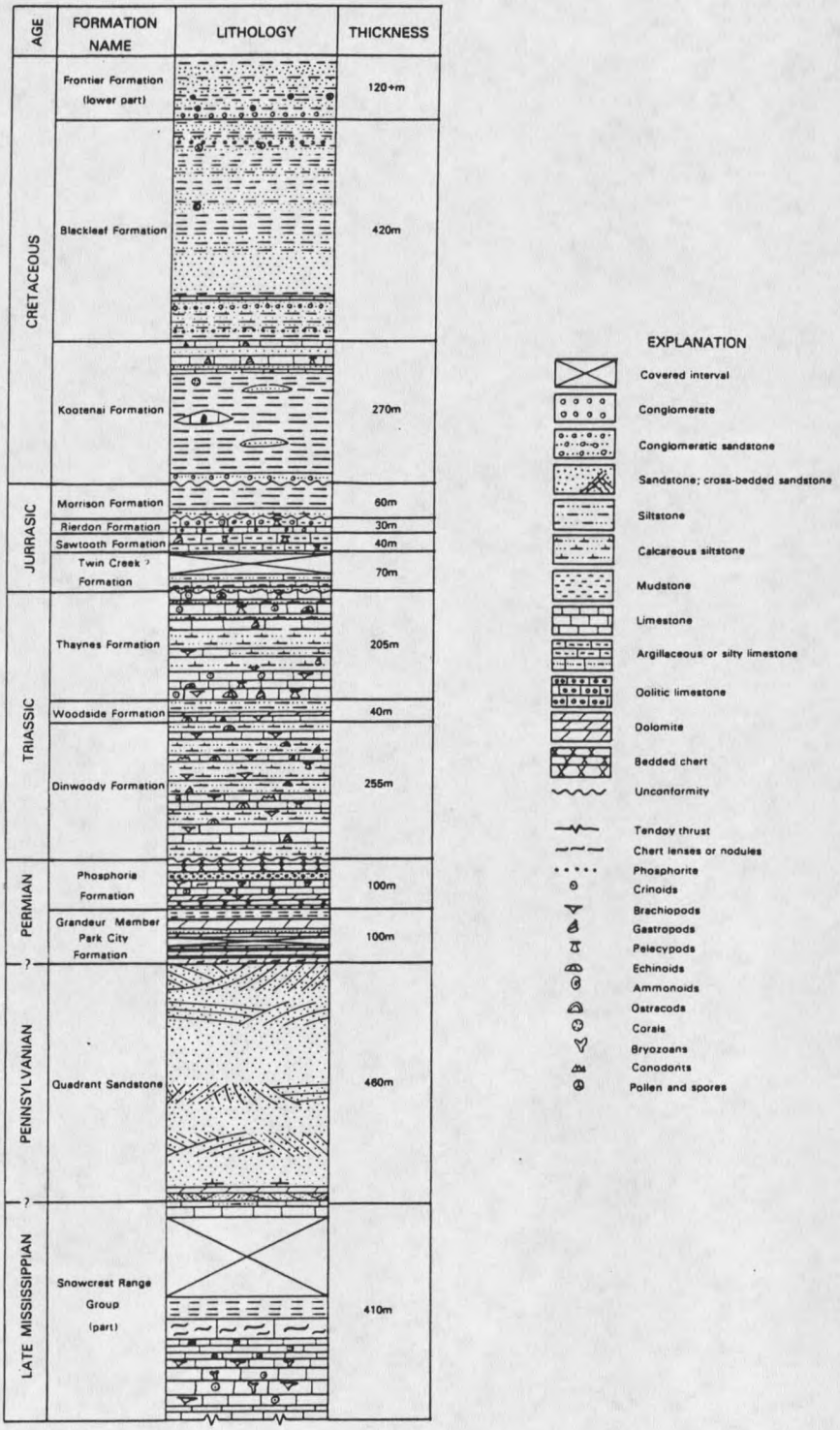


Figure 18: Pre-Beaverhead strata in the hanging wall of the Tendoy thrust near Lima Peaks (from Skipp, 1988).

McKnight Canyon area, Azevedo (1993) in the Grasshopper Creek area, and by Dyman et al. (1995) in their study of the Frontier and Divide conglomerate lithosomes.

Large, angular to sub-angular boulders and cobbles of limestone, sandstone and siltstone clasts suggest short transport. These non-resistant rock types are highly susceptible to destruction and would not remain as boulders over large distances. Therefore, the presence of large, angular labile clasts suggest minimal grain-grain interaction during transport and supports the inference of a nearby source.

The possibility that the Pennsylvanian through Triassic clasts came from a deeply eroded Medicine Lodge thrust plate is unlikely. The Medicine Lodge thrust has overridden the Knob Mountain conglomerate lithosome, implying that latest movement on the Medicine Lodge thrust post-dated Knob Mountain deposition. Either two episodes of movement are required to both generate the relief in the Medicine Lodge hanging wall to source the conglomerates, and subsequently override the deposits, or thrust movement was relatively continuous during deposition. The Medicine Lodge thrust has much greater tectonic transport compared to the Tendoy (Perry, et al., 1988; Sterne, 1996). If conglomerate was continually shed from a far-traveled thrust sheet, the dominant clast composition of the youngest conglomerates should be Mississippian limestones. It is unlikely that the youngest conglomerates would be composed of Pennsylvanian through Triassic clasts, as these rocks should have been eroded, deposited, and overridden further toward the west. A simpler, more parsimonious interpretation is that detritus was shed in an antithetic (westward) transport direction from the Tendoy thrust sheet.

The restricted clast suite (Pennsylvanian to Triassic rock types) and alluvial fan depositional environment implies a small, proximal drainage basin. Alluvial fans form as high-order streams exit feeder channels and expand radially due to abrupt change in topography and loss of confinement; hence, alluvial fans are adjacent to regions with

significant relief, and their radii are typically less than 10 km (Blair and McPherson, 1994a, b). The Tendoy source area easily lies within 10 km of the deposits of the Knob Mountain conglomerate lithosome. Therefore, in addition to clast lithology, the alluvial fan depositional environment (determined by lithofacies analysis) supports a nearby source region.

DIVIDE CONGLOMERATE LITHOSOME

Lithofacies

Massive, Bimodal Conglomerate (*Gmb, Gmib*)

Description. Massive, clast-supported and unstratified to crudely stratified conglomerate with a bimodal grain size distribution (*Gmb)* (Figure 19) is the characteristic lithofacies type for the Divide conglomerate lithosome. Framework clasts are rounded to well-rounded; the matrix, which is easily discernible from the framework clasts, is moderately to well-sorted, fine to medium-grained sand. Bimodal conglomerates with imbricated framework clasts (*Gmib)* (Figure 20) are found with *Gmb* beds. The imbricate fabric of these bimodal conglomerates is generally well-developed.

The largest maximum particle size average for *Gmb* and *Gmib* beds is 20 cm, and bed thicknesses are generally between 1 - 4 m. These lithofacies types are in sharp contact with horizontally stratified conglomerate (*Gh*) and massive sandstone (*Sm*). *Gmb* and *Gmib* are poorly cemented and bed geometry is difficult to assess due to poor outcrop exposure. This lithofacies is probably more prevalent than the measured section indicates.

Interpretation. The bimodal sorting represented by a clast-supported framework composed of pebbles, cobbles, and boulders with moderately to well-sorted sand matrix suggests selective deposition by turbulent, fluid-gravity flow (Smith, 1986; Costa, 1988; Miall, 1996, p. 101-102). Massive beds of conglomerate with well-sorted,



Figure 19: Massive, bimodally-sorted conglomerate (*Gmb*) from Irving Creek (Canyon 1), Divide conglomerate lithosome. Framework clasts are sub-rounded to well-rounded, and matrix is fine- to medium-grained sand (hammer handle is 3 cm wide).



Figure 20: *Gmib* from measured section D (at base), Divide conglomerate lithosome. Field book is oriented parallel to imbrication, hammer is approximately parallel to bedding. View is to northeast (hammer is 40 cm long).

interstitial sand have been interpreted by previous workers to be longitudinal bars or bedforms that evolved from diffuse gravel sheets into crudely stratified or massive bars (Hein and Walker, 1977; Harvey, 1984, Miall, 1978, 1985, 1996, p. 101-102). These *Gmb* beds may form when water flow and sediment discharge is high and diffuse gravel sheets grow rapidly both vertically and in a downstream direction with the addition of gravel layers. If the rate of downstream expansion exceeds that of vertical accretion, the low-relief gravel bedform will not develop an avalanche slip face on its downstream margin (Hein and Walker, 1977). Massive conglomerates with crude horizontal stratification may also develop where the development of avalanche slip faces is inhibited by shallow depths (Rust, 1978).

Imbrication in *Gmib* is also a character associated with gravel-bed rivers (Rust, 1972, 1978; Hein and Walker, 1977; Harvey, 1984; Miall, 1996, p. 101) and turbulent flow in streams (Smith, 1986). Imbrication develops on gravel bars or diffuse gravel sheets as fluid-gravity flows either roll elongate clasts by traction currents or pick up and re-deposit platey clasts during flood stages so that clasts stack against each other (Rust, 1972; Bluck, 1982; Harms et al., 1982).

Stratified Conglomerate (*Gh, Gp*)

Description. Horizontally stratified conglomerate (*Gh*) is composed of horizontal layers of fine- to medium-grained sand, pebbles, and cobbles. *Gh* beds are not as common as *Gmb* or *Gmib* beds; one is exposed in section D (at 4.75 m) and another is in Canyon 1. Beds are 0.75 - 1.50 m thick and appear to be tabular but are difficult to trace laterally due to lack of exposure.

Planar-cross-bedded conglomerate (*Gp)* is composed of well rounded to sub-rounded pebbles and small cobbles with medium to coarse-grained sand. Only one *Gp* bed is present in the study area (Section D, 32.5 m above base) (Figure 21). The 0.5 m



Figure 21: *Gp* bed (behind hammer) from measured section D (32.5 m above base), Divide conglomerate lithosome. Cross beds dip gently to right. Conglomerate bed is approximately 50 cm thick, overlies a low-angle cross-stratified sandstone (*Sl*) and is overlain by massive sandstone (*Sm*). View is to northeast (hammer is 40 cm long).

thick bed overlies a low-angle, cross-stratified sandstone (*Sl*) with a abrupt, flat contact and is overlain by massive sandstone (*Sm*) with a abrupt, wavy contact.

Interpretation. *Gh* beds in this lithosome are interbedded with poorly-sorted, massive conglomerate tongues of the Knob Mountain conglomerate lithosome; assessing depositional processes is difficult without a clear understanding of relations between underlying and overlying beds. *Gh* beds consisting of gravel and fine-grained to medium-grained sand may be deposited by fluid-gravity flows. Gravel may be deposited by high-discharge, super-critical flow, and sand may infiltrate the deposit during waning flow (Miall, 1978; Rust, 1978; Nemec and Steel, 1984). Deposition of different grain sizes indicates a selective deposition of particles depending upon flow velocity, which is a characteristic of fluid-gravity flows (Pierson and Costa, 1987; Costa, 1988).

Cross-bedded gravel (*Gp*) is widely interpreted to be deposited in association with longitudinal gravel bars in a fluid-gravity flow environment (Hein and Walker, 1977; Rust, 1972, 1978; Miall, 1978; Kraus, 1984; Middleton and Trujillo, 1984; DeCelles et al., 1987). Cross-stratification may develop as a result of rapid aggradation relative to downstream bar growth during high discharge, resulting in formation of an avalanche slip face. In addition, Hein and Walker (1977) propose that these sedimentary structures are found in transverse bars which form under lower discharge conditions than longitudinal bars (discussed in the interpretation of *Gmb* lithofacies).

Conversely, *Gp* may be the result of migrating gravel bedforms. Bluck (1982) suggests that small bars migrate downstream until they coalesce or accrete to form larger bedforms which do not migrate; foresets in these smaller bars would develop as gravel is redistributed from the lee to the stoss side resulting in a cross-bedded deposit. Miall (1996, p. 102-103) also suggests that *Gp* may be the result of gravel overpassing where

rounded gravel clasts roll across the smooth surface of a sand wave and accumulate on the lee side. The cross-bedded conglomerate deposit would grade upward to a planar cross-stratified sandstone, although this upper portion of the bedform may not be preserved.

Massive Sandstone (*Sm*)

Description. Massive ungraded sandstone beds in the Divide conglomerate lithosome consist of medium- to coarse-grained sand (*Sm*). Beds are 0.10 to 0.50 m thick and tabular in shape, and contacts with overlying and underlying lithofacies types are abrupt. *Sm* beds are interbedded with massive, conglomerate with bimodal sorting (*Gmb* and *Gmib*) or low-angle cross-stratified sandstone beds (*Sl*).

Interpretation. The lack of internal fabric suggests high sediment concentration and dampened turbulence (Costa, 1988; Miall, 1996, p. 123). However, *Sm* beds are commonly found in contact with bimodally sorted, massive or imbricated conglomerate, which are clearly deposits of fluid-gravity flows. Wet, saturated sand is commonly subjected to soft sediment deformation or bioturbation, destroying sedimentary structures (Miall, 1996, p. 123). The original fabric (such as cross-stratification) of these massive sandstones may not be preserved and, therefore, deposition by fluid-gravity flow should also be considered.

Stratified Sandstone (*Shg, Sl, Sr*)

Description. Gravelly, horizontally stratified sandstone beds (*Shg*) are not common in this lithosome. Grain size is coarse-grained sand to granule, and bed thickness is generally less than 0.5 m. *Shg* beds are interbedded with bimodal, massive and imbricated conglomerates (*Gmb* and *Gmib*).

Low-angle, cross-stratified sandstone (*Sl*) contain cross-strata which dip <10° to the lower bounding surface. Sl beds overlie a bimodal and imbricated conglomerate (*Gmib*) and is overlain by a planar cross-bedded gravel (*Gp*; section D at 32 m). *Sl* is also not common.

Cosets of ripple cross-laminated, coarse-grained sandstone (Sr_2) (Figure 22) constitute one of the rare, cross-stratified lithofacies types in the Divide lithosome. Only one sandstone bed in this study is described as Sr_2; it overlies a massive sandstone bed (*Sm*) and is overlain by a massive, gravelly sandstone in Canyon 1 at Irving Creek.

Interpretation. *Shg* and *Sl* were deposited by upper-flow regime, fluid-gravity flow. Horizontally stratified sand with gravel indicates deposition under upper plane-bed conditions (Harms and Fahnestock, 1965) or possibly deposition by hyperconcentrated flow (Smith, 1986). Deposition by shallow, upper-flow regime, fluid-gravity flow is favored for *Shg* and *Sl* in this lithosome because they are associated with bimodally-sorted, imbricated conglomerate (*Gmib*) and cross-stratified conglomerate (*Gp*), also interpreted to be deposited by fluid-gravity flows.

