



Sedimentary deposits and processes of the Late Cretaceous Adel Mountain volcanoclastic apron,
west-central Montana
by Julie Veronica LaBranche

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science In
Earth Sciences
Montana State University
© Copyright by Julie Veronica LaBranche (1999)

Abstract:

The Late Cretaceous Adel Mountain Volcanic (AMV) center was characterized primarily by mafic to intermediate, effusive volcanism and deposition of primary eruptive products and volcanoclastic sediments in coastal plain and marginal marine environments along the Western Interior Cretaceous seaway. The AMV succession consists of sequences of lava flows and associated intrusive and sedimentary rocks, including sequences of coarse-grained volcanoclastic deposits interbedded with fine-grained fluvial deposits. Sedimentary rocks are dominated by pebble to boulder, matrix- and clast-supported conglomerates and stratified, graded and massive sandstone and mudrock units.

This study applies delineation of lithofacies and lithofacies assemblages to define sedimentary transport processes and depositional environments that typify AMV volcanoclastic apron and intertonguing foreland basin deposits. Sedimentary rocks were divided into lithofacies, based on texture, grain size, fabric and geometry, and lithofacies assemblages, groups of lithofacies produced by common flow types and sediment support mechanisms. Five main flow types were recognized in the AMV succession: tidal currents, normal or dilute stream flow, hyperconcentrated flow, debris flow and lava flow. Associations of lithofacies assemblages are characteristic of particular depositional environments: lava flow and tidal current assemblages comprise tidal flat deposits of the coastal plain environment; normal or dilute stream flow and hyperconcentrated flow assemblages comprise deposits of the braidplain environment; and debris flow and hyperconcentrated flow assemblages comprise deposits of the volcanoclastic fan environment.

Late Cretaceous volcanic activity in western Montana induced significant changes in foreland basin depositional processes which are recorded by volcanoclastic sequences of the AMV center. Sedimentary deposits and primary igneous rocks of the AMV volcanoclastic apron were deposited in tidal flat, braidplain and volcanoclastic fan environments that record progradation of the volcanoclastic apron into the retroarc foreland basin. The lateral and vertical distribution of lithofacies assemblages record depositional processes in proximal, medial and distal regions of the volcanic center and distinctive lateral changes in sedimentation that correspond to distance from the volcanic source area. The lithofacies architecture of the AMV volcanoclastic apron and intertonguing foreland basin deposits is distinguished by widespread interruptive sedimentation, dominated by debris flow and hyperconcentrated flow deposition, in response to denudation of the volcanic center.

SEDIMENTARY DEPOSITS AND PROCESSES OF THE LATE CRETACEOUS
ADEL MOUNTAIN VOLCANICLASTIC APRON, WEST-CENTRAL MONTANA

By

Julie Veronica LaBranche

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

of

Master of Science

In

Earth Sciences

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

May, 1999

N378
21149

APPROVAL

of a thesis submitted by

Julie Veronica LaBranche

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.

Dr. James G. Schmitt

James Schmitt
(signature)

5-19-99
Date

Approved for the Department of Earth Sciences

Dr. Andrew Marcus

Andrew Marcus
(signature)

5/19/99
Date

Approved for the College of Graduate Studies

Dr. Bruce R. McLeod

Bruce R. McLeod
(signature)

5-25-99
Date

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University-Bozeman, 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

Julie V. LaBranche

Date

5/12/99

ACKNOWLEDGEMENTS

I would like to thank Prof. Jim Schmitt for helping me formulate this research project, for his financial support and for his patience, guidance and humor throughout the last three years. Also, thank you to my committee members, Prof. Steve Custer and Prof. Todd Feeley, for their thorough review of my thesis manuscript and helpful comments and inquiries during my thesis defense. This research was funded by grants from the Wyoming Geological Association and the Geological Society of America and a Teaching Assistantship from the Department of Earth Sciences, Montana State University, Bozeman.

Special thanks to the Blackman Family and Tom Siebel for allowing me to conduct field research on their properties. I would like to express my unending gratitude to Pat O'Connell, owner of the Bungalo Bed & Breakfast, for her gracious hospitality and support during my field work. Thank you, Pat, for giving me a safe, warm place to rest my weary body and a warm heart to come home to at the end of a long day! Thank you to the ESCI graduate students for their advice and support throughout this project. Thank you Ruth O'Neil for help in the field. Special thanks to Paul Azevedo for his assistance in the field and for being there when I needed him the most. Lastly, thanks to my parents, Bob and Nancy, and the rest of the extended LaBranche clan and to Caroline, "my biggest fan".

