



Tectono-sedimentary evolution of a Late Cretaceous alluvial fan, Beaverhead Group, southwestern Montana

by Paul Alex Azevedo

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences

Montana State University

© Copyright by Paul Alex Azevedo (1993)

Abstract:

The lower conglomeratic member of the Late Cretaceous Beaverhead Group east of Bannack, Montana contains a progressive unconformity which provides a direct link between sedimentation and deformation in the leading edge of the Cordilleran fold and thrust belt of southwest Montana. The recognition of a progressive unconformity within the lower Beaverhead conglomerate along Grasshopper Creek directly ties the deposition of the strata to uplift of the Madigan Gulch anticline. In addition, it provides an alternate interpretation for the structural configuration of the Beaverhead strata in the study area.

Along Grasshopper Creek, the lower Beaverhead conglomerate consists of approximately 354 m of synorogenic pebble/cobble conglomerate with subordinate sandstone and minor volcanic rocks. Consideration of lithofacies types, bed geometries, and facies associations suggests deposition on an alluvial fan characterized by cohesionless debris flows, hyperconcentrated flows, and proximal, braided gravel-bed river processes. The preserved remnants of a large fanhead channel is evidence that the surface of the fan actively went through periods of fanhead entrenchment which probably occurred in response to a tectonic stimulus.

Paleocurrent and clast composition data suggest the source area for the lower Beaverhead conglomerate was the east limb of the Madigan Gulch anticline. Formation of this eastward-verging asymmetrical fold may be related to movement of the Ermont thrust over a subsurface ramp. The progressive unconformity records the kinematic evolution of the fold.

The progressive unconformity is defined by the existence of three wedge-shaped packages of sediment. Each package of sediment formed in response to basinward rotation of the proximal part of the fan during uplift of the Madigan Gulch anticline. The rotative offlap geometry of the progressive unconformity indicates that the rate of uplift was episodic and exceeded the rate of sedimentation.

**TECTONO-SEDIMENTARY EVOLUTION OF A LATE CRETACEOUS
ALLUVIAL FAN, BEAVERHEAD GROUP,
SOUTHWESTERN MONTANA**

by

Paul Alex Azevedo

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Earth Sciences

**MONTANA STATE UNIVERSITY
Bozeman, Montana**

August 1993

APPROVAL

of a thesis submitted by

Paul Alex Azevedo

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.

7/30/93
Date

Tames Smith
Chairperson, Graduate Committee

Approved for the Major Department

8/2/93
Date

DR Cooper
Head, Major Department

Approved for the College of Graduate Studies

8/12/93
Date

PA Brown
Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature



Date

8/9/93

ACKNOWLEDGMENTS

I would like to thank Dr. Jim Schmitt for serving as my thesis advisor and for his patient guidance. It was a honor to be one of his students. Dr. Steve Custer and Dr. Dave Lageson served on my thesis committee and provided constructive criticism regarding the presentation of my results. Although the interpretations presented are solely my own, many of them arose out of discussions with Dr. Bob Pearson of the USGS, Dr. Tim Lawton, Dr. Peter DeCelles, and Scott Singdahlsen. Partial financial support from the Geological Society of America, and the Yellowstone Center for Mountain Environments is gratefully acknowledged.

I would also like to thank the many friends who provided support and assistance of one type or another especially; Becky Moore, Terry Panasuk, Margaret Hiza, and Amanda Werner. I am deeply indebted to Jonathan and Stephanie Cooley for three years of warm friendship and great conversation. Kelly Harvill believed in me more than I believed in myself. Calvin and Hobbes helped to keep it all in perspective. Finally, I would like to thank my family, especially my parents, for their unending love, support, and encouragement. I could not have completed this project without them.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	iv
LIST OF TABLES	viii
LIST OF FIGURES	ix
LIST OF PLATES	xii
ABSTRACT	xiii
INTRODUCTION	1
Purpose of study	4
Location	6
METHODS	9
Field Procedures	9
Laboratory Methods	12
REGIONAL STRUCTURAL AND STRATIGRAPHIC SETTING	14
GENERAL GEOLOGY OF THE STUDY AREA	17
Local Stratigraphy	17
Local Structural Geology	21
Folds	21
Faults	24
STRATIGRAPHY AND AGE OF THE BEAVERHEAD GROUP	28
LITHOFACIES	36
Conglomerate Lithofacies (G)	36
Introduction	36
Massive, Disorganized, Polymodal	
Conglomerate (Gcd)	36
Description	36
Interpretation	38
Massive, Disorganized	
Conglomerate (Gcm)	41
Description	41
Interpretation	43
Horizontally Stratified	
Conglomerate (Gch)	47

TABLE OF CONTENTS - continued

Description	47
Interpretation	48
Organized, Pebble	
Conglomerate (Gcp)	49
Description	49
Interpretation	49
Trough Cross-Stratified	
Conglomerate (Gct)	50
Description	50
Interpretation	50
Sandstone and Mudstone Lithofacies (S/F)	51
Introduction	51
Massive Sandstone (Sm)	52
Description	52
Interpretation	53
Horizontally Laminated	
Sandstone (Sh)	54
Description	54
Interpretation	55
Ripple Cross-laminated	
Sand (Sr)	55
Description	55
Interpretation	56
Fine-Grained Lithofacies (Fm/Fl)	56
Description	56
Interpretation	57
Volcanogenic Lithofacies (V)	57
Introduction	57
Volcanic Rocks (V)	57
Description	57
Interpretation	58
LOWER BEAVERHEAD STRATIGRAPHY	59
DEPOSITIONAL SYSTEMS	62
PALEOCURRENTS	69
PETROGRAPHY	71
Conglomerate	71
Texture	71
Composition	71
Limestone Clasts	71
Chert Clasts	72
Sandstone Clasts	72
Modal Composition	74
Sandstone	75
Texture	75

TABLE OF CONTENTS - continued

Composition	75
Monocrystalline Quartz (Qm)	75
Polycrystalline Quartz (Qp)	76
Lithic Fragments	76
Sandstone Petrofacies	76
Chertarenites	78
Calclithites	79
Volcanic Rocks	80
PROVENANCE	82
SYNTECTONIC UNCONFORMITIES	92
TECTONO-SEDIMENTARY EVOLUTION OF THE GRASSHOPPER CREEK ALLUVIAL FAN	102
SUMMARY OF INTERPRETATIONS	117
REFERENCES CITED	120
APPENDICES	130
APPENDIX A: CONGLOMERATE CLAST COMPOSITION DATA	131
APPENDIX B: SANDSTONE DETRITAL MODES	134

LIST OF TABLES

Table	Page
1. Summary descriptions of lithologic units . . .	19
2. Summary of lithofacies	37
3. Formation names and ages for clast lithologies recognized in the lower Beaverhead Conglomerate in the study area . . .	83
4. Probable source formations for unique clast lithologies recognized in hand samples and thin-section	85
5. Conglomerate clast count data	132
6. Conglomerate clast modal percentage	133
7. Sandstone point count data	135
8. Sandstone modal percentage calculated for QFL ternary diagrams	136
9. Sandstone modal percentage calculated for QmFLt ternary diagrams	137

LIST OF FIGURES

Figure	Page
1. Generalized map of southwestern Montana showing location of study area and major regional structures.	7
2. Thesis location map	8
3. Overview of field area and location of measured sections	10
4. Relative stratigraphic position of measured sections in the lower Beaverhead conglomerate	11
5. Major divisions of the Cordilleran fold belt in southwest Montana and east-central Idaho	15
6. Generalized stratigraphic column of study area and northern portion of the Armstead Hills	18
7. Generalized geologic map of study area	22
8. Distribution of Beaverhead Group rocks in southwestern Montana and east-central Idaho	29
9. Stratigraphy of Beaverhead Group east of Bannack, Montana	30
10. Contact between the lower Beaverhead conglomerate and Lombard Limestone on the east limb of the Madigan Gulch anticline	31
11. Ages and stratigraphic relationships of formal and informal units within the Beaverhead Group	34

LIST OF FIGURES - continued

12. Facies Gcd interbedded with thin, discontinuous beds of massive sandstone (Sm)	39
13. Facies Gcm overlain by facies Gch	42
14. Facies Gct overlain by facies Gcd and underlain by facies Gcm	51
15. Generalized vertical lithofacies profile of the lower Beaverhead conglomerate	60
16. Steep walled channel incised into conglomerates (Gcm and Gcd) and sandstones (Sm)	63
17. Large channel incised into deposits of conglomerate and sandstone	67
18. Rose diagrams showing paleocurrent measurements from imbricated clasts in conglomerates	70
19. Modal percentage of conglomerate clasts at each clast count location	74
20. Compositional ternary diagrams of Beaverhead sandstones in study area	77
21. Photomicrograph of chertarenite from the lower Beaverhead conglomerate	78
22. Photomicrograph of calclithite from within the large channel	79
23. Photomicrograph of vitric tuff from deposits in the lower Beaverhead conglomerate	81
24. Photomicrograph of lower Beaverhead conglomerate matrix sample	86
25. QmFLt ternary diagram of Beaverhead sandstones	89

LIST OF FIGURES - continued

26. Overview and sketch of Beaverhead strata on the south side of Grasshopper Creek	93
27. Genetic model of progressive and syntectonic angular unconformities	95
28. Equal-area stereonet of poles to bedding planes from strata within the lower Beaverhead conglomerate	96
29. Cross-sections of three progressive unconformities in the Upper Eocene-Oligocene Montsant conglomerates of the NE Ebro Basin, Spain	100
30. Schematic diagram showing progressive uplift of the Madigan Gulch anticline and deformation of the Grasshopper Creek alluvial fan in response to propagation of the Ermont thrust	108
31. Klippe of Madison limestone truncating a portion of the lower Beaverhead conglomerate on the north side of Grasshopper Creek	115

LIST OF PLATES

Plate	Page
1. Measured stratigraphic sections of the lower conglomerate unit of the Upper Cretaceous Beaverhead Group east of Bannack, Montana .	in pocket
2. Photomosaic and sketch of the lower Beaverhead strata on the south side of Grasshopper Creek	in pocket

ABSTRACT

The lower conglomeratic member of the Late Cretaceous Beaverhead Group east of Bannack, Montana contains a progressive unconformity which provides a direct link between sedimentation and deformation in the leading edge of the Cordilleran fold and thrust belt of southwest Montana. The recognition of a progressive unconformity within the lower Beaverhead conglomerate along Grasshopper Creek directly ties the deposition of the strata to uplift of the Madigan Gulch anticline. In addition, it provides an alternate interpretation for the structural configuration of the Beaverhead strata in the study area.

Along Grasshopper Creek, the lower Beaverhead conglomerate consists of approximately 354 m of synorogenic pebble/cobble conglomerate with subordinate sandstone and minor volcanic rocks. Consideration of lithofacies types, bed geometries, and facies associations suggests deposition on an alluvial fan characterized by cohesionless debris flows, hyperconcentrated flows, and proximal, braided gravel-bed river processes. The preserved remnants of a large fanhead channel is evidence that the surface of the fan actively went through periods of fanhead entrenchment which probably occurred in response to a tectonic stimulus.

Paleocurrent and clast composition data suggest the source area for the lower Beaverhead conglomerate was the east limb of the Madigan Gulch anticline. Formation of this eastward-verging asymmetrical fold may be related to movement of the Ermont thrust over a subsurface ramp. The progressive unconformity records the kinematic evolution of the fold.

The progressive unconformity is defined by the existence of three wedge-shaped packages of sediment. Each package of sediment formed in response to basinward rotation of the proximal part of the fan during uplift of the Madigan Gulch anticline. The rotative offlap geometry of the progressive unconformity indicates that the rate of uplift was episodic and exceeded the rate of sedimentation.

INTRODUCTION

Synorogenic conglomerates have long been recognized as a valuable tool in deciphering the tectonic history of their source area (Ryder and Scholten, 1973; Haley, 1985; Lawton, 1986; DeCelles and others, 1987, 1991a, Haley and Perry, 1991). However, incomplete exposures and lack of accurate chronologic markers often make direct links between sedimentation and deformation difficult (Holl and Anastasio, 1993). Recent studies (Riba, 1976; Anadon and others, 1986; DeCelles and others, 1987, 1991a;b) have suggested that synorogenic conglomerates produced in compressional tectonic settings may contain suites of structures that are characteristic of contractional deformation and are directly attributable to deformation of their adjacent source terranes. These structures include intraformational thrust faults, folds, and progressive unconformities.

Progressive unconformities develop as wedge-shaped packages of sediment deposited on the flanks of growing structures such as anticlines, high angle faults and nappe fronts. The geometry of a progressive unconformity is usually interpreted to be directly controlled by the interplay between the rate of tectonic uplift and the rate of sediment accumulation along the flank of the structure (Riba, 1976).

The recognition of progressive unconformities is important because the geometry or stacking characteristics of successive depositional wedges may provide insight into the kinematic evolution of the adjacent source terrane (DeCelles and others, 1991a; Verges and Burbank, 1992; Holl and Anastasio, 1993). However, descriptions of syntectonic sediments containing progressive unconformities are scarce in the geological literature (Riba, 1976; Anadon and others, 1986; DeCelles and others, 1987, 1991a;b; Holl and Anastasio, 1993). Those that have been described are found in alluvial fan deposits adjacent to foreland basin margins and intrabasinal uplifts. These studies suggest that progressive unconformities may be an important characteristic of thrust generated conglomerates that have been widely overlooked. One stratigraphic unit in the North American Cordillera which might be expected to contain progressive unconformities is the Late Cretaceous Beaverhead Group of southwestern Montana.

Strata of the Beaverhead Group comprise the synorogenic Upper Cretaceous to lower Tertiary (?) stratigraphic sequence in southwestern Montana. Beaverhead Group strata are dominated by conglomerates that are thought to have been shed from structural elements which rose in response to contractional deformation in the Rocky Mountain foreland to the east and the fold and thrust belt to the west (Ryder and Scholten, 1973, Haley, 1985). Lithofacies analysis of the Beaverhead Group conglomerates suggest they were deposited on alluvial fans and

in the proximal portions of braided gravel-bed fluvial systems (Ryder and Scholten, 1973; Haley, 1985; Haley and Perry, 1991). Although the depositional environment and structural setting are favorable for the development of progressive unconformities no structures of this type have been described to date in the Beaverhead strata.

East of Bannack, Montana synorogenic strata of the Late Cretaceous Beaverhead Group crop out along Grasshopper Creek. Previous work by Goodhue (1986), Johnson and Sears (1988) and Coryell and Spang (1988) suggests that the lower conglomerate member of the Beaverhead Group in this area may be a promising location to look for progressive unconformities. In this area the lower conglomerate member is dominated by framework-supported limestone-clast conglomerate with interbeds and lenses of sandstone and minor volcanic rocks (Goodhue, 1986; Johnson, 1986; Johnson and Sears, 1988). By analogy with other Beaverhead Group strata in southwestern Montana, Goodhue (1986) hypothesized that the lower conglomerate unit east of Bannack represented deposition on the surface of small alluvial fans and in the proximal portions of braided gravel-bed stream systems. The uplifted structural elements which shed these deposits resulted from compressional deformation in the frontal fold and thrust zone of the Cordilleran fold and thrust belt in southwestern Montana (Johnson and Sears, 1988; Coryell and Spang, 1988).

Purpose of study

The purpose of this study is to explore the question, "Does the lower Beaverhead conglomerate east of Bannack, Montana contain a progressive unconformity?" In testing this hypothesis the following questions were addressed:

1) What depositional environment(s) characterized the lower conglomeratic unit? To date, progressive unconformities have only been recognized in proximal alluvial fan environments adjacent to compressional uplifts. Therefore it is important to establish the depositional environment of the lower Beaverhead strata. Alluvial fan deposits can be recognized by a distinctive association of lithofacies (Miall, 1978; Rust, 1978).

2) What is the provenance of the lower conglomeratic unit? Knowledge of the sediment provenance is important for determining the location and composition of the source area. Paleocurrents from an individual alluvial fan deposit should have a flow pattern radiating outward from the fan apex (Nilsen, 1982). However, this radial pattern may become hard to detect if the fan apex is not preserved. Coalescing of adjacent fan sequences may produce complex paleoflow patterns. Possible paleoflow indicators include channel orientation, cross-stratification in sandstones and conglomerates, and conglomerate clast long-axis orientation. Measurement of the largest clast sizes in alluvial fan sequences may also be a

useful paleoflow indicator. There is generally a rapid decrease in the maximum and average clast size downfan from the fan apex (Bluck, 1964; Lustig, 1965; Bull, 1972; Nilsen, 1982). However, the uniformity of particle size decrease may be greatly affected by the amount of temporary channel entrenchment during the history of the fan (Bull, 1972). Compositional trends in the ^acoarse-grained and fine-grained fractions of the sediments may provide additional insight into the structural evolution of the source area. The character of clast compositional trends may be indicative of the structural setting of the source area (Steidtmann and Schmitt, 1988).

3) What evidence can be found in the lower Beaverhead strata which might suggest the existence of a progressive unconformity? Determining the depositional environment and provenance will not in itself document the existence of a progressive unconformity within the lower Beaverhead deposits. Progressive unconformities are recognized in proximal alluvial fan deposits of the Tertiary Ebro Basin, Spain by a series of overlapping, wedge-shape sedimentary packages which thin in an upfan direction (Riba, 1976). Such sedimentary wedges might be documented in the lower Beaverhead conglomerate by recording bedding attitudes throughout the stratigraphic section. It is hypothesized here that uplift of the source terrane, which is integral to the development of a progressive unconformity, should cause the initial sedimentary packages to be deformed to a greater degree than later deposits. However, each

sedimentary package should contain an internally consistent set of bedding attitudes. Plotting bedding attitudes on a photomosaic of the outcrops may also serve to highlight the existence and geometry of individual sedimentary packages. It may also be possible to distinguish individual packages based on lithology and association of lithofacies.

4) If a progressive unconformity is present in the lower Beaverhead conglomerate does its geometry reveal any information regarding the kinematic evolution of the source terrain? When the rate of uplift exceeds the rate of sedimentation along the flanks of the structure the individual sedimentary-wedge packages will offlap each other in a basinward direction (Riba, 1976, Anadon and others, 1986). If the rate of sedimentation exceeds the rate of deformation the sedimentary wedges will onlap each other towards the hinterland (Riba, 1976, Anadon and others, 1986).

Location

The study area is located along Grasshopper Creek in the northern portion of the Armstead Hills approximately 3 km east of Bannack State Park in Beaverhead County, Montana (Figure 1 and 2). The study area covers approximately 6 km² (Sections 8, 9, 16, and 17 T8S; R11W) of the U.S. Geological Survey Bannack 7.5 minute topographic quadrangle.

Beaverhead strata in this area crop out in a north-south trending arcuate band for several kilometers on either side of

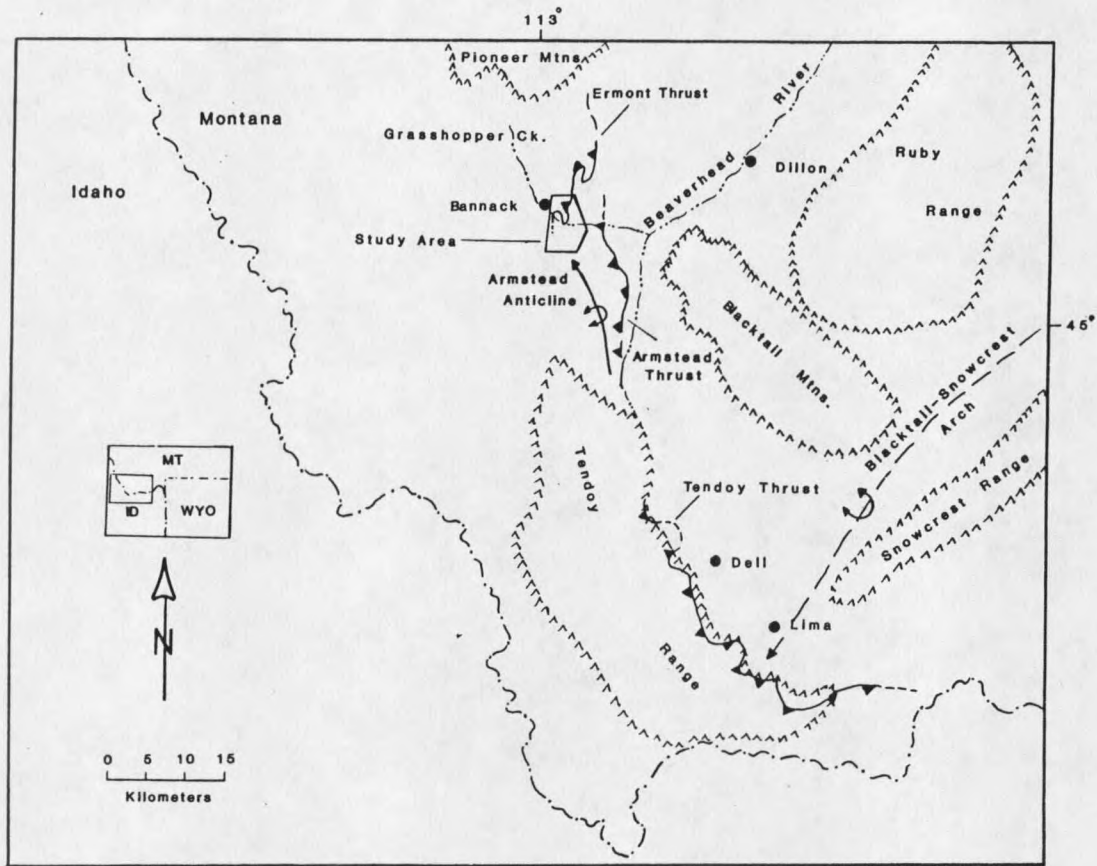


Figure 1. Generalized map of southwestern Montana showing location of study area and major regional structures. Modified from Johnson (1986).

Grasshopper Creek. In general, good to fair out crops are limited to several of the northeast-southwest trending gulches which bisect the area. The most prominent outcrops are located immediately adjacent to Grasshopper Creek where up to 354 m of strata are exposed. These outcrops adjacent to Grasshopper Creek were chosen for the focus of this study because they offered the greatest extent of high quality exposures.

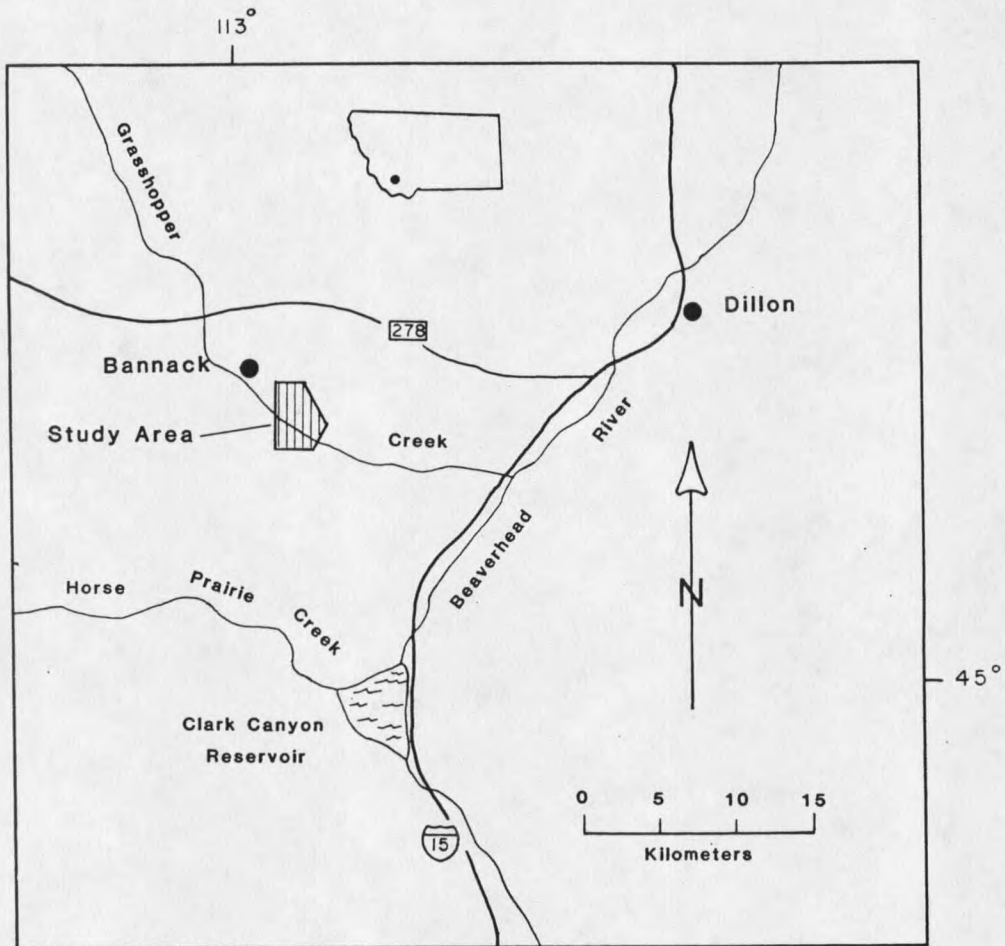


Figure 2. Study area location map.

METHODS

Field Procedures

The lower conglomerate member of the Beaverhead Group in the study area was measured using a Brunton Pocket Transit, Jacob's staff and a 30 m (100 ft) steel tape (Compton, 1962). Seven partial sections were measured and described (Figure 3) (Plate 1). The partial sections were combined by determining their approximate stratigraphic positions relative to each other to form a nearly complete section through the lower conglomerate (Figure 4). The location of each section was chosen as a balance between accessibility and quality of exposures. Descriptions of depositional units within each section included lithology, texture (clast size, clast shape, and sorting), fabric, grading, stratification, bed thickness, lateral continuity of beds, nature of bounding surfaces, bed geometry, and sedimentary structures. A lithofacies classification system based on the system developed by Miall (1977, 1978) and appended by Rust (1978) was used to classify the lithofacies present.

Clast counts were performed on pebble-cobble conglomerates to ascertain the composition of strata exposed in the source area and to illuminate any stratigraphic compositional trends.

A



B

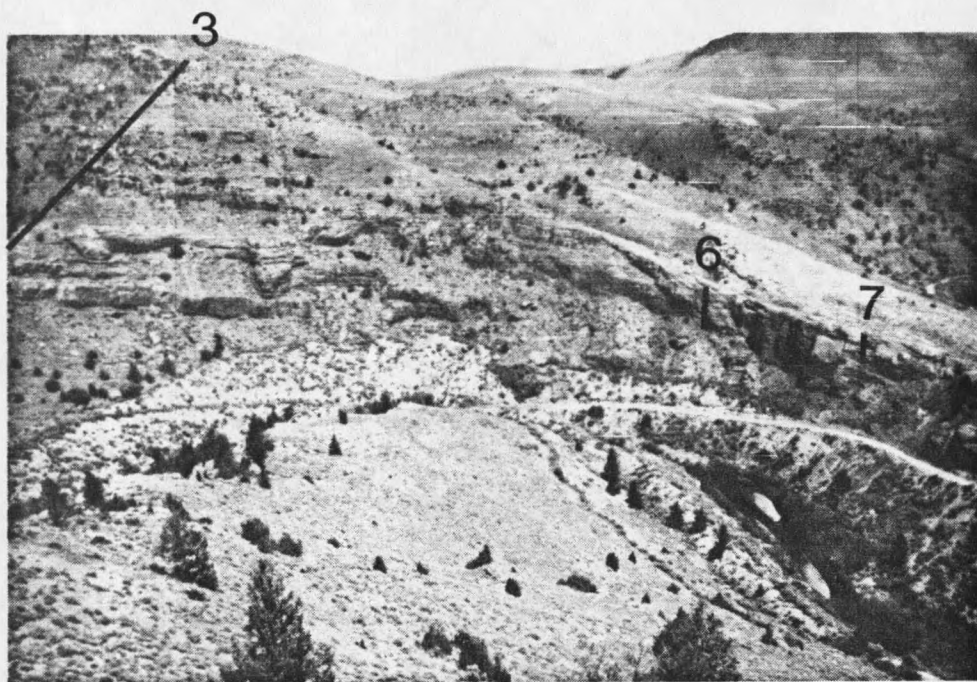


Figure 3. Overview of field area and location of measured sections. A) Outcrops on south side of Grasshopper Creek. East limb of Madigan Gulch anticline is just out of view to right. View S20W. B) Outcrops on north side of Grasshopper Creek. View N50E. Measured sections numbered as follows: 1=NG01; 2=NG02; 3=NG03; 4=NG04; 5=NG05; 6=CH1; 7=CH2.