Sr_2 units were deposited by migrating sandy current ripples under lower-flow regime conditions (Harms et al., 1982; Miall, 1985). Ripple bedforms are often found on other bedforms such as sandwaves or gravel bars and may be the products of deposition during waning flow (Williams and Rust, 1969; Bluck, 1974; Miall, 1996, p. 149).

Lithofacies Assemblages

The Divide conglomerate lithosome is dominated by massive, clast-supported conglomerate (*Gmb* and *Gmib*) with bimodal sorting (Table 3). There is a distinct size difference between the framework clasts (pebbles, cobbles, and rare boulders) and



Figure 22: Coset of ripple cross-laminated sandstone (Sr_2) from Irving Creek (Canyon 1), Divide conglomerate lithosome. Sr_2 overlies a horizontally stratified sandstone bed (of the Knob Mountain conglomerate lithosome) and is overlain by a gravelly, massive sandstone (Divide conglomerate lithosome) (lens cap is 4 cm).

matrix (fine- to medium-grained sand). These conglomerates are frequently well-imbricated and invariably clast-supported. Framework clasts are generally moderately to well-sorted. The matrix is moderately well-sorted "salt and pepper" sand containing quartz, chert, and other lithic fragments. In section D, a bed of cross-stratified conglomerate is present (*Gp*); this bed is the only cross-stratified, coarse-grained deposit observed in the study area.

Sandstone beds are litharenites and are found as thin, massive beds (*Sm*) associated with conglomerate and low-angle cross-bedded sandstone (*Sl*). Cosets of cross-laminated sandstones (Sr_2) are present only in this lithosome.

The bimodal sorting of the conglomerate unit suggests selective deposition during fluid-gravity flow (Smith, 1986; Costa, 1988). The coarse fraction was deposited during flood stages as diffuse gravel sheets or migrating bars, and the finer sand component was deposited as stream competence dropped during waning flow. Cross-stratified conglomerate does not develop during deposition by hyperconcentrated flow or sediment-gravity flow (Smith, 1986; Costa, 1988). Therefore, the cross-stratified conglomerate bed (*Gp*), although extremely rare in the study area, also suggests deposition by fluid-gravity flow. In addition, the moderate- to well-imbricated arrangement of clasts in the bimodally-sorted conglomerates is a fabric commonly developed in gravelly streams under either upper or lower flow regime fluid-gravity flow (Rust, 1972; Bluck, 1974; Miall, 1996, p. 101).

The massive sandstone beds are interpreted to be deposited by either clast-poor debris flow, hyperconcentrated flow, or fluid-gravity flow (Table 3). When considered in conjunction with the bimodally-sorted conglomerates and cosets of cross-laminated sandstones, however, fluid-gravity flow is inferred. Additional evidence to support this inference, such as channelized bed geometry or association with additional lower-flow

Table 3: Summary of lithofacies and flow types for Divide conglomerate lithosome

Code	Rock Description	Sedimentary Structures	Type of Flow	Flow Characteristics
Gmb	pebbles, cobbles, rare boulders with a sand matrix clast-supported bimodal sorting rounded to well-rounded clasts	unstratified to crudely stratified	fluid-gravity	high velocity, unsteady flow, deposition by traction current
Gmib	pebbles, cobbles, rare boulders with a sand matrix clast-supported bimodal sorting rounded to well-rounded clasts	unstratified to crudely stratified imbricated clasts, often well-developed	fluid-gravity	turbulent flow
Gh	pebbles, cobbles and sand	horizontally bedded	fluid-gravity	turbulent, supercritical flow, antidune washouts and sand fallout by suspension initially high velocity flow with subsequent waning flow
Gp	pebbles and sand	planar cross-bedded	fluid-gravity	turbulent flow, avalanche slip face development on migrating bar during flood stages
Sm	sand	massive	fluid-gravity hyperconcentrated sediment-gravity	flow characteristics unknown; deposit extensively bioturbated turbulent or dampened turbulent flow, high sediment concentration clast-poor, non-cohesive debris flow
Sl	sand	low-angle cross-stratified	fluid-gravity	upper-flow regime, standing waves, antidune migration
Sr_2	sand	ripple cross-laminated cosets	fluid-gravity	subcritical, lower-flow regime

regime bedforms is, unfortunately, lacking. However, bioturbation or soft sediment deformation may have destroyed these sedimentary structures in sandstone beds.

The massive sandstone beds are interpreted to be deposited by either clast-poor debris flow, hyperconcentrated flow, or fluid-gravity flow (Table 3). When considered in conjunction with the bimodally-sorted conglomerates and cosets of cross-laminated sandstones, however, fluid-gravity flow is inferred. Additional evidence to support this inference, such as channelized bed geometry or association with additional lower-flow regime bedforms is, unfortunately, lacking. However, bioturbation or soft sediment deformation may have destroyed these sedimentary structures in sandstone beds.

Depositional Environment

Conglomerate of the Divide conglomerate lithosome was deposited in a high-energy, gravelly, braided stream consisting of multiple, low-sinuosity channels and various types of gravel bars. Conglomerate and minor sandstone interbeds described in the study area best fit the proximal outwash gravel model of Rust (1978), a Scott-type braided stream of Miall (1978), or using Miall's (1996, p. 203, 208-209) revised classification, a shallow, gravel-bed braided river. All of these constitute high energy streams characterized by gravel bar deposits that form during flood stage and a lack of fine-grained mudrocks.

The Divide conglomerate lithosome is composed predominantly of massive, bimodally sorted conglomerates (*Gmb*), with occasional well-developed imbrication (*Gmib*), which are inferred to be longitudinal bar deposits (Bluck, 1974; Rust, 1978; Miall, 1996, p. 101). Evidence of current ripples (Sr_2) found in association with these conglomerate beds suggests deposition during waning flow on bar tops (Williams and Rust, 1969; Bluck, 1974; Miall, 1996, p. 149). Low-angle cross-stratified sandstone

(*Sl*) and cross-bedded conglomerate (*Gp*) also suggest shallow water depths which hindered the development of avalanche slip faces on migrating bedforms.

The lack of abundant planar or trough cross-bedded sandstones and fine-grained mudrocks supports the predominately high energy state and shallow channel depths (<1 m) characteristic of these gravelly, braided streams (Miall, 1996, p. 208). Extensive development of cross-stratification (*Gp, Gt, Sp, St, Sr,* of Miall, 1978) is inhibited in this type of stream by relatively shallow flow depths and unstable low-sinuosity channels. The Divide conglomerate lithosome contains sparse evidence for subcritical flow and lacks bounding surfaces which allow delineation of fluvial architectural elements (Miall, 1985). Limited exposure of the Divide lithosome could account for the lack of these typical fluvial features.

Provenance

Clast Composition.

The Divide conglomerate lithosome contains two petrofacies: quartzite-clast (the dominant petrofacies) and mixed-clast (a minor petrofacies). The clast suite of the quartzite petrofacies is dominated by well-rounded, polished quartzite clasts (Table 4; Appendix B). Quartzite clasts are black, maroon, gray, white, and cream colored; some are highly fractured or exhibit crescentic marks. The remainder of the clasts are sandstone, limestone, igneous rock, and pebble conglomerate clasts. The mixed-clast petrofacies contains subequal amounts of quartzite and limestone with lesser amounts of other clast types (Table 4; Appendix B) and is distinguished readily by subequal proportions of polished, rounded clasts and rough, angular clasts.

Table 4: Petrofacies of the Divide conglomerate lithosome

petrofacies	quartzite	limestone	sandstone	igneous	other	rounded	angular
quartzite	63%	12%	17%	5%	3%	95%	5%
mixed	46%	42%	10%	1%	1%	50%	50%

Quartzite clasts are interpreted to be derived from the metasedimentary rocks of the Proterozoic Belt Supergroup, Lemhi Group, and Swauger Formation, Cambrian Flathead Sandstone, and Ordovician Kinnikinic Formation (Lindsey, 1972; Ryder and Scholten, 1973; Haley, 1986; Link et al., 1993). No source formations were identified for the limestone or sandstone clasts due to lack of diagnostic fossils. Composition and texture of igneous clasts is difficult to identify due to extreme alteration; clasts may be either porphyritic volcanic or phaneritic plutonic lithologies. The Ordovician Beaverhead Mountains pluton (exposed in the Hawley Creek thrust sheet) (Skipp, 1988) and the Late Cretaceous Idaho batholith, both of which are west of the study area, are possible volcanic and plutonic sources for igneous clasts deposited in the Divide conglomerate lithosome.

Sandstone beds contained in the Divide conglomerate lithosome are calcite-cemented litharenites. Thin sections show monocrystalline quartz (73%), rare polycrystalline quartz, and chert grains (14% of the rock) and carbonate fragments (13%)..

Paleocurrent Indicators

Imbrication is moderately- to well-developed in the quartzite-clast conglomerate. However, limited exposure and lack of elongate and tabular clasts precluded extensive measurement of clast orientation. The attitude of the average orientation of groups of imbricated clasts was measured at Irving Creek (Section D, at base, 37 m, and 47 m; Canyon 1). Two locations contained enough imbricate cobbles to measure the trend and

plunge of several individual clasts. Each of these imbrication directions indicated paleoflow from the south-southwest.

Source of Divide Quartzite Conglomerate Lithosome

The similarity in composition, lithofacies, and age of the Divide quartzite conglomerate to the Harebell Formation and Pinyon Conglomerate in Wyoming has been observed by several previous workers (Ryder and Scholten, 1973; Love, 1972; Lindsey, 1972; Schmitt and Steidtmann, 1990). Although continuity of these conglomeratic units is interrupted by the Snake River Plain, the source area is likely similar (Lindsey, 1972). Due to the scarcity of Divide conglomerate exposures in the study area, interpretation of source area location and general transportation path for the Divide conglomerate lithosome relies on interpretations put forth by previous workers in their studies of the Divide, Harebell and Pinyon conglomerates (Lindsey, 1972; Ryder and Scholten, 1973; Haley, 1986; Schmitt and Steidtmann, 1990; Lawton et al., 1994).

Quartzite clasts in the Divide, Harebell and Pinyon conglomerates are probably Proterozoic quartzite derived from either the Middle Proterozoic Belt Supergroup in southwest Montana or the Middle Proterozoic Swauger Formation and Lemhi Group in east-central Idaho (Ryder and Scholten, 1973; Lindsey, 1972; Haley, 1986). Quartz-rich source rocks may include Upper Proterozoic - Lower Cambrian Wilbert Formation and Ordovician Kinnikinic sandstones which are also present to the west (Skipp and Link, 1992; Link et al, 1993). Therefore, quartzite clasts were probably derived from the west (east-central Idaho and southwest Montana) from rocks of the Middle Proterozoic Belt basin and Late Proterozoic to early Paleozoic miogeoclinal wedge.

Paleocurrent indicators for the Divide quartzite conglomerate lithosome indicate transport to the north-northeast (Lindsey, 1972; Ryder, 1968, p. 69; this study). Paleocurrent directions for the Harebell Formation and Pinyon Conglomerate are

northeast, east, and southeast (Love, 1972; Lindsey, 1972) (Figure 23). The differences in paleocurrent directions between the Divide conglomerate units in Montana and northern exposures of the Harebell and Pinyon conglomerate units in Wyoming are minor, and support a general western source for quartzite clasts.

Transport of large amounts of coarse-grained material may have occurred along a major transverse structural zone in the thrust belt (e.g. Lawton et al., 1994; Vincent and Elliott, 1997). Lawton et al. (1994) propose that quartzite detritus comprising the Divide, Harebell Formation, and Pinyon Conglomerate (Snake River conglomerate complex) was transported toward the foredeep along the Monida transverse zone (Figure 23). This structurally-controlled transverse zone may be related to a diffuse shear zone (the Great Falls tectonic zone of O'Neill and Lopez, 1985) developed in the Middle to Late Proterozoic which separates Archean basement to the south from Middle and Late Proterozoic rocks to the north. In the local Lima area, the Great Falls tectonic zone may be represented by the Dillon cutoff (O'Neill et al., 1990; Lawton et al., 1994). Therefore, at the southern terminus of the Montana-Idaho thrust belt, the Monida transverse zone may have occupied a long-lived, structural weakness which funneled coarse material (including Proterozoic quartzite clasts) eastward and potentially controlled the locus of deposition of large amounts of detritus generated in hinterland regions of thrust belt.

Several viable hypotheses have been proposed to account for exposure of quartzite source rocks to erosion in east-central Idaho/southwest Montana. Emplacement of the Idaho Batholith may have caused thermal arching and regional uplift in central Idaho. The deeply eroded flanks of the uplift exposed Middle Proterozoic Swauger, Lemhi, and Belt rocks, from which detritus was shed eastward (Ryder and Scholten, 1973; Haley, 1986). Conversely, detritus may have been progressively recycled during the evolution of the thrust belt and eventually transported

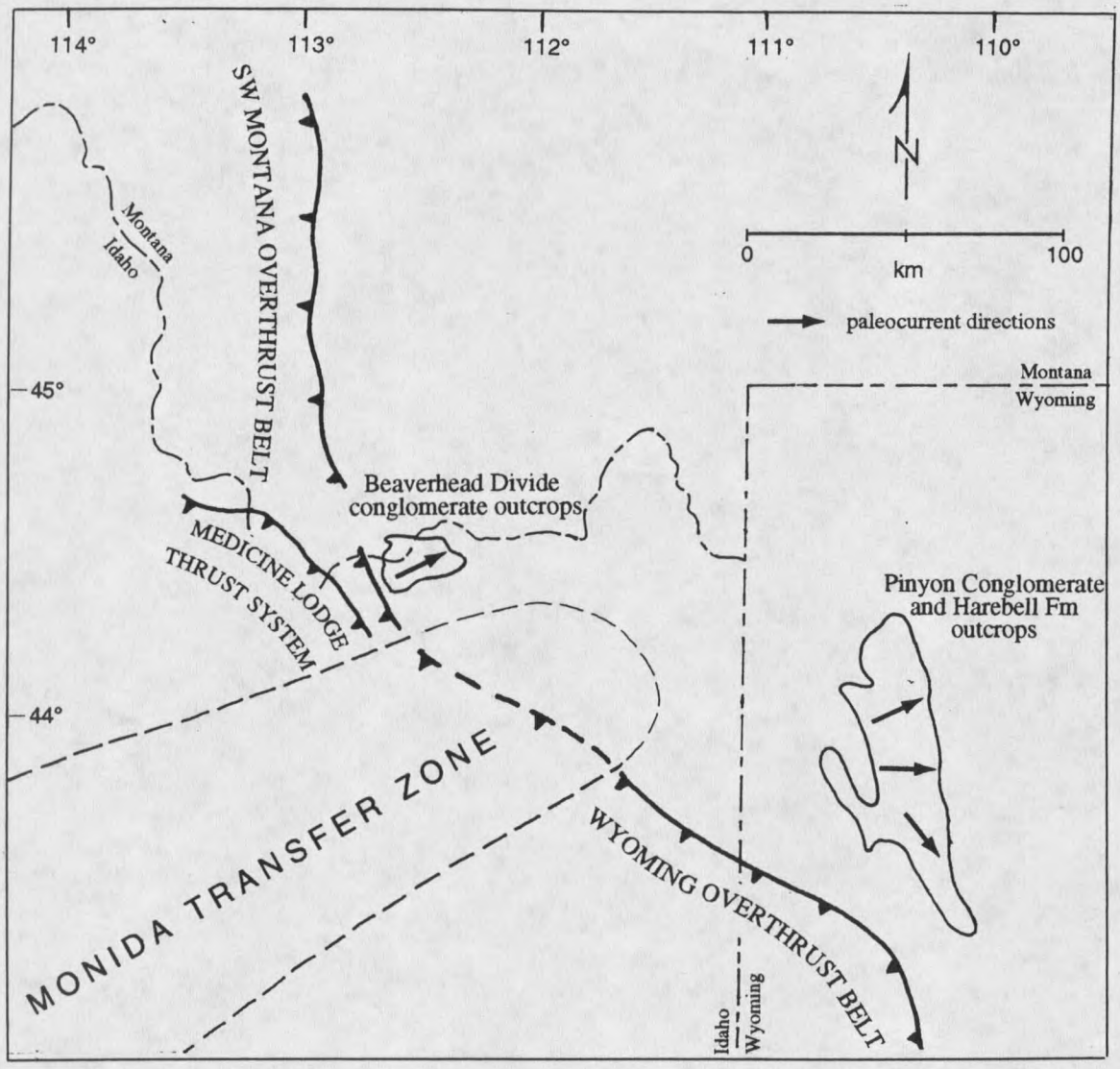


Figure 23: Orientation of major paleorivers during Late Cretaceous and early Tertiary Beaverhead Divide conglomerate, Harebell Formation, and Pinyon Conglomerate deposition (after Lindsey,1972; Lawton et al., 1994).