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iv
LIST OF TABLES	viii
LIST OF FIGURES	ix
ABSTRACT	xiii
INTRODUCTION	1
Purpose of Study	4
GEOLOGIC SETTING	5
Volcanic Setting	5
Study Area	10
Previous Work	12
Stratigraphy	13
METHODS	18
Field Methods	18
Analytical Methods	21
Lithofacies Analysis	22
LITHOFACIES	24
Introduction and Terminology	24
Descriptions and Interpretations	28
Conglomerate Lithofacies	28
Massive, Matrix-supported Conglomerate (<i>Gmm</i>)	28
Description	28
Interpretation	32
Massive, Normally-graded, Matrix-supported Conglomerate (<i>Gmn</i>)	34
Description	34
Interpretation	34

TABLE OF CONTENTS - continued

	Page
Massive, Reversely-graded, Matrix-supported Conglomerate (<i>Gmr</i>)	35
Description	35
Interpretation	35
Massive, Clast-supported Conglomerate (<i>Gcm</i>)	36
Description	36
Interpretation	37
Massive, Normally-graded, Clast-supported conglomerate (<i>Gcn</i>)	40
Description	40
Interpretation	40
Massive, Ungraded, Imbricated, Clast-supported Conglomerate (<i>Gci</i>)	41
Description	41
Interpretation	41
Massive, Reversely-graded, Clast-supported Conglomerate (<i>Gcr</i>)	42
Description	42
Interpretation	42
Sandstone Lithofacies	43
Massive Sandstone (<i>Sm</i> , <i>Smg</i> , <i>Sgn</i> , <i>Sgr</i> , <i>Smp</i>)	43
Description	43
Interpretation	46
Stratified or Laminated Sandstone (<i>Sh</i> , <i>Shg</i> , <i>Sl</i> , <i>Sr</i>)	49
Description	49
Interpretation	51
Massive, Deformed Sandstone (<i>Sd</i>).....	52
Description	52
Interpretation	53
Mudrock Lithofacies	54
Massive Mudrock (<i>Fm</i>)	54
Description	54
Interpretation	54
Laminated Mudrock (<i>Fl</i>)	56
Description	56
Interpretation	56
Lava Flow Lithofacies	57
Volcanic Breccia (<i>Vb</i>)	57
Description	57

TABLE OF CONTENTS - continued

	Page
Interpretation	59
LITHOFACIES ASSEMBLAGES	60
Lava Flow Assemblage (LF)	63
Debris Flow Assemblage (DF)	65
Hyperconcentrated Flow Assemblage (HF)	66
Normal or Dilute Stream Flow Assemblage (SF)	69
Tidal Current Assemblage (TC)	72
DEPOSITIONAL ENVIRONMENTS	76
Tidal Flat Environment	76
Braidplain Environment	79
Volcaniclastic Fan Environment	85
DISCUSSION	90
Sediment Production	90
Depositional Model	92
Comparison of Effusive and Explosive Volcanic Systems	95
CONCLUSIONS	100
REFERENCES CITED.....	102
APPENDICES	110
Appendix A	111
Locations of Measured Sections	112
Appendix B	114
Summary of Petrographic Analysis of Thin Sections.....	115

LIST OF TABLES

Table	Page
1. Geologic map descriptions of AMV rock units Tve, Tvd, Tvc and Tvab from the Craig and Coburn Mountain Quadrangles, Lewis and Clark and Cascade Counties, Montana.	16
2. Summary of lithofacies codes and descriptions, sedimentary structures, flow types and flow characteristics.	29
3. Summary of constituent lithofacies present in each lithofacies assemblage, lithofacies assemblage codes and flow types.	60
4. Summary of petrologic analysis of thin sections of AMV sedimentary rocks.	115