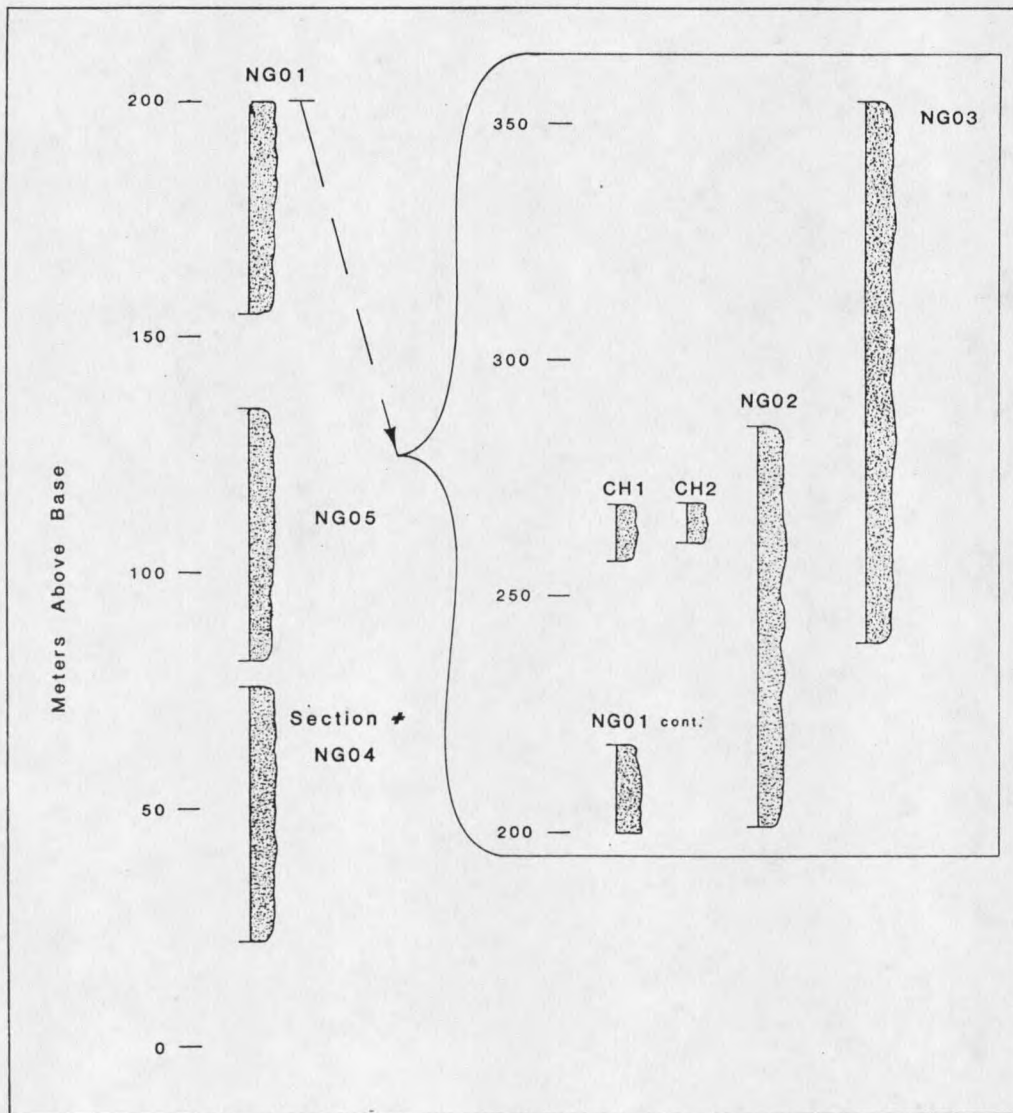


Figure 4. Relative stratigraphic position of measured sections in the lower Beaverhead conglomerate.

The lithology of a minimum of 250 clasts was recorded at 12 different locations using a fixed grid system designed to exceed the mean observed clast size. At two locations less than 250 clasts (142 minimum) were counted due to limited exposures. Qualitative estimates of clast composition modes

were also made in order to detect clast types present in trace amounts. At each clast count locality the maximum diameter of the 15 largest clasts was recorded in order to illuminate any trends in maximum particle size. Samples of Beaverhead sandstone lenses, conglomerate matrix, and volcanic units were collected for petrographic analysis.

Paleoflow data were gathered from measurements of the orientation of clast imbrication, trough axes and sole marks where possible. Additional insight into the tectono-sedimentary evolution of the Beaverhead strata was achieved by plotting apparent bedding attitudes onto a photomosaic of outcrops on the south side of Grasshopper Creek. Outcrops on the north side of the creek are of poor quality and were not photographed in detail.

Laboratory Methods

Seven Beaverhead sandstone samples and one conglomerate matrix sample were thin-sectioned, stained for potassium feldspar, and examined under a petrographic microscope. Point counts were done on the sandstone thin sections in order to: 1) determine the composition of the sandstones; 2) distinguish any compositional trends which occur vertically through the lower beaverhead section based on the fine-grained component; and 3) integrate sandstone composition data into an interpretation of provenance. Sandstones selected for point counting were chosen as representative samples from different

stratigraphic levels throughout the section. In addition, four volcanic rock samples from the lower conglomerate member were also thin-sectioned, stained for potassium feldspar, and examined petrographically to determine composition and mode of emplacement.

Modal composition of each sandstone sample was determined by identifying the composition of a minimum of 250 framework grains per sample. Point counts were performed using a fix-grid spacing that exceeded the visually estimated mean grain size of each sample. To petrologically classify the sandstones and to discern possible petrofacies, sandstone compositional data were plotted on a QFL ternary diagram (Folk, 1980, p. 127). To discern possible source area provenance, the sandstone compositional data were also plotted on a QmFLt ternary diagram (Dickinson and others, 1983). The conglomerate matrix sample was examined qualitatively to determine the composition of the fine-grained component of the matrix. Compositional data from both sandstone thin-sections and conglomerate clast counts were plotted stratigraphically to determine compositional trends within the stratigraphic section.

All paleocurrent orientation data were rotated about structural strike on an equal-area net to determine paleocurrent trends. Vector orientation and magnitude were calculated using the methods of Potter and Pettijohn (1977, p. 374-377) and Tucker (1989, p. 95-96).

REGIONAL STRUCTURAL AND STRATIGRAPHIC SETTING

Ruppel and Lopez (1984) recognized three divisions of the Cordilleran fold and thrust belt in southwest Montana and central Idaho. These include the Medicine Lodge thrust plate, Grasshopper thrust plate, and frontal fold and thrust zone (Figure 5). Each of the thrust plates, as well as the frontal fold and thrust zone, are characterized by a discrete sequence of sedimentary rocks and differences in structural style.

The frontal fold and thrust zone is the leading part of the Cordilleran fold and thrust belt in southwest Montana and fringes the eastern edge of the Grasshopper and Medicine Lodge thrust plates (Figure 5). Rocks within the frontal fold and thrust zone consist of Paleozoic and Mesozoic sedimentary rocks of the cratonic shelf along with Archean crystalline rocks incorporated in some imbricate thrusts (Ruppel and Lopez, 1984). Deformation in the zone is characterized by tight, partly overturned folds and multiple imbricate thrust faults that commonly cut through the limbs of the overturned folds. Within the frontal fold and thrust zone, thrust-related folding and faulting gradually become less intense and pervasive eastward, dying out against the crystalline rocks of the craton (Ruppel and Lopez, 1984). The study area lies within the frontal fold and thrust zone.

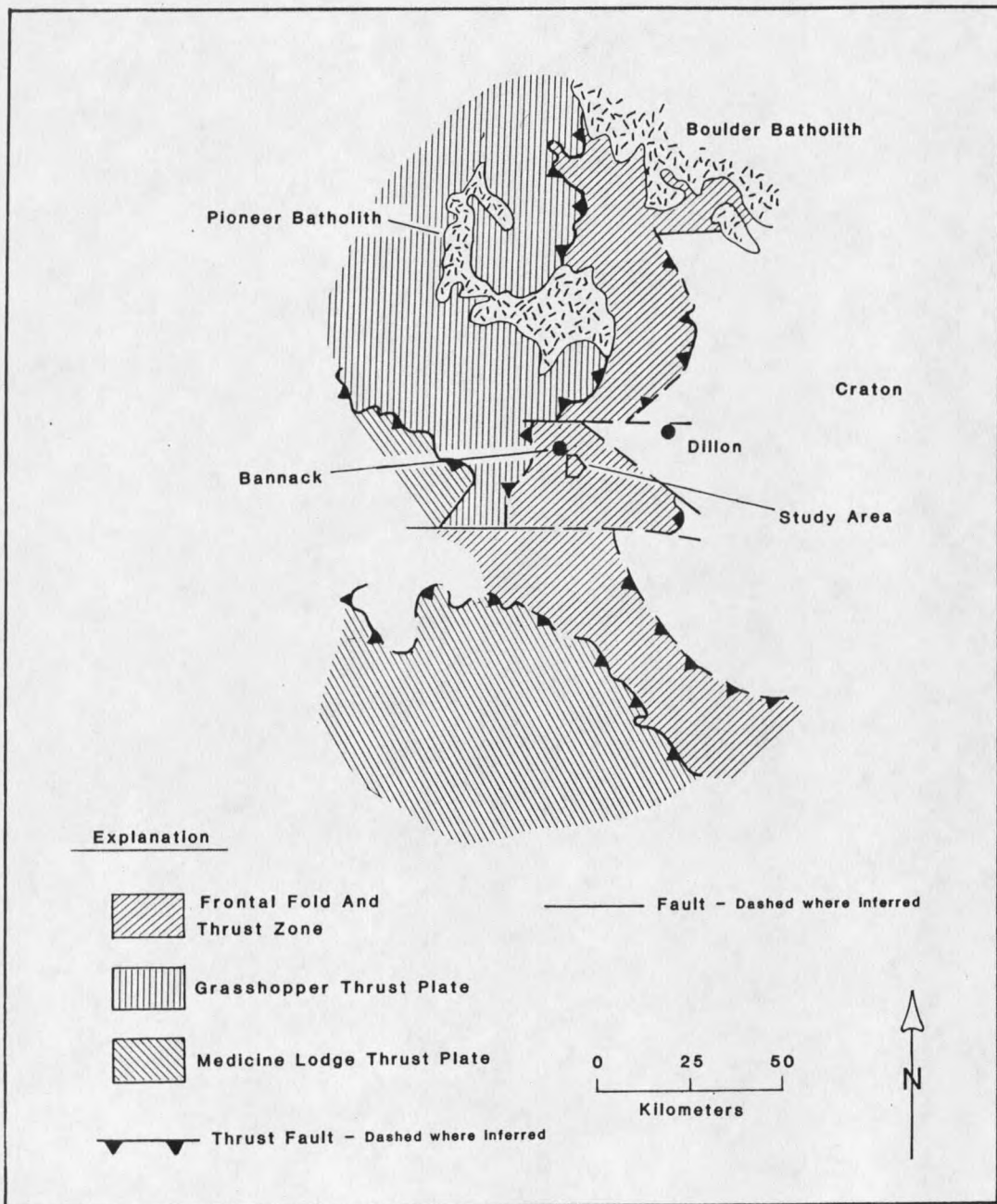


Figure 5. Major divisions of the Cordilleran fold belt in southwest Montana and east-central Idaho. Modified from Ruppel and Lopez (1984).

The Grasshopper plate lies structurally above the frontal fold and thrust zone (Figure 5). This plate carries a thick sequence of quartzite and finer-grained clastic rocks belonging to the upper part of the Proterozoic Belt Supergroup (Missoula Group). The Missoula Group rocks are locally underlain by carbonates of the middle part of the Belt Supergroup and are locally overlain by Cambrian and Devonian rocks. Upper Paleozoic and Mesozoic rocks are not known to be preserved on the Grasshopper plate. The Grasshopper plate is gently folded and cut by multiple imbricate thrusts that appear to sole into the basal decollement (Ruppel and Lopez, 1984).

The Medicine Lodge plate lies structurally above the Grasshopper plate and frontal fold and thrust zone and consists of a thick sequence of Proterozoic Y quartzite overlain by Ordovician through Triassic miogeoclinal rocks. It is deformed by tight, locally isoclinal, east-verging folds and cut by multiple interlacing imbricate thrusts that appear to dip down into the basal decollement (Ruppel and Lopez, 1984).

GENERAL GEOLOGY OF THE STUDY AREA

Local Stratigraphy

The study area is underlain by approximately 2,100 m of unmetamorphosed Paleozoic and Mesozoic sedimentary rocks deposited with angular unconformity over Archean metamorphic and intrusive igneous rocks (Coryell, 1983) (Figure 6). No Proterozoic strata are present in the study area. Along Grasshopper Creek, strata of the Upper Cretaceous Beaverhead Group are deposited on strata of the Mississippian Lombard Formation. The Beaverhead rocks are locally overlain by Tertiary volcanic rocks and Quaternary alluvial deposits.

A brief synopsis of the local stratigraphic sequence is shown in Table 1. A more complete discussion of the local Beaverhead Group stratigraphy is presented in a later section. Descriptions of the Precambrian through Early Cretaceous units are compiled from work done by Coryell (1983), Clark (1986), and Goodhue (1986) in the Armstead Hills, immediately south of the field area and Thomas (1981) in the Badger Pass area, immediately north of the field area. Descriptions of the Beaverhead Group and later rocks are compiled from my own work as well as from work done by Coryell (1983), Johnson (1986), Ivy (1989), Pearson and Childs (1989), and Gonnermann (1992).

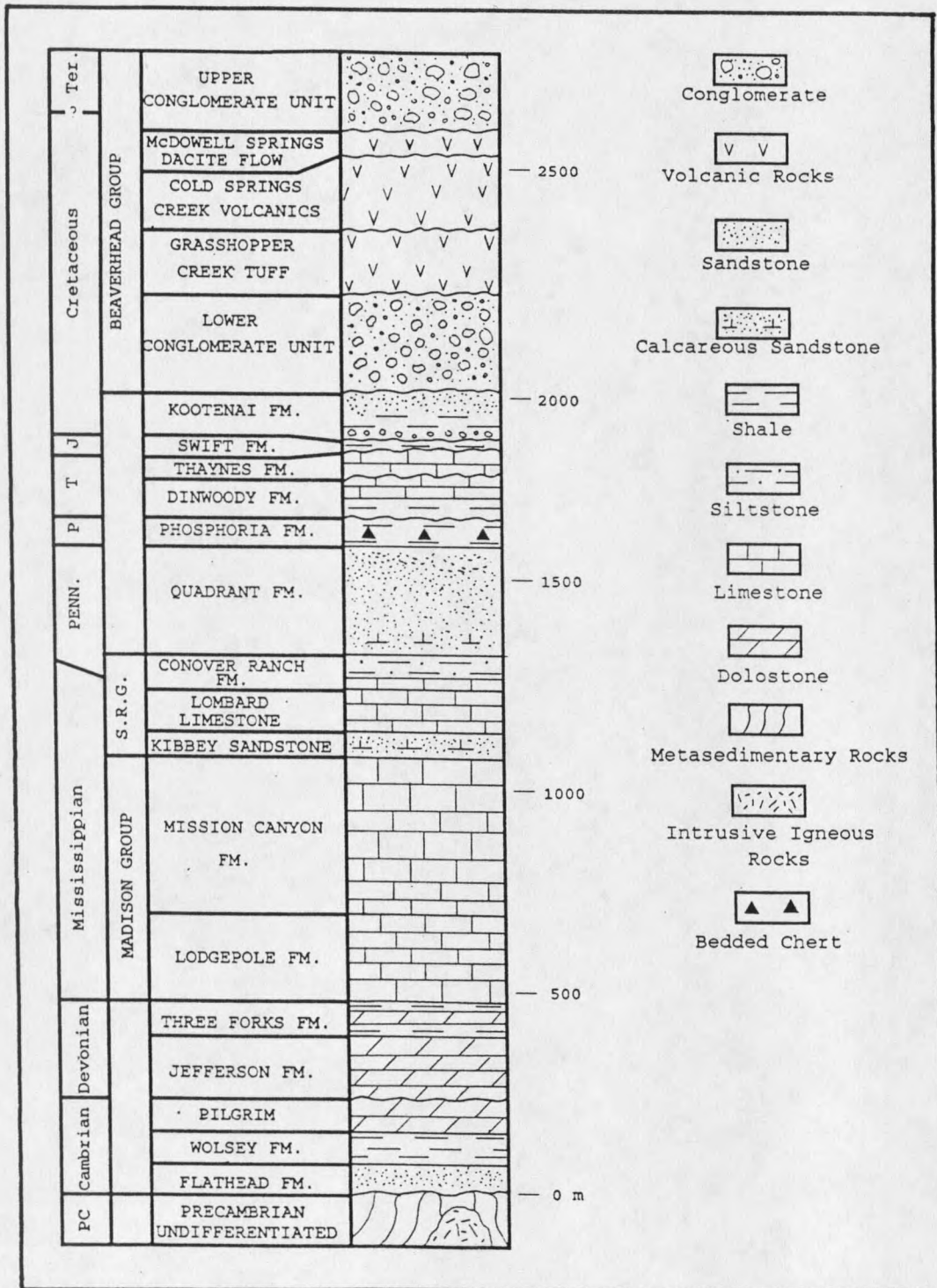


Figure 6. Generalized stratigraphic column of study area and northern portion of the Armstead Hills. S.R.G.=Snowcrest Range Group. Compiled from Coryell (1983) and Goodhue (1986).

Table 1. Summary descriptions of lithologic units.

Formation Name	Thickness (Range in m)	Lithologic Description
<u>Lower Tertiary-Upper</u>		
<u>Cretaceous</u>		
Beaverhead Group	0-396	Quartzite and limestone pebble/cobble conglomerate; clast supported; minor interbeds of carbonate cemented sandstone and siltstone.
Upper conglomerate unit		
McDowell Springs Dacite flow	165	Dacite flow. Basal monolithic breccia grades upwards into massive columnar-jointed dacite capped by flow ridges.
Cold Springs Creek volcanics	30-488	Heterogeneous assemblage of volcanic breccias, ash-flow tuffs, lava flows and volcanoclastic strata of intermediate composition.
Grasshopper Creek tuff	30-304	Pyroclastic-flow and fallout-tuff deposits; very slightly porphyritic; siliceous, feldspathic, and zeolitic.
Lower conglomerate unit	0-357	Limestone pebble/cobble conglomerate; clast supported; minor interbeds of carbonate cemented sandstone.
<u>Cretaceous</u>		
Kootenai Fm.	0-366	Basal chert pebble conglomerate overlain by fine-grained siltstone capped by coarse-grained, moderately sorted sandstone.
<u>Jurassic</u>		
Swift Fm.	13	Interbedded marl and conglomerate; glauconitic; conglomerate contains black elongate chert and quartz chips.
<u>Triassic</u>		
Thaynes Fm.	75-122	Limestone with small interbeds of argillaceous and sandy material; may become glauconitic toward top.
Dinwoody Fm.	30-274	Shale and limestone. Shale, thin-bedded, flaggy, calcareous. Limestone, thin to med.-bedded pelecypod-bearing biomicrites and biosparites; characteristic chocolate brown color on weathered surfaces.

Table 1. - continued

Formation Name	Thickness (Range in m)	Lithologic Description
<u>Permian</u> Phosphoria Fm.	80-110	Dolomite, cherty dolomite, bedded chert, phosphatic mudstone, and sandstone.
<u>Pennsylvanian</u> Quadrant Fm.	190-366	Sandstone, fine- to med.-grained, supermature, quartzarenite; massive to thick-bedded; extremely hard when silica cemented; friable and poorly indurated when calcite cemented.
<u>Pennsylvanian/Mississippian</u> Conover Ranch Fm.	45	Limestone, silty limestone, dolomite, siltstone, and shale.
<u>Mississippian</u> Lombard Limestone	129	Limestone, thin- to thick-bedded, micrite, and biomicrite; chert nodules and chert stringers found in upper part.
Kibbey Sandstone	27	Sandstone, siltstone, dolomitic siltstone; sandstone calcareous, fine- to med.-grained, thin- to med.-bedded.
Mission Canyon Fm.	180-700	Limestone, massive- to very thickly-bedded; bioclastic; nodules and stringers of chert found throughout formation; solution breccia present in the upper 20 m.
Lodgepole Fm.	200-384	Limestone, thin- to medium-bedded, micrite and biomicrite; contains nodules and lenses of chert.
<u>Devonian</u> Three Forks Fm.	50-111	Interbedded limestone, dolomitic siltstone, and silty shale.
Jefferson Fm.	0-200	Dolomite, med.- to thick-bedded; distinctive petroliferous odor on freshly broken surfaces; zones of dolomite breccia.
<u>Cambrian</u> Pilgrim Fm.	0-94	Dolomite, thickly bedded, sucrosic texture.

Table 1. - continued

Formation Name	Thickness (Range in m)	Lithologic Description
Wolsey Fm.	18-69	Finely fissile shale with interbeds of fine-grained sandstone; sandstone rich in hematite and glauconite.
Flathead Fm.	5-91	Sandstone, thin- to thick bedded, med.- to coarse-grained, silica cemented, supermature quartzarenite; thin beds and lenses of pebble conglomerate common.
<u>Precambrian</u> Precambrian undifferentiated		Quartzo-feldspathic gneiss, schist, amphibolite, marble, quartzite, and pegmatite.

Local Structural Geology

In a broad sense, the structural geology of the Bannack area resulted from hanging wall deformation along the leading edge of the frontal fold and thrust belt (Coryell, 1983). Structural features within and surrounding the study area include three large-scale folds and three major faults (Figure 7).

Folds

The Madigan Gulch anticline is an eastward-verging, southward plunging asymmetrical anticline cored by Mississippian carbonate rocks. Steeply dipping to overturned strata exposed in the east limb of this anticline range in age from Upper Cretaceous Beaverhead conglomerates to Lower Mississippian Lodgepole Limestone. The fold has a sinuous

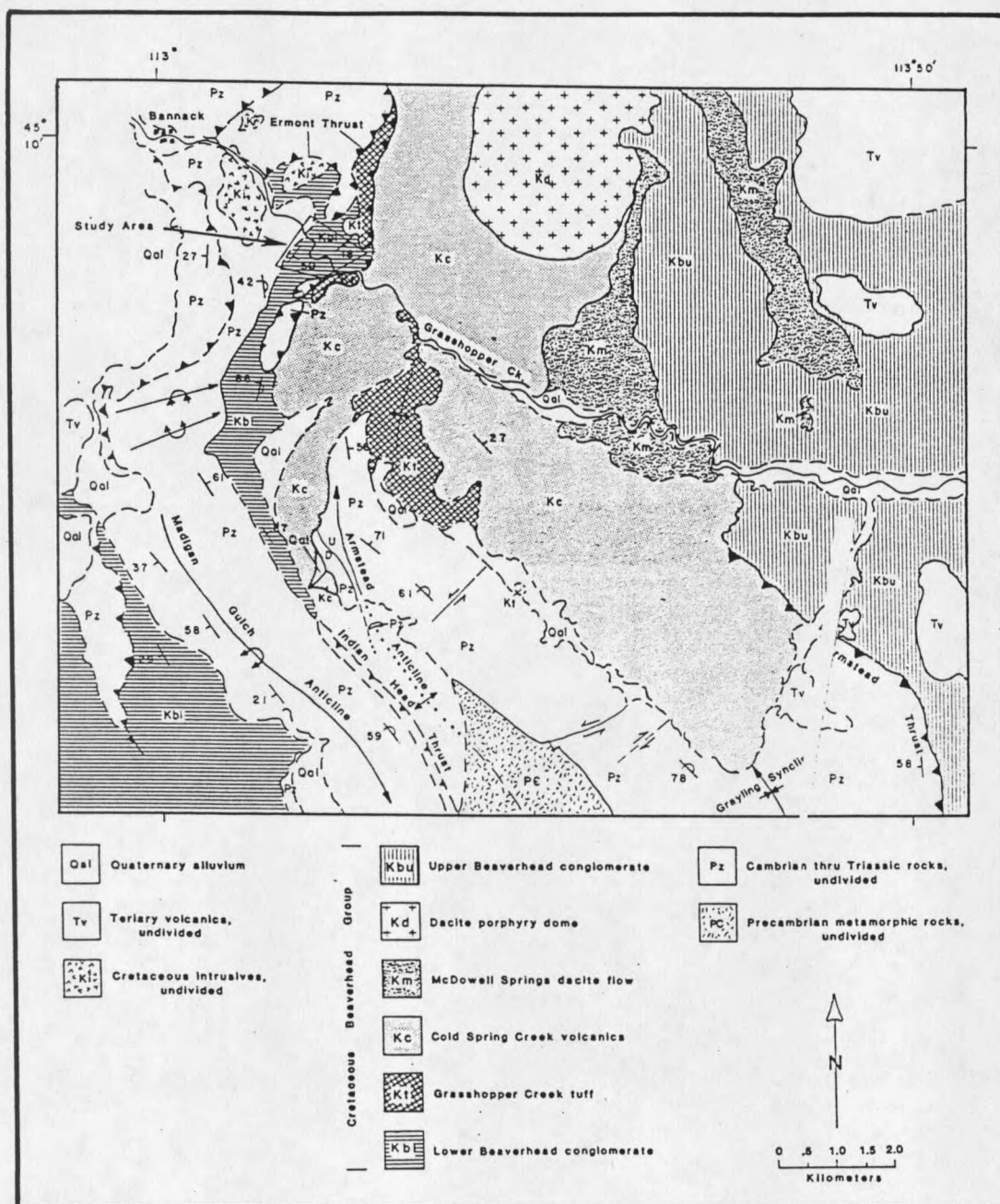


Figure 7. Generalized geologic map of study area. Adapted from Johnson and Sears (1988) and Gonnermann (1992).

trace but generally trends southeast (Coryell, 1983). The northern part of the fold has been cut by a possible southern extension of the Ermont thrust.

The Armstead anticline is an north plunging, east-verging, arcuate, asymmetric fold cored by Archean metamorphic rocks. Consistent north- to northwest- striking foliation in the metamorphic rocks of the core of the anticline (Lowell, 1965) suggests they were folded concordantly with the overlying sedimentary strata (Goodhue, 1986). The axial surface has a sinuous trace with the southern part of the fold trending north, central part trending northwest, and northern part swinging abruptly to the north and northeast (Figure 7). Just south of the field area, Paleozoic strata wrap around the nose of anticline where it plunges beneath strata of the Upper Cretaceous Cold Springs Creek volcanics. The southern extension of the fold is covered by the Clark Canyon Reservoir. Strata exposed on the east limb are steeply dipping to overturned and range in age from Cambrian through Pennsylvanian. The Armstead anticline is bounded to the west by a fault that places Paleozoic rocks against the Archean core.

Adjacent to the east flank of the Armstead anticline is a broad synclinal structure termed the Grayling syncline by Lowell (1965). This eastward-verging fold is asymmetric with a steep west limb and shallow east limb. Trend and plunge of the fold mimics that of the neighboring Armstead anticline

(Goodhue, 1986). Strata exposed in the limbs of the syncline range in age from the Upper Mississippian Conover Ranch Formation to the Lower Triassic Dinwoody Formation. The broad east limb of the fold is truncated by the Armstead thrust. The Grayling syncline plunges to the north and is buried beneath the Upper Cretaceous Cold Spring Creek Volcanics (Figure 7). The syncline is truncated by thrusting to the south (Coryell, 1983).

Faults

The Ermont thrust was named by Myers (1952) and is the western most and structurally highest thrust in the study area. Along this fault, Mississippian and upper Paleozoic rocks have been brought over Upper Cretaceous conglomerates and volcanic rocks of the Beaverhead Group. Thomas (1981) mapped the north-northeast trend of the surface trace of the fault 24 km from the north side of Grasshopper Creek to its disappearance under Tertiary strata north of Badger Pass. He suggested that the thrust may die out in a series of fold structures north of the Tertiary cover. On the north side of Grasshopper Creek the trace of the fault is lost in a series of complex structures and intrusions. The westward dip of the fault plane gradually steepens as one proceeds south from less than 15° north of Badger Pass (Thomas, 1981) to 35° - 40° near Bannack (Johnson, 1986). This change in the dip of the fault plane may indicate the presence of a subsurface ramp. Thomas

(1981) and Johnson (1986) have suggested that the Ermont thrust is the source for what they have interpreted to be klippen of Madison Limestone resting on top of the lower limestone conglomerate of the Beaverhead Group on the north and south sides of Grasshopper Creek (Secs. 9 and 17, T8S, R11W).

Johnson (1986) mapped a possible southern extension of the Ermont thrust south of Grasshopper Creek. This fault places Upper Mississippian and Pennsylvanian rocks over Lower to Middle Mississippian rocks and Beaverhead conglomerate. Further south, Coryell (1983) mapped a west dipping thrust fault that places Pennsylvanian rocks over strata of the lower Beaverhead conglomerate. He hypothesized that this fault may be the southern most extension of the Ermont thrust.

The Armstead thrust (Johnson, 1986) is the eastern most and structurally lowest thrust in the Bannack area where the fault is exposed for approximately 8 km (Johnson, 1986). Along its generally northwest trending surface trace, the fault places Mississippian carbonate, Pennsylvanian sandstone, and Upper Cretaceous volcanic rocks over strata belonging to the upper conglomerate member of the Beaverhead Group. Previous workers (Lowell, 1965; Coryell, 1983; Goodhue, 1986) have mapped this fault as a northern extension of the Tendoy thrust which places Mississippian rocks over Late Cretaceous to early Paleocene(?) Beaverhead conglomerates in the region of Dell and Lima, Montana. However, Johnson (1986) reported that

structural complications associated with the McKenzie thrust system of Perry and others (1985) south of Bannack do not permit the northward extension of the Tendoy thrust into the Armstead Hills.

Displacement along the thrust decreases from south to north (Gonnermann, 1992). Two kilometers south of Grasshopper Creek in Section 31 (T8S, R10W) displacement along the thrust dies out in a zone of fractured and sheared quartzite clasts within the Beaverhead conglomerate (Gonnermann, 1992). Maximum displacement is unknown, but Goodhue (1986) suggests it is greater than 500 m.

The east flank of the Madigan Gulch anticline is separated from the east flank of the Armstead anticline by a fault of ambiguous origin. This fault was termed the Indian Head thrust by de La Tour-du-Pin (1983; in Goodhue, 1986). The fault plane dips southwest at 60° - 80° and the fault trace is subparallel to the axial surface trace of the major folds (Coryell, 1983). There are several interpretations of fault style which include normal faulting (Brant and others, 1949 in Johnson, 1986; Kupsch, 1950 in Johnson, 1986); younger-over-older thrust faulting (Lowell, 1965; Goodhue, 1986; Johnson, 1986); and listric normal faulting over a subsurface ramp (Coryell, 1983). Schmidt (personal communication in Coryell, 1983) has suggested that the fault was a west-directed high angle reverse fault that was later rotated to the east by thrusting. Along the south and central parts of the Armstead anticline

this fault juxtaposes Mississippian and older rocks against the Archean metamorphic rocks of the anticlinal core. To the north where the fault cuts the nose of the Armstead anticline the Mississippian Mission Canyon Formation has been faulted over progressively younger rocks from Archean metamorphic rocks to Mission Canyon Formation in a down plunge direction.