toward the foreland (Perry and Sando, 1983; Kraus, 1984). Uplift of the source rocks for the quartzite-dominated conglomerate by interior ramp-supported uplift was suggested by Schmitt and Steidtmann (1990). As thrust activity shifts toward the foreland, inactive thrusts were passively transported over footwall ramps, generating significant relief deep within the thrust-belt interior. In the Montana-Idaho segment of the thrust belt, the far-traveled Medicine Lodge thrust system, carrying rocks from east-central Idaho, may have been eroded during the Late Cretaceous, shedding coarse sediment to the east (Schmitt and Steidtmann, 1990).

INTERTONGUING OF LITHOSOMES

Description

The Knob Mountain and Divide conglomerate lithosomes intertongue along a southwest-northeast trend in part of the Irving Creek drainage basin (the Bull Pen) and along the northeast flank of the Thumb (Plate 1). Northwest of the study area, a quartzite conglomerate lithosome (possibly the Divide) intertongues with the Knob Mountain lithosome and other, limited exposures of limestone-clast conglomerate on the footwall of the Medicine Lodge thrust (Figure 2); however, exposures of these intertonguing relations are extremely poor. Alternating beds of limestone-clast and quartzite-clast conglomerate are best exposed at the Bull Pen where the Knob Mountain and Divide conglomerate lithosomes are exposed in the small cliffs north of the access road.

Beds of the two lithosomes alternate vertically and pinch out laterally over an area approximately 13 km long and 3.5 km wide (Skipp et al., 1979). The geometry of the intertonguing zone is best defined by tongues of the Knob Mountain conglomerate lithosome. Quartzite-clast conglomerate is preserved in the regions between the well-cemented limestone-clast conglomerate, and good outcrop exposure of quartzite-clast conglomerate diminishes abruptly away from the zone. A measured stratigraphic section (Section D; plate 8) is located where approximately 50 m of interfingered conglomerate (limestone-clast and quartzite-clast) and sandstone (litharenite and quartz arenite) are exposed; this outcrop is one of the thickest exposed vertical sections in the zone of intertonguing lithosomes. Lateral extent of individual conglomerate tongues is

on the order of tens of meters. Each lithosome tongue can be as thick as one bed (less than a meter thick) or composed of many beds (tens of meters thick), although commonly the tongues consist of only a few beds of conglomerate and sandstone.

Lithosomes are specifically defined by lithofacies type and easily identified by outcrop expression. The Knob Mountain conglomerate lithosome is a poorly-sorted, massive, and disordered conglomerate, and the Divide conglomerate lithosome is characterized by bimodally-sorted, massive, conglomerate with disordered or imbricated clasts. The major petrofacies of the Knob Mountain conglomerate lithosome contains limestone (78%), chert (14%), and sandstone (8%). Clast composition for most of the Divide conglomerate lithosome is quartzite (63%), sandstone (17%), limestone (12%), and igneous (5%). Minor sandstone interbeds are either white quartzarenites or light gray litharenites, similar to sandstones described earlier for each lithosome.

The Knob Mountain and Divide conglomerate lithosomes each contain beds of conglomerate which are mixed compositionally (Table 5; Appendix B). The mixed-clast petrofacies are restricted to the intertonguing zone and are observed as distinct, usually isolated conglomerate beds which retain the textural and lithofacies characteristics of one lithosome but contain clasts of the other lithosome (Figure 24). Mixed-clast conglomerates also consist of a mixture of rough, angular clasts with polished, round clasts. The mixed-clast petrofacies of the Knob Mountain conglomerate lithosome is dominated by quartzite clasts and contains lesser amounts of limestone and sandstone; most clasts are rounded (Figure 25). The mixed-clast conglomerates of the Divide conglomerate lithosome contain almost equal amounts of quartzite and limestone clasts, and the percentage of rounded and angular clasts is the same (Figure 26).

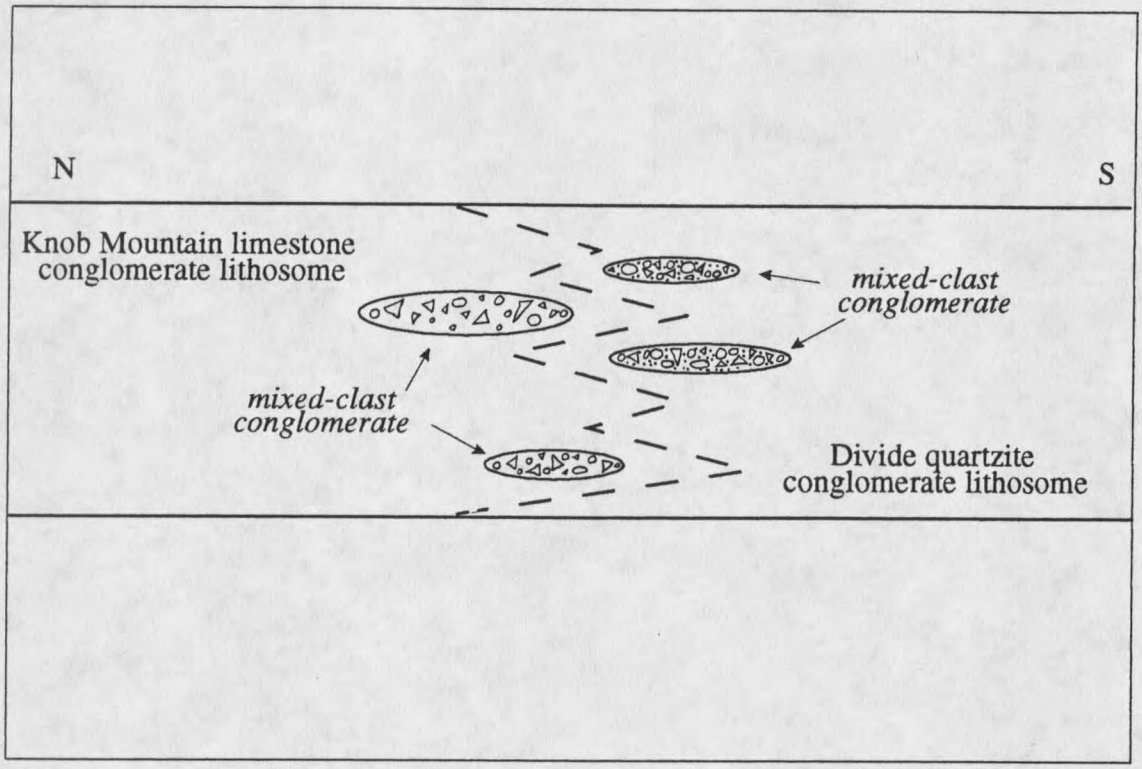


Figure 24: Schematic cross-section showing the intertonguing relation between the Knob Mountain conglomerate lithosome (north) and Divide conglomerate lithosome (south), and the presence of both mixed-clast petrofacies. The poorly-sorted, mixed-clast conglomerates are grouped with the Knob Mountain lithosome, and the bimodally-sorted, mixed-clast conglomerates are included in the Divide lithosome.



Figure 25: Poorly-sorted, mixed-clast conglomerate of the Knob Mountain conglomerate lithosome from Irving Creek (Canyon 1) (lens cap is 4 cm).



Figure 26: Bi-modally sorted, imbricated mixed-clast conglomerate of the Divide conglomerate lithosome from measured section D (46.35 m) (lens cap is 4 cm).

Table 5: Composition, texture, and depositional processes of the mixed-clast petrofacies

Lithosome	Composition	Roundness	Lithofacies Types	Depositional Processes and Flow Types
Knob Mountain conglomerate (mixed-clast)	49% quartzite 29% limestone 14% sandstone 4% igneous 2% other	70% rounded 30% angular	*Gm*	sediment-gravity flow, deposition *en masse* by clast-rich, non-cohesive debris flows
Divide conglomerate (mixed-clast)	46% quartzite 42% limestone 10% sandstone 1% igneous 1% other	50% rounded 50% angular	*Gmb* *Gmib*	fluid-gravity flow, selective deposition during waning flow, formation of gravel bars

Interpretation

The Knob Mountain conglomerate lithosome was deposited in an alluvial fan setting adjacent to the fluvial plain of the Divide conglomerate lithosome. Therefore, the alternating conglomerate beds of the two lithosomes are interpreted to record the lateral migration of both depositional systems over time. The presence of the mixed-clast petrofacies in the intertonguing zone suggests that mixing of material from the two depositional environments occurred. Here, the lithosome concept is particularly useful in understanding the significance of the mixed-clast petrofacies. At the margins of the two environments, depositional and sedimentologic processes remain distinctive, but the mixed clast composition and roundness characteristics reflect the incorporation of material from one system into the other. Therefore, the mixed-clast petrofacies indicate an interaction between the two adjacent depositional settings. Although modern analogs of such interactions between alluvial fan and fluvial depositional environments exist, rarely is evidence of this interaction observed in the rock record.

Knob Mountain Mixed-clast Conglomerates

Poor sorting in the mixed-clast conglomerates suggests these beds were deposited *en masse* by a clast-rich, cohesionless debris flow (Table 5). Clast composition and roundness suggest quartzite clasts were recycled, probably from recently deposited braided stream material. Special conditions are required to produce the mixed composition of the conglomerates whether the clast-rich debris flows were deposited in either the alluvial fan or braided stream environment.

If the deposition of the Knob Mountain mixed-clast conglomerates was coeval with limestone-clast debris flows on the surface of an alluvial fan, then braided stream deposits (composed of the quartzite petrofacies) not only had to be removed from the fluvial environment but elevated to the source area drainage basin which sourced the bulk of the alluvial fan sediment. Given the structural position of this piggyback basin, such a process could occur during deformation of the underlying thrust sheet.

A modern example of uplifted and abandoned stream terrace deposits is described in the northern Pakistan fold and thrust belt where transpressive tectonic uplift and block tilting resulted in the southeast migration of the Indus River drainage (McDougall, 1989). Paleoriver conglomerates of the Indus River are found uplifted to as high as 630 m above current river elevation (McDougall, 1989), although no mention is made regarding the reworking and redeposition of these deposits. A similar process of migration, abandonment, and uplift is envisioned for the Knob Mountain study area. Local deformation by growing folds, which generated the source area for the Knob Mountain conglomerate lithosome, may also have caused the lateral migration of the fluvial environment, uplift and eventual incorporation of the recently abandoned stream deposits, and recycling of sediment on alluvial fans (Figure 27).

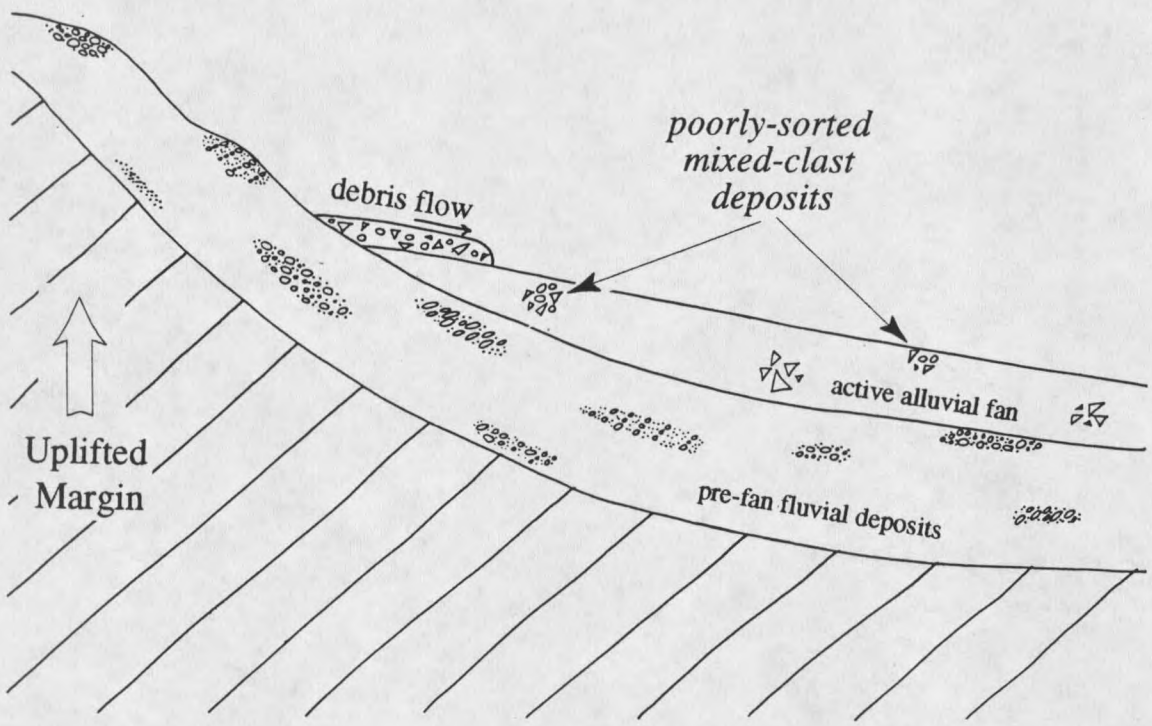


Figure 27: Schematic diagram showing debris flows sourced by detritus from uplifted braided stream deposits mixed with detritus derived from the drainage basin.