LIST OF FIGURES

Figure	Page
1. Generalized geologic map showing distribution of Upper Cretaceous rocks of the Adel Mountain Volcanic center (green), the Two Medicine Formation (gray) and Paleozoic rocks.(blue).....	3
2. Diagrammatic illustration of the paleogeographic setting of the Adel Mountain Volcanic center during Late Cretaceous time.....	6
3. Dike sarms and arcuate laccoliths radiating from the Three Sisters Stock of the Adel Mountain Volcanic center	9
4. Locations of the Coburn Mountain Quadrangle (A) and Craig Quadrangle (B).....	11
5. Upper Cretaceous stratigraphy of western Montana.....	14
6. Locations of measured stratigraphic sections DB-1, DB-2, DB-3, DB-4 and DB-5 in the Coburn Mountain field area.....	19
7. Locations of measured stratigraphic sections Tvd-1,2,3,4, ST-1,2,3,4,6,7,8 and Hwy-N in the Craig field area	20
8. Flow processes and sediment support mechansims that define tidal current, normal stream flow, hyperconcentrated flow and debris flow assemblages.....	25
9. Massive matrix-supported conglomerate (Gmm) from measured section ST-7.....	31
10. A. Poorly-sorted, massive clast-supported conglomerate (Gcm) with pebble to boulder size framework clasts from section DB-1 (hammer is 32 cm in length). B.Coarse-grained, poorly-sorted, massive, clast-supported conglomerate (Gcm) with cobble to boulder size clasts from measured section ST-5.....	38

LIST OF FIGURES - (continued)

Figure	Page
11. Interbedded massive sandstone (Sm), massive mudrock (Fm), massive sandstone with gravel (Smg) and low-angle cross-bedded sandstone (Sl) lithofacies from measured section Tvd-1 (Jacob staff is 1.5 m in length)	45
12. Massive sandstone (Smg), massive sandstone (Sm) and massive sandstone with pedogenic features (Smp) (from measured section DB-1)	47
13. Climbing ripples (Sr) in tidal current assemblage from measured section Tvd-1 (hammer head is 12 cm in width)	50
14. Massive mudrock (Fm), laminated mudrock (Fl), massive sandstone (Sm) and horizontally stratified sandstone (Sh) of the tidal flat assemblage from measured section Tvd-1 (hammer is 32 cm in length)	55
15. Brecciated lava flow (Vb) from measured section Tvd-3 (hammer is 32 cm in length)	58
16. Generalized volcanoclastic fan facies model illustrating proximal, medial and distal facies: A) plan view B) cross-sectional view	62
17. A) Boulder size clasts, exhibiting radial cooling joints in brecciated lava flow (Vb) in gradational contact with massive, poorly-sorted, clast-supported conglomerate (Gcm) and B) spheroidal weathering pattern of clasts from measured section Tvd-3 (notebook is 19 cm in length)	64
18. A) Massive, matrix-supported conglomerate (Gmm) fills a channel incised into underlying massive, clast-supported conglomerate (Gcm). B) Massive sandstone (Sm) wedge fills left side of channel (from highway outcrop Hwy-N)	67
19. Sandstone lense chaotically interbedded with massive clast-supported conglomerate (Gcm) from measured section ST-6 (notebook at center of circle is 19 cm in length).....	68

LIST OF FIGURES - (continued)

Figure	Page
20. Horizontally stratified sandstone with gravel (Shg) overlain by massive, normally-graded conglomerate (Gcn) with sharp, slightly irregular contact from measured section DB-3 (Jacob staff is 1.5m in length)	70
21. Stream flow and hyperconcentrated flow assemblage lithofacies including massive sandstone (Sm) and laminated and massive mudrock (Fl, Fm) lithofacies from measured section DB-1 (Jacob staff is 1.5 m in length)	71
22. Outcrop of tidal current assemblage lithofacies including interbedded massive mudrock (Fm) and massive sandstone (Sm).....	73
23. Tidal current assemblage lithofacies exhibiting wavy flaser bedding (A) , wavy bedding (B) and flame structures (C) from measured section Tvd-1.....	74
24. Illustration of an outcrop including measured sections Tvd-1,2,3 and 4 showing lateral and vertical stratigraphic relations of lava flow, tidal current and debris flow assemblages (outcrop width is approx. 50 m)	77
25. Laterally extensive hyperconcentrated flow and normal stream flow assemblage lithofacies interbedded with five paleosol horizons (lithofacies Smp) from measured section DB-1	80
26. AMV braided stream systems exhibit sedimentologic features common to: A) distal, sheetflood, sand-bed rivers and B) flashy, ephemeral, sheetflood, sand-bed rivers described by Miall	81
27. Generalized stratigraphic column of debris flow, hyperconcentrated flow and normal stream flow assemblages in the distal braidplain environment (from measured section DB-1)	84
28. Lithofacies assemblages of the volcanoclastic fan environment including channelized (confined flow) and debris flows debris flow sheets (unconfined flow) with incised channels infilled with hyperconcentrated flow and debris flow deposits (top). Eight, 3 m measured sections from highway outcrop, Hwy-N (bottom)	87