STRATIGRAPHY AND AGE OF THE BEAVERHEAD GROUP

Strata of the of Upper Cretaceous to lower Tertiary (?) Beaverhead Group crop out over an area of approximately 1,700 km² in southwestern Beaverhead County, Montana and adjacent Clark County, Idaho (Figure 8). In general, Beaverhead Group strata are dominated by complexly interfingering limestone and quartzite clast conglomerate and sandstone with minor amounts of lacustrine limestone, mudstone, volcanic rocks, and exotic limestone blocks. The deposits exhibit marked changes in facies and thickness. Locally the deposits may be up to 4,500 m thick (Ryder and Scholten, 1973). Structural elements which acted as source areas for the terrigenous clastic deposits are thought to have been located in both the Rocky Mountain foreland to the east and the fold and thrust belt to the west (Ryder and Scholten, 1973; Haley, 1985; Haley and Perry, 1991).

The Beaverhead Group in the study area east of Bannack, Montana is divided into: 1) a lower limestone-pebble/cobble conglomerate with minor volcanic rocks; 2) an intermediate volcanic unit of ash flow tuffs, lava flows, volcanic breccias, a dacite dome, and associated shallow level intrusions; and 3) an upper quartzite-limestone pebble/cobble conglomerate (Figures 6 and 9). The lower unit consists of

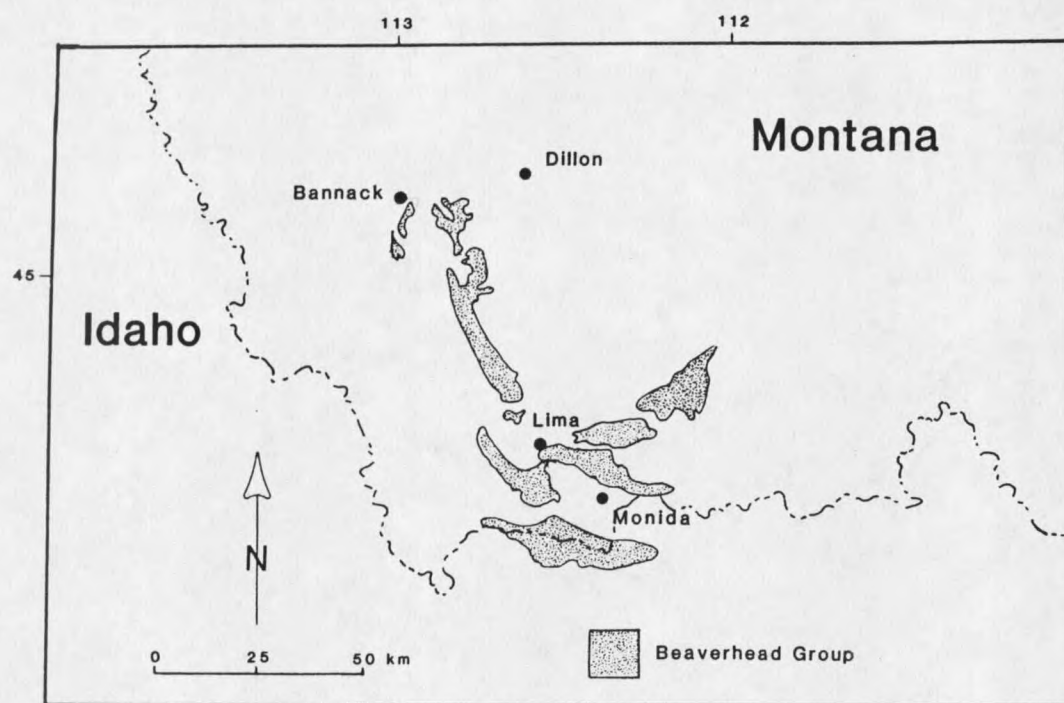


Figure 8. Distribution of Beaverhead Group rocks in southwestern Montana and east-central Idaho. Modified from Wilson (1967).

approximately 354 m of clast-supported limestone-clast conglomerates with lenses of fine- to coarse-grained sandstone and minor mudstone. Approximately 21 m above the basal contact of the Beaverhead Group is a 6 m thick sequence of fine- to medium-grained tuffs. Poor exposures of these greenish-grey to purple bedded tuffs crop out in the prominent northeast-southwest trending gulch just above the basal contact on both sides of Grasshopper Creek.

The lower most conglomerate unconformably overlies folded Mississippian Lombard Limestone (Figure 10). To the south, the

AGE Ma	AGE	UNIT	THICKNESS meters	LITHOLOGIC DESCRIPTION
70	Maastrichtian	?		Clast supported, quartzite & limestone pebble/cobble conglomerate with interbeds of reddish-brown, carbonate cemented sandstone and siltstone. Conglomerates contain 50%-80% red to maroon quartzite clasts of probable Proterozoic origin.
		Upper Quartzite Conglomerate	0-396	Greenish-brown, porphyritic dacite.
	Campanian 758	McDowell Springs Dacite Flow	0-165	Heterogeneous assemblage of porphyritic volcanic breccias, ashflow tuffs, lava flows, and volcanoclastic strata.
		Cold Springs Creek volcanics	30-488	Light-grey, yellowish-gray, pinkish-grey, and white rhyolitic, pyroclastic flows and fallout tuff deposits; lithic fragments of volcanic and sedimentary origin are common.
80		Grasshopper Creek Tuff	30-304	Clast-supported limestone pebble/cobble conglomerate with lenses and interbeds of red to brown, fine- to coarse-grained, carbonate cemented sand. Sequence of greenish-grey to purple, aphanitic to phaneritic tuffs present near base of unit.
		?		
		Lower Limestone Conglomerate	0-354	

Figure 9. Stratigraphy of Beaverhead Group east of Bannack, Montana. Information compiled from Johnson (1986); Ivy (1989); Pearson and Childs (1989); Gonnermann (1992); and work from this study.

unconformity overlies progressively older rocks from the Kibbey Sandstone to the Mission Canyon Limestone. Evidence for an unconformable contact within the study area includes: 1) presence of a red karst paleosol directly beneath the basal conglomerate; 2) conglomerates of the basal Beaverhead filling depressions on the surface of the underlying limestone; 3) pieces of Lombard Limestone within the Beaverhead stratigraphically higher than the projected plane of the contact; and 4) discontinuous pods of rounded to subangular Lombard clasts with a carbonate sand dominated matrix between

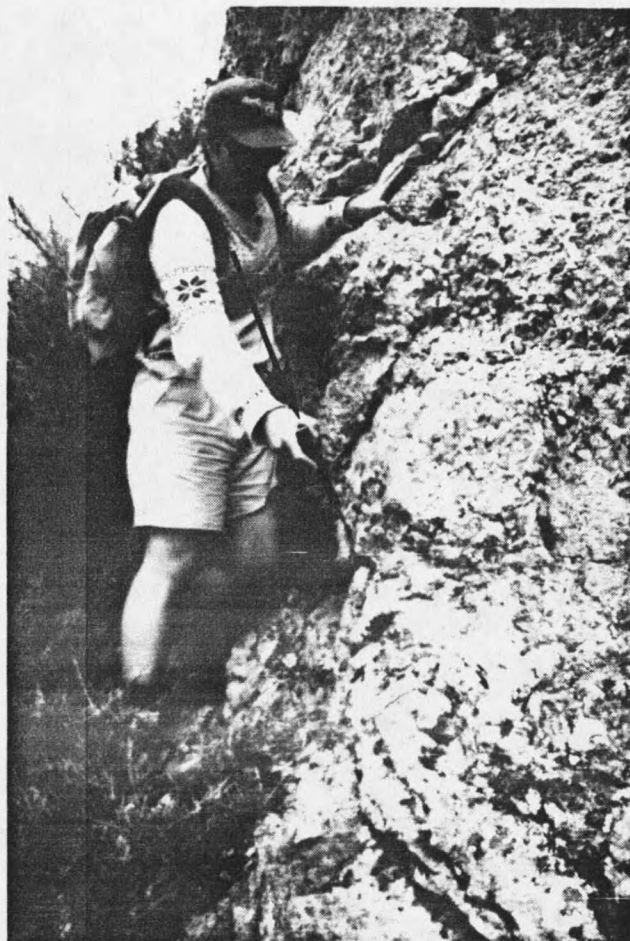


Figure 10. Contact between the lower Beaverhead conglomerate and Lombard Limestone on the east limb of the Madigan Gulch anticline. Hammer is in line with the depositional surface which is dipping approximately 65° . Dr. Schmitt's left hand is on a large boulder of Lombard Limestone. When depositional surface is projected skyward, this clast is in the lower Beaverhead conglomerate.

the basal Beaverhead and top of the Lombard. These pods are interpreted to be remnants of scree deposits that collected in low areas of the pre-Beaverhead surface.

Above the lower conglomerate unit (Figures 6 and 9) is a volcanic sequence which Ivy (1989) informally divided into the

Grasshopper Creek tuff and the Cold Springs Creek volcanics. The nature of the relationship between the volcanic rocks and conglomerates of the Beaverhead Group in this area was ambiguous until Gonnermann (1992) recognized that the "McDowell Springs intrusive sheet" (part of the Cold Springs Creek volcanics) of Pearson and Childs (1989) and Ivy (1989) was actually a dacite flow underlying the upper quartzite-limestone-clast conglomerate. Gonnermann (1992) based this interpretation on the recognition of a basal monolithic breccia which grades upward through a transition zone into massive, columnar-jointed dacite, capped by prominent flow ridges. Recognition of the McDowell Springs dacite as a lava flow establishes the volcanic rocks as part of the Beaverhead Group (Gonnermann, 1992).

The upper conglomeratic unit consists of up to 396 m (Pearson and Childs, 1989) of clast-supported quartzite-limestone conglomerate. The quartzite clasts were probably derived from Proterozoic quartzites of the thrust belt to the west (Ryder and Scholten, 1973; Ruppel and Lopez, 1984). The unit also contains highly weathered andesite clasts derived from the underlying Cold Springs Creek volcanic unit (Johnson and Sears, 1988). The remainder of the clasts are limestone, white quartzite, and chert probably derived from Paleozoic formations (Johnson and Sears, 1988; Gonnermann, 1992).

Contact relationships between rocks of the Beaverhead Group and the underlying strata vary by location. In the study

area and south of Lima, Montana, near the Lima Peaks (Haley, 1985; Haley and Perry, 1991) an angular unconformity separates the Beaverhead Group rocks from underlying strata of Paleozoic age. South and east of Monida, Montana, the Beaverhead rocks may rest disconformably or conformably on strata of the Late Cretaceous Frontier Formation (Dyman and others, 1991).

Because of its synorogenic nature, the Beaverhead Group consists of a number of spatially isolated, individually-mappable units which differ in lithology, thickness, and age (Haley, 1985; Haley and Perry, 1991) (Figure 11). Determining the temporal relationships between individual depositional units is difficult because few datable palynomorphs or other fossils have been recovered from Beaverhead strata. Thus, relative ages must be established by indirect methods such as stratigraphic correlation.

On the basis of lithological similarities, Johnson (1986) correlated the lower Beaverhead conglomerate in the study area with the Lima Conglomerate of the Beaverhead Group of Nichols and others (1985). The Lima Conglomerate, which crops out east of Lima, Montana, 70 km southeast of the study area, was dated palynologically as mid-Campanian (78-81 Ma) by Nichols and others (1985). If Johnson's (1986) correlation is correct, a similar age is inferred for the lower limestone conglomerate in the study area. Radiometric dating ($^{40}\text{Ar}/^{39}\text{Ar}$) of the overlaying volcanic rocks of the Cold Springs Creek unit

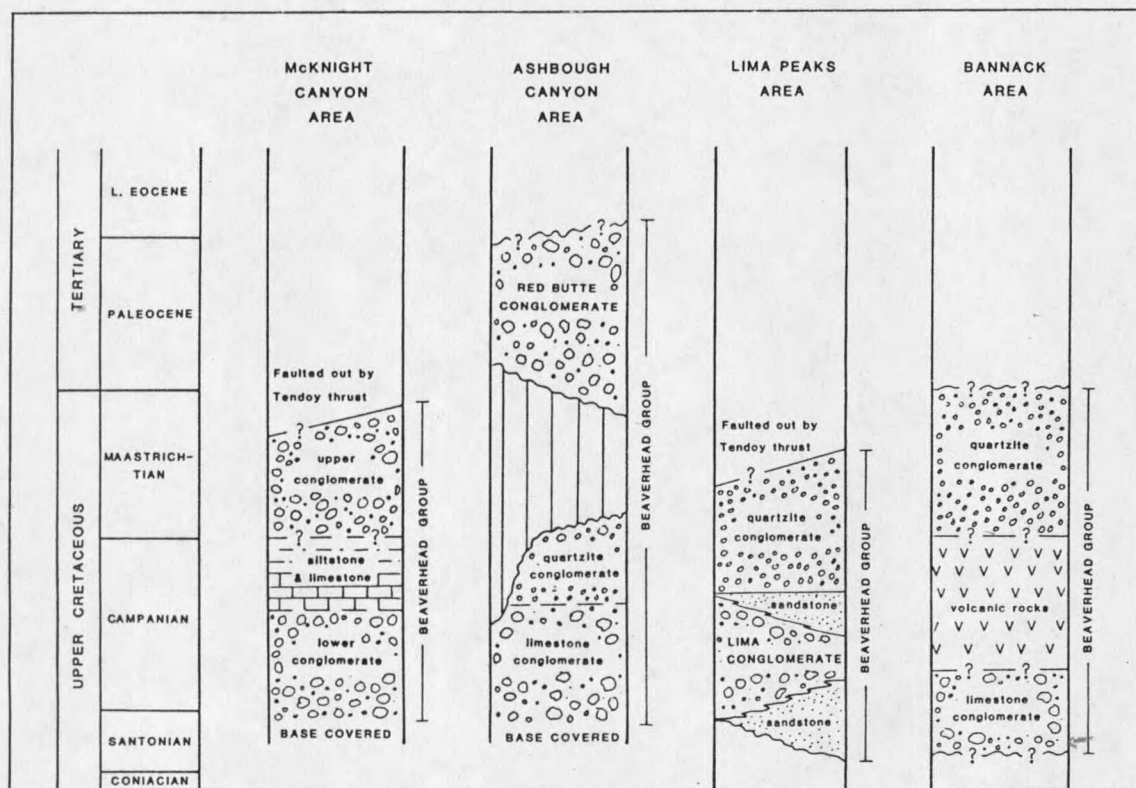


Figure 11. Ages and stratigraphic relationships of formal and informal units within the Beaverhead Group. Adapted from Haley and Perry (1991).

demonstrate that this phase of volcanism began approximately 80 Ma (analysis by L.W. Snee *in* Ivy, 1989). The age of the underlying Grasshopper Creek tuffs is unknown. Thus, the minimum age of the lower limestone conglomerate is no younger than middle Campanian but its maximum age is uncertain. The existence of the thin sequence of volcanic rocks within the lower conglomerate was unrecognized by previous workers. Radiometric dating of these tuffs could help to constrain the age of the lower conglomerate unit.

The upper quartzite-limestone conglomerate unit was mapped as part of the informal "Kidd quartzite conglomerate" of the Beaverhead Group by Ryder and Scholten (1973). Haley (1985) included these rocks in his "Kidd outcrop belt of undifferentiated quartzite conglomerates of the Beaverhead Group". Southeast of the study area these conglomerates are unconformably overlain by the Red Butte Conglomerate of the Beaverhead Group which Haley and Perry (1991) have suggested is probably no older than Maastrichtian and no younger than middle Eocene in age. West of the study area the upper quartzite-limestone conglomerate stratigraphically overlies the McDowell Springs dacite flow and a portion of the dacite dome (Figure 9) (Gonnermann, 1992). Radiometric dating ($^{40}\text{Ar}/^{39}\text{Ar}$) of the dome indicates extrusion occurred approximately 75.8 Ma (analysis by L.W. Snee in Ivy, 1989). Thus, the upper quartzite conglomerate of the Beaverhead Group in the Bannack area is probably Maastrichtian in age.

LITHOFACIES

Lithofacies analysis of the lower Beaverhead Group conglomerate involved establishment of the lithofacies present and detailed recording of their lateral and vertical distribution. The major lithofacies present in the study area include; conglomerate (G), sandstone (S), fine-grained units (F), and volcanic rocks (V). Each lithofacies is discussed below and is summarized in Table 2.

Conglomerate Lithofacies (G)

Introduction

Conglomerate lithofacies are clast-supported with both organized or disorganized fabrics. Framework clasts are subrounded to angular and are generally equidimensional making recognition of preferred orientations difficult. Conglomerate lithofacies are divided into five subfacies which together make up approximately 85% of the lower Beaverhead strata in the study area.

Massive, Disorganized, Polymodal Conglomerate (Gcd)

Description. Lithofacies Gcd is characterized by polymodal framework gravels with a poorly- to very poorly-sorted matrix of calcite-cemented quartz-rich sand and

Table 2. Summary of lithofacies. Lithofacies codes modified from Miall (1977) and Rust (1978).

Lithofacies Code	Description	Sedimentary Structures	Interpretation
Gcd	Clast-supported, very poorly sorted, disorganized, cobble-boulder conglomerate	Massive, some crude inverse grading	Cohesionless debris flows, hyper-concentrated flood flows
Gcm	Clast-supported, moderately-to poorly-sorted, pebble-cobble conglomerate	Massive, some crude normal to inverse grading and imbrication	Longitudinal gravel bars; high-density gravelly traction carpets
Gch	Clast-supported, moderately- to well-sorted, horizontally stratified, pebble-cobble conglomerate	Horizontal stratification, imbrication	Longitudinal gravel bars
Gcp	Clast-supported, well-sorted, well-packed, pebble conglomerate	Imbrication, normal grading	Waning-stage minor channel fills and bar flank accretions
Gct	Clast-supported, moderately- to well-sorted, cross-stratified, pebble-cobble conglomerate	Cross-stratification parallel to lower bounding surface	Infilling of shallow channels and bar top scours by migrating gravel sheets
Sm	Fine- to coarse-grained, very poorly- to well-sorted sand, gravel as isolated clasts or stringers	Massive, some inverse grading, bioturbation	Sandy debris flows; sheet flood deposits; waning-stage channel and bar-top deposits; overbank deposits
Sh	Very-fine- to medium-grained, moderately- to well-sorted sand	Horizontal lamination	Waning-stage channel and bar-top deposits
Sr	Very-fine- to medium-grained, well-sorted sand	Ripple cross-lamination	Waning-stage channel and bar-top deposits, overbank deposits
Fm/F1	Massive to finely laminated mud	massive, bioturbation, fine laminations	Overbank deposits
V	Purple to greyish-green, fine-grained to aphanitic tuffs	Massive, some units have slaty partings	Tuff deposits

granular to small pebble size clasts of chert and limestone. Due to the poor organization and textural polymodality of this facies, formal delineation of a boundary between matrix and framework clasts is difficult. Facies Gcd contains abundant clasts that are significantly larger than the visually estimated mean clast size. The largest of these "outsized" clast may exceed 2.4 meters in diameter. Where present, elongated or platy clasts have random orientations, including vertical. Clasts often protrude from the tops of beds. Typically, the deposits are ungraded to inversely graded although some units exhibit coarse-tail normal grading. Deposits of facies Gcd range in thickness from less than 0.3 to 2 m and are found as lobes or thin sheets with sharp, slightly erosive to nonerosive bases, or as channel-filling bodies (Figure 12). The upper surface of this facies may be capped by lenses of massive (Sm) sandstone which infiltrate between the clasts in the upper part of the unit. Additionally, units of Gcd may grade laterally and vertically into gravels of facies Gcm.

Interpretation. The poor organization, ungraded to inversely graded texture of the polymodal framework gravels, the very poorly sorted matrix, and the presence of abundant "outsized" clasts suggest that units of facies Gcd represent the deposits of clast-rich, cohesionless debris flows. The term "cohesionless" is used here in the sense of Nemec and Steel (1984) to emphasize the relative unimportance of matrix

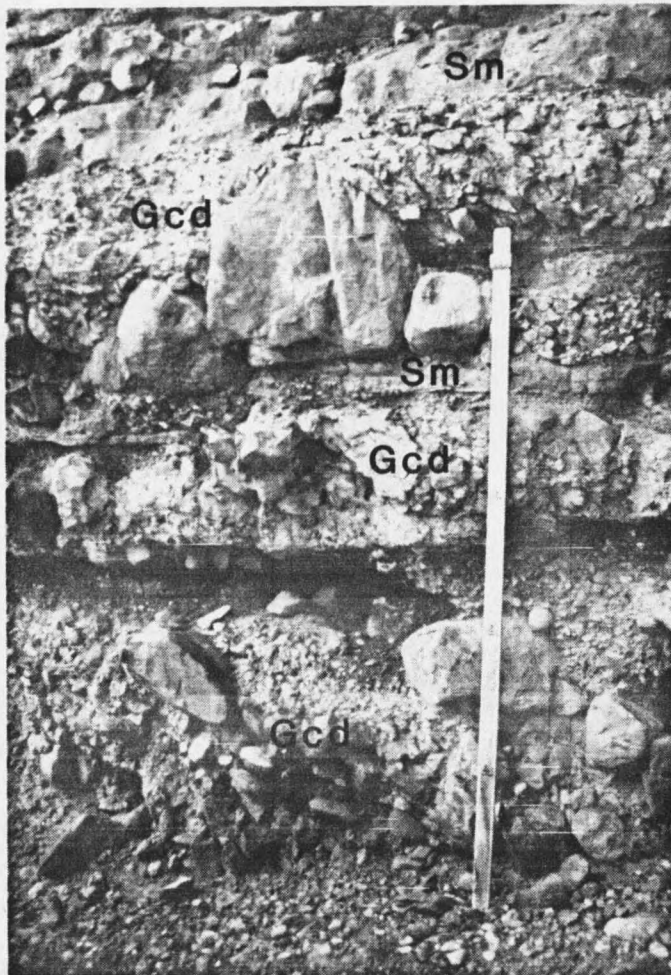


Figure 12. Facies Gcd interbedded with thin, discontinuous beds of massive sandstone (Sm). Jacob's staff is 1.5 m long.

cohesion in controlling flow behavior, particularly yield strength, mode of clast support, and mode of en masse deposition (cohesive freezing versus frictional freezing). The absence of a clay-rich matrix and the framework-supported nature of the deposits suggest that viscous debris flows could not have been the principal mechanism of clast transport (e.g. Schultz, 1984).

The flows probably consisted of a dense heterogeneous combination of boulders, cobbles and pebbles mixed with a fluid phase consisting of sand, silt, and water. Yield strength was controlled by internal friction originating from particle interlocking and sliding friction in the poorly sorted materials rather than cohesion of the matrix. Blair (1987a) described modern cohesionless debris flows on the Roaring River alluvial fan in Colorado containing 12.5% sand and 0.5% silt and clay. Clast support in these flows was provided by both turbulence and dispersive pressure. Pierson (1981) showed that in virtually cohesionless debris flows (4% clay), boulder size particles are readily held suspended by varying combinations of buoyancy, inertial dispersive pressure, turbulence, and grain-to-grain contact. Similar clast-supported debris flow deposits have been reported by Schultz (1984), Nemec and Steel (1984), Wells (1984), DeCelles and others (1987), and Waresback and Turbeville (1990).

Thin sheet geometries were produced as the flows spread out unconfined across the depositional surface. Lobate geometries probably represent levees on the side of the flows while channel-filling geometries represent flows within pre-existing alluvial channels. Inversely graded beds are probably the result of flows where the forces of buoyancy, and inertial dispersive pressure acted in concert to keep the large particles on top of the flow. Normally graded beds may be the

result of the settling of clast within the flow during transport (Schultz, 1984; Denlinger and others, 1984).

On first inspection, some of the channel-filling deposits appear to resemble deposits of longitudinal bars (facies Gm of Miall, 1977). However, the polymodal distribution of grain sizes and poor sorting suggest the conglomerates were formed by mass immobilization rather than selective deposition. Furthermore, the matrix is too coarse-grained and poorly sorted to have infiltrated between the larger clasts after gravel framework deposition (Smith, 1986).

Massive, Disorganized
Conglomerate (Gcm)

Description. Lithofacies Gcm is typically a bimodal clast-supported conglomerate having a unorganized to poorly organized fabric of pebble to cobble size framework clasts in a sandy matrix (Figure 13). Framework clasts are moderately- to poorly-sorted with a closed framework packing. Rarely, some units exhibit a local open framework packing. Although the deposits are essentially internally unstratified, abrupt lateral and vertical variations in grain size do occur. Grading is generally absent although, crude inverse or normal grading is apparent in some units. "Outsized" clasts are distributed irregularly, either as isolated individuals or in clusters. Elongated or platy clasts may have a weakly-developed imbrication. Matrix is generally poorly- to well-sorted, fine- to medium-grained, calcite cemented, quartz-rich

sand. Locally the matrix may be very poorly-sorted, very coarse-grained sand with granule to small pebble size clasts. Areas of poorly-sorted matrix are associated with the presence of "outsized" clasts.

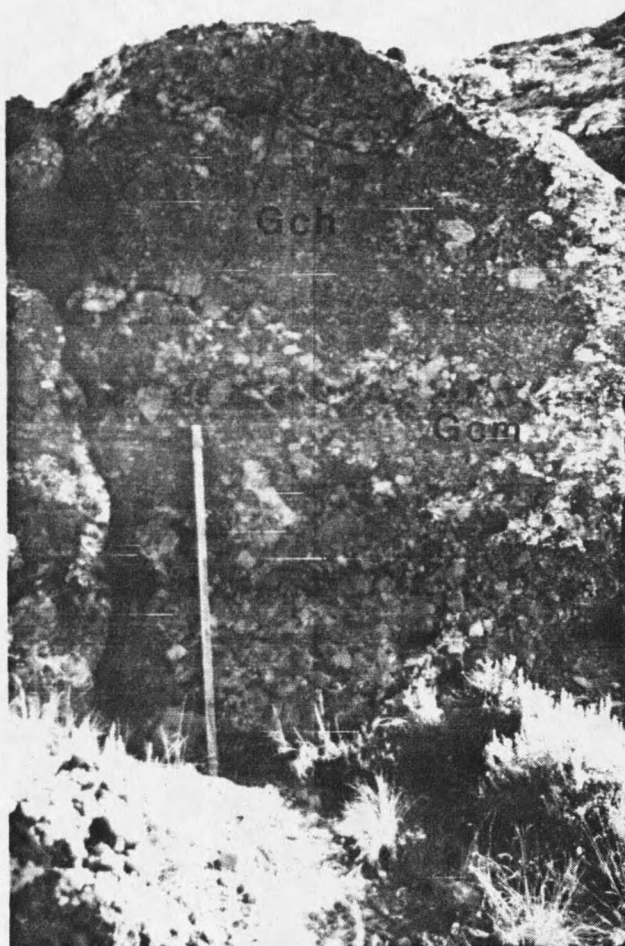


Figure 13. Facies Gcm overlain by facies Gch. Jacob's staff is 1.5 m long.

Bedding planes are indistinct to distinct and range from planar to irregularly concave-upward. Indistinct bedding planes often make it difficult to determine bed thickness and

lateral continuity. Individual beds, where visible, range in thickness from 0.5 to 2 m and extend laterally for up to 45 m. Some of these units have well-defined planar to slightly scoured bounding surfaces while in others, the bounding surfaces may be locally deeply scoured. Amalgamated stacked beds of facies Gcm, separated by thin, discontinuous lenses of sandstone, may reach 10 m in thickness.

Lithofacies Gcm may grade laterally into gravels of lithofacies Gcd and Gch or vertically into conglomerates of facies Gch or sandstones. Where sandstones cap units of facies Gcm, they typically form discontinuous lenses less than 0.25 m thick and generally do not extend laterally for more than 1.5 m before being truncated by the overlying conglomerates. These sandstone lenses are composed of medium-to very coarse-grained sand that may be massive (Sm), or horizontally stratified (Sh). The sandstones have sharp bases that drape the irregular topography formed by clasts projecting from the top of the underlying conglomerate unit.

Interpretation. Deposits of lithofacies Gcm are the most abundant in the study area. This lithofacies also shows the greatest variation in texture and fabric of framework clasts and matrix. Because the variations between deposits were frequently gradational and the gradations subtle, the deposits were not broken into subfacies. The interpretations that follow cover a range of possible depositional processes that may have led to these deposits.

Clast-supported, poorly organized gravel deposits with a poorly sorted coarse-grained sandy matrix and a general lack of reverse grading similar to deposits of facies Gcm have been interpreted by Smith (1986) to be the product of high-density sheet floods or hyperconcentrated flood flows. Smith (1986) uses the term "hyperconcentrated flood flow" to describe high-density flows intermediate in sediment/water ratio between fully turbulent dilute stream flow and viscous debris flows. The texture and fabric of these poorly-sorted sediments suggest rapid traction and suspension deposition from high-concentration dispersions in which turbulence and grain interactions are the primary support mechanisms (Smith 1986). Although deposition is rapid it does not occur en masse (Smith, 1986). Deposits with similar inferred modes of transport and deposition were described by Ballance (1984), Wells (1984), Wells and Harvey (1987), and Waresback and Turbeville (1990). These authors inferred the flows to be deposited on the surface of alluvial fans.