The mixed-clast conglomerates of the Knob Mountain lithosome may be the deposits of small mass-wasting events on the fringes of a braided stream environment where fluvial terraces incorporate both fluvial and fan deposits (Figure 28). A poorly-sorted deposit may result if oversteepened stream terraces composed of poorly-consolidated material collapsed or slumped on the stream floodplain. If the stream terraces were composed of tongues of alternating limestone-clast and quartzite-clast conglomerate beds, then the composition of the slumped deposits would be mixed. The presence of poorly-sorted mixed-clast conglomerates only where the two conglomerate lithosomes intertongue supports the localized remobilization of stream terrace material within the braided stream environment.

Terraces form in braided stream environments when the river is incising due to either a change in climate, base level, or tectonism (Butler, 1984; Merritts et al., 1994; Miall, 1996, p. 465). The degree of influence each of these factors has on the development of terraces is not well understood, nor is it known how to identify and interpret the formation of terrace deposits in the rock record. Therefore, no inferences regarding tectonism can safely be made about the presence of terraces, if indeed they existed in the Knob Mountain study area during deposition of the Divide conglomerate lithosome. In addition, documented modern examples of slumped terrace deposits of braided streams are difficult to find. Rust and Jones (1987) describe "transverse-retrogressive slump scars" in the Triassic Hawkesbury Sandstone in Australia; however, these features are interpreted to be associated with a sandy braided stream setting rather than the high-energy gravelly stream interpreted for the Divide conglomerate lithosome.

Divide Mixed-clast Conglomerates

The bimodally-sorted, mixed-clast conglomerates of the Divide conglomerate lithosome represent gravel bar bedforms in a braided stream (Table 5). The mixed

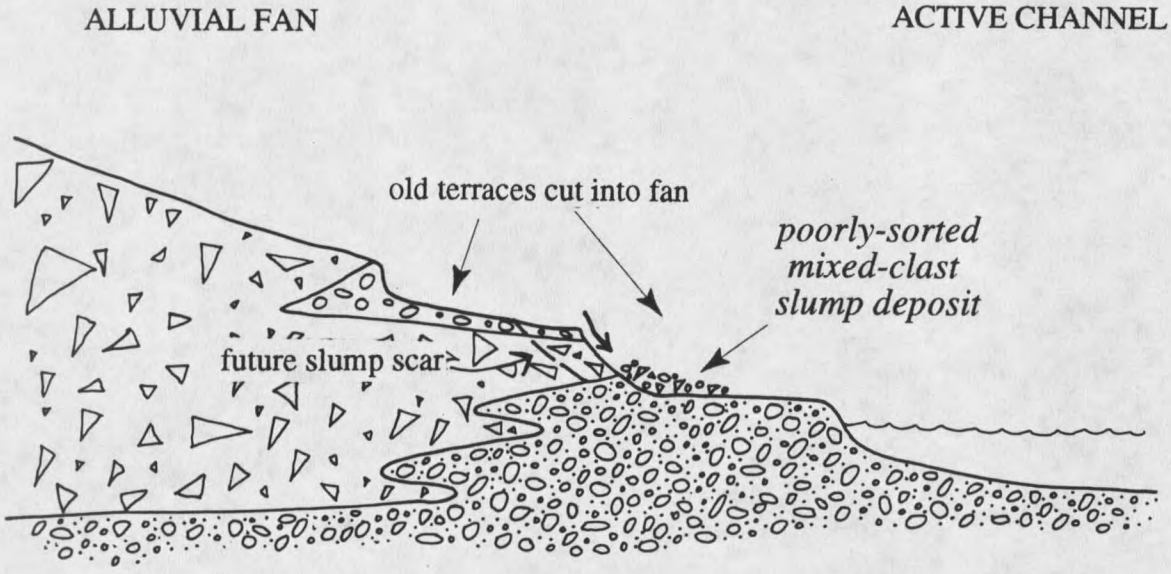


Figure 28: Schematic diagram showing terraces comprising intertongued alluvial fan and braided stream deposits slumping to produce poorly-sorted, mixed-clast deposits

composition and texture of conglomerate clasts are the result of the incorporation of alluvial fan material into the braided stream. Two processes could generate bimodally-sorted, mixed conglomerate beds. As sediment from alluvial fan source areas was delivered to the toe of the fan, catastrophic debris flows or sheetfloods could extend beyond the toe into the river (Figure 29). In addition to the direct delivery of locally derived fan sediment to the stream channel, the stream may have cut into the distal ends of the fan, reworking older debris flow and sheetflood deposits of the distal fan and incorporating this recycled fan material into the channel system (Figure 30).

Examples of both processes can be found operating today. The influx of large amounts of sediment into a fluvial system from catastrophic debris flows on alluvial fans often causes stream modification such as channel braiding (due to the formation of gravel bars) and minor deflection of the stream bed (e.g. Blair, 1987; Webb et al., 1988). Examples of streams incorporating and reworking fan material are not discussed in detail in the literature; however this process is illustrated in southern Death Valley along the Amargosa River (Butler et al., 1988), and the Waimakariri (Reinfelds and Nanson, 1993) and Rangitata Rivers of New Zealand (Miall, 1996, p. 213) where fans prograde out onto braided river floodplains and are subjected to erosion during flood stages.

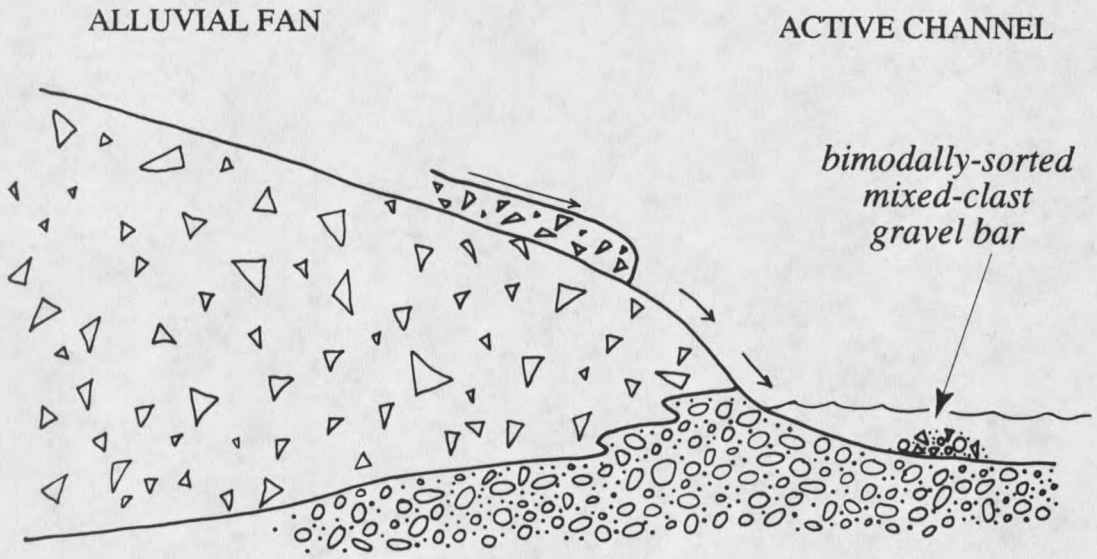


Figure 29: Schematic diagram showing a debris flow overrunning the toe of the alluvial fan and directly delivering detritus from the fan source area to an adjacent stream.

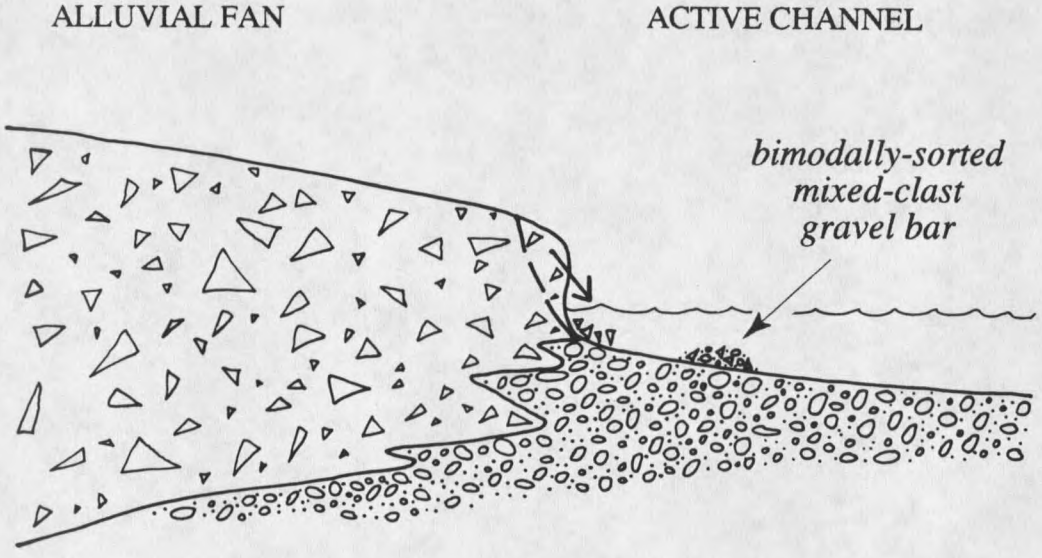


Figure 30: Schematic diagram showing a stream eroding the toe of an alluvial fan resulting in the addition of fan source-area detritus to braided stream deposits.

GALLAGHER SPRING CONGLOMERATE LITHOSOME

Description

An isolated outcrop of poorly-sorted conglomerate of the Beaverhead Group is exposed on the hanging wall of the Tendoy thrust near Gallagher Spring (Sadler, 1980; Haley, 1986; Skipp, 1988) (Figure 2). Lithofacies types for the Gallagher Spring conglomerate are similar to those in the Knob Mountain conglomerate lithosome, but the dominant clast composition differs. Because the Gallagher Spring conglomerate is spatially close to the study area and in the same structural position as the Knob Mountain and Divide conglomerate lithosomes, the depositional environment and provenance of this unit were investigated to determine if these conglomerates are related to those exposed in the Sawmill Creek and Irving Creek areas.

Overall, rocks exposed in the Gallagher Spring area are very coarse-grained. The main lithofacies type is massive, poorly sorted, clast-supported conglomerate (*Gm*). In some beds, framework clasts have a weak bedding-parallel arrangement. Maximum particle average for the framework clasts ranges between 7 to 63 cm, and some *Gm* beds contain outsized clasts up to 2 m (Figure 31). Clasts are angular and rough in texture. Matrix is not abundant and is composed of a very poorly-sorted mixture of mud to granules. Clast imbrication is not present.

Sandstone beds are extremely rare; massive, gravelly sandstone (*Smg*) is present as thin (<30 cm thick) stringers in massive conglomerate beds, but these are not common. Massive sandstone beds or cross-stratified beds are either absent or not exposed at Gallagher Spring.

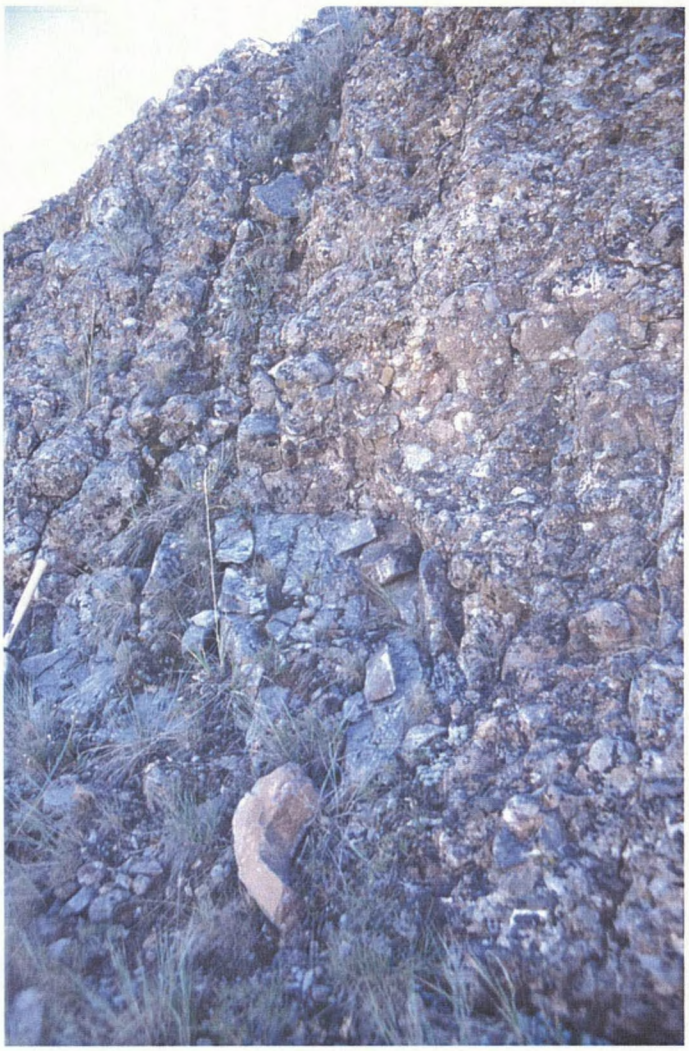


Figure 31: Massive, poorly-sorted conglomerate (*Gm*) in the Gallagher Spring conglomerate lithosome. Hammer is next to 115 cm outsized clast of Pennsylvanian Quadrant sandstone; maximum particle size average is 63 cm (hammer is 40 cm).

Clasts are primarily sandstone (Table 6; Appendix B). Most of the sandstone clasts are resistant, silica cemented, quartzarenite which are probably derived from the Pennsylvanian Quadrant Formation. The outsized clasts are identified as quartzarenite or cherty limestone from the Pennsylvanian Quadrant and Permian Phosphoria Formations, respectively. Triassic Dinwoody Formation limestone clasts are the only other recognizable clast type; no Triassic Thaynes Formation clasts were identified, although clasts of limestone with chert nodules may have come from either this unit or the Phosphoria Formation.

Table 6: Clast composition of conglomerates at Gallagher Spring

sandstone	limestone	chert	siltstone	other	angular
52%	43%	7%	1%	1%	100%

Interpretation

The depositional environment for the Gallagher Spring area is an alluvial fan, probably similar to the alluvial fans that are represented by the Knob Mountain conglomerate lithosome. The complete lack of stratified beds, the clast-supported, massive, and poorly-sorted character of the conglomerates, and the presence of outsized boulders all indicate non-selective deposition by sediment-gravity flows (Shultz, 1984; Costa, 1988; Beaty, 1989; Blair and McPherson, 1994a, b). Conglomerate clast composition also suggests these deposits were locally derived. Pennsylvanian Quadrant, Permian Phosphoria, and Triassic Dinwoody Formations are all exposed northeast of Gallagher Spring in the southeast plunging, steep-limbed fold on the Tendoy plate. Lithofacies type, the angularity of clasts (including fissile Dinwoody clasts), and the overall immature character of the conglomerate suggests short transport distance by debris flows.

DYNAMIC STRATIGRAPHIC MODEL

The Knob Mountain, Divide, and Gallagher Spring conglomerate lithosomes lie structurally on the hanging wall of the Tendoy thrust. The Tendoy allochthon is part of the frontal thrust system which has experienced less tectonic transport than the Medicine Lodge and Four Eyes Canyon thrust plates, but has interacted extensively with foreland deformational structures (Perry, 1988; Skipp, 1988; McDowell, 1997). The Tendoy thrust sheet and, possibly, the basement-involved Blacktail-Snowcrest uplift are considered the major structural elements that are directly related to the deposition of the Knob Mountain and Gallagher Spring alluvial fans, the migration of the Divide gravelly, braided stream, and the interaction between the two depositional environments. The Medicine Lodge and Four Eyes Canyon thrusts are part of a far-traveled thrust system with a history of multiple transport events. Neither of these two thrust sheets supplied detritus to the localized, alluvial fan deposits in the study area, and both thrusts override all three conglomerate lithosomes. Therefore, the Medicine Lodge and Four Eyes Canyon thrusts are considered late and minor structural elements in the synorogenic depositional history of the Knob Mountain, Divide, and Gallagher Spring conglomerate lithosomes.

The Tendoy thrust trends northwest-southeast from the McKnight Canyon area, where Mississippian limestones are thrust over Beaverhead Group conglomerate, to the Lima area where Lower Cretaceous rocks are placed over Upper Cretaceous rocks. Near the study area, Pennsylvanian through Lower Cretaceous strata constitute the tight upper-plate fold which trends in the same orientation as the Tendoy thrust (Ryder and Scholten, 1973; Hammons, 1981, McDowell, 1997). Evidence of foreland deformation, such as a deviation of the thrust trace near Lima Peaks, the lateral ramp

which coincides with the projection of the Blacktail-Snowcrest uplift beneath the thrust belt, and out-of-sequence thrusting of the Medicine Lodge and other thrusts in the area, has been investigated and discussed by several previous workers (Hammons, 1981; Perry et al., 1981; Haley, 1986; Kulik and Perry, 1988; Perry et al., 1988; Skipp, 1988; McDowell, 1997). Determining the sequence of deformational styles in the Lima Peaks area is beyond the scope of this study; it is apparent, however, that foreland activity overlapped with thrust-belt activity both temporally and spatially. The sedimentology of the Knob Mountain conglomerate lithosome indicates the source area is restricted to nearby areas, eliminating the possibility that material was derived by Blacktail-Snowcrest deformation beyond the frontal thrust. However, because the Snowcrest-Greenhorn thrust projects beneath the Tendoy plate, activity on the Blacktail-Snowcrest system may have uplifted the Tendoy thrust sheet creating the necessary topographic relief in the Lima Peaks region to generate alluvial fan deposits (Haley et al., 1995).

Only two palynologic dates are available that are indirectly connected to the Beaverhead Group rocks on the Tendoy plate. The Frontier Formation, conformably overlain by the Divide conglomerate lithosome in part of the study area, has been dated as Cenomanian to Turonian (Nichols, et al., 1985). The Tendoy thrust cuts the Lima Conglomerate, the uppermost deposits of which have been dated as mid-Campanian (Nichols, et al., 1985). Movement on the Tendoy possibly extended into the early Paleocene (Dyman, et al., 1995). Therefore, deposition of the conglomerate lithosomes on the Tendoy thrust sheet took place sometime between Coniacian to early Paleocene time.

The Divide quartzite conglomerate lithosome was deposited conformably on the quartzite-clast conglomerate of the Frontier Formation in the southern part of the study area (Dyman et al., 1995). Frontier quartzite conglomerates contain discreet

porcellanite layers, and Dyman et al. (1995) selected the upper-most porcellanite layer as the contact between the Frontier and the overlying Divide quartzite conglomerate. Otherwise, the transition between the two conglomerate lithosomes of similar lithology is characterized by a general increase in conglomerate clast size (Dyman et al, 1995). Although difficult to establish due to poor outcrop exposure, deposition of braided stream material was probably continuous from Frontier to Divide time.

Paleocurrent data and stratigraphic relations in the Irving Creek area indicate that a braided fluvial system continued to transport detritus from the thrust-belt interior to the northeast after Turonian time (Figure 32). Intertonguing relations between the Divide and Knob Mountain lithosomes indicate coeval deposition of alluvial fan material derived from a region to the north. Because the rock types exposed in the anticline on the hanging wall of the Tendoy thrust are present in the Knob Mountain conglomerates, and because the axial trace of the fold is parallel to the Tendoy thrust, alluvial fans are inferred to have formed due to the growth of this anticline during movement on the Tendoy thrust. Clasts in the Gallagher Spring conglomerate may have been derived from erosion of the same fold. The overall southeast plunge of the fold would expose the deeper Pennsylvanian Quadrant Formation in the area of Gallagher Springs, and the preponderance of Quadrant clasts in the debris flow deposits of this lithosome support linking the Gallagher Spring alluvial fan with the same Tendoy thrust activity.

The alluvial fans prograded south-southwestward as the magnitude of the fold grew during Tendoy thrusting, leading to the interaction of the fluvial and fan environments and deposition of the mixed-clast petrofacies in the Divide and Knob Mountain conglomerate lithosomes (Figure 33). As the alluvial fans encroached on the braided stream alluvial plain, debris flows contributed material directly to the gravelly stream, and/or the stream periodically eroded the distal portions of the fans. Either

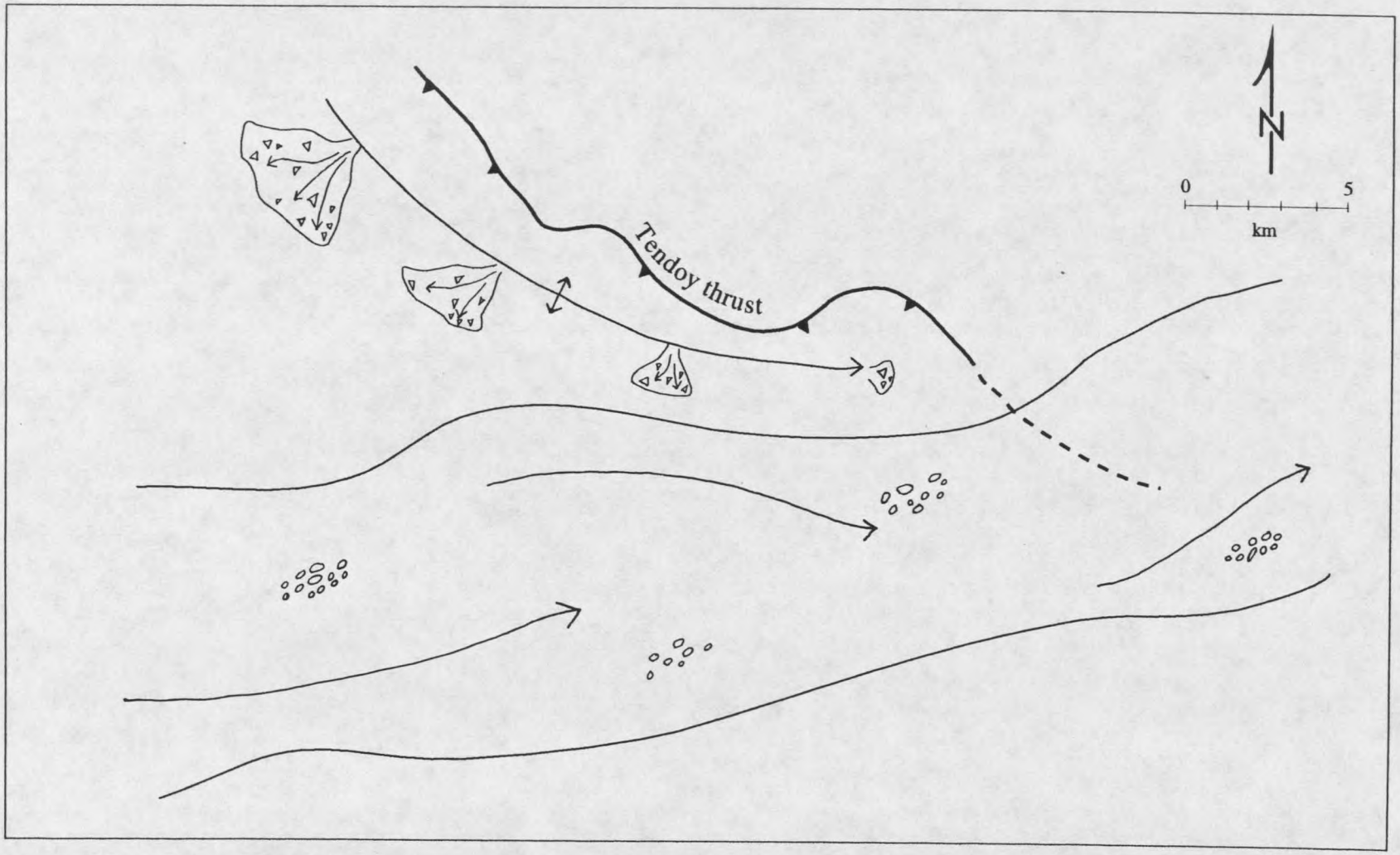


Figure 32: Schematic diagram showing the position of the paleoriver that deposited the Frontier and Divide quartzite conglomerate lithosomes near or after Turonian time.

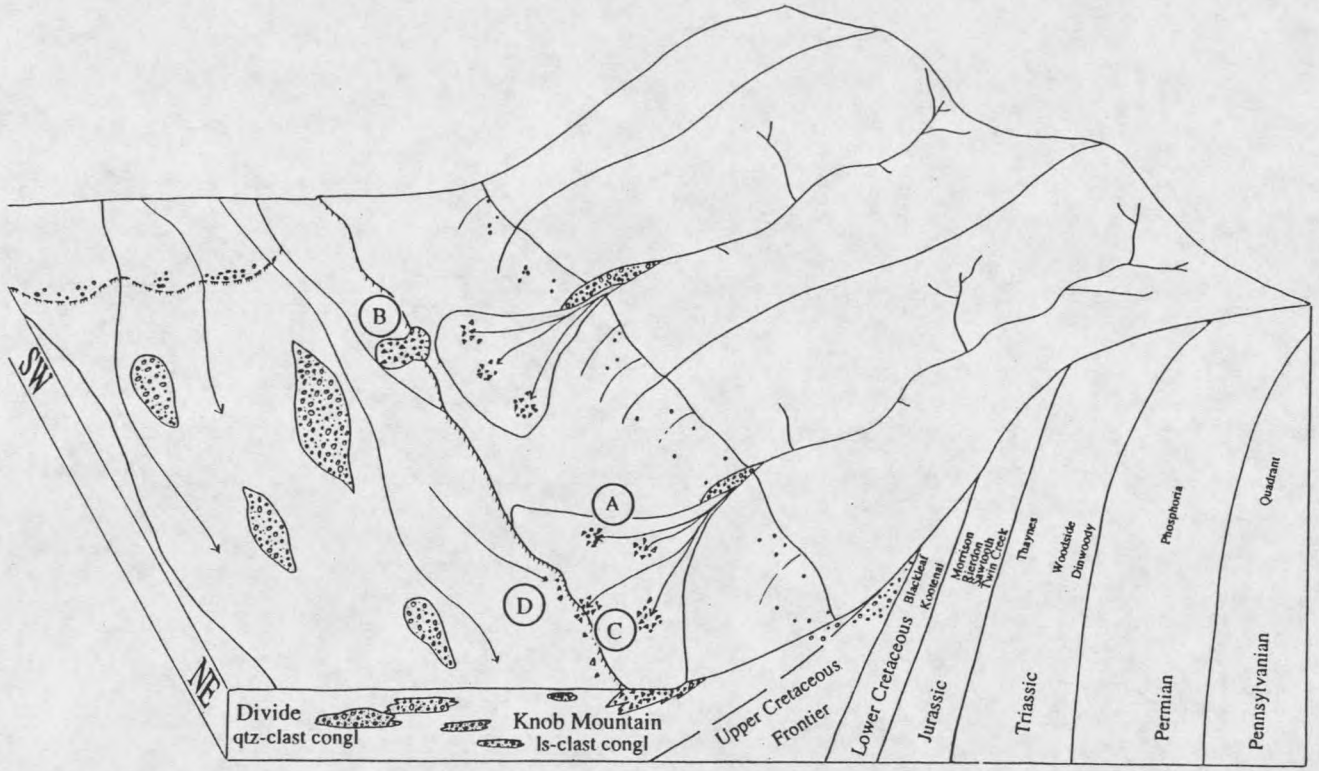


Figure 33: Schematic diagram showing the interaction between the debris-flow-dominated alluvial-fan environment and shallow, gravelly braided stream environment due to the migration of the two depositional facies away from the growing hanging-wall anticline. Material is transferred from one environment to another by various processes: A) previously-deposited braided-stream deposits are incorporated into the limb of the fold and redeposited as debris-flow lobes on alluvial fan surface; B) unconsolidated stream terraces comprising intertonguing limestone and quartzite lithosomes fail by bank collapse resulting in poorly-sorted, mixed-clast slump deposits; C) debris flows overrun the distal ends of alluvial fans and contribute limestone clasts directly into the braided stream; D) the braided stream cuts into the toes of prograding alluvial fans and incorporates debris-flow material into the fluvial system (vertical exaggeration approximately 10x).

process would result in the bimodally-sorted Divide conglomerates composed of both angular limestone and rounded quartzite clasts. Poorly-sorted Knob Mountain conglomerates (also containing rounded quartzite and angular limestone clasts) could have formed as terraces consisting of intertongued fluvial quartzite and alluvial-fan limestone deposits slumped.

Fold growth could also incorporate older alluvial deposits into the limb of the hanging-wall anticline (Figure 33). Divide (and possibly Frontier) quartzite-clast conglomerate may have been uplifted and partially eroded with rounded quartzite clasts mixing with detritus derived from the upper reaches of the alluvial fan drainage basins. Sediment containing this mixture of rounded quartzite clasts and angular limestone clasts was then transported down-fan as clast-rich debris flows and deposited as debris-flow lobes or levees on the surfaces of prograding alluvial fans.

If braided stream deposits were elevated sufficiently to become source material for debris flows deposited on alluvial fans, then the poorly-sorted mixed-clast petrofacies of the Knob Mountain lithosome strongly support nearby deformation of strata on the Tendoy thrust plate. However, if the mixed conglomerates of the Knob Mountain lithosome were not deposited on an alluvial fan, but represent slumped terrace deposits adjacent to an incising river, the role of tectonism is less clear. Local tectonic activity may have triggered river downcutting and the formation of terraces, but other factors, such as a decrease in sediment input, changes in drainage basin size and bedrock geology, and climate change, could effect the same result.