Todd (1989) interpreted sheet-like deposits in the Early Devonian Trabeg Conglomerate Formation of the Dingle Group (Lower Old Red Sandstone) in southwest Ireland that are similar to lithofacies Gcm to be the deposits of stream-driven, high-density gravelly traction carpets. These high-density bedload carpets move as high density dispersions along the bottom of channels during high magnitude floods and are thought to be somewhat analogous to the traction carpets

driven by high-density turbidity currents (Lowe, 1982). Todd (1989) suggests that these traction carpets are driven by tangential shear stress exerted by the overflowing turbulent portion of the sediment-laden stream flow under peak flow conditions. This shear stress is transmitted downwards and converted to dispersive pressure which supports much of the weight of the clasts within the flow. Additional support is derived from the buoyant lift enhanced by the dense nature of the interstitial fluid of watery sand (Todd, 1989). Variable types of grading are thought to be controlled by differences in the apparent viscosity of the traction carpets. Lack of sorting and internal stratification suggests that deposition occurred en masse by frictional freezing during waning of the stream flood (Todd, 1989). As the floods dissipated, sand was deposited on top of the gravel sheets. Conglomerate deposits of this type, up to 3 m thick, are found on stream-dominated, 'flashy' (ephemeral) alluvial fans (Todd, 1989).

Massive, moderately-sorted, pebble and cobble conglomerates similar to some deposits of lithofacies Gcm have been widely recognized and interpreted as the result of deposition by longitudinal bars in gravel-dominated braided streams (Smith, 1970, 1974; Rust, 1972, 1978; Boothroyd and Ashley, 1975; Miall, 1977; Hein and Walker, 1977;). These bedforms develop and grow during periods of moderate to high stage discharge. Typical dimensions for individual gravel bars range up to 1 m in thickness although superimposed units may

reach 4 m or more in thickness (Miall, 1977). Bar lengths of several hundred meters are possible, but these larger examples probably represent composite or coalesced forms (Miall, 1977).

Hein and Walker (1977) suggested that these bedforms grow from the emplacement of channel lag deposits as diffuse gravel sheets during maximum flow stages. These lag deposits, which initially may be only a few clasts thick (Boothyrod and Ashley, 1975; Hein and Walker, 1977), act as nuclei for subsequent development of longitudinal bars. Bars with massive or horizontally stratified internal structures develop when water and sediment discharges are high and the rate of downstream bar migration exceeds the rate of vertical aggradation (Hein and Walker, 1977). These conditions are most often met in the proximal reaches of braided streams (Hein and Walker, 1977).

Rust (1975, 1978) suggests that longitudinal gravel bars are primary bedforms that are stable under flood conditions when all bed material is in motion. The resulting deposits are characteristically massive to horizontally stratified because the low ratio of water depth to mean particle diameter suppresses the development of slip faces and the development of cross-stratification on the lee side of the bar (Rust, 1975, 1978).

Massive conglomerates above trough-shaped scour surfaces were deposited as channel lags (Miall, 1977). The bimodal clast population is the result of infiltration of finer grains

into an open gravel framework as flow strength decreased (Enyon and Walker, 1974; Miall, 1977). Scoured bounding surfaces between individual units and the discontinuous sand lenses indicate modification by subsequent high stage flows (Rust, 1978). Abrupt changes in clast size reflect varying discharge and discontinuous accretion (Nemec and Steel, 1984). The clusters of large clasts may be the remnants of cohesionless debris flows (Gcd) which were later modified by fluvial processes so that their initial origin is now obscured. The presence of very poorly-sorted sand to pebble matrix, similar to that found with lithofacies Gcd in association with the clast clusters, lends to support this view.

Horizontally Stratified Conglomerate (Gch)

Description. Units of lithofacies Gch consist of organized, moderately- to well-sorted pebble to cobble conglomerate with a crude to well-developed horizontal stratification (Figure 13). Stratification is defined by changes in clast size or sorting. Fining-upward sequences are the dominant textural trend although in many units there is no apparent change in clast size. One example of a crudely developed coarsening-upward sequence was observed. When present, elongate clasts have a moderate to well-developed imbrication. Matrix is fine- to medium-grained, moderate to well-sorted, calcite cemented, quartz-rich sand.

Units of lithofacies Gch display several different geometries. Thin, discontinuous sheets up to 0.5 m thick and 3.0 m wide with flat or concave-upward bases are normally found within units of facies Gcm. Broad channel-shaped or apparently tabular bodies up to 2 m thick and 10 m wide form distinct beds with planar to slightly irregular bounding surfaces. Discontinuous lenticular bodies of sand may be interbedded with these larger units.

Interpretation. Moderately-sorted, pebble and cobble conglomerates with crude- to well-developed horizontal stratification have been widely recognized and interpreted as the result of deposition by longitudinal bars in gravel-dominated braided streams (Smith, 1970, 1974; Rust, 1972, 1978; Hein and Walker, 1977; Boothroyd and Ashley, 1975; Miall, 1977). The genesis and evolution of the longitudinal gravel bars that gave rise to lithofacies Gch is envisioned to be the same as that for those deposits of lithofacies Gcm interpreted as longitudinal bars as discussed above. The thin discontinuous beds of Gch found within beds of Gcm were deposited on top of or within shallow channels incised into the surface of the Gcm beds. The thicker and more laterally extensive beds of Gch were deposited within larger channels.

The bimodal clast population is the result of infiltration of finer grains into an open gravel framework as flow strength decreased (Enyon and Walker, 1974; Miall, 1977). Scoured bounding surfaces between individual units and the

discontinuous sand lenses indicate modification by subsequent high stage flows (Rust, 1978). The one example of a coarsening-upward sequence is probably the result of deposition during rising-stage flow (Enyon and Walker, 1974).

Organized, Pebble
Conglomerate (Gcp)

Description. Facies Gcp consists of organized, stratified, bimodal, well-sorted, tightly packed pebble conglomerate. Beds of Gcp fine upwards and have well-defined lenticular or wedge shaped geometries, generally less than 0.5 m thick and 2 m wide with concave-up erosional bases. Matrix is fine- to medium-grained, moderately- to well-sorted quartz-rich sand. Units of facies Gcp usually occur within or on top of beds of Gcm or Gch.

Interpretation. Fluvial gravels similar to facies Gcp have been described in the deposits of modern gravelly braided streams (Smith, 1970, 1974; Rust, 1972, 1978; Hein and Walker, 1977). Units of Gcp are interpreted to be waning stage flood deposits that accumulated within channels that developed on the tops and margins of larger bars made up facies Gcm and Gch. The bimodal clast population is the result of infiltration of finer grained sediments into an open gravel framework as flow strength decreased (Enyon and Walker, 1974; Miall, 1977). Deposits analogous to these were reported by DeCelles and others (1991b) in the Paleocene Beartooth conglomerate in Wyoming and Montana.

Trough Cross-Stratified
Conglomerate (Gct)

Description. Units of Gct are rare in the lower Beaverhead conglomerate. Four units of this lithofacies were recorded; three of these were poorly exposed. Lithofacies Gct consists of trough cross-stratified pebble conglomerate that fines upward and is similar to facies Gch in texture and matrix. Individual troughs appear to be broad, shallow, features up to 1 m deep and have a concave-up erosional base. The largest lateral dimension measured was 1.5 m; however, poor outcrop exposures likely obscured the true dimensions. Trough-filling strata generally appear to conform to the shape of the basal scour surface, but some merge tangentially with the lower bounding surface (Figure 14). Trough-filling strata dip at angles of less than 10° .

Interpretation. Lithofacies Gt is interpreted to represent deposition in shallow channels and bar top scours by migrating gravel sheets during flood and waning flow stages in braided streams (Miall, 1977). Larger channels developed by avulsion during high-stage flow (Miall, 1977) while the smaller channels and scours were produced by waning flow modification of bar surfaces and margins (Williams and Rust, 1969). Stratification parallel to the lower bounding surface of the channels and scours suggests deposition under upper flow regime conditions (Miall, 1977).

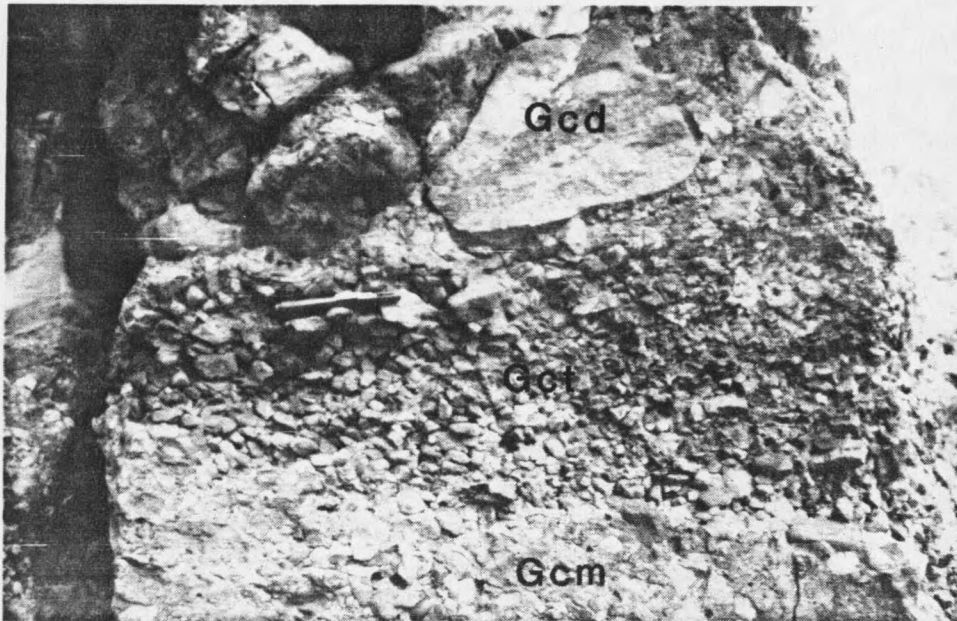


Figure 14. Facies Gct overlain by facies Gcd and underlain by facies Gcm. Pen is 13 cm long.

Sandstone and Mudstone Lithofacies (S/F)

Introduction

Sandstones and mudstones account for approximately 15% of the overall volume of the lower Beaverhead conglomerate. The rarity of these lithofacies suggests low preservation potential during subsequent flood events (Rust, 1984). These fine-grained rocks are most commonly preserved as discontinuous lenses or trough-shaped bodies between or within stacked conglomerate beds. The highest percentage of sandstones and mudstones are found in the lower part of the section where the beds have apparently tabular geometries that extend laterally for approximately 60 m. Basal contacts are

generally sharp and slightly irregular with the sand filling in around the clasts at the top of the underlying conglomerates. Upper bounding surfaces are planar or contain irregularly scoured troughs. Scours are infilled by conglomerates of lithofacies Gcd, Gcm, or Gch. Sandstone and mudstone beds are generally truncated by conglomerates of lithofacies Gcm and Gch. Any combination of the three sandstone lithofacies recorded (Sm, Sh, and Sr) can be found adjacent to each other within a single sandstone unit.

Massive Sandstone (Sm)

Description. Deposits of lithofacies Sm are quite variable ranging from well- to very poorly-sorted, fine- to very coarse-grained quartz-rich sand. In some units, abundant granule- to small cobble-sized clasts are scattered randomly throughout or arranged in stringers or clusters while other units contain only occasional clasts. Clast concentrations vary widely both vertically and horizontally within different parts of the same unit. Sm units generally have lenticular, trough-shaped, or tabular geometries. Beds of Sm range in size from a few centimeters thick by tens of centimeters wide up to 3.5 m thick with a lateral extent of approximately 60 m. The lower bounding surfaces are generally sharp and irregular with clasts from underlying conglomerates extending up into the base of the beds.

Deposits with lenticular or trough-shaped geometries generally are more poorly-sorted and have higher

concentrations of gravel-size clasts. Sand-filled burrows are visible in some of the tabular units near the base of the section. Lithofacies Sm often grades vertically into sandstones of facies Sh. Where it is not capped by other sandstones, beds of Sm are overlain along an irregularly scoured surface by conglomerates.

Interpretation. The presence of sand-filled burrows in some the Sm units indicate that bioturbation is in part responsible for the massive, structureless sandstones. Faint, discontinuous patches of horizontal lamination (Sh) and ripple cross-lamination (Sr) within the sandstones suggest that the massive beds originally contained sedimentary structures. Direct evidence of bioturbation is limited to the tabular sandstones found near the base of the section. Similar sandstones described by DeCelles and others (1987, 1991b) were interpreted to be ephemeral flood deposits on inactive areas of an alluvial fan.

Deposits of lithofacies Sm containing abundant granule to small cobble clasts are interpreted to result from deposition by sandy debris flows or fluidal sediment flows (Nemec and Steel, 1984). In flows of this type, turbulence are considered to be the main particle support mechanism. Stringers of clasts are interpreted to be the result of traction transport along the base of the bed. Waresback and Turbeville (1990) interpreted similar units (their facies Gmsu) in the Plio-Pleistocene Puye Formation of north-central New Mexico to be

the deposits of clast-poor sandy debris flows. DeCelles and others (1991b) interpreted deposits of massive pebbly sands in the Paleocene Beartooth conglomerate of southwest Montana that are similar to facies Sm to be the deposits of sandy mudflows. Wells (1984) suggested that deposits of this nature may have been formed by waning sheetfloods, dewatering of debris flows, or reworking of surficial deposits by sheetwash during storms.

Blatt and others (1980, p. 118) suggest massive bedding of primary origin may result from processes lacking a tractional phase during deposition such as very rapid sedimentation from suspension or deposition from highly concentrated sediment dispersions. Some of the apparently massive sandstones may actually contain sedimentary structures, but the structures are not evident in the outcrops.

Horizontally Laminated Sandstone (Sh)

Description. Lithofacies Sh is a horizontally laminated, fine- to medium-grained, moderately- to well-sorted quartz-rich sand. Facies thickness ranges from a few millimeters to 20 cm and units are generally laterally discontinuous. Thin (<1 cm) interbeds of siltstone are periodically found in the upper parts of the facies. When present, facies Sh is always found overlying sandstones of facies Sm. Units of facies Sh is either conformably overlain by fine-grained sediments of

lithofacies Fl/Fm or conglomerates along a planar or irregularly scoured surface.

Interpretation. The horizontally laminated sandstones of lithofacies Sh are interpreted to have been deposited under upper plane bed conditions during falling stage flow over bar tops or in shallow channels. Harms and others (1975, 1982) note that horizontally laminated sandstones can form under both lower and upper flow regime conditions. Lower flow regime plane beds are limited to sands coarser than that observed (Harms and others, 1982) so this interpretation is rejected. Upper plane bed conditions may be inferred if current or parting lineations are present or if lithofacies Sh is associated with trough cross-stratified sandstones (Harms and others, 1982). Unfortunately, neither of these potentially diagnostic relationships were observed. However, shallow flow in channels or over bar tops during falling stage could maintain upper flow regime conditions favorable for the transport and deposition of fine sand by traction processes (Harms and Fahnestock, 1965). The thin lenticular nature of the Sh sandstones and their association with lithofacies Fl/Fm also suggests shallow flow conditions (DeCelles and others, 1987).

Ripple Cross-laminated
Sand (Sr)

Description. Lithofacies Sr is characterized by ripple cross-laminated, very fine- to fine-grained, moderately- to

well-sorted quartz-rich sand. Units of Sr are laterally very discontinuous and generally 2 to 6 cm thick. This lithofacies is usually found in the upper portions of the same beds containing lithofacies Sm and Sh. Asymmetric ripple crests are preserved only locally. Lithofacies Sr is either overlain by fine-grained sediments of facies Fl/Fm or conglomerates along a planar or irregularly scoured surface.

Interpretation. The ripple cross-laminated sandstones of lithofacies Sr are interpreted to be generated under lower flow regime conditions by the migration of asymmetric ripples across the surfaces of bars or within bar top channels during late stage, shallow waning flow (Harms and Fahnestock, 1965; Miall, 1977). The association of lithofacies Sr with lithofacies Sm suggests occurrences of Sr may have at one time been more prevalent, but were subsequently destroyed by bioturbation.

Fine-Grained Lithofacies (Fm/Fl)

Description. Fine-grained lithofacies include red and brown massive mudstone (Fm) and laminated siltstone and mudstone (Fl). Interbedding of fine-grained sand, silt, and mud on a small scale is common. Bioturbation, small scale ripples and undulatory bedding may be present. Units of this facies may reach up to 0.5 m in thickness in the lower part of the section. Facies Fm/Fl are found either overlying the

sandstone lithofacies or interbedded with them on a small scale.

Interpretation. The siltstone and mudstones of lithofacies Fm/F1 are interpreted to represent deposition of fines from suspension during very low velocity flow conditions in shallow bar top swales, inactive channels, and overbank areas (Miall, 1977).

Volcanogenic Lithofacies (V)

Introduction

Volcanic rocks make up less than 1% of the lower Beaverhead strata. Outcrops of this lithofacies are sparse. Contact relationships with the underlying and overlying Beaverhead strata are uncertain. The basal contact is covered while the upper contact, where it is exposed, appears to be gradational with the overlying sandstones and conglomerates.

Volcanic Rocks (V)

Description. The volcanic rocks form a series of six interbedded units divisible primarily by color. Units range from 0.8 to 1.5 m thick and have apparently tabular geometries. Contacts between units appear to be sharp or slightly gradational. Units are purple, purplish-green to grayish-green, massive to platy or flaggy, fine-grained to aphanitic with phenocrysts of quartz, feldspar, and mafic

fragments. Sedimentary rock fragments of limestone, chert, and sandstone may be present in pods or as individual clasts.

Interpretation. The fine-grained to aphanitic texture of hand samples and the massive to platy or flaggy bedding characteristics of the outcrops suggests the deposits are tuffs. The presence of sedimentary rock fragments suggest that some of the deposits may have been reworked. However, an unequivocal interpretation of the genesis of these deposits is not possible due to the high degree of weathering and limited outcrop extent.

LOWER BEAVERHEAD STRATIGRAPHY

Detailed measurement of the lower Beaverhead section began approximately 21 m above the Lombard/Beaverhead contact. Steep, rugged terrain prevented a careful lithofacies analysis of the basal deposits. However, cursory examination suggest that they were dominated by conglomerates of facies Gcm and Gch. Conglomerate lithofacies make up approximately 85% of the lower Beaverhead conglomerate in the study area (Figure 15). Sandstone (15%) and volcanic rocks (less than 1%) make up volumetrically minor components of the deposits.

The basal conglomerate is overlain by approximately 6 m of volcanic rocks which are in turn overlain by 32 m of interbedded sandstone and mudstone of facies Sm, Sr, and Fm/Fl. The sandstone beds range from 0.5 to 3.5 m thick while the mudstone beds range from less than 0.25 to 0.5 m thick. These interbedded fine-grained units are in turn overlain by 10 m of interbedded sandstone (Sm and Sr) and conglomerate (Gcm and Gcd). The sandstones found in the first 48 m of the measured section account for the vast majority of sandstone in the lower Beaverhead. These lower sandstones have apparent tabular geometries. The remaining approximately 300 m of section is almost completely dominated by conglomerates. Sandstones, primarily Sm, in the remainder of the section are

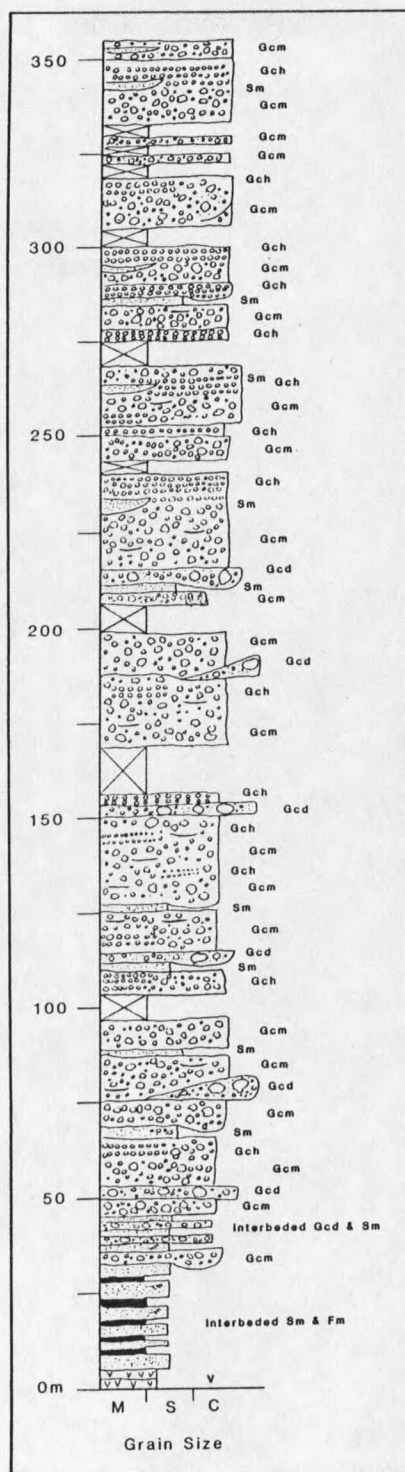


Figure 15. Generalized vertical lithofacies profile of the lower Beaverhead conglomerate. Note the dominance of lithofacies Gcm.

found only as lenses that are often laterally truncated or have scoured upper surfaces.

Conglomerates of lithofacies Gcm are by far the most dominant conglomerate lithofacies found throughout the lower Beaverhead strata. Deposits of lithofacies Gcd, although never prominent, are most often found in the interval from approximately 69 to 220 m above the basal contact. Conglomerates of lithofacies Gch are most prevalent in the interval between 200 and 322 m. This same interval also contains the largest and most abundant sandstone lenses. Lenses may be up to 1.5 m thick and 60 m wide. Deposits of facies Gch are most often present as discontinuous beds less than 1 m thick within amalgamated units of Gcm. Thick units, up to 2 m, have lenticular shapes and fill channels scoured into deposits of facies Gcm or into the tops of sandstone lenses.

DEPOSITIONAL SYSTEMS

The suite of facies present in the lower Beaverhead conglomerate indicates deposition by channelized and nonchannelized high energy alluvial systems. The deposits which characterized these systems include the products of cohesionless debris flows (Gcd), hyperconcentrated flood flow (Gcm), longitudinal bar formation (Gcm and Gch), and waning stage accretion on bar tops and in interbar channels (Gcp, Gct, Sm, Sh, Sr, Fm/Fl) (Plate 1). The facies assemblages present are characteristic of alluvial fans and proximal gravel-bed braided river depositional systems (Hooke, 1967; Bull, 1972; Miall 1977, 1978; Rust, 1978) and are analogous to Rust's (1978) facies assemblages G_I and G_{II} . The facies assemblages present in the lower Beaverhead conglomerate of the study area are interpreted to be the deposits of the proximal portion of a single alluvial fan. This alluvial fan will be referred to as the Grasshopper Creek alluvial fan.

Other observations which support a proximal alluvial fan interpretation are the dominance of conglomerate facies over sandy facies (Boothroyd and Ashley, 1975; Miall, 1977, 1978), presence of deeply incised, vertical walled channels (Haley, 1985) (Figure 16), and locally high degree of clast angularity (Nilsen, 1982). Another characteristic of alluvial fans is the

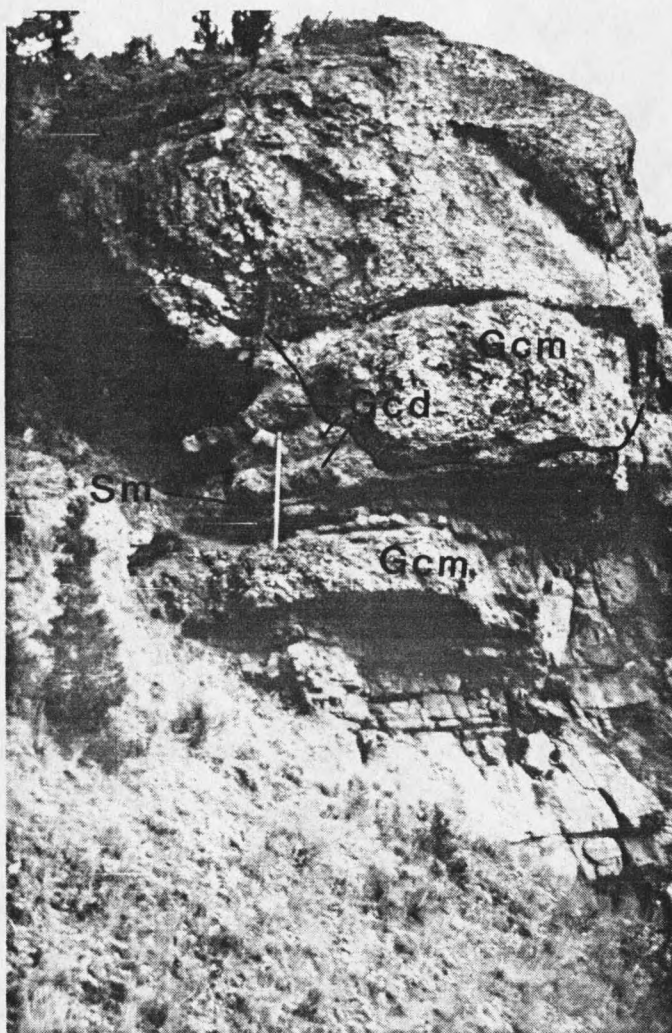


Figure 16. Steep walled channel incised into conglomerates (Gcm and Gcd) and sandstones (Sm). Channel is filled with gravels of facies Gcm and is approximately 2 m deep. Jacob's staff is 1.5 m

relatively rapid downfan decrease in both average and maximum clasts size (Nilsen, 1982). Tracing of the proximal conglomerate deposits into more distal deposits was not possible due to faulting and burial by Upper Cretaceous volcanic rocks. Thus the relationship between grain size and distance from source area is uncertain. This lack of

significant lateral exposure also prevented any documentation of a fan-like distribution of paleocurrents. Nevertheless, the types and distribution of facies present are similar to that reported in other modern and ancient alluvial fan deposits.

Debris flow facies are characteristic of deposits found on the proximal part of alluvial fans (Hooke, 1967; Bull, 1972; Harvey, 1984). The development of debris flows is favored in areas where abundant loose debris is temporarily stored in the source drainage basin and subject to short periods of intense rainfall (Blissenbach, 1954; Bull, 1972; Blair and McPherson, 1992). Thus, the proximal portions of fans developed in semiarid regions should be dominated by debris flow deposition (Blissenbach, 1954; Bull, 1972). Graham and others (1986) have suggested that during the Late Cretaceous the climate in southwestern Montana was seasonally temperate. If this is true, debris flow deposits appear to be under represented in the lower Beaverhead conglomerate.

The relative paucity of debris flow deposits may have several explanations. Blair (1987a) and Blair and McPherson (1992) showed that post depositional events on fan surfaces may completely obscure evidence of the depositional process primarily responsible for fan formation. Blair and McPherson (1992) showed that gravel deposits previously interpreted by Hooke (1967) to be of fluvial origin are actually the result of post-depositional winnowing of fines from debris flow deposits. The localized areas in some massive conglomerates

(Gcm) that contain "outsized" clasts in a poorly sorted matrix suggests some of these deposits may have a debris flow origin. If so, debris flows may have been a more important process in delivering sediment to the fan than is suggested by the volume of their preserved deposits. Alternatively, uplift of the source area may have led to cannibalization of the most proximal portions of the fan and the reworking and redistribution of gravels initially deposited by debris flows to medial or distal portions of the fan.

Conglomerates of facies Gcm and Gch were deposited on the surface of the fan by hyperconcentrated flood flow and proximal gravel-bed braided stream flow processes (Miall, 1978; Rust, 1978; Ballance, 1984; Harvey, 1984; Wells, 1984). Hyperconcentrated flood flow sediments (facies Gcm) were deposited when high concentration flood flows within fluvial channels spread out over the fan surface. Deposition was probably caused by a widening of the flow due to loss of confinement and a concurrent decrease in depth and velocity of flow (Bull, 1972).

Deposits of facies Gch and some deposits of facies Gcm are interpreted to represent longitudinal bars formed in the proximal portion of a braided gravel-bed fluvial system on the fan surface (Rust, 1978; Miall, 1978). The dominance of massive (Gcm) and horizontally stratified (Gch) gravels to the almost total exclusion of cross-bedded gravels (Gct) supports

the interpretation that deposition took place in the proximal reaches of the system (Rust, 1978).

Interbedded sandstones and mudstones with tabular geometries found near the base of the Beaverhead strata were deposited on the fan surface by ephemeral sheet floods outside of areas subject to active channel migration and scouring (Heward, 1978; Mack and Rasmussen, 1984; DeCelles and others, 1987). Evidence of bioturbation indicates deposition in these area was sporadic enough to allow for colonization of the deposits by burrowing organisms.

One of the most salient features of the lower Beaverhead conglomerate in the study area is a very large channel-shaped structure incised into deposits of conglomerate and sandstones approximately 249 m above the Lombard/Beaverhead contact (Figure 17). This structure is approximately 200 m across and 20 m deep and has a highly erosive lower bounding surface with up to several meters of relief. The deposits within this structure consist of interbedded conglomerate and sandstone of facies Gcm, Gch, Sm, and Sr. This facies association is interpreted to represent deposits of a gravelly braided stream system. Based on the size, geometry and internal lithofacies association, this structure is interpreted to be a major fanhead trench that was incised into the fan surface and subsequently backfilled. Fanhead trenches of similar size and geometry have been described on modern fans by Bull (1964) and Lustig (1965). Decelles and others (1991b) described a similar

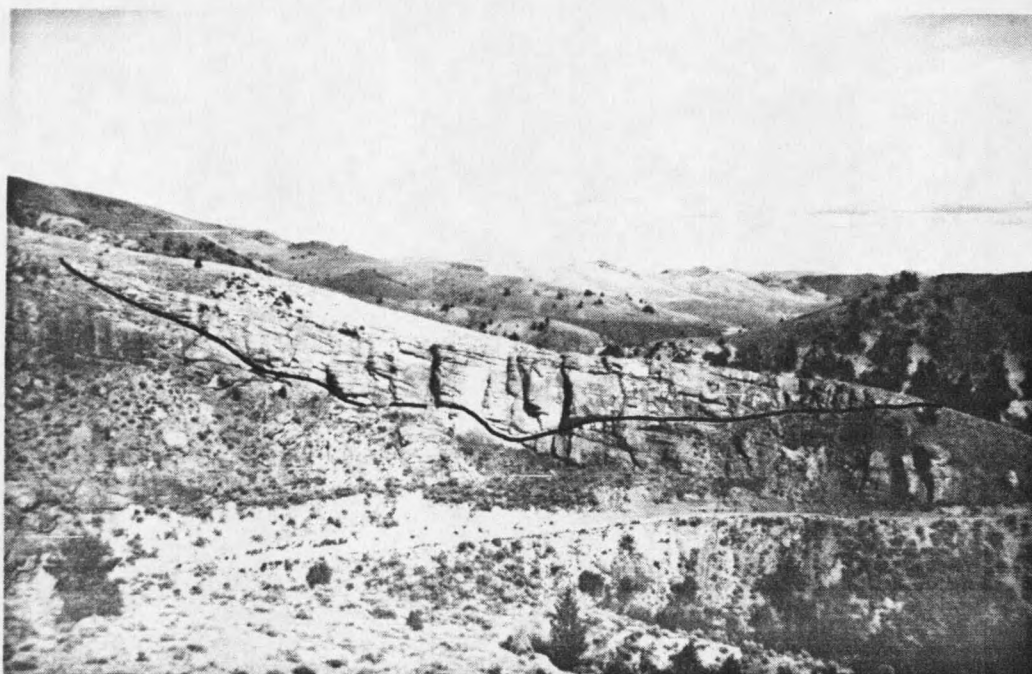


Figure 17. Large channel incised into deposits of conglomerate and sandstone. Channel is filled with conglomerates and sandstones of facies Gcm, Gch, Sm and Sr. Channel is approximately 200 m across and 20 m deep. View is S75E.

lithofacies association backfilling what they interpreted as major fanhead trenches in the Paleocene Beartooth conglomerate of Montana and Wyoming.