In the Knob Mountain study area, lithofacies analysis is an important component in the development of a stratigraphic model showing the evolution of this piggyback basin over time. The deposits of alluvial fans are recognized in the rock record by a distinctive lithofacies assemblage produced by primary hydrologic and depositional processes inherent to this environment. Alluvial fans are characterized by

unconfined, catastrophic flow over steep slopes (>1.5°) with material derived from small drainage basins (Blair and McPherson, 1994b). Braided streams possess complex, extensive, drainage networks with sediment transported large distances over gentle gradients (<0.5°) primarily by fluid-gravity flows, with flow generally confined to a linear zone (Rust, 1978; Blair and McPherson, 1994b; Miall, 1996). The distinction between alluvial fan and fluvial depositional environments is often not made due to the misconception that braided streams are elements found on some alluvial fans (Blair and McPherson, 1994b). However, the set of hydraulic and depositional processes for each environment is distinctive. These distinctions are ultimately used to differentiate basin margin from axial sedimentation and to identify of the role of local deformation as depositional facies migrate and interact.

The Knob Mountain, Divide, and Gallagher Spring conglomerate lithosomes were deposited in a piggyback basin within the wedge-top depozone of the thrust belt. As defined by DeCelles and Giles (1996), wedge-top depozones in thrust belts occupy the frontal part of the thrust belt, consist of coarse, immature sediment deposited in alluvial fan and fluvial settings, and commonly contain growth structures indicative of syndepositional tectonism. The intertonguing relations between the Knob Mountain and Divide lithosomes and the complex interaction between alluvial fan and fluvial environments document the migration of the margins of the two environments due to growth of a hanging-wall fold on the Tendoy thrust sheet.

Clasts of the Knob Mountain conglomerate lithosome were derived from the folded rocks on the Tendoy thrust which, remarkably, are presently being eroded today. Therefore, the present-day erosional surface approximates the Late Cretaceous erosion surface which has been exhumed recently due to uplift on normal faults. The Tendoy thrust sheet does not show evidence of significant burial during Sevier and Laramide contractional events (low vitrinite reflectance and conodont color alteration index values

from Perry et al., 1983); therefore, footwall uplift on local normal faults and the resultant denudation of Paleocene and younger rocks on the Tendoy thrust is probably recent.

CONCLUSION

Provenance and sedimentologic analysis of the Knob Mountain limestone-clast conglomerate indicates that detritus was derived from the Tendoy thrust sheet, transported a short distance, and deposited in alluvial fans which prograded from a region of nearby uplift. The limited provenance and sedimentologic data from the Gallagher Spring conglomerate suggest that these conglomerates were also deposited in a localized, alluvial fan setting; the dominance of Upper Paleozoic (Quadrant-Phosphoria) and Lower Mesozoic (Dinwoody) clasts suggests that detritus was shed in an antithetic (westward) direction from a growing fold on the Tendoy thrust sheet. In contrast, detritus of the Divide conglomerate lithosome was transported northeastward in a synthetic direction in an extensive transverse braided stream system that drained various thrust sheets and delivered sediment from distant regions within the thrust-belt interior.

The intertonguing of the Knob Mountain and Divide conglomerate lithosomes records the migration of two distinct depositional environments. The fringe of alluvial fans that formed at the base of growing folds on the Tendoy thrust sheet advanced toward the existing, transverse braided stream. Over time, the two depositional environments shifted laterally, delineating a zone of intertonguing. In addition, material from each depositional system was transferred to the other by a variety of processes, documenting an interaction between two distinct depositional environments.

The growth of the hanging wall anticline on the Tendoy thrust and associated deposition of the Knob Mountain and Gallagher Springs alluvial fan deposits document syndepositional, basin-margin deformation. Progressive unconformities, basin margin features identified in conglomerate units elsewhere in contractional settings including

southwest Montana, were not recognized in the Knob Mountain study area. Specific elements that define a progressive unconformity, such as a syntectonic angular unconformity and wedge-shaped conglomerate beds, are not exposed. However, syndepositional, basin-margin deformation is inferred from the migration and interaction of two juxtaposed depositional environments in response to contractional deformation on the underlying thrust sheet.

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APPENDICES

APPENDIX A

LOCATION OF MEASURED SECTIONS

Sections A, B_1, B_2, and B_3 (plates 2, 3, 4, and 5) are located on the Montana side of the Continental Divide in the upper reaches of the Sawmill Creek drainage basin (plate 1). Section A is on the northeast flank of the knoll immediately north of Red Conglomerate Peaks. Sections B_1 - B_3 are located below the saddle between Knob Mountain and Red Conglomerate Peaks. Section B_4 (plate 6) is located on the south side of the Continental Divide, close to B_3, and finishes near the top of Red Conglomerate Peaks. Access to Section C (plate 7) is from the Bull Pen area of Irving Creek in Idaho; the section begins near the saddle between Knob Mountain and The Thumb and continues up the eastern flank of Knob Mountain. Section D (plate 8) also is accessed from the Bull Pen and is located in one of the small gullies on the north side of the creek.

The transect in the Thumb area begins in the NE 1/4 of the NE 1/4 of Section 26, T15S R8W in Beaverhead County, Montana (plate 1). The transect line follows a ridge through the southwest 1/4 of Section 25, and ends at the base of a cliff in the NW 1/4 of the SW 1/4, Section 36.

APPENDIX B

CONGLOMERATE CLAST COUNT DATA

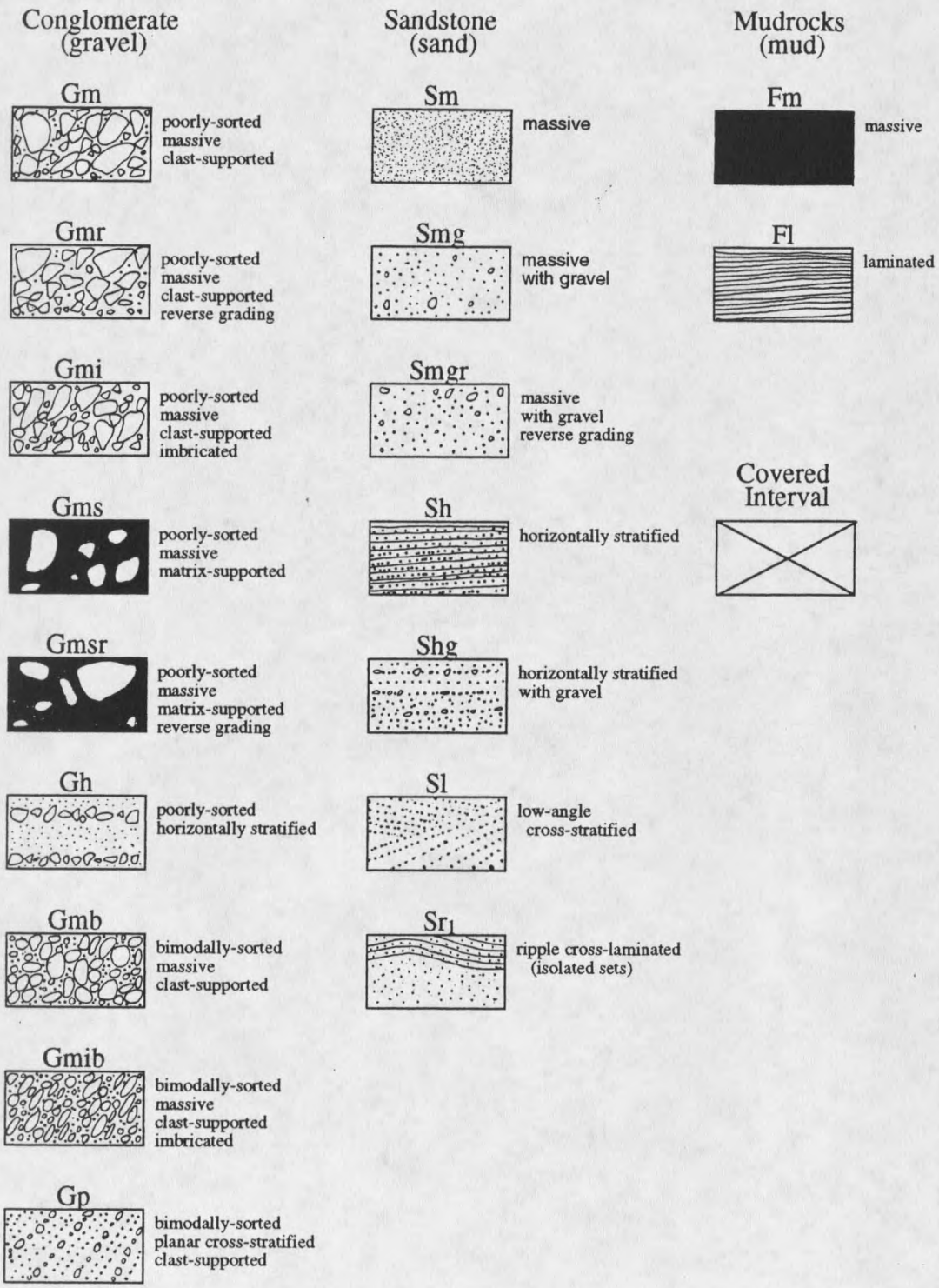
Table 7: Conglomerate clast count data from Knob Mountain and Gallagher Spring areas

Location																	
Section	meters above base	lithosome	sandstone	limestone	siltstone	limestone w/ chert	chert	quartzite	igneous	Quadrant	Phosphoria	Dinwoody	Thaynes	other	total	clast angularity	comments
A-1	base	Kbkm	3	144		11	19					12	11		200	all angular	
A-2	115	Kbkm	2	162	4	11	16					13	30		238	all angular	
A-3	245	Kbkm	11	132	10	8	22					14	11	3	211	all angular	
B1-1	10	Kbkm	10	108	5	3	29					22	24		201	all angular	
B1-2	100	Kbkm	12	121	3	3	31				4	16	17	2	209	all angular	
B2-1	base	Kbkm	12	110		24	19					12	19	4	200	all angular	
B2-2	40	Kbkm	11	107	22	5	7					19	29		200	all angular	
B2-3	45	Kbkm	10	109	1	2	28					32	16	2	200	all angular	
B3-1	base	Kbkm		82		5	98					5	9	1	200	all angular	
B3-2	75	Kbkm	5	122	2	3	33					23	11	1	200	all angular	
B4-1	base	Kbkm	4	119	2	8	24				2	19	22	1	201	all angular	
B4-2	205	Kbkm	20	139	3	3	18					6	10	1	200	all angular	
B4-3	210	Kbkm	8	121	5	8	30			4		23	11	4	214	all angular	
C-1	base	Kbkm	27	93	13	2	14				7	41	10	1	208	all angular	
C-2	60	Kbkm	32	100	10		22				7	20	11	1	203	all angular	
D-1	base	Kbd	14	12				69	7					1	103	102 rounded, 1 angular	
D-2	9.75	Kbkm	13	127	10	11	26					12	3		202	all angular	
D-3	30	Kmd	17	35				46				2		1	101	51 rounded, 50 angular	mixed petrofacies of Kbd
D-4	46.5	Kbd	3	47			2	48	2				1		103	52 rounded, 51 angular	mixed petrofacies of Kbd
Irv Ck-1		Kbkm	15	35			6	44				1	2		103	65 rounded, 38 angular	mixed petrofacies of Kbkm
Irv Ck-2		Kbd	21	11				58	3				1	6	100	90 rounded, 10 angular	
Irv Ck-3		Kbkm	17	14			5	59	9						104	89 rounded, 15 angular	mixed petrofacies of Kbkm
Irv Ck-4		Kbkm	10	38			3	47	2						100	62 rounded, 38 angular	mixed peterofacies of Kbkm
Thumb	site 6	Kbkm	17	133	1	1	39				3	11		1	206	all angular	
Gal Sp		Kbgs	20	56	2	4	7			88		30		1	208	all angular	

APPENDIX C

LEGEND OF LITHOFACIES TYPES USED IN MEASURED SECTIONS

Figure 34: Legend of lithofacies types used in measured stratigraphic sections (Plates 2-8, Figure 8)



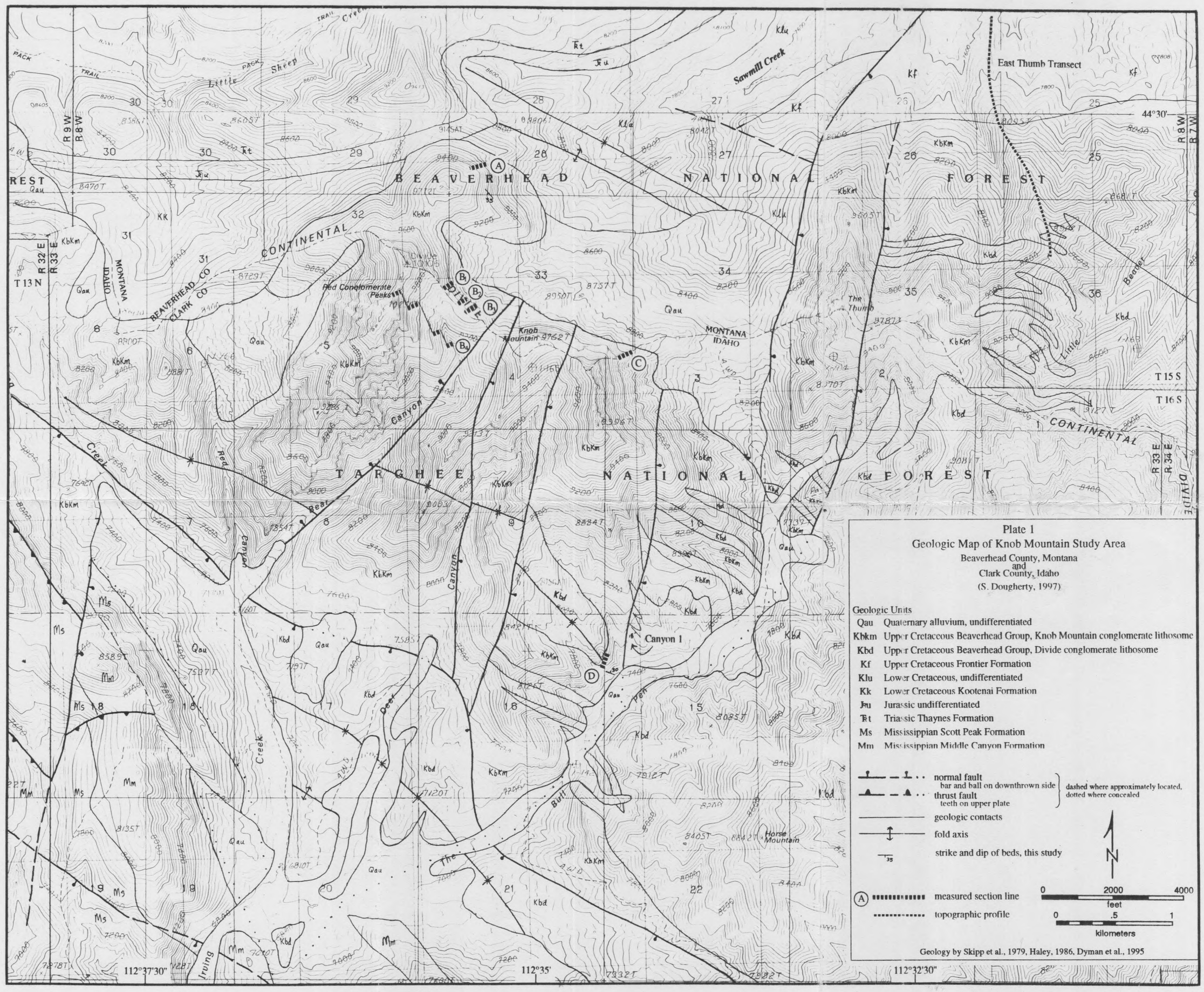


Plate 1

Geologic Map of Knob Mountain Study Area

Beaverhead County, Montana
and
Clark County, Idaho
(S. Dougherty, 1997)

Geologic Units

Qau	Quaternary alluvium, undifferentiated
Kbkm	Upper Cretaceous Beaverhead Group, Knob Mountain conglomerate lithosome
Kbd	Upper Cretaceous Beaverhead Group, Divide conglomerate lithosome
Kf	Upper Cretaceous Frontier Formation
Klu	Lower Cretaceous, undifferentiated
Kk	Lower Cretaceous Kootenai Formation
Jru	Jurassic undifferentiated
Trt	Triassic Thaynes Formation
Ms	Mississippian Scott Peak Formation
Mm	Mississippian Middle Canyon Formation

normal fault — bar and ball on downthrown side
thrust fault — teeth on upper plate
(dashed where approximately located, dotted where concealed)

geologic contacts

fold axis

strike and dip of beds, this study

measured section line

topographic profile

0 2000 4000 feet

0 .5 1 kilometers

Geology by Skipp et al., 1979, Haley, 1986, Dyman et al., 1995

Plate 2: Section A

Upper Cretaceous Beaverhead Group

Susan Dougherty

August 1995

location: Beaverhead County, Montana
SW 1/4, SW 1/4, Sec 29, T1S S R8W

scale: 1 cm = 1 meter

contacts
covered
gradational

Kbkm — Knob Mountain conglomerate lithosome

Meters above measured base	Meters above base of Kbkm	Lithofacies	Thickness (meters)	Bedding thickness (meters)	Remarks
250	250	Gm	4.00	19	poor exposure to top of hill
246	246	Gm	4.00	62	
242	242	Gm	3.00	18	weak bedding-parallel fabric
239	239	Gm	3.75	30	clasts: Thaynes, chert
236	236	Gm	0.25	4	weak bedding-parallel fabric
235	235	Fl	1.00		
234	234	Gm	0.50	10	
233	233	Gm	6.50	33	
227	227				lens of Fm, 20 cm thick
221	221				
220	220				lens of Gm with weak bedding-parallel fabric, mps=10
217	217	Smg	0.50	-	gravelly sandstone, coarser at top, pebbles up to 6 cm
216	216				
215	215				
214	214	Gmc?	7.00	34	very weak imbrication
207	207				
206	206	Gm	1.00	8	crudely stratified bed of pebbles and cobbles
205	205	Gm	2.50	31	
203	203	Gm	1.50	8	crudely stratified bed of pebbles and cobbles
202	202	Gm	1.50	7	weak bedding-parallel fabric
200	200	Gm	4.00	29	clasts: Thaynes, Dimecody; two oversized clasts at base
196	196	Gmx	0.25	12	mud matrix
196	196	Gm	0.25	12	weak bedding-parallel fabric
194	194	Gm	4.50	27	weak bedding-parallel fabric; clasts: Thaynes
185	185	Gm	3.00	12	weak bedding-parallel fabric
182	182	Gm	1.50	28	weak bedding-parallel fabric
180	180	Gmi	2.50	34	weak imbrication in direction 295
175	175	Gm	3.75	27	
171	171	Gm	2.75	10	weak bedding-parallel fabric
170	170	Gm	2.50	39	bed is wedge shaped over approx. 15 m
167	167	Gm	0.75	15.5	crudely stratified bed of pebbles and cobbles
166	166	Gm	0.50	31	
166	166	Gmx	3.00	12	mud matrix, v. weak bedding- parallel fabric
163	163	Gm	1.50	18	weak bedding-parallel fabric Gmx lens (mps=0 cm) has mud matrix
161	161	Gm	0.75	48	
160	160	Gm	0.25	10	weak bedding-parallel fabric
158	158	Gm	8.00	38	isolated outcrops, laterally discontinuous but vertically continuous over an area ~30 m wide
150	150	Gm	2.50	19	weak bedding-parallel fabric c.g. sandstone lens
149	149				pebbly sandstone lens
147	147	Gm	0.50	19	
146	146	Gm	1.25	20	
145	145	Gm	0.25	8	weak bedding-parallel fabric
144	144	Gm	0.50	14	
143	143	Gm	0.25	19	
142	142	Gm	1.75	8	
139	139	Gmx	0.25	14	c.g. sandy matrix
139	139	Gm	0.50	14	
138	138	Gm	0.50	9	
132	132	Gm	1.50	18	clasts are limestone, siltstone, Dimecody
128	128	Gm	0.50	12	(not well exposed)
119	119	Gm	0.75	19	
119	119	Gmx	0.50	5	weak bedding-parallel fabric
118	118	Gm	1.00	10	
117	117	Gmx	1.00	6	large 5-10 cm clasts at top
116	116	Gm	0.75	35	
115	115	Gm	0.50	23	weak bedding-parallel fabric
115	115	Gmx	0.25	6	weak bedding-parallel fabric
115	115	Gm	0.25	6	mps=0 cm
115	115	Gm	0.25	4	2 cm pebbles, pebbly sandstone
115	115	Gm	0.25	4	weakly stratified, rubbled cobbles at base (22, 27 cm)
114	114	Gm	0.25	8	bulbous/ash sheet
113	113				
112	112				
109	109				
108	108	Gm	2.00	37	oversized Thaynes clasts, Dimecody
104	104	Gm	3.00	35	
101	101	Smr?	1.00	-	poorly exposed pebbly sandstone
100	100	Gm	5.00	39	
95	95	Gm	2.00	39	weak bedding-parallel fabric
93	93				0.25 m thick wedge of Gm (mps=7 cm)
91	91	Gm	2.50	33	large 60 cm clast, weak bedding-parallel fabric
89	89	Gm	0.50	6	weak bedding-parallel fabric
88	88	Gm	2.50	33	weak bedding-parallel fabric
85	85	Gm	3.50	34	
81	81	Gm	3.15	21	weak bedding-parallel fabric
79	79	Sh	0.05	4	
		Gm	0.05	-	
		BREAK IN SECTION			
6	6	Gm	0.20	20	
5	5	Gm	0.50	7	sandy matrix
		Gm	0.50	16	
4	4				
3	3	Gm	0.40	8	weak bedding-parallel fabric
		Gm	0.10	3	
2	2	Gm	1.50	18	weak bedding-parallel fabric
1	1	Gm	0.75	15	
		Gm	0.25	8	
	(base covered)				

Kbkm

Kbm

Kbm

Kbm

Kbm

Kbm

stacksount A-3

stacksount A-2

stacksount A-1

Prof. J. Schmitt

Fall Creek Quad

Plate 3: Section B_1

Upper Cretaceous Beaverhead Group

Susan Dougherty

August 1995

location: Beaverhead County, Montana
NE 1/4 and SW 1/4, Sec 33, T15 S R8W

scale: 1 cm = 1 meter

Kbkm — Knob Mountain conglomerate lithosome

contacts ———————
covered — — — —
gradational – – – – –

lithosome	meters above base	max. part. avg. (< 1 cm, 1-10 cm, 11-20 cm, 21-30 cm, 31-40 cm, 41-50 cm, 50 + cm)	lithofacies	thickness (meters)	max. part. avg (centimeters)	Remarks	
	113	(section continues up)					
	112		Gm	2.00	58		
	111						
	110		Sh	-	-	pebbly sandstone	
	109		Gm	1.75	44		
	108		Gm	1.75	10	weak bedding-parallel fabric at base	
	107						
	106		Gm	4.00	58	clasts: f.g. sandstone, Phosphoria	
Kbkm	105						
	104						
	103		Gm	1.00	35		
	102		Gm	0.50	-	crudely stratified bed of pebbles and cobbles	
	101		Gm	0.70	29		
	100		Gm	0.50	12	v. little matrix	
	99		Gm	0.30	4	rare, outsized, 15 cm clasts	
	98		Gm	1.50	38	clasts: Thaynes	clast count: B1-2
	97						
	96		Gm	7.00	79	weak bedding-parallel fabric	
	95						
	94						
	93						
	92						
	91						
	90						
	89						
	88						
	87						
	86						
	85						
	84						
	83		Gm	3.00	42		
	82						
	81						
	80						
	79		Gm	4.00	30	v. weak bedding-parallel fabric	
	78						
	77						
	76						
	75						
	74						
	73						
	72						
	71		Gm	2.20	48	clasts: Thaynes	
	70						
	69						
	68		Shg	0.30	-	pebbly sandstone	
	67		Gm	1.00	29	outsized 55 cm limestone clast; clasts: Dinwoody, Thaynes, Phosphoria, f.g. sandstone, limestone	
	66		Gms	4.00	20	mud matrix, clasts: Dinwoody, Thaynes, limestone with brachiopods	
	65						
	64						
	63		Gmsr	0.50	<10		
Kbkm	62						
	61						
	60						
	59		Gm	2.50	37	clasts: limestone, f.g. buff sandstone	
	58						
	57		Gm	0.50	12	weak bedding-parallel fabric	
	56		Gm	0.50	8	weak bedding-parallel fabric	
	55						
	54						
	53						
	52		Gm	3.00	28	weak bedding-parallel fabric clasts: limestone, f.g. sandstone, chert	
	51						
	50						

BREAK IN SECTION

lithosome	meters above base	max. part. avg.	lithofacies	thickness (meters)	max. part. avg (centimeters)	Remarks	
	23		Gm	1.00	21	clasts: Thaynes, Dinwoody, Phosphoria, limestone, chert	
	22						
	21		Gm	1.50	12	weak bedding-parallel fabric	
	20		Gm	9.75	99	large clasts are Thaynes and f.g. buff sandstone contains lens of Gms (MFA=10)	
	19						
	18						
	17						
	16						
	15						
	14						
	13						
	12						
	11						clast count: B1-1
	10		Gm	0.25	5		
	9		Gms	1.00	8	f.g. sand matrix	
	8		Shg	0.50	-	pebbly sandstone	
	7						
	6		Gms	0.25	7	f.g. sand matrix	
	5		Gm	1.00	30		
	4		Gm	2.50	43		
	3						
	2		Gm	1.50	28		
	1		Gmi	0.25	17		
	0		Gm	1.00	16		

(base covered)

Kbkm

Kbkm

Kbkm

Kbkm

N378
D.H.H.

Sections

Plate 4: Section B_2

Upper Cretaceous Beaverhead Group

Susan Dougherty
August 1995

N378
D7449

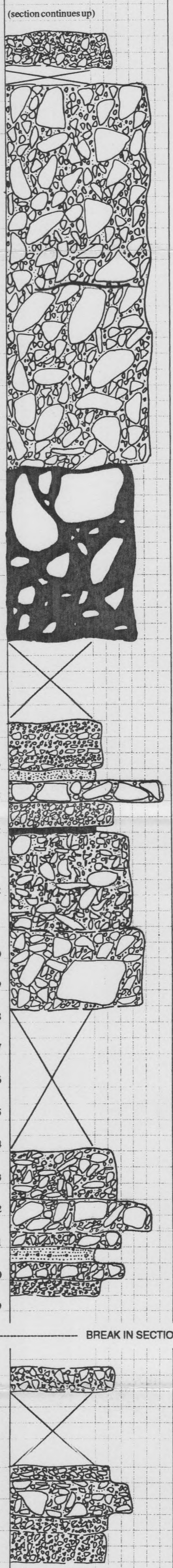
location: Beaverhead County, Montana
NE 1/4, SW 1/4, Sec 33, T15 S R8W

scale: 1 cm = 1 meter

Kbkm — Knob Mountain conglomerate lithosome

contacts ————————
covered —— —— ——
gradational — — — — —

msu Lib rarities



meters above base	lithofacies	thickness (meters)	max. part. avg (centimeters)	Remarks	
59–58	Gm	1.00	15		
57–46	Gm	12.00	44	thin, massive, mudstone drape	clast count: B2-3
45–40	Gms	5.50	30	contains outsized clasts: 200 cm Phosporia, 150 cm and 50 cm Thaynes, coarse-tail, reverse grading	clast count: B2-2
39–38	Gm	1.50	-	crudely stratified bed of pebbles and cobbles	
37–36	Smg	0.40	-	pebbly sandstone	
36–35	Gm	0.60	56		
35–34	Gm	0.75	12		
34–33	Fm	0.25	-		
33–31	Gm	3.00	28		
31–30	Gm	2.50	38	contains an outsized limestone clast (64 cm)	
28–24	Gm	1.50	16	weak bedding-parallel fabric	
23–22	Gm	1.00	43		
21	Gm	0.50	20		
21	Shg	0.50	-	pebbly, coarse-grained sandstone	
20	Gm	0.50	23		
20–19	Gm	0.50	6	weak bedding-parallel fabric	

BREAK IN SECTION

meters above base	lithofacies	thickness (meters)	max. part. avg (centimeters)	Remarks	
6–5	Gm	0.75	15	clasts: Dinwoody, Thaynes	
3	Gm	0.50	12		
2	Gm	1.00	29	weak bedding-parallel fabric	clast count: B2-1
1	Gmi	0.50	10	weak imbrication in the direction 000	
0	Gm	1.00	8		