The conglomerates and sandstones within the channel differ from those stratigraphically above and below the channel in several respects. Conglomerate units within the channel are generally less than 1 m thick while the sandstone units are generally less than 5 cm thick and laterally discontinuous. There also appears to be a higher ratio of sand to gravel in channel deposits. Additionally, conglomerate

clasts were sourced exclusively from Mississippian formations and the sandstones are dominated by carbonate lithic fragments. The modal composition of the conglomerates and sandstones within the channel indicate that at the time the channel floor was aggrading a very restricted range of formations in the source area was supplying detritus to the fan in comparison to deposits stratigraphically above and below the channel.

The presence of the channel along with the distinctive petrological make up of its deposits offer valuable insight into the tectono-sedimentary evolution of the Grasshopper Creek alluvial fan and its source area. These topics are examined in following sections.

The volcanic rocks were deposited on the surface of the fan as tuffs soon after the commencement of fan sedimentation. The presence of pods of limestone-clast conglomerate with a volcanoclastic sand matrix within parts of the volcanic sequence suggests the volcanic rocks have been reworked by surficial processes. Alternatively, the deposits may be the result of unwelded ash-flows which picked up clasts as they flowed across the fan surface.

PALEOCURRENTS

Paleocurrent interpretations are based on clast imbrication measurements collected from massive (Gcm) and horizontally stratified (Gch) conglomerates. Due to the paucity of elongated or platy clasts with three-dimensional exposure suitable for measuring imbrication, interpretations of paleocurrents are based on measurements of 54 clasts from three locations (Figure 18). In addition, the orientations of two scour-and-fill structures from the base of a massive conglomerate (Gcm) bed were also used to assess paleocurrent direction.

Clast imbrications indicate that sediment transport within the alluvial fan system was to the southeast. Vector means range from 124 degrees to 189 degrees. The two scour-and-fill structures have a vector mean of 105 degrees. The composite vector mean for all paleocurrent data is 133 degrees.

A southeasterly paleoflow direction agrees with a qualitative estimate of paleocurrent direction based on observations of apparent clast imbrication within outcrops that were unsuitable for direct measurement of imbrication. The inferred paleocurrent direction is approximately normal to both the trend of Beaverhead outcrops within the study area

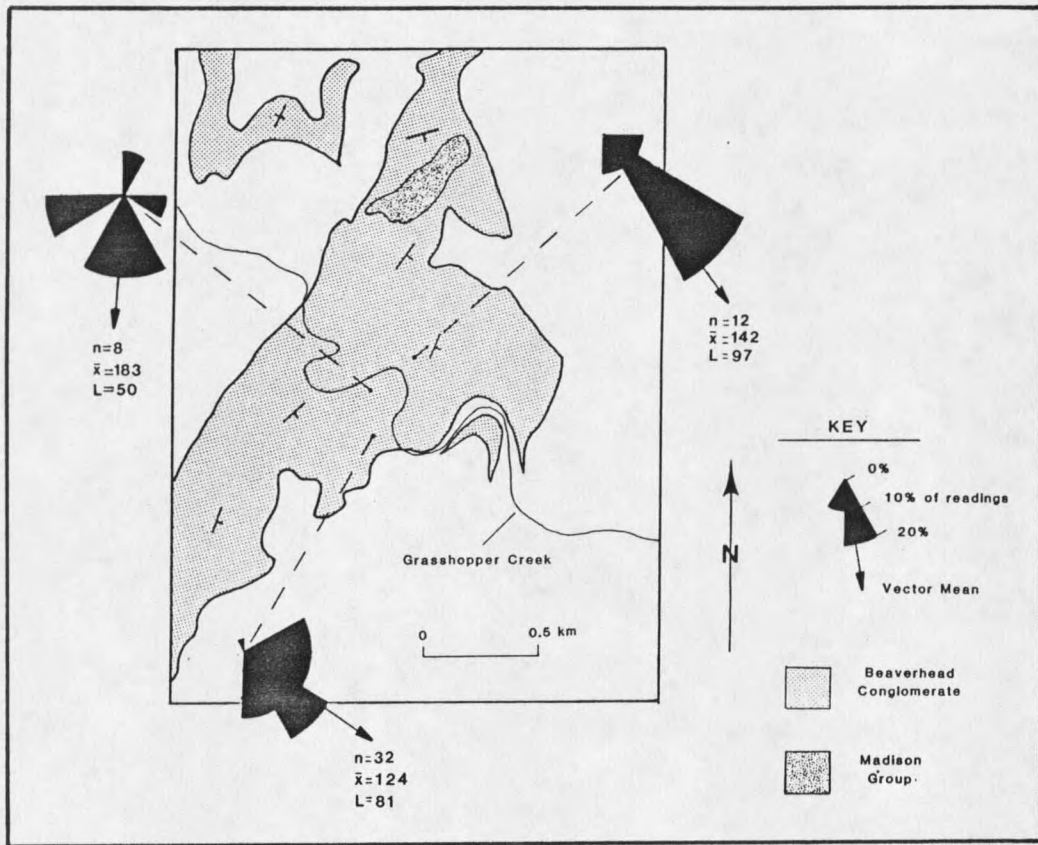


Figure 18. Rose diagrams showing paleocurrent measurements from imbricated clasts in conglomerates. Symbols are as follows; n is the number of measurements at each location, $\bar{x}$ is the vector mean expressed in degrees, and L is the length of the resultant vector expressed as a percentage of readings.

and the trend of the Ermont thrust north of Grasshopper Creek as mapped by Thomas (1981).

PETROGRAPHY

Conglomerate

Texture

Coarse-grained units of the Beaverhead Group in the study area are composed of clast-supported pebble/cobble conglomerate dominated by limestone clasts with minor chert and sandstone components. Boulder size clasts are present, but boulder conglomerates are rare. Clasts are angular to rounded and generally tend to be equidimensional.

Composition

Limestone Clasts. Limestone clasts are composed of micrite, silty micrite, sparite, and biosparite. Colors include dark blue-gray, light-gray, yellowish-gray, yellowish-brown, and brown. Clast size ranges from granule to boulder. Nodules and ribbons of dark gray to black chert are present in some of the larger limestone clasts. Fossils identified in hand samples include echinoderm fragments, brachiopods, bryozoans, rugose corals and pelecypods. Dolomite clasts are not present.

The most unique limestone lithology present is a red silt-bearing limestone breccia which occurs very rarely. Only one clast of this type was recorded. The constituent

components within this large cobble-size clast are angular to subrounded, granular- to pebble-size intraclasts of micrite, biomicrite, biosparite, and limestone and chert breccia. Fragments of crinoid stems are the most abundant fossils present within the intraclasts. Chert fragments within the intraclastic breccias are black.

Chert Clasts. Chert clasts range in color from black, to dark-gray, light-gray, red, butterscotch, and brown. Clasts range in size from granules to large pebbles. Small cobble-size clasts are present locally, but are rare. In many cases an individual clast will have both smooth and jagged surfaces giving the impression the clast is a fragment of a larger, rounded pebble or cobble that was fractured during transport.

Sandstone Clasts. Sandstone-clast composition ranges from pure quartzarenite to chert litharenite. Clasts range in color from white to tan, pink, or red, and may be either silica or calcite cemented. Clast size ranges from pebble to boulder.

Silica-cemented sandstones account for approximately 20% of the sandstone clasts identified. These sandstones are compositionally mature, white to gray, fine-grained, very well-sorted quartz arenites. Quartz grains are rounded to well-rounded and vitreous. Thin bands of hematite staining are locally present. Some of these quartz arenites may contain up

to a few percent lithic fragments composed primarily of dark chert grains.

The remaining sandstone clasts are calcite cemented and show more variation in color, grain size, and composition. These clasts are white, gray, pink, red, or red with black speckles. Hematite staining gives red and pink colors while dark lithic grains produce the speckled appearance. Eighty percent of these sandstone clasts are very fine- to fine-grained and well- to very well-sorted. The remaining clasts are medium- to very coarse-grained and moderately to well-sorted. In hand sample these sandstone clasts range in composition from quartz arenite to chert litharenite. Lithic grains are predominately black, gray, or brown chert with lesser amounts of unidentifiable lithic fragments and possibly glauconite. Other clasts identified in trace amounts include silica cemented, chert granule conglomerate and gray to white metaquartzarenite. Clasts of chert conglomerate are moderately- to well-sorted with rounded to well-rounded granule to small pebble size clasts of chert set in a silica cemented quartz sand matrix. Chert clasts are black, cloudy-white, cloudy-gray, and red in color. Metaquartzarenite clasts are fine- to very fine-grained, very well-sorted and may contain bands of hematite staining. Individual clast have both smooth and jagged surfaces giving the impression the clast is a fragment of a larger, rounded pebble or cobble that was fractured during transport.

Modal Composition

To determine the modal composition of the conglomerates the composition of 2,986 large pebble to cobble size clasts were recorded during clast counts (Figure 19) (Appendix A). The conglomerates are dominated by limestone (91.1%) with lesser amounts of chert (7.4%) and sandstone (1.5%). Of the sandstones clasts, 80% are calcite cemented.

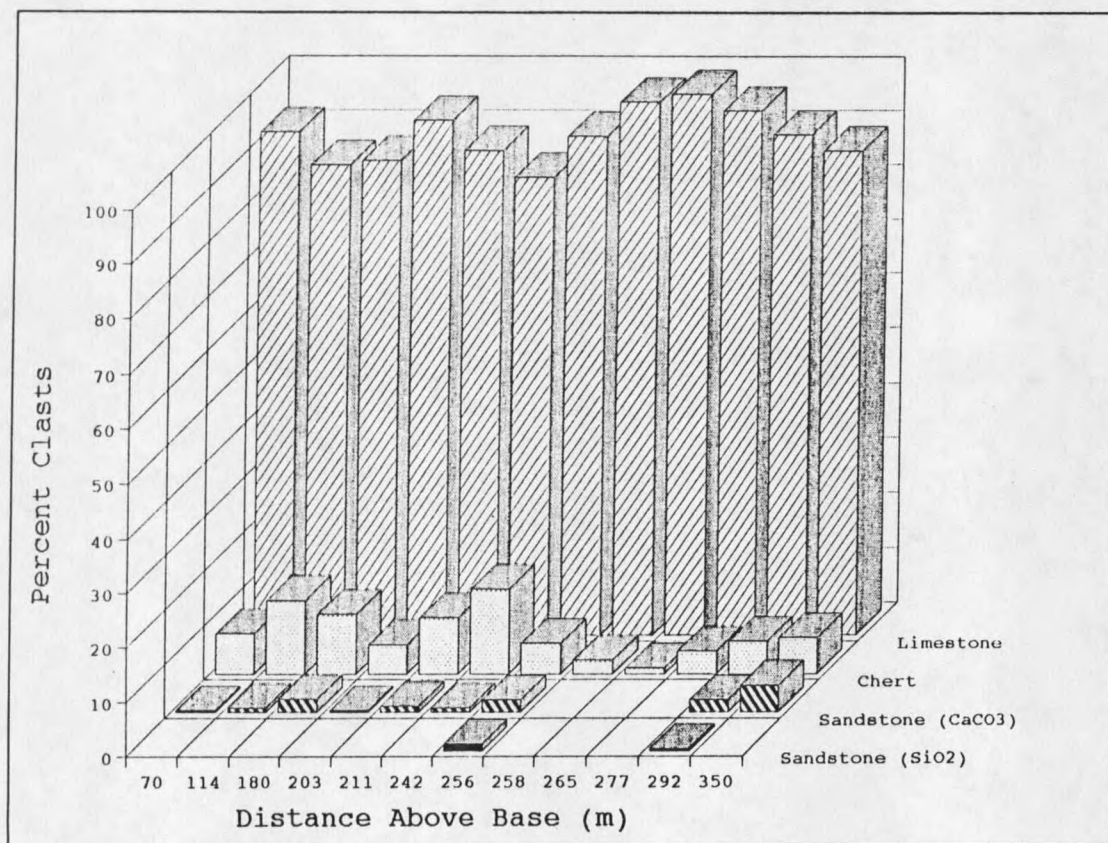


Figure 19. Modal percentage of conglomerate clasts at each clast count location. CaCO₃=calcite cemented, SiO₂=silica cemented.

SandstoneTexture

Sandstones from the lower Beaverhead conglomerate are textually submature to mature based on the criteria of Pettijohn and others (1987, p. 523). Sandstones range from very fine- to very coarse-grained and well-sorted to very poorly-sorted. Framework grains are angular to rounded. Grain to grain contacts are primarily tangential to long. Cement is fine-grained anhedral sparry calcite with minor hematite.

Composition

Sandstone modal composition was determined by point counting. Primary framework grains include monocrystalline quartz (Qm), polycrystalline quartz (Qp), and lithic fragments (L). Framework grains were identified and described based on the criteria of Pettijohn and others (1987, p. 29-48). Modal analysis data are presented in Appendix B.

Monocrystalline Quartz (Qm). Monocrystalline quartz grains are characteristically angular to rounded, fine- to medium-grained and exhibit straight to slightly undulose extinction. A small percentage (less than 5%) of grains exhibit very strong undulatory extinction. Abraded quartz overgrowths are present on approximately 4% of the grains. Microlites (zircons) are present in some grains.

Polycrystalline Quartz (Op). Framework grains of polycrystalline quartz are dominated by fine- to coarse-grained, very angular to subrounded chert (86%). Chert varieties include inclusion free, specular, silty, phosphatic, reddish hued (jasper) and chalcedonic chert. Many of the chert grains contain small blebs of calcite interpreted to represent incomplete replacement of limestone by silica. Relic unidentifiable silicified fossil fragments are present in some grains. Composite quartz grains composed of a coarse interlocking mosaic of crystals with slightly sutured boundaries make up the remaining polycrystalline quartz.

Lithic Fragments. Carbonate grains of micrite, biomicrite, and sparite make up 95% of the sedimentary lithic fragments present. Carbonate grains are very fine- to very coarse-grained sand and are subangular to rounded. Approximately 30% to 50% of the carbonate grains have hematite coatings. The remaining sedimentary lithic fragments are composed of very fine-grained sandstone or siltstone cemented by either calcite, hematite, and/or clay(?).

Sandstone Petrofacies

To petrologically classify the sandstones, modal composition data were plotted on ternary diagrams (Folk, 1980, p. 127) (Figure 20A). These ternary plots show that the Beaverhead sandstones can be classified as litharenites and sublitharenites. Under Folk's (1980) classification, chert is

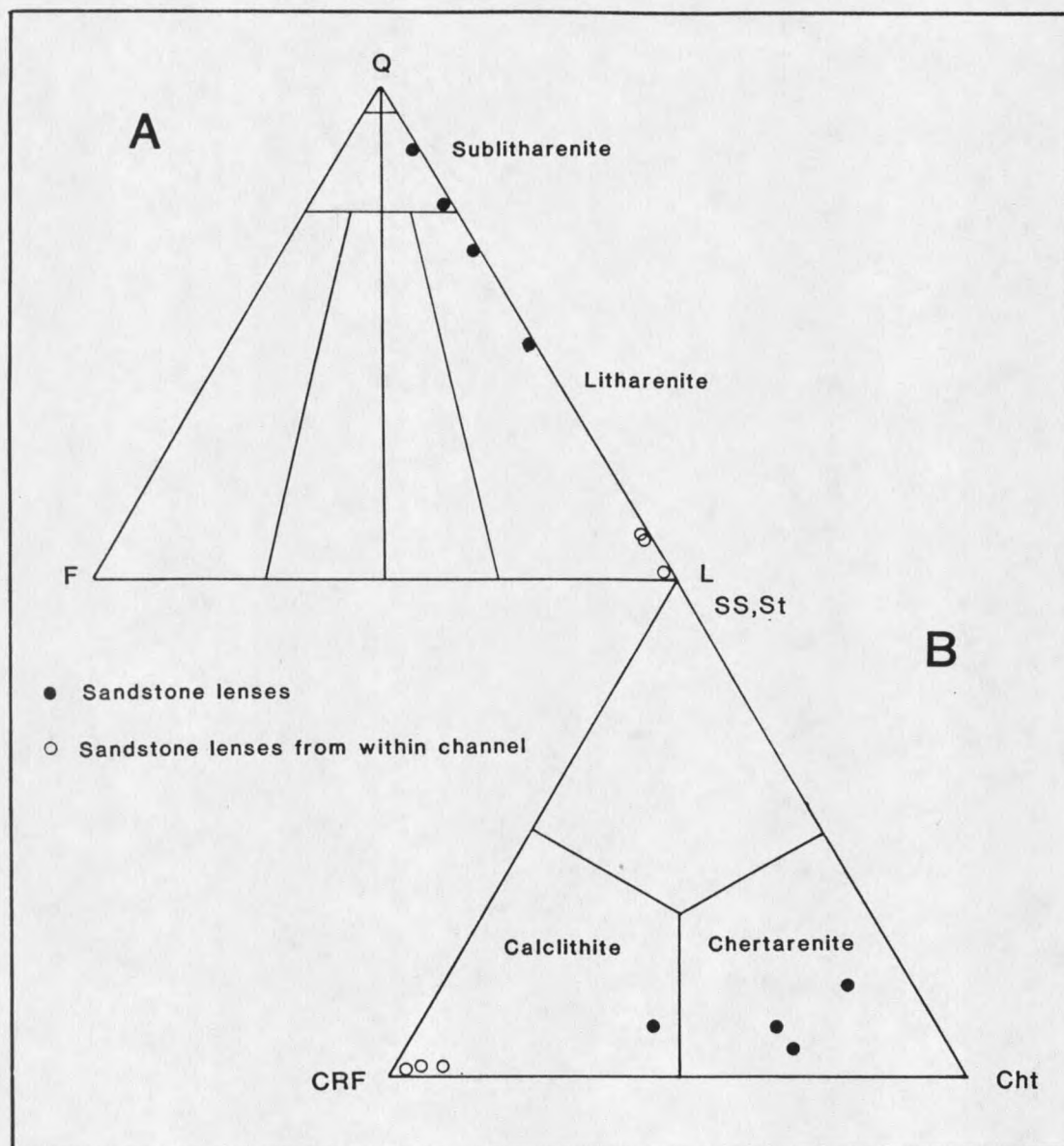


Figure 20. Compositional ternary diagrams of Beaverhead sandstones in study area. Modal percentage of lithic components from diagram A are replotted in diagram B. Q=monocrystalline quartz; F=feldspar; L=lithic fragments including chert; SS, St=sandstone and siltstone; CRF=carbonate rock fragments; Cht=chert. After Folk (1980, p. 127).

plotted at the lithic fragment pole. The litharenites show a wide variation in the amount of monocrystalline quartz ($Q=2-67\%$) and lithic fragments ($L=33-98\%$) present. The sublitharenites are dominated by monocrystalline quartz ($Q=76-88\%$) with the remaining framework grains composed of lithic fragments ($L=12-24\%$). Based on the modal composition of the lithic component, the sandstones can be divided into two distinct petrofacies: chertarenites and calclithites (Figure 20B).

Chertarenites. In the chertarenites, the quartz content varies between 67-88% while the lithic component varies between 12-33% (Figure 21). The lithic components are divided

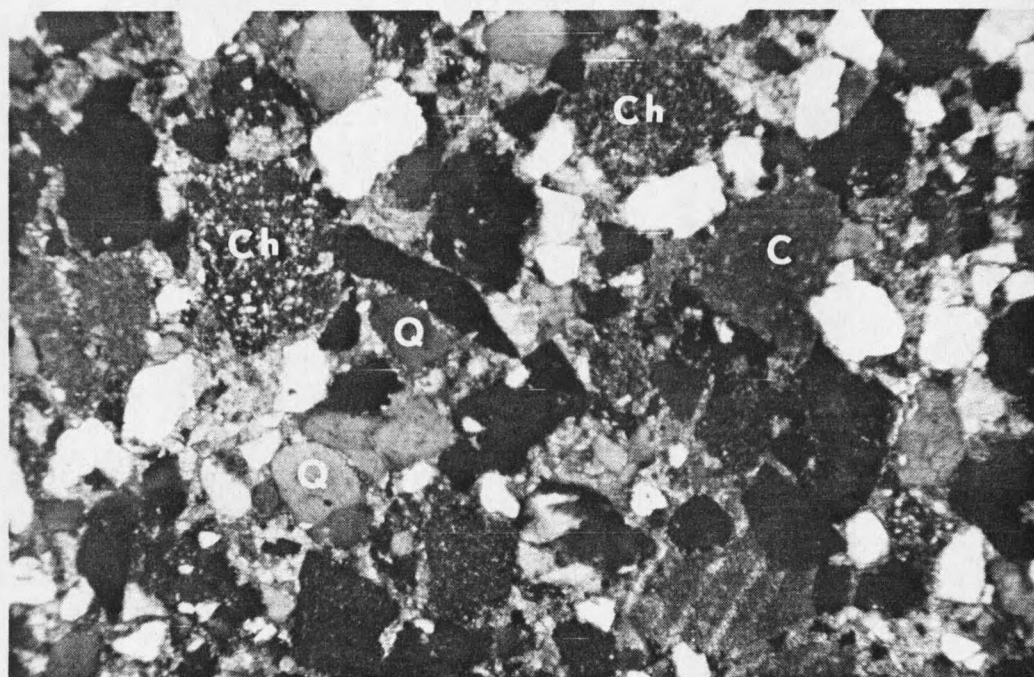


Figure 21. Photomicrograph of chertarenite from the lower Beaverhead conglomerate. Q =Quartz; Ch =Chert; C =Carbonate lithic fragment. Sample No. NG02/10A. Crossed nicols, 40x.

into chert (Cht=55-61%), carbonate rock fragments (CRF=20-35%), and fragments of siltstone to very fine-grained sandstone (SS,St=8-19%). Sandstones of this petrofacies are found in the lower half of the lower Beaverhead conglomerate section.

Calclithites. In the calclithite petrofacies, between 51-98% of the modal composition is composed of sedimentary lithic fragments. The lithic component is dominated by carbonate rock fragments (CRF=57-98%) with the remainder composed of chert (Cht=2-32%) and fragments of siltstone to very fine-grained sandstone (SS,St=0-11%) (Figure 22). The quartz component varies between 2-49%. Sandstones of this

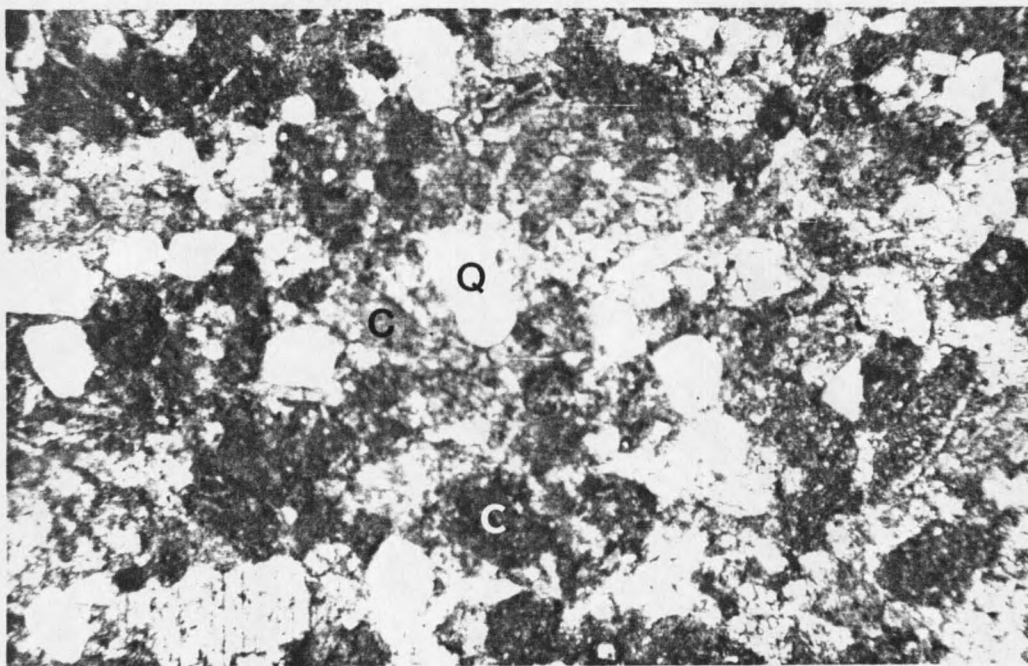


Figure 22. Photomicrograph of calclithite from within the large channel. Q=Quartz; C=Carbonate lithic fragment. Sample No. CH1/01. Uncrossed nicols, 40x.

petrofacies are found within the large channel and in Beaverhead strata stratigraphically above the channel.

Volcanic Rocks

The volcanic rock units are composed of unwelded crystal tuffs, vitric tuffs, and crystal vitric tuffs of rhyolitic to dacitic composition. Phenocrysts are primarily plagioclase feldspar with lesser sanidine and minor quartz. Fragments of unidentifiable mafic and opaque minerals are also present.

The crystal tuffs are characterized by broken and highly altered grains of plagioclase feldspar and sanidine. The feldspars have been replaced by calcite and clay. Any glass that may have been present in the groundmass has been completely altered to clay.

In the vitric tuffs, easily identifiable curved and Y-shaped glass shards have been replaced by silica, clay, and calcite (Figure 23). Broken phenocrysts of plagioclase and sanidine have been partially replaced by calcite and clay. Lithic fragments of glassy volcanic rocks have been completely silicified.

The crystal vitric tuffs are characterized by broken and altered grains of plagioclase and sanidine in a matrix of devitrified glass shards. The feldspars have been replaced to varying degrees by calcite and clay. Glass shards have been replaced by calcite, clay, and silica. Glassy volcanic rock fragments have been replaced by silica and clay.

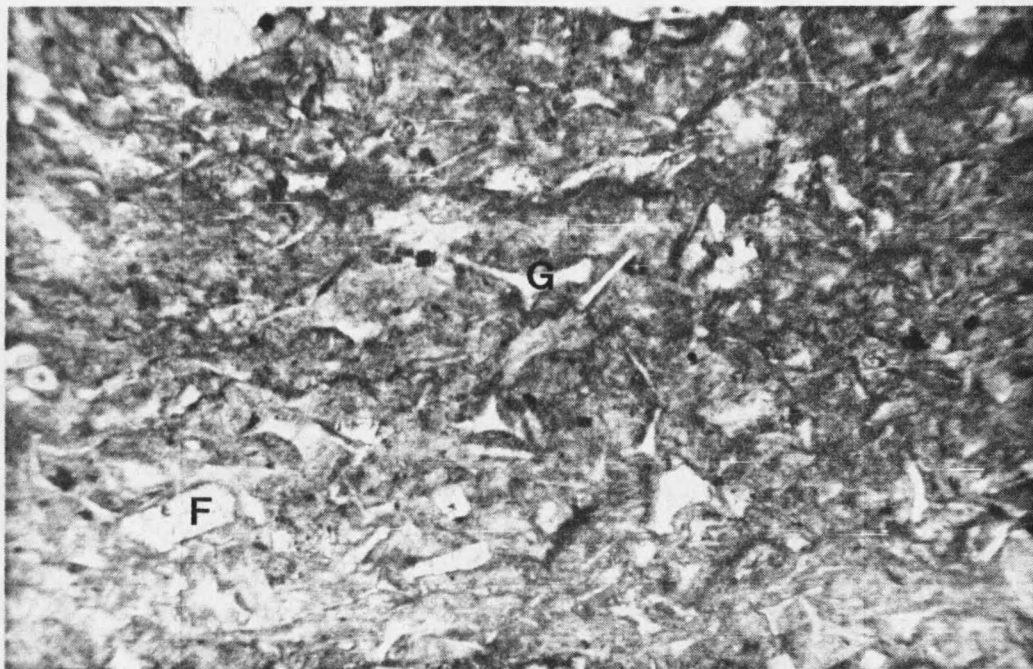


Figure 23. Photomicrograph of vitric tuff from deposits in the lower Beaverhead conglomerate. G=Glass shard; F=Feldspar. Sample from volcanic unit D. Uncrossed nicols, 40x.

PROVENANCE

Results of paleocurrent analysis indicate that the fluvial systems which deposited the lower Beaverhead conglomerate in the study area had a generally northwest to southeast paleoflow direction. The alluvial fan interpretation for these deposits suggests that the source area flanked the basin of deposition.

Results of conglomerate clast counts demonstrate that the source area for the lower Beaverhead conglomerate in the study area was dominated by Upper Paleozoic and Lower Mesozoic sedimentary rocks. Evidence that Lower Paleozoic formations were not exposed during Beaverhead deposition includes the absence of Devonian and Cambrian dolomite clasts as well as the absence of pebbly quartz arenite clasts of the Cambrian Flathead Formation. Table 3 lists the names and ages of formations that may have been exposed in the source area and thus contributed the clast lithologies recognized.

Due to the lithologic similarity of many of the formations present in the source area, it is not always possible to relate every clast identified in the Beaverhead back to a particular formation. However, in some cases the probable source can be narrowed to one or two formations on the basis of lithology and color of hand samples.

Table 3. Formation names and ages for clast lithologies recognized in the lower Beaverhead conglomerate in the study area.

FORMATION	AGE	LIMESTONE	CHERT	SANDSTONE
Kootenai	K	X	X	X
Thaynes	Tr	X		
Dinwoody		X		
Phosphoria	P	X	X	X
Quadrant	Pen			X
Conover Ranch		X		
Lombard	M	X	X	
Kibbey				X
Mission Canyon		X	X	
Lodgepole		X	X	

Clasts of dense, dark blue-gray micrite were probably sourced from the Mississippian Lodgepole Formation (Table 4). Light-gray echinoderm biosparites may have been sourced from either the Mississippian Mission Canyon or Lodgepole Formations. These clasts are characterized by a dense packing of echinoderm fragments cemented by large crystals of sparite. The clast of limestone breccia can be linked back to a 20 m thick breccia zone at the top of the Mission Canyon Formation (Goodhue, 1986). Yellow-gray, grayish-orange to pale yellowish-brown fossiliferous micrites and biomicrites were probably derived from the Mississippian Lombard Limestone. Where present, fragments of small horn corals, brachiopods, bryozoan, and echinoderm fossils weather out in relief. Pale-

brown to pale-red silty to sandy biomicrites were sourced from the Mississippian Conover Ranch Formation. Pale-brown to chocolate-brown pelycypod biomicrites are characteristic of the upper part of the Triassic Dinwoody Formation. These clast often display undulatory bedding surfaces formed from numerous depressions of pelycypod shells.

Clasts of black chert and limestone clasts containing nodules or stringers of black chert may have been derived from either the Lodgepole or Mission Canyon Formations. Pink, red, or white chert was attributed to the Mission Canyon Formation (Clark, 1986; Goodhue, 1986). Brown to butterscotch chert is characteristic of the Permian Phosphoria Formation (Clark, 1986; Goodhue, 1986).

Fine- to medium-grained, mature, silica cemented quartz arenites are identical to clasts from the Pennsylvanian Quadrant Formation. Sandstones rich in black chert fragments were probably sourced from the Cretaceous Kootenai Formation. Clasts of granular chert conglomerate and gray metaquartzarenite are very similar to clast seen in outcrops of the Kootenai Formation in the Armstead Hills.

As mentioned previously, a single Beaverhead conglomerate sample was thin-sectioned to determine the fine-grained component of the conglomerate matrix. Some of the gravel-size clast present in this sample can be linked back to probable source formations based on the work of Goodhue (1986). Foraminiferal biomicrites seen in this sample were probably

Table 4. Probable source formations for unique clast lithologies recognized in hand samples and thin-section.

LITHOLOGY	FORMATION
<u>Limestone</u>	
Dark blue-gray micrite	Lodgepole
Light-gray echinoderm biosparite	Mission Canyon; Lodgepole
Foraminiferal biomicrites	Lombard
Yellow-gray to grayish-orange fossiliferous micrites and biomicrite	Lombard
Yellow-brown to pale-red silty to sandy biomicrite	Conover Ranch
Pale-brown to chocolate-brown pelycypod biomicrite	Dinwoody
<u>Chert</u>	
Black	Lodgepole; Mission Canyon
Pink, red, white	Mission Canyon
Brown, butterscotch	Phosphoria
Clear, inclusion free	Lodgepole; Mission Canyon
Silty, phosphatic, or glauconitic	Phosphoria
<u>Sandstone</u>	
Fine- to medium-grained, mature, silica cemented quartz arenite	Quadrant
Chert arenite with abundant black chert	Kootenai
<u>Other</u>	
Granular chert conglomerate	Kootenai
Grey metaquartzite	Kootenai
Limestone breccia	Mission Canyon
Calcareous siltstone/	Dinwoody; Conover Ranch

sourced from the Mississippian Lombard Formation (Figure 24). Clear, inclusion free chert may have been sourced from either the Mississippian Mission Canyon or Lodgepole Formations. Silty, phosphatic, or glauconitic chert can be link back to the Permian Phosphoria Formation. Calcareous siltstones present in the conglomerate thin-section may have been derived from either the Conover Ranch or Dinwoody Formations.

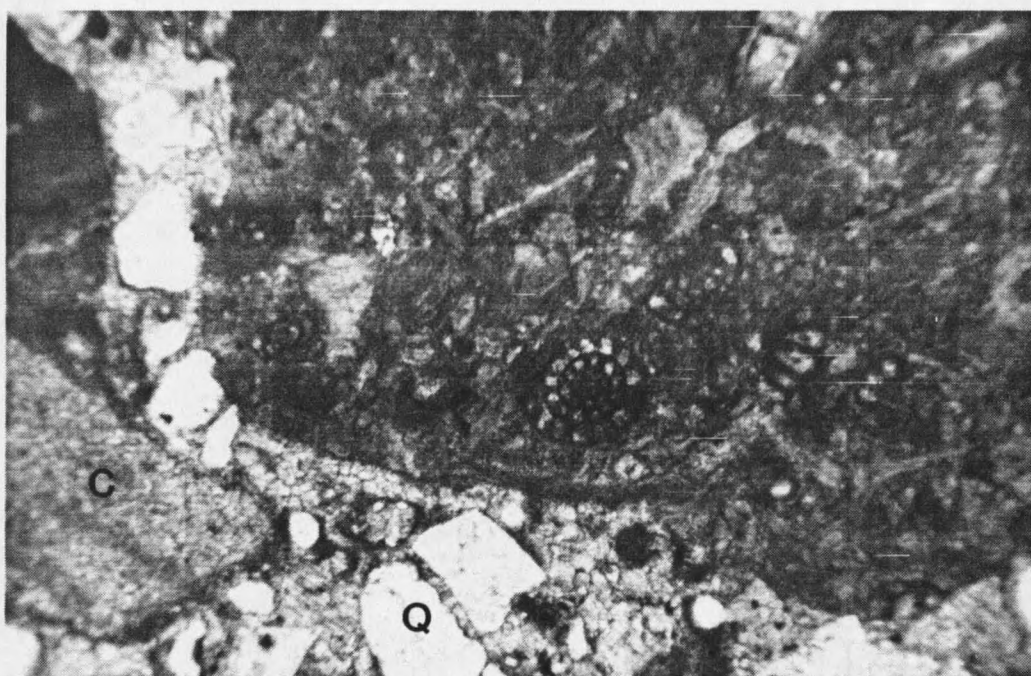


Figure 24. Photomicrograph of lower Beaverhead conglomerate matrix sample. Largest grain is a foraminiferal biomicrite that was probably derived from the Mississippian Lombard Formation. Other grains include quartz (Q), and a carbonate lithic fragment (C) of unknown origin. Uncrossed nicols, 40x.

Quartz sand grains observed in thin-sections of Beaverhead sandstones show several characteristics which suggest they have been reworked from Upper Paleozoic

sandstones. Rounded, fine- to medium-grained quartz sand grains with abraded overgrowths and straight to slightly undulose extinction were likely derived from the Pennsylvanian Quadrant Formation (Goodhue, 1986). Very fine sand to silt size quartz grains with undulatory extinction may have been derived from the Pennsylvanian Quadrant Formation or the Shedhorn Sandstone member of the Permian Phosphoria Formation (Goodhue, 1986).

In addition to recording clast lithology, an attempt was made to identify the oldest and youngest formations represented by clasts at each clast count location. Data of this type provide insight into the range of formations exposed in the source area without the difficulty of trying to associate every clast with a specific formation. This method is especially useful when clast identifications on the formational level are uncertain because gravel-yielding lithologies of different stratigraphic units may closely resemble each other (DeCelles, 1988; Pivnik, 1990).

Throughout deposition of the Beaverhead strata measured, the range of formations exposed in the source area remained fairly constant. Upper Paleozoic limestones of the Mississippian Madison Group (Lodgepole and Mission Canyon Formations) are consistently the oldest clasts present. In the lower part of the section, the youngest clasts are Mesozoic in age and are either sandstones of the Cretaceous Kootenai Formation or limestones of the Triassic Dinwoody Formation. In

the stratigraphically higher parts of the section no Kootenai clasts were identified and there was a noticeable decrease in the percentage of clasts identified as Dinwoody.

Clast count data collected from deposits within the large channel (258 and 265 meters above the base) show a significant divergence from clast count data collected elsewhere in the lower Beaverhead section. Data collected from these deposits suggest that during the time interval of channel back filling, the range of formations exposed in the source area was limited to the Early Mississippian Lodgepole through Late Mississippian Lombard Formations (Figure 20).

The results of the clast count data suggest that a crudely developed inverted clast stratigraphy may be present in the lower Beaverhead conglomerate. The unroofing sequence is defined by the disappearance of Cretaceous Kootenai clasts and a decrease in the percentage of Triassic Dinwoody clasts observed in stratigraphically higher portions of the section. Steidtmann and Schmitt (1988) suggest that the absence of a well defined unroofing sequence may be characteristic of proximal synorogenic deposits developed in thin-skinned thrust fault environments. The restricted range of formations providing detritus during channel back filling is probably related to the tectonic evolution of the source area and the fan itself as will be discussed in the next section.

When Beaverhead sandstone modal composition data are plotted on the QmFLt ternary diagram of Dickinson and others

(1983) they fall in the recycled orogen provenance field (Figure 25). The calcilithites from within the channel cluster together near the Lt pole while the chertarenites from stratigraphically below the channel plot along a line near the Qm pole. Within recycled orogens, sediment sources are primarily sedimentary strata exposed to erosion by uplift in fold-thrust belts (Dickinson and others, 1983). The composition of the Beaverhead sandstones is similar to other suites of sandstones derived from thin-skinned thrust

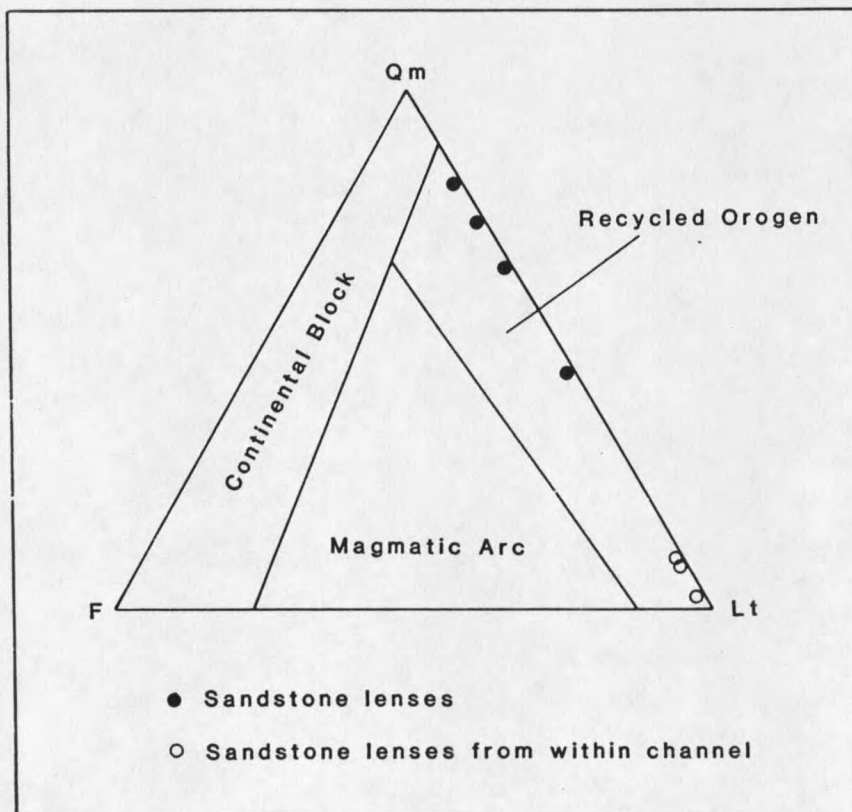


Figure 25. QmFLt ternary diagram of Beaverhead sandstones. Qm=monocrystalline quartz; F=feldspar; Lt=total lithic fragments including chert. After Dickinson and others (1983).

terrain in western North America (Dickinson and others, 1983). The one sandstone sample stratigraphically above the channel plots between the other two groups.

Immediately to the north and south of the study area, silica cemented sandstones of the Pennsylvanian Quadrant Formation form highly resistant tree covered ridges with blocky talus slopes. However, Quadrant clasts appear to be under represented in the lower Beaverhead conglomerate of the study area. Less than 1% of the total clasts counted could be assigned a Quadrant origin. One way to explain the paucity of Quadrant clasts is through the disaggregation of Quadrant clasts eroded from the source area prior to final deposition. Ryder (1968) and Corner (1992) also noted a scarcity of Quadrant clasts in strata of the Beaverhead conglomerate near Dell and Lima, Montana. These workers concluded that the Quadrant Formation is now represented by quartz grains in the Beaverhead sandstones. These studies along with the present one suggest that the paucity of Quadrant gravel is characteristic of the Beaverhead in southwest Montana and controlled by the weathering characteristics of the sandstone.

The volcanic rocks probably represent a very early eruptive phase of the magmatic system associated with the Grasshopper Creek tuffs and Cold Spring Creek volcanics. These upper Cretaceous volcanic rocks, which form the middle member of the Beaverhead Group in the Bannack area, were investigated by Ivy (1989). She hypothesized that the Cold Spring Creek

volcanic rocks represent the eruptive equivalents of the Pioneer batholith while the Grasshopper Creek tuffs represent an early stage of magma infiltration into the upper crust. The eruptive history of the Cold Springs Creek volcanics and their relationship to the cogenetic Pioneer batholith closely parallels that of the Elkhorn Mountain volcanics and Boulder batholith. These two groups of rocks are similar in age and composition (Ivy, 1989). Although the Cold Spring Creek volcanics and Elkhorn Mountain volcanics were probably not erupted from the same volcanic center, they are both members of a broad Late Cretaceous volcanic front in southwestern Montana and Idaho (Ivy, 1989).

SYNTECTONIC UNCONFORMITIES

The Beaverhead strata along Grasshopper Creek are deformed into what has been interpreted by some authors to be a large synclinal fold (Thomas, 1981; Johnson, 1986; Johnson and Sears, 1988). The structure is best exposed on the south side of Grasshopper Creek where the dip of the strata change from steeply dipping near the basal contact to almost horizontal within a distance of less than 0.75 km (Figure 26; Plate 2). Previous workers (Thomas, 1981; Johnson, 1986; Johnson and Sears, 1988) have attributed the folding to movement on the Ermont thrust which is thought to have deformed the strata when the Beaverhead was overridden by the thrust. An alternate interpretation is proposed here. The structure may instead be a syntectonic cumulative wedge system or progressive unconformity related to the growth of the Madigan Gulch anticline.

The first general review of syntectonic cumulative wedge systems was made by Riba (1976) in the northern margins of the Tertiary Ebro Basin of NE Spain. Riba (1976) called these features "progressive unconformities" or "syntectonic unconformities". These structures can develop over a depositional surface which is tilted by relative uplift of one side and subsidence of the other, with no interruption of

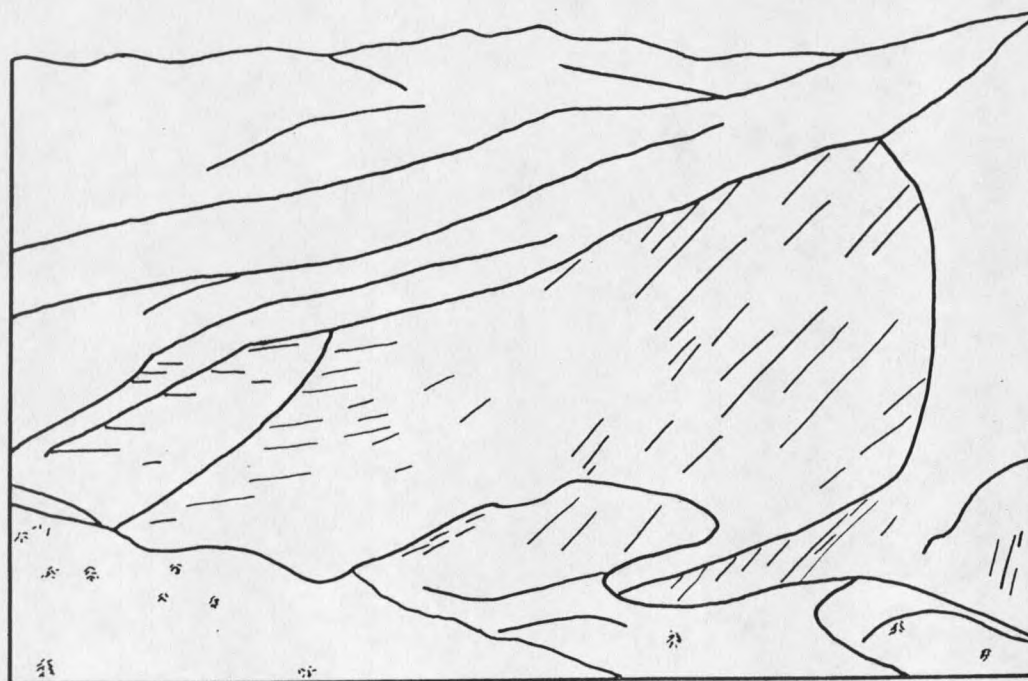


Figure 26. Overview and sketch of Beaverhead strata on the south side of Grasshopper Creek. Note that the strata appear to be folded into a gentle open syncline. Base of lower Beaverhead conglomerate and eastern limb of Madigan Gulch anticline are just out of view to right. View S20W.

sedimentation (Riba, 1976). Such features can be generated adjacent to anticlinal flanks, high angle faults, nappe fronts, and diapiric flanks. Syntectonic unconformities record the evolution of uplift (Riba, 1976).

The formation of these structures is interpreted to be directly related to the interplay between rates of tectonic uplift and rates of sediment accumulation along the flanks of the uplift (Riba, 1976). If the rate of uplift exceeds the rate of sedimentation, a cumulative wedge system with wedges in offlap (rotative offlap) is developed (Figure 27A). The geometric surface of pinch-out of these wedges, the envelope surface A, forms a single progressive unconformity (Riba, 1976). In the case of a decelerating rate of uplift a progressive unconformity with rotative onlap geometry will develop (Figure 27B). If a pulse of uplift is followed by a period of quiescence, the rotative offlap wedge system will be overlain by a rotative onlap wedge system to form a composite progressive unconformity (Figure 27C). Depending on the relationship between uplift and sedimentation a syntectonic angular unconformity may be generated within the composite progressive unconformity.

Plate 2 is a outcrop photomosaic and sketch of the Beaverhead strata on the south side of Grasshopper Creek. The apparent fold is interpreted here to be the result of a syntectonic cumulative wedge system or progressive unconformity with a rotative offlap geometry. The progressive

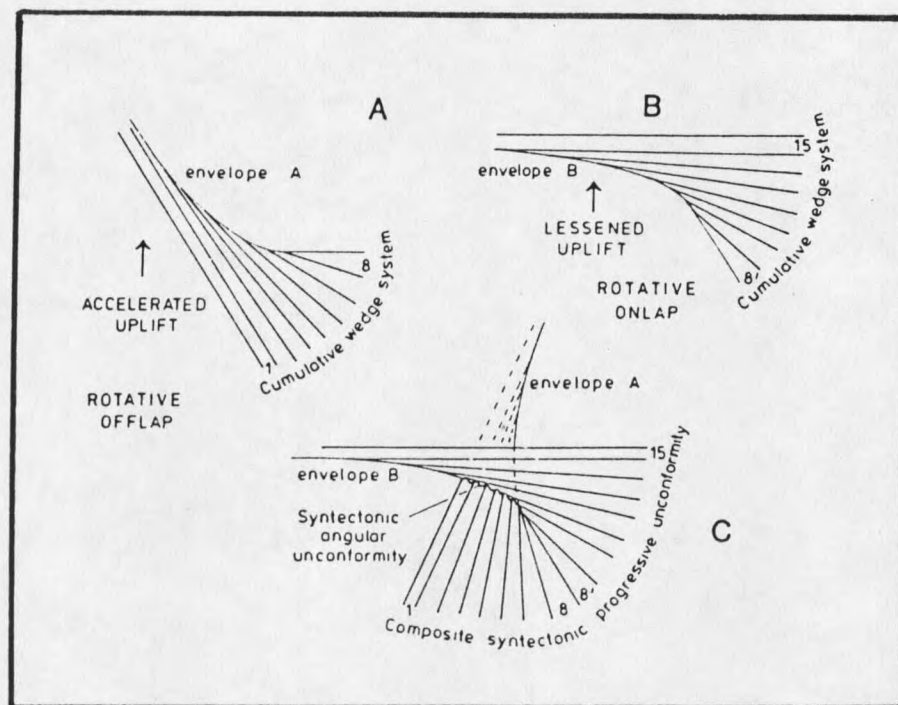


Figure 27. Genetic model of progressive and syntectonic angular unconformities. A) Rotative offlap geometry developed during accelerated uplift of block adjacent to basin. B) Rotative onlap geometry results from a decrease in the rate of uplift. C) Combination of A and B forming a composite syntectonic progressive unconformity containing a syntectonic angular unconformity. From Anadon and others (1986).

unconformity contains three wedge-shaped packages of sediment (A, B, and C) which are defined by a set of relatively consistent internal bedding attitudes. Strata within each of the packages have average dips, measured in the field, of $A=61^{\circ}$, $B=43^{\circ}$ and $C=12^{\circ}$. Plotting poles to bedding planes on a equal-area stereonet reveals that the data points cluster into three groups (Figure 28). Each group corresponds to a sedimentary package. Projecting the bounding surfaces between packages skyward shows that the geometric surface of pinch-out

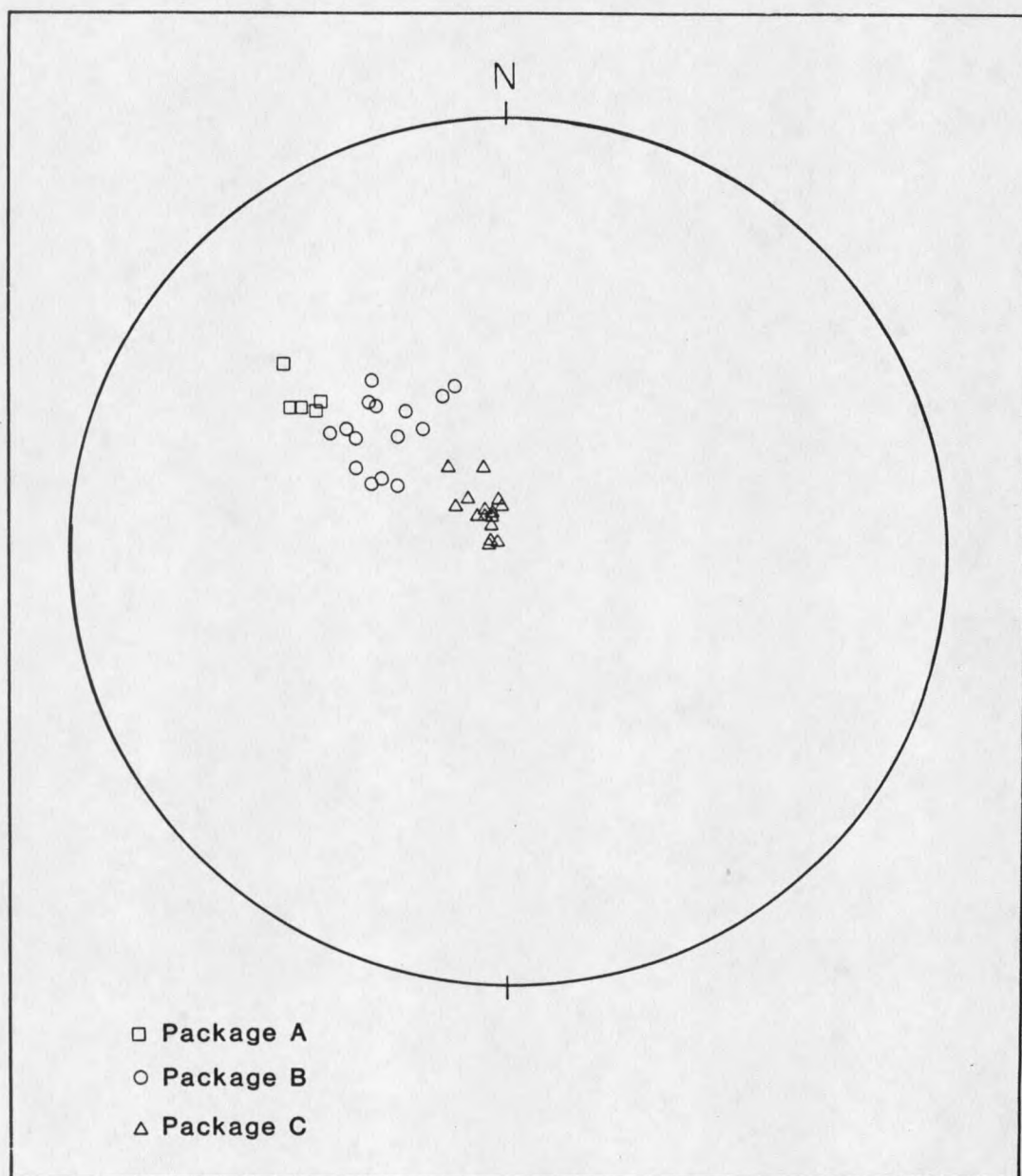


Figure 28. Equal-area stereonet of poles to bedding planes from strata within the lower Beaverhead conglomerate.

has a rotative offlap geometry (Plate 2). Each sedimentary package also differs slightly in its lithology and lithofacies associations.

Steep, rugged terrain prevented a careful lithofacies analysis of the strata in package A. However, cursory examination suggest that the deposits are dominated by conglomerates of facies Gcm and Gch. In Plate 2, the upper boundary of package A was placed at the last dominant conglomerate outcrop before the incised valley. This valley is underlain by deeply weathered volcanic strata and interbedded sandstones and mudstones. The paucity of outcrops in this area made it difficult to determine bedding attitudes. However, one unit of the volcanic sequence dipped at 61° suggesting that the volcanic strata should be included in package A.

Strata in package B consist of interbedded sandstone and mudstone overlain by conglomerate with interbedded sandstone lenses. Conglomerate units in this package are dominated by lithofacies Gcm with lesser amounts of facies Gch and Gcd.

Strata in package C are also dominated by conglomerates of lithofacies Gcm, but lack the interbedded sandstones and mudstones. Deposits of facies Gcd are found in the lower third of the package while deposits of facies Gch are more common in the upper two-thirds. Sandstone, predominantly Sm, is only found as lenses. The preserved fanhead channel is located approximately in the middle of package C.

The argument in favor of a progressive unconformity would be strengthened if it had been possible to trace an individual bed in one package to the point where it pinches out against the bounding surface of the adjacent sedimentary package.

However, due to the relative scarcity of suitable marker horizons and poor outcrop exposure in critical areas this relationship could not be verified.

Although the presence of a progressive unconformity is the favored interpretation for the structural configuration of the lower Beaverhead strata in the study area, the alternate interpretation that the beds have been folded can not be unequivocally ruled out. Poles to bedding planes for sedimentary packages A and C form relatively tight clusters; however, the data for package B is comparatively scattered (Figure 28). It could be argued that bedding plane poles from all three groups fall roughly on one half of a great circle which defines the western limb of a fold. However, the differences in lithology and lithofacies associations between the sedimentary packages do not appear to be compatible with the fold model.

The volcanic rocks, and interbedded sandstones and mudstones in the lower part of the section are unique marker horizons in the lower Beaverhead strata. If these beds were deposited and later folded it is not unreasonable to expect that these units should appear again in the eastern part of the study area. These units were only recognized in the western part of the study area. It could be argued that the same horizons are present, but that the sandstones and mudstones have graded into conglomerates making them unrecognizable. This would suggest that the sediments were

coarsening in a down-fan direction which is an unreasonable assumption. If the strata had been folded it is also not unreasonable to expect to see such mesoscopic features as faulting, jointing, or evidence of bedding plane slip. With the exception of a few relatively minor offsets, none of these features were observed in the study area.

The progressive unconformity in the field area is similar in size and geometry to several progressive unconformities found flanking the Ebro Basin in Spain. Figure 29 shows several syntectonic progressive unconformities developed in proximal alluvial fan deposits of the Upper Eocene-Oligocene Montsant Formation (Scala Dei Group) in the NE Ebro Basin, Spain. These syntectonic cumulative wedge systems record uplift related to movement on the Falset and Ulldemolins-Gandesa faults (Anadon and others, 1986). Notice that these progressive unconformities, in the areas boxed, have a rotative offlap geometry similar to the progressive unconformity in the Grasshopper Creek alluvial fan deposits. Also notice that the structures may occupy a horizontal distance of less than 1 km. The length of the outcrop shown in Plate 2 is slightly less than 0.75 km.