Plate 5: Section B_3

Upper Cretaceous Beaverhead Group

Susan Dougherty

August 1995

N378 D7449

location: Beaverhead County, Montana
NE 1/4, SW 1/4, Sec 33, T15 S R8W

scale: 1 cm = 1 meter

contacts ———————
covered —— —— ——
gradational — — — — —

Kbkm Knob Mountain conglomerate lithosome

lithosome	meters above base	max. part. avg. (< 1 cm / 1-10 cm / 11-20 cm / 21-30 cm / 31-40 cm / 41-50 cm / 50 + cm)	lithofacies	thickness (meters)	max. part. avg (centimeters)	Remarks	
	84						
	83	(section continues up)					
	82		Gm	1.15	31	limestone clasts with brachiopods and crinoids	
	81		Gm Sm	0.10 0.25	4 -	m.g. sandstone (quartz arenite)	
	80		Gm	0.25	10	weak bedding-parallel fabric	
	79		Gm	1.50	15		
	78		Fm	0.25	-		
	77		Gm	3.45	38		
	76						clast count B3-2
Kbkm	75		Fl	0.05	-		
	74		Gm	1.95	12		
	73		Gmr	0.05	8		
	72		Gms	1.35		mudstone with rare pebbles	
	71		Fm	0.15	-		
	70		Gm	0.60	6		
	69		Fl	0.40	-		
	68		Gm	3.90	20	large cobbles (45-50 cm) at top 50 cm lens of Gms with rare pebbles	
	67						
	66		Sh Fl	0.50 0.10	- -	v.c.g. sandstone (quartz arenite)	
	65		Sm	0.40	-	f.g. sandstone (quartz arenite)	
	64		Gm	2.95	30		
	63						
	62		Sm Gm	0.05 0.50	- 7	c.g. sandstone (quartz arenite)	
	61		Gm	0.50	25		
	60		Gm Fm	0.85 0.15	6 19	~35 cm cobbles at top	
	59						
	58						
	57						
	56						
	55						
Kbkm	54		Gm	3.00	47	weak bedding-parallel fabric	
	53						
	52					20 cm lens of Gms with 1 cm pebbles limestone clasts with brachiopods	
	51		Gm	0.15	4		
	50		Gm	5.00	20	weak bedding-parallel fabric	
	49						
	48						
	47						
	46						
	45						
	44		Gm	3.00	62		
	43						
	42					f.g. sandstone lens	
	41						
		BREAK IN SECTION					
	17						
	16		Gm	3.85	45		
	15						
	14						
	13		Fm	0.15	-		
	12						
	11						
	10						
	9						
	8						
	7		Gm	0.15	4		
	6						
	5						
	4		Gm	2.50	15	30 cm black chert clast	clast count B3-1
Kbkm	3		Gm	0.10	3	clasts mostly black chert	
	2		Gm	1.00	15		
	1						
	0	(base covered)	Gm	1.00	6	weak bedding-parallel fabric	

Plate 6: Section B_4

Upper Cretaceous Beaverhead Group

Susan Dougherty

August 1995

location: Clark County, Idaho
W 1/2, Sec 4, T16 S R33E

scale: 1 cm = 1 meter

contacts
covered
gradational

Kbkm Knob Mountain conglomerate lithosome

Stratigraphic section (bottom-to-top)	max. part. sz. <1 cm 1-10 cm 11-30 cm 31-40 cm 41-50 cm 50+ cm	(section continues up)	lithofacies	thickness (meters)	max. part. sz.(cm) (estimated?)	Remarks	
Kbkm		220	Gm	2+	10	m.g. sandstone	
		219	Sm	0.05	-		
			Gm	0.50	10	m.g. sandstone	
		218	Sm	0.60	-	f.g. sandstone	
			Sm	0.05	-		
		217	Shg	0.15	-	f.g. sandstone with gravel	
			Shg	1.00	-		
		216	Gms	0.50	4	f.g. sand matrix	
			Sm	1.50	-	f.g. sandstone	
		215			3	lens of Gm (MPA=3)	
		214	Gm	0.50	6		
			Sm	0.50	-	f.g. sandstone	
		213	Gm	7.00	30	matrix is quartz-rich sand; clasts: Quadrant, Phosphoria	
		212					clast count: B4-3
		211					
		210					
		209					
		208					
		207	Sm	0.05	-	f.g. sandstone	
		206	Gms	1.95	12	f.g. sand matrix, clast poor; clasts: 22cm, bright red siltstone, 75 cm chert	
		205	Sm	0.35	-	f.g. sandstone	
		204	Gm	9.50	41		clast count: B4-2
		203				lens of Smg	
		202					
		201					
		200					
		199				lenses of c.g. sandstone	
		198					
		197					
		196	Gms	0.50	8		
		195					
		194					
		193					
		192					
		191					
		190	Gm	5.00	12	weak bedding-parallel fabric, sandy matrix	
		189					
		188					
		187					
		186					
		185					
		184	Gm	2.00	15		
		183					
		182					
		181	Gm	2.00	25		
		180					
		179	Gm	5.00	12		
		178					
		177					
		176					
		175	Sm	0.50	-	c.g. sandstone	
		174	Gm	0.50	8	weak bedding-parallel fabric	
		173	Smg	1.00	-	contains 2 outsized boulders	
		172					
		171					
		170	Fl	0.15	-		
			Gm	0.50	15	weak bedding-parallel fabric	
		169	Gm	0.50	-	crudely stratified bed of pebbles and cobbles	
			Gm	0.50	6		
		168	Sl	0.25	-	m.g. to c.g. sandstone	
			Sm	0.40	-		
		167	Gms	0.35	-	clast-poor	
		166	Gms	0.15	-	clast-poor, rare 1 cm pebbles	
			Smg	0.35	-		
		165	Fm	0.25	-		
		164					
		163					
		162					
		161	Gm	0.25	3	weak bedding-parallel fabric	
		160	Gm	1.00	28	weak bedding-parallel fabric	
		159	Gms	0.75	-	clast-poor, rare 15-20 cobbles	
			Sm	0.50	-	c.g. sandstone	
		158	Gm	8.10	10	weak bedding-parallel fabric	
		157					
		156					
		155				lens of Gms; muddy matrix	
		154					
		153					
		152					
		151					
		150	Sl	0.30	-	f.g. sandstone	
			Sm	0.10	-		
			Gm	0.50	10		
		149	Gm	1.00	18		
		148	Sm	0.30	-	muddy, f.g. sandstone	
			Gm	0.20	4	weak bedding-parallel fabric	
		147	Gm	1.50	31		
		146	Gh	0.50	-	stratified bed of pebble and sand-size particles	
			Sh	0.25	-		
			Sl	0.50	-	m.g to c.g. sandstone	
		145	Gm	0.25	4	weak bedding-parallel fabric	
			BREAK IN SECTION				
		41					
		40	Gm	0.25	4	weak bedding-parallel fabric	
		39	Gm	3.00	25	contains outsized115 cm sandstone clast, 60 cm Thaynes clast	
		38					
		37					
		36	Gm	0.50	10	weak bedding-parallel fabric	
			Gm	0.50	6	weak bedding-parallel fabric	
		35					
		34					
		33					
		32					
		31	Gm	15.00	37	contains outsized 100 cm sandstone boulder	
		30					
		29					
		28					
		27					
		26					
		25					
		24					
		23					
		22					
		21					
		20					
		19					
		18					
		17	Fl	0.10	-		
		16	Gm	5.50	28		
		15					
		14					
		13					
		12	Gm	5.00	12		
		11					
		10					
		9					
		8					
		7	Gm	4.50	30	contains oversized 60 cm boulder	
		6					
		5					
		4					
		3	Gm	0.50	12	weak bedding-parallel fabric	
		2					
		1	Gm	2.00	27	weak bedding-parallel fabric, sandy matrix	clast count: B4-1
		0	(base covered)				

Plate 7: Section C

Upper Cretaceous Beaverhead Group

Susan Dougherty

August 1995

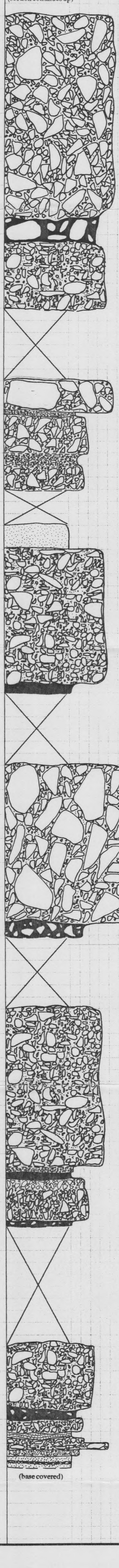
N378
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location: Beaverhead County, Montana
SE 1/4, SE 1/4, Sec 33, T15 S R8W

scale: 1 cm = 1 meter

Kbkm — Knob Mountain conglomerate lithosome

contacts ————————
covered —— —— ——
gradational – – – – – –



lithosome	meters above base	lithofacies	thickness (meters)	max. part. avg (centimeters)	Remarks	
	61	Gm	8.00	46		clast count: C-2
Kbkm	52	Gms	1.50	~30	contains outsized clasts (125-175 cm), bed laterally continuous for ~13 meters	
	51	Gm	2.00	37		
	46	Gm	1.40	44	contains a 67 cm, rounded, rectangular clast of Quadrant	
	45	Gm	0.10	7	weak bedding-parallel fabric	
	44	Gm	2.00	20		
	43	Gm	0.50	7	weak bedding-parallel fabric	
	42	Gm	1.00	18		
	40	Sm	1.00	-	m.g. sandstone, white at base, grades up to pink	
	39	Gm	5.75	39	clasts: friable, fissile sandstone/siltstone and sandstone with ripples on exposed surface	
Kbkm	33	Fm	0.25	-		
	30	Gm	6.50	64	upper 1 m has weak bedding-parallel fabric; clasts: Thaynes, Dinwoody, sandstone, chert	
	23	Gms	0.50	21		
	20	Gm	7.60	31	clasts: Phosphoria, Thaynes, Dinwoody	
Kbkm	12	Gm	0.30	3		
		Fm	0.10	-		
	11	Gm	1.80	18		
	10	Gms	0.20	-	clast-poor	
	5	Gm	2.45	23		
	2	Gms	0.30	7	clast-poor	
		Gm	0.50	10		
	1	Sr_1	0.25	-	f.g. sandstone	
		Gm	0.25	12		
		Gm	0.40	38		clast count: C-1
		Gm	0.10	7		
	0	Sm	0.50	-	f.g. sandstone, contains layer of mudstone with granules	

max. part. avg.: < 1 cm; 1-10 cm; 11-20 cm; 21-30 cm; 31-40 cm; 41-50 cm; 50 + cm

M354 L.6 rares

Plate 8: Section D

Upper Cretaceous Beaverhead Group

Susan Dougherty

August 1995

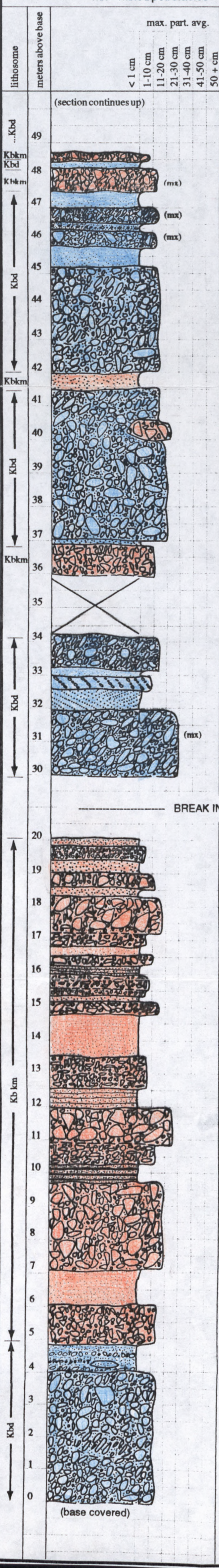
location: Clark County, Idaho
NE 1/4, NE 1/4, Sec 16, T16S R33E

scale: 1 cm = 1 meter

Kbkm — Knob Mountain conglomerate lithosome
mx = mixed petrofacies

Kbd — Divide conglomerate lithosome
mx = mixed petrofacies

contacts ———
covered — — —
gradational - - - - -



lithosome	meters above base	lithofacies	thickness (meters)	max. part. avg (centimeters)	Remarks	
					(poor exposure to top of hill, float is mostly quartzite pebbles)	
...Kbd	49					
Kbkm		Gm	0.15	10		
Kbd	48	Sm	0.10	-	m.g. sandstone (litharenite)	
Kbkm		Gm	0.85	16		
	47	Sm	0.35	-	m.g. sandstone with stringer of 4 cm qtz pebbles (litharenite)	
		Gmib	0.80	15	imbricated in direction 235	
		Shg	0.10	-	m.g. gravelly sandstone	clast count: D-4
	46	Gmb	0.50	16		
		Sm	0.50	-	m.g. sandstone (litharenite)	
	45	Gmb	3.50	16	contains lenses of imbricated clasts (general south direction)	
Kbd	44					
	43					
	42					
Kbkm		Sm	0.50	-	f.g. sandstone (quartz arenite)	
	41	Gm	1.00	16		
	40	Gm	0.50	22	Kbkm lens in Kbd; clasts: Thaynes, Phosphoria, Dinwoody	
		Gmb	3.00	20	becomes imbricated at top, direction 220.	
	39					
	38					
	37					
Kbkm		Sm	0.25	-	c.g. sandstone (litharenite)	
	36	Gm	1.00	11	w/ rare quartzite clasts	
	35					
	34	Gmib	1.00	15		
	33	Sm	0.25	-	c.g. sandstone (litharenite)	
		Gp	0.50	10		
	32	Sl	0.50	-	m.g. sandstone (litharenite)	
		Gmib	2.00	30		
Kbd	31					
	30					clast count D-3
		BREAK IN SECTION				
	20	Sm	0.15	-	m.g. sandstone (quartz arenite)	
		Gm	0.45	3		
	19	Sm	0.30	-	c.g. sandstone (quartz arenite)	
		Gm	0.50	12		
		Sm	0.25	-	m.g. sandstone (quartz arenite)	
	18	Gm	1.00	15		
	17	Gm	0.40	5	weak bedding-parallel fabric	
		Sm	0.30	-	m.g. sandstone (quartz arenite)	
		Gm	0.30	10		
	16	Sh	0.25	-	m.g. sandstone (quartz arenite)	
		Gm	0.50	6	weak bedding-parallel fabric	
		Gm	0.15	3		
	15	Sm	0.10	-	m.g. sandstone (quartz arenite)	
		Gm	0.50	14		
	14	Sm	1.25	-	f.g. sandstone (quartz arenite)	
	13	Gm	1.00	6	weak bedding-parallel fabric	
Kb km	12	Sh	0.50	-	f.g. laminated sandstone (quartz arenite)	
		Gm	1.30	25		
	11					
		Gm	0.55	12	weak bedding-parallel fabric	
	10	Sm/Fm	0.50	-	thin interbeds of sandstone and mudstone	
	9	Gm	3.00	19		clast count D-2
	8					
	7	Sm	0.60	-	f.g. sandstone (quartz arenite), lens of Gm, lens of pebbly sandstone	
	6					
	5	Gm	1.20	12	rare quartzite pebbles; clasts: Dinwoody, limestone, limestone with chert	
		Gh	0.75	3	stratified bed of sand and pebbles with 30 cm thick lenses of f.g. sandstone	
	4					
		Gmb	4.00	12	contains lenses of imbricated clasts, in direction 128; clasts: quartzite, limestone, sandstone, volcanics, and rare, angular limestone	clast count: D-1
Kbd	3					
	2					
	1					
	0					

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