Single progressive unconformities occur at basin margins which have experienced a relatively simple tectonic evolution, one that is generally dominated by uplift (Anadon and others, 1986). Some progressive and angular syntectonic unconformities may have regional tectonic significance, but generally they

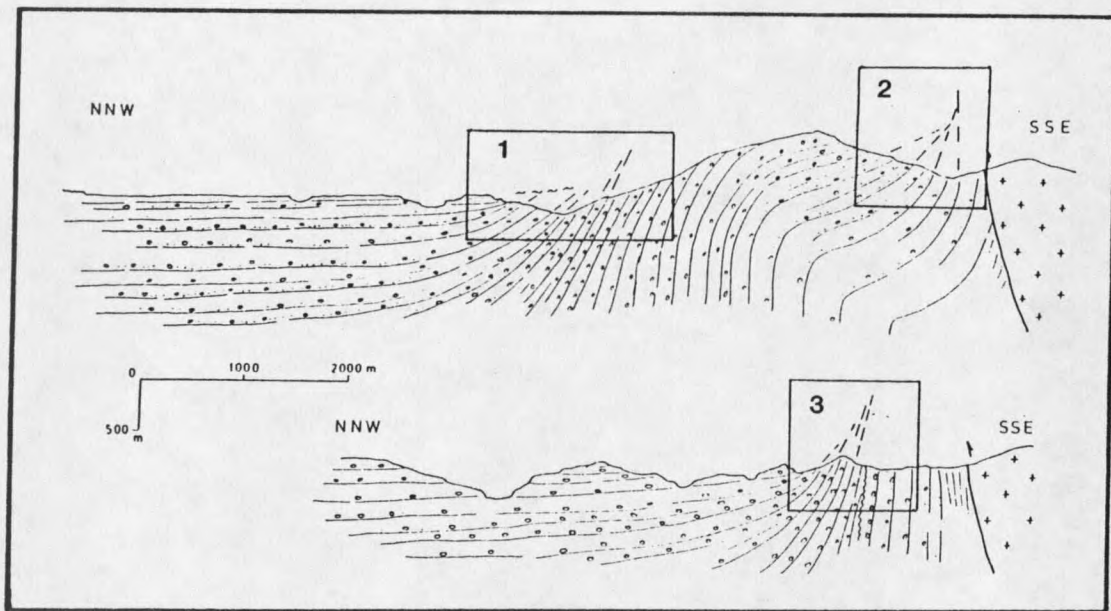


Figure 29. Cross-sections of three progressive unconformities in the Upper Eocene-Oligocene Montsant conglomerates of the NE Ebro Basin, Spain. These proximal alluvial fan deposits contain a composite progressive unconformity (see box no.1) and two, single progressive unconformities (see boxes no. 2 & 3). Notice that these syntectonic cumulative wedge systems are similar in size and geometry to the progressive unconformity in the study area. From Anadon and others (1986).

record the occurrence of rapid, localized uplift contemporaneous with sedimentation along the basin margin (Anadon and others, 1986). Paleontological dating of Tertiary sequences in the Ebro Basin, Spain, suggests progressive unconformities may develop over a short period of time (Anadon and others, 1986).

Progressive unconformities are restricted to the marginal areas of basins and die out quickly towards the center of the basin where the sedimentary sequences are continuous and not affected by synsedimentary deformation and erosion (Anadon and

others, 1986). Progressive unconformities have been reported in other basin margin alluvial fan deposits by Riba (1976); Anadon and others (1986); DeCelles and others (1987, 1991a;b); and T. F. Lawton (personal communication, 1991). The use of progressive unconformities to delineate syntectonic stratigraphic intervals has allowed these authors to establish direct links between basin margin deformation and alluvial fan deposition.

TECTONO-SEDIMENTARY EVOLUTION OF THE
GRASSHOPPER CREEK ALLUVIAL FAN

The recognition of a progressive unconformity within the lower Beaverhead conglomerate allows the development of the Grasshopper Creek alluvial fan to be directly tied to uplift of structures in the source area (Riba, 1976; Anadon and others, 1986). As previously mentioned, the study area is in the frontal fold and thrust zone of the Cordilleran fold and thrust belt in southwest Montana. Deformation in this zone is characterized by folded Paleozoic and Mesozoic sedimentary rocks and multiple imbricate thrusts that commonly cut through the limbs of the overturned folds (Ruppel and Lopez, 1984). The major structures in the area which could have served as a source area for the Grasshopper Creek fan deposits are the Madigan Gulch and Armstead anticlines. At least two hypotheses have been suggested for the formation of these structures.

Johnson (1986) and Johnson and Sears (1988) suggested that the Madigan Gulch anticline, along with the Armstead anticline to the south, were uplifted as part of a Rocky Mountain foreland structure related to the development of the Blacktail-Snowcrest uplift. These structures were partially eroded and then decapitated by east-directed thrusting along the Ermont thrust and its extension (?) on the south side of

Grasshopper Creek. The thrust is thought to have overridden the Beaverhead strata turning it up on end (Thomas, 1981; Johnson, 1986; Johnson and Sears, 1988).

There are at least two inconsistencies with this interpretation. First, as noted by Goodhue (1986) the Armstead Hills lack the prominent northeast-trending folds which characterize areas affected by the Blacktail-Snowcrest uplift. Secondly, Johnson (1986) Johnson and Sears (1988) imply that the Madigan Gulch and Armstead anticlines formed contemporaneously and that they predate thrusting. They later state that the Madigan Gulch anticline formed as a hanging wall anticline over the Indian Head thrust (de La Tour-du-Pin 1983; in Goodhue, 1986) which cuts out the west limb of the Armstead anticline.

Coryell (1983) and Coryell and Spang (1988) suggested that the Madigan Gulch and Armstead anticlines are the result of east-directed thrusting on the Armstead thrust. These structures formed in the hanging wall of the thrust as it moved over a subsurface ramp. These authors believe that all of the structures present in the Armstead Hills can be accounted for by a single, progressive, east-directed phase of compressional deformation. According to Coryell (1983) and Coryell and Spang (1988), foreland styles of deformation involving basement uplifts had little effect on the structural development of the area. Coryell (1983) interprets the Indian Head thrust of de La Tour-du-Pin (1983 in Goodhue, 1986) to be

a normal fault over a subsurface ramp. One of the major drawbacks of Coryell's (1983) and Coryell and Spang's (1988) model is that it requires a basal detachment within the Precambrian rocks.

While Coryell (1983) and Coryell and Spang (1988) discussed the genesis of the Armstead anticline they did not directly address the origin of the Madigan Gulch anticline. One interpretation offered here is that the development of the Madigan Gulch anticline is related to movement of the Ermont thrust. The Madigan Gulch anticline may have developed as a fault-propagation fold in front of the Ermont thrust as the fault ramped towards the surface. This interpretation is based on the following observations. The westward dip of the fault plane increases from less than 15° north of Badger Pass (Thomas, 1981) to 35° - 40° in the field area near Bannack (Johnson, 1986). This change in the dip of the fault plane may indicate the presence of a subsurface ramp. The dip of the fault plane in the field area is consistent with that of other thrust ramps (McClay, 1992). Movement on the Ermont thrust decreases in a north to south direction (Thomas, 1981). At its southern extent, on the north side of Grasshopper Creek, the trace of the fault becomes lost in a series of complex structures and intrusions. On the south side of Grasshopper Creek the Madigan Gulch anticline plunges to the south (Coryell, 1983; Johnson, 1986; Coryell and Spang, 1988; Johnson and Sears, 1988). The relationship between the two

structures suggests that displacement on the Ermont thrust dies out in the Madigan Gulch anticline. This association is characteristic of fault-propagation folds (Suppe, 1985 p. 350). Additionally, the Ermont thrust cuts the east limb of the fold (Johnson, 1986; Johnson and Sears, 1988).

Fault-propagation folds are generated at the tips of blind thrusts in response to the development of a footwall ramp (Jamison, 1987). Unlike a fault-bend fold which develops subsequent to the ramp formation, the fault-propagation fold develops simultaneously with and immediately above the ramp (Jamison, 1987). As the thrust tip migrates, the advancing fold front is continuously being cut by the propagating thrust (Boyer, 1986; Fischer and others, 1992). Important field evidence for the recognition of fault-propagation folds is the observation that some thrust faults die out in the cores of folds (Suppe, 1985 p. 350). Other examples of thrust faults terminating along strike into folds are given by Boyer (1986).

Regardless of the kinematic nature of these two structures the results of this study favor the Madigan Gulch anticline as the source area for the Grasshopper Creek alluvial fan deposits. This interpretation is based on: 1) paleocurrent and clast count data which suggest the Madigan Gulch anticline was a topographically high area during deposition of the Grasshopper Creek alluvial fan; 2) the proximal alluvial fan interpretation of the deposits; 3) recognition of the depositional contact between the folded

Lombard Limestone and lower Beaverhead conglomerate on the east limb of the Madigan Gulch anticline (Figure 10); and 4) recognition of the progressive unconformity. The existence of the progressive unconformity is evidence that the proximal portion of the Grasshopper Creek alluvial fan was actively under going deformation synchronous with its formation thus demonstrating the true synorogenic nature of these deposits. The results of this study do not completely rule out the Armstead anticline as a potential source area for the lower Beaverhead strata. However, this structure lies almost due south of the field area which is inconsistent with the paleocurrent data.

The presence of a syntectonic cumulative wedge system or a progressive unconformity within the deposits indicates that uplift of the Madigan Gulch anticline was episodic. The rotative offlap geometry of the wedge-system indicates the rate of uplift exceeded the rate of sedimentation (Riba, 1976).

The initial stages of uplift are not recorded in any of the deposits found in the field area. At the beginning of uplift, predominantly Mesozoic and uppermost Paleozoic rocks would be exposed in the source area. Since these formations are dominated by mudstones and siltstones very little coarse clastic detritus was produced. Fluvial systems draining the source terrain were probably able to pass much of this fine-grained sediment to more distal parts of the depositional

basin. Coarse alluvial fan sedimentation did not begin until the more resistant Mississippian carbonates were exposed. By the time the incipient Grasshopper Creek alluvial fan began to develop, erosion had removed most of the Pennsylvanian through Mesozoic strata from the eastern limb of the fold. The initial coarse grained sediments were deposited upon the karsted surface of the Mississippian carbonates.

Clast count data from stratigraphically lower parts of the Beaverhead section indicate that at the time the deposits began to accumulate along the east limb of the fold, Upper Paleozoic through Mesozoic formations were simultaneously exposed in the source area. Once coarse alluvial sedimentation was initiated, episodes of uplift were recorded by the wedge-shaped packages of sediment which make up the progressive unconformity (Figure 30). The three wedge-shaped packages (A, B, and C see Plate 2), are defined by relatively consistent internal bedding attitudes. The bounding surfaces of each package record the basinward rotation of the proximal part of the fan in response to uplift of the Madigan Gulch anticline. Alluvial deposits between the bounding surfaces record periods of relative tectonic quiescence.

The initial gravel deposits are contained within wedge A (Plate 2). Sometime after gravels began to accumulate, the surface of the fan was blanketed with up to 6 m of ashfall or ashflow tuffs. With the exception of several small pods of conglomerate, the volcanic units do not appear to have been

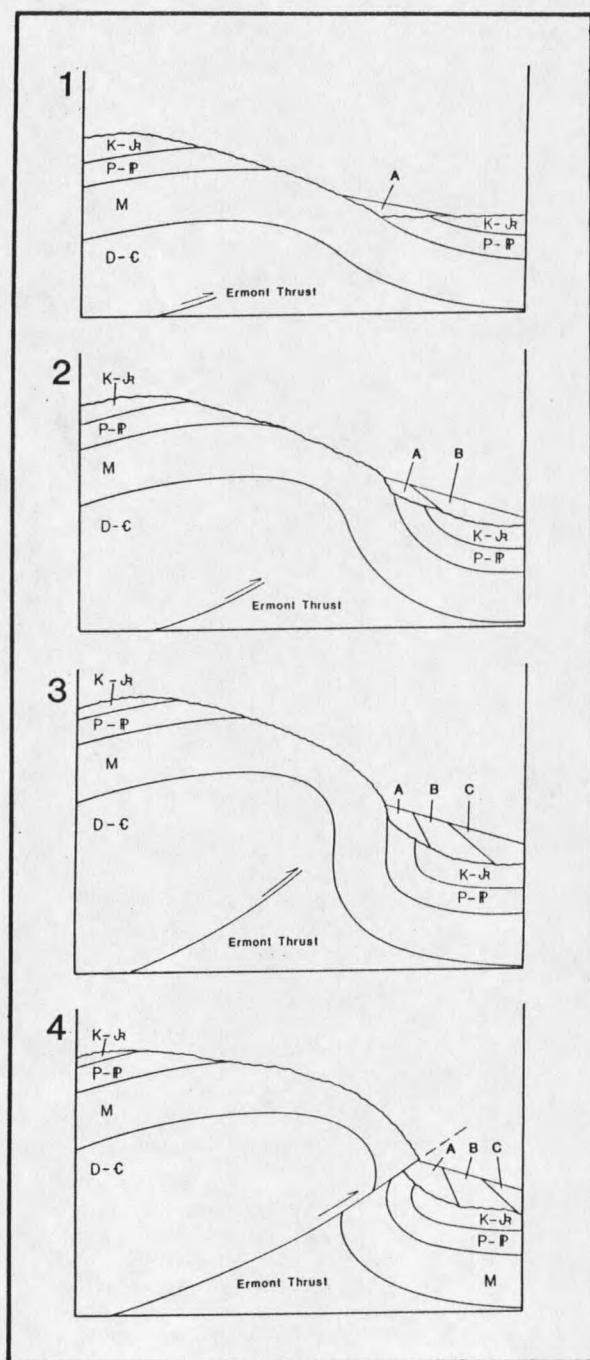


Figure 30. Schematic diagram showing progressive uplift of the Madigan Gulch anticline and deformation of the Grasshopper Creek alluvial fan in response to propagation of the Ermont thrust. A, B, and C correspond to the sedimentary wedges of the progressive unconformity shown in Plate 2.

heavily reworked. The preservation of these beds suggests that at the time they were deposited this portion of the fan was inactive. It is unknown whether these deposits are the result of a single or multiple eruption events or the time interval they represent.

The volcanic unit is overlain by approximately 32 m of interbedded sandstone and mudstone. These fine-grained rocks, which make up the initial deposits of wedge B, are interpreted to represent ephemeral flood deposits on an inactive portion of the fan surface. The sandstone-mudstone sequence is overlain by approximately 10 m of interbedded sandstone and conglomerate. These beds may signal a change in the locus of active fan deposition due to shifting of the fanhead trench. The preserved fanhead channel is evidence that the surface of the Grasshopper Creek alluvial fan actively went through periods of fanhead entrenchment.

A number of intrinsic and extrinsic factors have been identified or hypothesized as causing entrenchment of the most proximal part of alluvial fans. Intrinsic factors that may lead to entrenchment include capture of the main fan feeder channel by minor channels heading on the fan (Denny 1965; Hooke 1967; Schumm and others 1987); the alteration of debris flow and stream flow processes (Bluck, 1964; Hooke, 1967); and exceeding the critical slope threshold at the apex of the fan (Schumm and others, 1987). Extrinsic factors include long term climate change (Lustig, 1965) or short term change in

precipitation (Eckis 1928; Bull, 1964); lowering of local base level as a result of the lowering of a major trunk river at the toe of the fan (Blissenbach 1954; Ryder, 1971); and tectonic changes in the source area (Bull 1964; Hooke 1972; Blair 1987b). Considering the active tectonic setting of the Grasshopper Creek alluvial fan, entrenching of the fanhead channel is probably a response to a tectonic stimulus.

In extensional tectonic settings, fanhead entrenchment is considered to be indicative of a period of tectonic quiescence when the rate of erosion in the source drainage basin exceeds the rate of relative tectonic subsidence in the adjacent depositional basin (Blair, 1987b). However, this relationship might not be true in contractional settings where the proximal part of fans may be uplifted with their source area. Hooke (1972) notes that the alluvial fans on the west side of Death Valley have been deeply incised as a result of eastward tilting of the valley. In the study area the proximal part of the Grasshopper Creek alluvial fan was actively being tilted due to uplift of its source terrain. If incision of the Death Valley fans resulted from tilting of the fan surface due to differential subsidence of the basin, then it seems logical that tilting of the fan surface during uplift should also lead to incision. For the Grasshopper Creek alluvial fan entrenching of the fanhead is probably a response to uplift in the source area. DeCelles and others (1991b) made a similar interpretation for the formation of fanhead trenches in the

Paleocene Beartooth conglomerate of northwestern Wyoming and southwestern Montana.

Deposition of the strata which make up package B was followed by another period of uplift which is recorded by the deposits of package C. The preserved fanhead trench is located stratigraphically in the middle of this final sedimentary wedge package. Since the channel is located in the middle of package C, channel formation can not be related to the episode of uplift which initiated the development of this sedimentary wedge. However, the channel may be related to a smaller, secondary period of uplift.

Longterm backfilling of the channel began sometime after uplift of the fan had ceased and overall gradient of the system had equilibrated. The dominance of Mississippian clasts in the backfill deposits may have several explanations. DeCelles (personal communication, 1989) has suggested that the backfill facies of a major fanhead trench should be enriched in sediment derived directly from the source area because cannibalization of the older fan material should cease with the cessation of uplift. Faulting in the source terrain may have exposed a panel of Mississippian carbonate rocks to erosion. Uplift may have temporarily increased the rate of down cutting by streams in the drainage basin. Thus, formations which make up the floor of the drainage basin, in this case Mississippian carbonates, would be preferentially eroded over those found on the sides of the drainage basin. At

the time of channel backfilling, the main fan feeder channel may also have tapped a portion of the drainage basin where the Mississippian formations happened to be the dominant source rock.

Compositional trends in the conglomerate clast count and sandstone point count data suggest that an overall, poorly developed, inverted clast stratigraphy exists within the blended clast composition of the lower Beaverhead strata. Conglomerate deposits in the stratigraphically higher portions of the section show a qualitative decrease in the percentage of Triassic Dinwoody clasts and a complete absence of Cretaceous Kootenai clasts relative to deposits stratigraphically lower in the section. This suggests that during the later stages of fan deposition the Kootenai Formation had been removed from the source drainage basin while the Dinwoody Formation made up a volumetrically minor component of the source rocks. Sandstones from stratigraphically higher portions of the Beaverhead section show an increase in the relative percentage of carbonate lithic fragments compared to those lower in the section. This also suggests that over time, streams in the drainage basin were eroding a source area increasingly dominated by carbonate strata. The poorly developed inverted clast stratigraphy recognized in the lower Beaverhead conglomerate of the study area is interpreted to crudely define the gradual unroofing of the Madigan Gulch anticline.

The unroofing sequence developed in the lower Beaverhead conglomerate is similar to that found by DeCelles and others (1987) in alluvial fan deposits of the Upper Cretaceous Sphinx conglomerate of southwestern Montana. Clast counts by DeCelles and others (1987) show that during the time of Sphinx deposition, formations ranging in age from Mississippian to Cretaceous were simultaneously exposed in the source area. However, over the entire thickness of the Sphinx, there is a general decrease in the abundance of Mesozoic clasts from base to top. The source area for the Sphinx conglomerate was a hanging-wall anticline developed above a ramp in the Scarface thrust.

Deposition of the Grasshopper Creek alluvial fan was followed by deposition of the Grasshopper Creek tuffs and Cold Springs Creek volcanics. The contact between the conglomerates and the Grasshopper Creek tuffs may be conformable (Pearson and Childs, 1989) or unconformable (Johnson, 1986). Sometime after deposition of the volcanic rocks, the Ermont thrust truncated the eastern limb of the Madigan Gulch anticline. Deposits of the Grasshopper Creek alluvial fan and the volcanic sequence were overridden by the thrust. Thrusting proceeded in a north to south direction.

On the north side of Grasshopper Creek a large block of Madison Group limestone can be seen in contact with the conglomerates. The nature of this contact is uncertain and reconnaissance mapping around the block yielded no definitive

clues. Pearson and Childs (1989) interpreted the contact to be depositional. They suggested that the block broke off the front of a thrust sheet and slid or rolled into place across the surface of the Beaverhead deposits. Thomas (1981) and Johnson (1986) interpreted the block to be a klippe of the Ermont thrust. On the north side of Grasshopper Creek the system of sedimentary wedges which make up the progressive unconformity are hard to discern. The block appears to cut across the lower Beaverhead strata at a high angle and occupies the projected location of the upper portions of sedimentary wedge packages A and B (Figure 31). This relationship suggests a thrust fault origin for this block.

As previously mentioned descriptions of syntectonic sediments containing progressive unconformities are scarce in the geological literature (Riba, 1976; Anadon and others, 1986; DeCelles and others, 1987, 1991a;b; Holl and Anastasio, 1993). Those that have been described are found adjacent to foreland basin margins or intrabasinal uplifts. The recognition of progressive unconformities is important because their formation is directly attributable to deformation in the adjacent source terrane. The development of these structures and the information they contain regarding the kinematic evolution of their source terrane has been widely overlooked.

The geometry of a single progressive unconformity results from the interplay between rates of tectonic uplift and rates of sediment accumulation along the flanks of the uplift. An

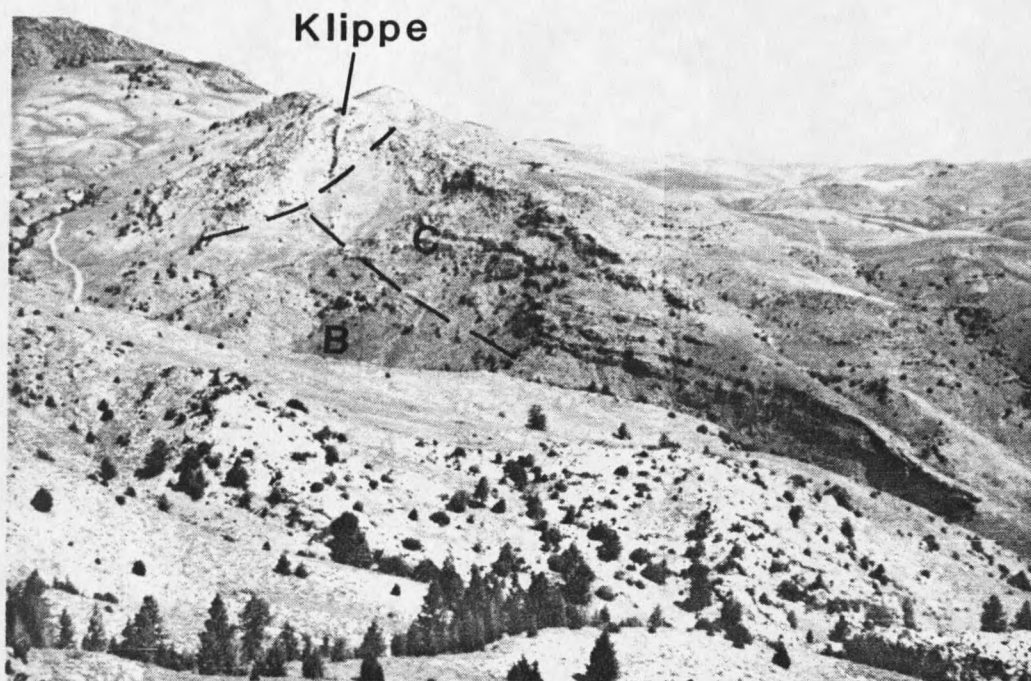


Figure 31. Klippe of Madison limestone truncating a portion of the lower Beaverhead conglomerate on the north side of Grasshopper Creek. Sedimentary wedge package C and a portion of package B are visible in center of photograph. Sedimentary wedge package A, and remainder of package B appear to have been faulted out by the Ermont thrust. The large channel is visible in the shadow to the lower right. View N40E.

offlap wedge geometry results if the rate of uplift exceeds the rate of sedimentation while an onlap wedge geometry indicates a decelerating rate of uplift (Riba, 1976) (Figure 26). The geometry or stacking characteristics of successive depositional wedges may also provide insight into the kinematics of the structure that generated the progressive unconformity. T. F. Lawton (personnel communication, 1991) used differences in the geometries of two progressive unconformities to differentiate between uplift associated with

the development of a ramp anticline and uplift associated with a west-verging duplex along the eastern margin of the Sevier orogenic belt in central Utah. DeCelles and others (1991a) used the stepwise retrodeformation of a progressive unconformity developed in the Paleocene Beartooth conglomerate to tightly constrain the kinematic history of the adjacent Beartooth uplift. In this study the recognition of a progressive unconformity within the Grasshopper Creek alluvial fan provides an alternate interpretation for the apparent folded nature of the Beaverhead strata in this area. It also directly ties the deposition of the lower Beaverhead conglomerate to uplift of the Madigan Gulch anticline.

To date, there have been no published papers describing intraformational progressive unconformities in Beaverhead Group strata for southwestern Montana. This study suggests they may be present in Beaverhead Group deposits shed from the fold and thrust belt (i.e. Red Butte Conglomerate and conglomerates of McKnight Canyon). Their recognition may shed additional light on the kinematic evolution of the fold and thrust belt in southwestern Montana.

SUMMARY OF INTERPRETATIONS

The results of this study allow the following interpretations to be drawn with regards to the depositional environment, provenance, and tectono-sedimentary significance of the lower conglomerate unit of the Late Cretaceous Beaverhead Group along Grasshopper Creek east of Bannack, Montana.

1) The lower Beaverhead conglomerate in the study area was deposited by channelized and nonchannelized high energy alluvial systems active on the surface of an alluvial fan. Deposits which characterized these systems include the products of cohesionless debris flows (Gcd), hyperconcentrated flood flow (Gcm), longitudinal bar formation (Gcm and Gch), and waning stage accretion on bar tops and in interbar channels (Gcp, Gct, Sm, Sh, Sr, Fm/Fl) (Plate 1). The depositional system interpreted to be responsible for these deposits is in this study termed the Grasshopper Creek alluvial fan.

2) Composition of the lower Beaverhead conglomerates indicate that the source area contained Mesozoic and Paleozoic strata ranging in age from the Cretaceous Kootenai Formation to the Mississippian Lodgepole Formation. However, the bulk of the deposits are dominated by Mississippian carbonates. The

deposits may contain a crudely developed inverted clast stratigraphy. Paleocurrent data, although sparse, suggests a southeast transport direction. The measured paleoflow direction is approximately normal to the trend of the Ermont thrust and Madigan Gulch anticline.

3) The basal deposits of the lower Beaverhead strata were deposited on the karsted surface of the Mississippian Lombard Limestone on the east limb of the Madigan Gulch anticline. Evidence for the unconformable nature of this contact includes: a) presence of a red karst paleosol directly beneath the basal conglomerate; and b) conglomerates of the basal Beaverhead filling depressions on the surface of the underlying limestone.

4) The association of lithofacies, provenance data, and the unconformable contact between the basal Beaverhead deposits and strata on the east limb of the Madigan Gulch anticline suggests that deposition of the Grasshopper Creek alluvial fan was initiated by uplift of the Madigan Gulch anticline. This east verging fold may have developed as a fault-propagation fold related to ramping of the Ermont thrust. The crudely developed inverted clast stratigraphy developed in the lower Beaverhead deposits records the gradual unroofing of the Madigan Gulch anticline.

5) The lower Beaverhead conglomerate in the study area contains what is interpreted to be a syntectonic cumulative wedge system or progressive unconformity. The progressive

unconformity is delineate by three wedge-shaped packages of sediment (A, B, and C, see Plate 2) which are defined by a set of relatively consistent internal bedding attitudes. Each wedge-shaped package of sediment formed in response to the proximal part of the fan being rotated basinward during uplift of the Madigan Gulch anticline. Uplift was episodic. The rotative offlap geometry of the wedge-system indicates the rate of uplift exceeded the rate of sedimentation. Each sedimentary package also differs slightly in its lithology and lithofacies associations.

6) Incision of the preserved fanhead trench was probably initiated by the southeastward tilting of the fan surface in response to uplift of the Madigan Gulch anticline.

REFERENCES CITED

- Anadon, P. Cabrera, L., Colombo, F., Marzo, M., and Riba, O., 1986, Syntectonic intraformational unconformities in alluvial fan deposits, eastern Ebro Basin margins (NE Spain), in Allen, P.A., and Homewood, P., eds., *Foreland Basins: International Association of Sedimentologist Special Publication No. 8*, p. 259-271.
- Ballance, P.F., 1984, Sheet-flow-dominated gravel fans of the non-marine middle Cenozoic Simmler Formation, central California: *Sedimentary Geology*, v. 38, p. 337-359.
- Blair, T.C., 1987a, Sedimentary processes, vertical stratification sequences, and geomorphology of the Roaring River alluvial fan, Rocky Mountain National Park Colorado: *Journal of Sedimentary Petrology*, v. 57, p. 1-18.
- , 1987b, Tectonic and hydrologic controls on cyclic alluvial fan, fluvial, and lacustrine rift-basin sedimentation, Jurassic-lowermost Cretaceous Todos Santos Formation, Chiapas, Mexico: *Journal of Sedimentary Petrology*, v. 57, no. 5, p. 845-862.
- Blair, T.C., and McPherson, J.G., 1992, The Trollheim alluvial fan and facies model revisited: *Geological Society of America Bulletin*, v. 104, p. 762-769.
- Blatt, H., Middleton, G., and Murray, R., 1980, *Origin of sedimentary rocks: Englewood Cliffs, Prentice-Hall*, 782 p.
- Blissenbach, E., 1954, Geology of alluvial fans in semiarid regions: *Geological Society of America Bulletin*, v. 65, p. 175-190.
- Bluck, B.J., 1964, Sedimentation of an alluvial fan in southern Nevada: *Journal of Sedimentary Petrology*, v. 34, p. 395-400.
- Boothroyd, J.C., and Ashley, G.M., 1975, Process, bar morphology and sedimentary structures on braided outwash fans northeastern Gulf of Alaska, in Jopling, A.V. and B.C. McDonald, eds., *Glaciofluvial and Glaciolacustrine Sedimentation: Society of Economic Paleontologist and Mineralogist Special Publication 23*, p. 193-222.
- Boyer, S.E., 1986, Styles of folding within thrust sheets: examples from the Appalachian and Rocky Mountains of the U.S.A. and Canada: *Journal of Structural Geology*, v. 8, no. 3/4, p. 325-339.

- Brant, R.A., Elmer, N.C., Gillespie, W.A., and Peterson, J.A., 1949, Geology of the Armstead area, Beaverhead County, Montana: [M.S. thesis] University of Michigan, in Johnson, 1986.
- Bull, W.B., 1964, Geomorphology of segmented alluvial fans in western Fresno County California: U.S. Geological Survey Professional Paper 352-E, p. 89-129.
- _____, 1972, Recognition of alluvial fan deposits in the stratigraphic record, in Rigby, J.K., and Hamblin, W.K., eds., Society of Economic Paleontologist and Mineralogist Special Publication 16, p. 68-83.
- Clark, C. W., 1986, The stratigraphy and structure of the Paleozoic and Mesozoic rocks of the west flank of the Armstead anticline area, Beaverhead county Montana: [M.S. thesis] Corvallis, Oregon State University, 86 p.
- Compton, R.R., 1962, Manual of Field Geology: New York, Wiley and Sons, 378 pp.
- Corner, H.J., 1992, The stratigraphy and provenance of the upper Cretaceous Beaverhead Group at McKnight Canyon, southwestern Montana [M.S. thesis]: Pullman, Washington State University, 99 p.
- Coryell, J.J., 1983, Structural geology of the Henneberry Ridge area, Beaverhead County, Montana [M.S. thesis]: Collage Station, Texas A&M University, 125 p.
- Coryell, J.J., and Spang, J.H., 1988, Structural geology of the Armstead anticline area, Beaverhead County, Montana in Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountain Foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 217-228.
- DeCelles, P.G., 1988, Lithologic provenance modeling applied to the Late Cretaceous synorogenic Echo Canyon Conglomerate, Utah: A case of multiple source areas: Geology, v. 16, p. 1039-1043
- Decelles, P.G., Tolson, R.B., Graham, S.A., Smith, G.A., Ingersoll, R.V., White, J., Schmidt, C.J., Rice, R., Moxon, I., Lemke, L., Handschy, J.W., Follo, M.F., Edwards, D.P., Cavazza, W., Caldwell, M., and Bargar, E., 1987, Laramide thrust-generated Alluvial-fan sedimentation, Sphinx conglomerate, Southwest Montana: American Association of Petroleum Geologist Bulletin, v. 71, no. 2, p. 135-155.

- Decelles, P.G., Gray, M.B., Ridgway, K.D., Cole, R.B., Srivastava, P., Pequera, N., and Pivnik, D.A., 1991a, Kinematic history of a foreland uplift from Paleocene synorogenic conglomerate, Beartooth Range, Wyoming and Montana: Geological Society of America Bulletin, v. 103, p. 1458-1475.
- Decelles, P.G., Gray, M.B., Ridgway, K.D., Cole, R.B., Pivnik, D.A., Pequera, N., and Srivastava, P., 1991b, Controls on synorogenic alluvial-fan architecture, Beartooth conglomerate (Paleocene), Wyoming and Montana: Sedimentology, v. 38, p. 567-590.
- De la Tour-du-pin, H., 1983, Contribution a l'etude geologique de l'Overthrust Belt du Montana (U.S.A.); Stratigraphie et Tectonique des Rocky Hills et du Tendoy Range (Sud-Ouest du Montana): [Ph.D. thesis] Brest, France, Universite de Bretagne Occidentale, 256 p.
- Denlinger, R.P., Scott, K., and Pierson, T., 1984, Granular resorting and its effects on resistance to flow in grain-supported lahars [abs.]: EOS (American Geophysical Union Transactions), v. 65, p. 1142.
- Denny, C., 1965, Alluvial fans in the Death Valley Region, California and Nevada: U. S. Geological Survey Professional Paper 466, 59 p.
- Dickison, W.R., Beard, L.S., Bradenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., and Ryberg, P.T., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, v. 94, p. 222-235.
- Dyman, T.S., Haley, J.C., and Perry, W.J., 1991, Redefinition of Frontier Formation-Beaverhead Group contact, Lima Peaks area, southwestern Montana and southeastern Idaho, in Contributions to Late Cretaceous stratigraphy and paleontology, western Montana: U.S. Geological Survey Bulletin 1962, Chapter A, p. 1-8.
- Eckis, R., 1928, Alluvial fans of the cucamonga district, southern California: Journal of Geology, v. 36, p. 224-247.
- Enyon, G., and Walker, R.G., 1974, Facies relationships in Pleistocene outwash gravels, southern Ontario: A model for bar growth in braided rivers: Sedimentology, v. 21, p. 43-70.

- Fischer, M. P., Woodward, N. B., and Mitchell, M. M., 1992, The kinematics of break-thrust folds: *Journal of Structural Geology*, v. 14, no. 4, p. 451-460.
- Folk, R.L., 1980, *Petrology of sedimentary rocks*: Hemphill Publishing Company, Austin, Texas, 184 pp.
- Gonnermann, H.M., 1992, An andesite-dacite stratovolcano within the Late Cretaceous Beaverhead Group, near Bannack, Montana: [B.S. thesis] Missoula, University of Montana, 43 p.
- Goodhue, W.V., 1986, Bedrock geology and stratigraphy of the northern parts of the Armstead and Madigan Gulch anticlines, Beaverhead County, Montana: [M.S. thesis] Corvallis, Oregon State University, 310 p.
- Graham, S.A., Tolson, R.B., Decelles, P.G., Ingersoll, R.V., Bargar, E., Caldwell, M., Cavazza, W., Edwards, D.P., Follo, M.F., Handschy, J.W., Lemke, L., Moxon, I., Rice, R., Smith, G.A., and White, J., 1986, Provenance modelling as a technique for analyzing source terrane evolution and controls on foreland sedimentation, in Allen, P.A., and Homewood, P. eds., *Foreland basins: International Association of Sedimentologist Special Publication 8*, p. 425-436.
- Haley, J.C., 1985, Upper Cretaceous (Beaverhead) synorogenic sediments of the Montana-Idaho thrust belt and adjacent foreland; Relationships between sedimentation and tectonism [Ph.D. thesis] Baltimore, Maryland, John Hopkins University, 542 p.
- Haley, J.C., and Perry, W.J., 1991, The Red Butte Conglomerate - A thrust-belt-derived conglomerate of the Beaverhead Group, southwestern Montana: *U.S. Geological Survey Bulletin* 1945, 19 p.
- Harms, J.C., and Fahnstock, R.K., 1965, Stratification, bedforms, and flow phenomena (with an example from the Rio Grande), in Middleton, G.V., ed., *Society of Economic Paleontologists and Mineralogists Special Publication 12*, p. 84-115.
- Harms, J.C., Southard, J.B., Spearing, D.R., and Walker, R.G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: *Society of Economic Paleontologist and Mineralogists Short Course 2*, Dallas, 161 p.

- Harms, J.C., Southard, J.B., and Walker, R.G., 1982, Structures and sequences in clastic rocks: Society of Economic Paleontologist and Mineralogists Short Course 9.
- Harvey, A.M., 1984, Debris flows and fluvial deposits in Spanish Quaternary alluvial fans: implications for fan morphology. in Koster, E.H., and Steel, R.J., eds., Sedimentology of gravels and conglomerates: Canadian Society of Petroleum Geologists Memoir 10, p. 123-132.
- Hein, F.J., and Walker, R.G., 1977, Bar evolution and development of stratification in the gravelly, braided Kicking Horse River, B. C.: Canadian Journal of Earth Science, v. 14, p. 562-570.
- Heward, A.P., 1978, Alluvial fan sequences and megasequence models: With examples from Westphalian D-Stephanian B coalfields, Northern Spain, in Miall, A.D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologist Memoir 5, p. 669-702.
- Holl, J.E., and Anastasio, D.J., 1993, Paleomagnetically derived folding rates, southern Pyrenees, Spain: Geology, v. 21, p. 271-274.
- Hooke, R.J., 1967, Processes on arid-region alluvial fans: Journal of Geology, v. 75, p. 438-460.
- , 1972, Geomorphic evidence for Late Wisconsin and Holocene tectonic deformation, Death Valley, California: Geological Society of America Bulletin, v. 83, p. 2073-2098.
- Ivy, S.D., 1989, Source, evolution, and eruptive history of the Cold Spring Creek volcanics, Beaverhead County, Montana: [M.S. thesis] Corvallis, Oregon State University, 91 p.
- Jamison, W.R., 1987, Geometric analysis of fold development in overthrust terranes: Journal of Structural Geology, v. 9, p. 207-219.
- Johnson, L.M., 1986, An overlap zone between a Laramide Rocky Mountain foreland structure and Sevier-style thrust structures near Bannack, Montana: [M.S. thesis] Missoula, University of Montana, 113 p.

- Johnson, L.M., and Sears, J.W., 1988, Cordilleran thrust belt-Rocky Mountain foreland interaction near Bannack, Montana, in Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountain Foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 229-236.
- Kupsch, W.O., 1950, Geology of the Tendoy-Beaverhead area, Beaverhead County, Montana: [Ph.D. thesis] University of Michigan, in Johnson, 1986.
- Lawton, T.F., 1986, Compositional trends within a clastic wedge adjacent to a fold-thrust belt: Indianola Group, Central Utah, U.S.A. in Allen, P.A., and Homewood, P., eds., Foreland Basins: International Association of Sedimentologist Special Publication No. 8, p. 411-423.
- Lowe, D.R., 1982, Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents: Journal of Sedimentary Petrology, v. 52, p. 279-297.
- Lowell, W.R., 1965, Geologic map of the Bannack-Grayling area, Beaverhead County, Montana: U.S. Geological Survey Miscellaneous Geologic Investigations Map, I-433, scale 1:31,680.
- Lustig, L.K., 1965, Clastic Sedimentation in Deep Springs Valley California: U.S. Geological Survey Professional Paper 352-F.
- Mack, G.H., and Rasmussen, K.A., 1984, Alluvial-fan sedimentation of the Culter Formation (Permo-Pennsylvanian) near Gateway, Colorado: Geological Society of America Bulletin, v. 95, p. 109-116.
- McClay, K.R., 1992, Glossary of thrust tectonic terms, in McClay, K.R., ed., Thrust Tectonics: New York, Chapman & Hall, p. 419-433.
- Miall, A.D., 1977, A review of braided-river depositional environments: Earth Science Reviews, v. 13, p. 1-62.
- _____, 1978, Lithofacies types and vertical profile models in braided river deposits: A summary, in Miall, A.D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologist Memoir 5, p. 597-604.
- Myers, W.B., 1952, Geology and mineral deposits of the northwest quarter Willis Quadrangle and adjacent Brown's Lake area, Beaverhead County, Montana: U.S. Geological Survey Trace Elements Investigations Report 259, 46 p.

- Nemec, W., and Steel, R.J., 1984, Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass-flow deposits, in Koster, E.H., and Steel, R.J., eds., *Sedimentology of Gravels and Conglomerates*; Memoir Canadian Society of Petroleum Geologist, v. 10 p. 1-31.
- Nichols, D.J., Perry, W.J., and Haley, J.C., 1985, Reinterpretation of the palynology and age of Laramide syntectonic deposits, Southwestern Montana, and revision of the Beaverhead Group: *Geology*, v. 13, p. 149-153.
- Nilsen, T.H., 1982, Alluvial fan deposits, in Scholle, P.A., and Spearing, D.A., eds., *Sandstone depositional environments*: American Association of Petroleum Geologist Memoir 31, p. 49-86.
- Pearson, R.C., and Childs, J.F., 1989, Field trip guide, roadlog, and summary of Cretaceous volcanic geology, Dillon to Bannack, Beaverhead County, Montana: in Sears, J.W., ed., *Structure, stratigraphy and economic geology of the Dillon area*, Tobacco Root Geological Society 14th Annual Field Conference, *Northwest Geology*, v.18, p. 36-59.
- Perry, W.J., Jr., Sando, W.J., and Sandberg, C.A., 1985, Structural geometry of the newly defined Blacktail salient of Montana thrust belt: *American Association of Petroleum Geologist Bulletin*, v. 69, no. 5, p. 858-859.
- Pettijohn, F.J., Potter, P.E., and Siever, R., 1987, *Sand and sandstone*: New York, Springer-Verlag, 553 p.
- Pierson, T.C., 1981, Dominant particle support mechanisms in debris flows at Mt. Thomas, North Canterbury, New Zealand, and implications for flow mobility: *Sedimentology*, v. 28, p. 48-60.
- Pivnik, D.A., 1990, Thrust-generated fan-delta deposition: Little Muddy Creek conglomerate, SW, Wyoming: *Journal of Sedimentary Petrology*, v. 60, no. 4, p. 489-503.
- Potter, P.E., and Pettijohn, F.J., 1977, *Paleocurrents and Basin Analysis*: New York, Springer-Verlag, 425 p.
- Riba, O., 1976, Syntectonic unconformities in the Alto Cardener, Spanish Pyrenees: a genetic interpretation: *Sedimentary Geology*, v. 15, p. 213-233.
- Ruppel, E.T., and Lopez, D.A., 1984, The thrust belt in southwest Montana and east-central Idaho: U.S. Geological Survey Professional Paper 1278, 41 p.

Rust, B.R., 1972, Structure and process in a braided river: *Sedimentology*, v. 18, p. 221-246.

_____, 1975, Fabric and structure in glaciofluvial gravels, in Jopling, A.V., and McDonald, B.C., eds., *Glaciofluvial and glaciolacustrine sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 23*, p. 238-248.

_____, 1978, Depositional models for braided alluvium, in Miall, A.D., ed., *Fluvial Sedimentology: Canadian Society of Petroleum Geologist Memoir 5*, p. 605-625.

_____, 1984, Proximal braidplain deposits in the Middle Devonian Malbaie Formation of eastern Gaspé, Quebec, Canada: *Sedimentology*, v. 31, p. 675-695.

Ryder, J.M., 1971, The stratigraphy and morphology of paraglacial alluvial fans in south-central British Columbia: *Canadian Journal of Earth Science*, v. 8, p. 279-298.

Ryder, R.T., 1968, The Beaverhead Formation: A Late Cretaceous-Paleocene syntectonic deposit in southwestern Montana and east-central Idaho [Ph.D. thesis]: University Park, Pennsylvania, Pennsylvania State University, 143 p.

Ryder, R.T., and Scholten, R., 1973, Syntectonic conglomerates in Southwestern Montana: Their nature, origin, and tectonic significance: *Geological Society of America Bulletin*, v. 84, p. 773-796.

Schultz, A.W., 1984, Subaerial debris-flow deposition in the upper Paleozoic Culter Formation, western Colorado: *Journal of Sedimentary Petrology*, v. 54, p. 759-772.

Schumm, S.A., Mosley, M.P., and Weaver, W.E., 1987, *Experimental Fluvial Geomorphology*: New York, John Wiley and Sons, 413 p.

Smith, G.A., 1986, Coarse-grained nonmarine volcanoclastic sediment: terminology and depositional process: *Geological Society of America Bulletin*, v. 97p. 1-10.

Smith, N.D., 1970, The braided stream depositional environment: Comparison of the Platte River with some Silurian clastic rocks, north central Appalachians: *Geological Society of America Bulletin*, v. 81, p. 2993-3014.

_____, 1974, Sedimentology and bar formation in the Upper Kicking Horse River, a braided outwash stream: *Journal of Geology*, v. 82, p. 205-223.

- Steidtmann, J.R., and Schmitt, J.C., 1988, Provenance and dispersal of tectogenic sediments in thin-skinned thrust terranes, in Kleinspehn, K., and Paola, C., eds., *New perspectives in sedimentary basin analysis*: New York, Springer-Verlag, p. 353-566.
- Suppe, J., 1985, *Principles of structural geology*: New Jersey, Prentice-Hall, 537 p.
- Thomas, G.M., 1981, *Structural geology of the Badger Pass area, southwestern Montana [M.S. thesis]*: Missoula, University of Montana, 58 p.
- Todd, S.P., 1989, Stream-driven, high-density gravelly traction carpets: possible deposits in the Trabeg Conglomerate Formation, SW Ireland and some theoretical considerations of their origin: *Sedimentology*, v. 36, p. 513-530.
- Tucker, M.E., 1989, *The field description of sedimentary rocks*: England, Open University Press, 112 p.
- Verges, J., and Burbank, D., 1992, Progressive unconformities: A key to understanding fold-and-thrust evolution: *EOS (American Geophysical Union Transactions)*, v. 73, no. 43, p. 545-546.
- Waresback, D.B., and Turbeville, B.N., 1990, Evolution of a Plio-Pleistocene volcanogenic-alluvial fan: The Puye Formation, Jemez Mountains, New Mexico: *Geological Society of America Bulletin*, v. 102, p. 298-314.
- Wells, N.A., 1984, Sheet debris flow and sheetflood conglomerates in Cretaceous cool-maritime alluvial fans, South Orkney Islands, Antarctica, in Koster, E.H., and Steel, R.J., eds., *Sedimentology of gravels and conglomerates*: Canadian Society of Petroleum Geologists Memoir 10, p. 133-145.
- Wells, N.A., and Harvey, A.M., 1987, Sedimentologic and geomorphic variations in storm-generated alluvial fans, Howgill Fells, northwest England: *Geological Society of America Bulletin*, v. 98, p. 182-198.
- Williams, P.F. and Rust, B.R., 1969, The sedimentology of a braided river: *Journal of Sedimentary Petrology*, v. 39, p. 649-679.
- Wilson, M.D., 1967, *The stratigraphy and origin of the Beaverhead Group in the Lima area, southwestern Montana [Ph.D. thesis]*: Evanston, Illinois, Northwestern University, 171 p.

APPENDICES

APPENDIX A
CONGLOMERATE CLAST COMPOSITION DATA

Table 5. Conglomerate clast count data

Location No.*	n	DAB** (m)	Limestone	Chert	Sandstone (CaCO ₃)	Sandstone (SiO ₂)
NG04;08	254	70	234	19	1	
NG05;10	148	114	127	20	1	
NG01;08	291	180	252	32	7	
NG02;01	276	203	260	15	1	
NG01;20	252	211	223	26	3	
NG02;07	287	242	240	45	2	
CH1;04/06	251	252	245	6		
NG03;05	257	256	234	14	6	3
CH2;03	202	265	200	2		
NG02;14	225	277	216	9		
NG03;13	283	292	259	17	6	1
NG03;24	260	350	230	17	13	

KEY

*Location No. = Section No.;Bed No.

**DAB = Distance above base

Table 6. Conglomerate clast modal percentage

Location No.	n	DAB** (m)	Limestone	Chert	Sandstone (CaCO ₃)	Sandstone (SiO ₂)
NG04;08	254	70	92	7.5	0.4	
NG05;10	148	114	85.8	13.5	0.7	
NG01;08	291	180	86.6	11	2.4	
NG02;01	276	203	94.2	5.4	0.4	
NG01;20	252	211	88.5	10.3	1.2	
NG02;07	287	242	83.6	15.7	0.7	
CH1;04/06	251	252	97.6	2.4		
NG03;05	257	256	91.1	5.5	2.3	1.2
CH2;03	202	265	99	1		
NG02;14	225	277	96	4		
NG03;13	283	292	91.5	6	2.1	0.4
NG03;24	260	350	88.5	6.5	5	

KEY

*Location No. = Section No.; Bed No.

**DAB = Distance above base

APPENDIX B
SANDSTONE DETRITAL MODES

Table 7. Sandstone point count data

Sample No.	DAB (m)	Total	Qm	Qp	Q	Lc	Ls	Lm	L	Other
NG04/08	51	252	164	54	218	26	7		33	1
NG01/01	157	249	206	29	235	11	3		14	
NG02/10A	260	258	190	42	232	12	11	1	24	2
CH1/01	262	254	26	10	36	217	1		218	
CH2/01	263	250	23	5	28	222			222	
CH2/02	269	257	4	22	26	228	2	1	231	
NG03/03	304	281	130	53	183	82			222	

KEY

DAB = Distance above base

Qm = Monocrystalline quartz

Qp = Polycrystalline quartz

Q = Total quartz (Qm + Qp)

Lc = Carbonate lithic fragments

Ls = Siltstone/sandstone lithic fragments

Lm = Metamorphic lithic fragments

L = Total unstable lithic fragments (Lc + Ls + Lm)

Lt = Total lithic fragments (L + Qp)

Other = Hornblende, phosphate, glauconite

Table 8. Sandstone modal percentage calculated for QFL ternary diagrams. After Folk (1968).

Sample No.	DAB (m)	Q	F	L	CRF	Cht	SS, St
NG04/08	51	67	0	33	32	60	8
NG01/01	157	88	0	12	35	55	10
NG02/10A	260	76	0	24	20	61	19
CH1/01	262	10	0	90	95	4	1
CH2/01	263	9	0	91	98	2	
CH2/02	269	2	0	98	91	8	2
NG03/03	304	49	0	51	57	32	11

KEY

DAB = Distance above base
 Q = monocrystalline quartz + metaquartzite
 F = Feldspar
 L = Lithic fragments including chert
 CRF = Carbonate rock fragments
 Cht = Chert
 SS, St = Sandstone and siltstone rock fragments

Table 9. Sandstone modal percentage calculated for QmFLt ternary diagrams. After Dickinson and others (1983).

Sample No.	DAB (m)	Qm	Qp	Q	L	Lt
NG04/08	51	65	22	87	13	35
NG01/01	157	82	12	94	6	17
NG02/10A	260	74	16	91	9	26
CH1/01	262	10	4	14	86	90
CH2/01	263	9	2	11	89	91
CH2/02	269	2	9	10	90	98
NG03/03	304	46	19	65	35	54

KEY

DAB = Distance above base

Qm = Monocrystalline quartz

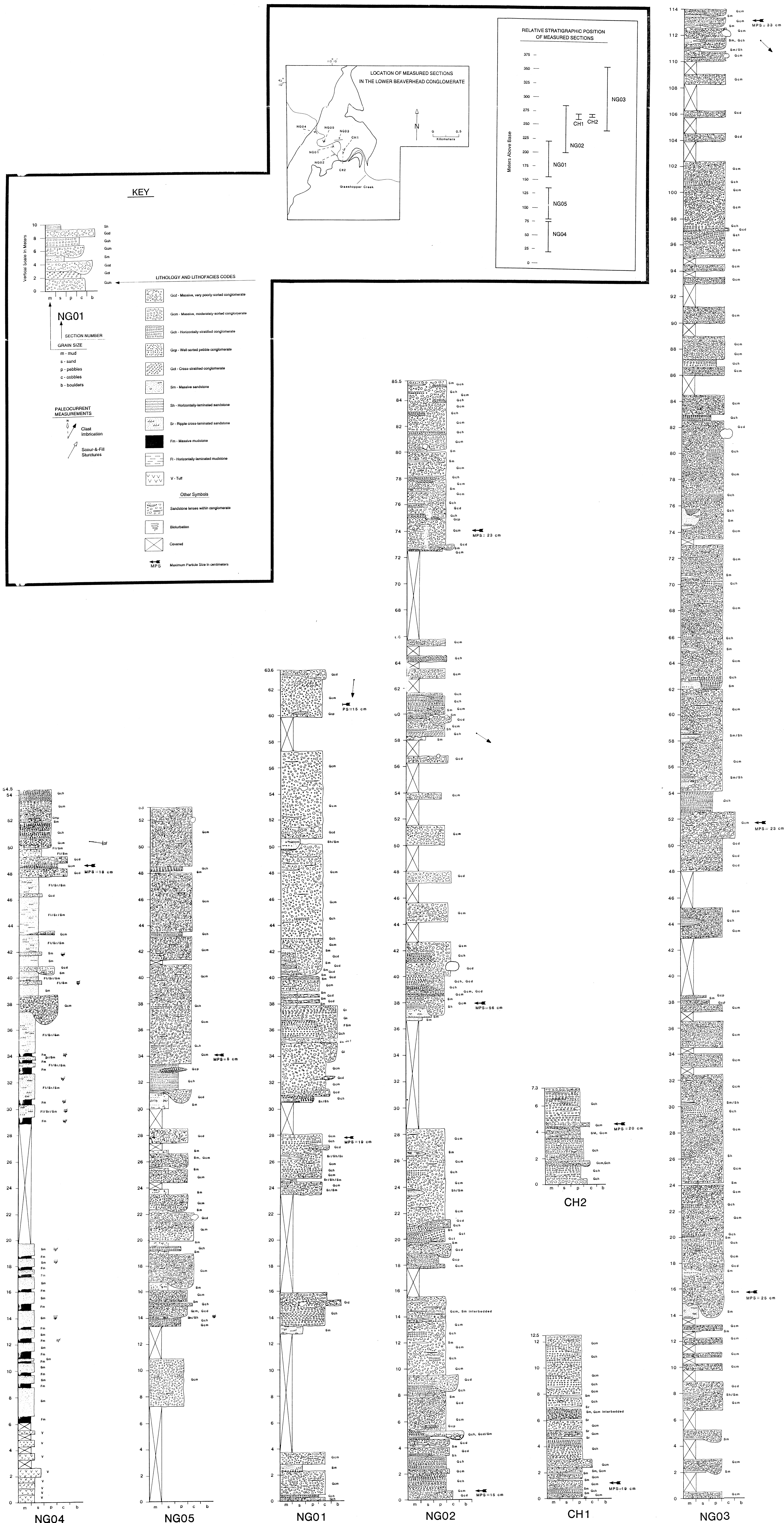
Qp = Polycrystalline quartz

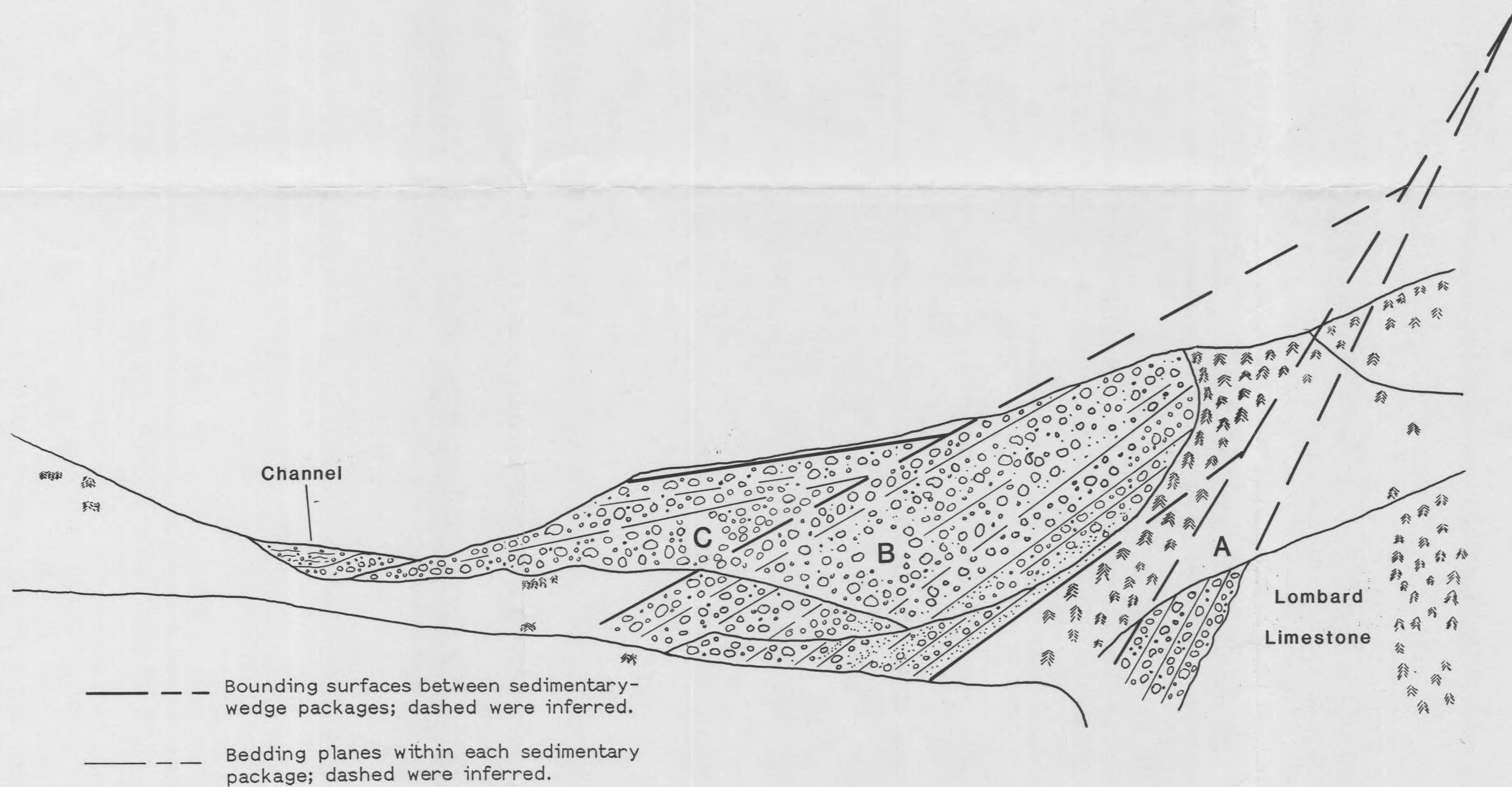
Q = Total quartz (Qm + Qp)

Lc = Carbonate lithic fragments

L = Unstable lithic fragments (carbonate, sandstone/siltstone, metamorphic)

Lt = Total lithic fragments (L + Qp)





Photomosaic and sketch of the lower Beaverhead strata on the south side of Grasshopper Creek. The lower Beaverhead strata are in depositional contact with the Mississippian Lombard Limestone on the eastern limb of the Madigan Gulch anticline. The three wedge-shaped packages (A, B, and C) are interpreted to be part of a single cumulative wedge system or a syntectonic progressive unconformity. Note that the right hand portion of skyline shown in sketch is extended beyond top of photomosaic. Also note that the oblique angle of photo and non-planar nature of outcrop causes a distortion in apparent dip angles on the left side of photomosaic. Direction of view varies from SSE to SW.

MONTANA STATE UNIVERSITY LIBRARIES



3 1762 10203137 2