LIST OF FIGURES - (continued)

Figure	Page
29. Generalized stratigraphic columns of sequences of lithofacies assemblages which define: A) tidal flat environment, B) braidplain environment; and C) volcaniclastic fan environment.....	93
30. Volcaniclastic facies model for the AMV center illustrating lateral variation of depositional processes and deposits of tidal flat, braidplain and volcaniclastic fan environments	96

ABSTRACT

The Late Cretaceous Adel Mountain Volcanic (AMV) center was characterized primarily by mafic to intermediate, effusive volcanism and deposition of primary eruptive products and volcanoclastic sediments in coastal plain and marginal marine environments along the Western Interior Cretaceous seaway. The AMV succession consists of sequences of lava flows and associated intrusive and sedimentary rocks, including sequences of coarse-grained volcanoclastic deposits interbedded with fine-grained fluvial deposits. Sedimentary rocks are dominated by pebble to boulder, matrix- and clast-supported conglomerates and stratified, graded and massive sandstone and mudrock units.

This study applies delineation of lithofacies and lithofacies assemblages to define sedimentary transport processes and depositional environments that typify AMV volcanoclastic apron and intertonguing foreland basin deposits. Sedimentary rocks were divided into lithofacies, based on texture, grain size, fabric and geometry, and lithofacies assemblages, groups of lithofacies produced by common flow types and sediment support mechanisms. Five main flow types were recognized in the AMV succession: tidal currents, normal or dilute stream flow, hyperconcentrated flow, debris flow and lava flow. Associations of lithofacies assemblages are characteristic of particular depositional environments: lava flow and tidal current assemblages comprise tidal flat deposits of the coastal plain environment; normal or dilute stream flow and hyperconcentrated flow assemblages comprise deposits of the braidplain environment; and debris flow and hyperconcentrated flow assemblages comprise deposits of the volcanoclastic fan environment.

Late Cretaceous volcanic activity in western Montana induced significant changes in foreland basin depositional processes which are recorded by volcanoclastic sequences of the AMV center. Sedimentary deposits and primary igneous rocks of the AMV volcanoclastic apron were deposited in tidal flat, braidplain and volcanoclastic fan environments that record progradation of the volcanoclastic apron into the retroarc foreland basin. The lateral and vertical distribution of lithofacies assemblages record depositional processes in proximal, medial and distal regions of the volcanic center and distinctive lateral changes in sedimentation that correspond to distance from the volcanic source area. The lithofacies architecture of the AMV volcanoclastic apron and intertonguing foreland basin deposits is distinguished by widespread interruptive sedimentation, dominated by debris flow and hyperconcentrated flow deposition, in response to denudation of the volcanic center.

INTRODUCTION

Analysis of volcanoclastic deposits is critical to understanding the paleogeography and the physical and magmatic evolution of volcanic centers. Previous research in and facies models of volcanoclastic environments have focused on explosive continental volcanism, including andesitic-dacitic stratovolcanoes (Rowley et al., 1985; Hackett and Houghton, 1989; Turbeville et al., 1989; Waresback and Turbeville, 1990; Palmer et al., 1993) and rhyolitic calderas (Walton, 1986). In comparison, volcanoclastic sedimentation associated with effusive, continental volcanism is limited to a few studies of small-volume, monogenetic dome fields (White, 1991; and Riggs et al., 1997). Consequently, facies models for modern and ancient examples of mafic effusive volcanic centers in continental settings are poorly defined (White, 1991; Riggs et al., 1997). In these settings, detailed investigation of volcanoclastic sedimentation is lacking in : 1) definition of sediment transport processes at and radially away from the eruptive center; 2) characteristic lithofacies architecture; and 3) the influence of eruptive activity on adjacent depositional systems. The goals of this study are to document continental volcanoclastic sedimentation adjacent to an effusive, mafic volcanic center and thereby contribute to the knowledge base of volcanoclastic facies models.

The Late Cretaceous Adel Mountain Volcanic (AMV) complex evolved in paleogeographic and tectonic settings unusual in both modern and ancient examples of terrestrial volcanism. This mafic to intermediate, dominantly effusive, volcanic complex formed adjacent to the Western Interior Cretaceous seaway and within the retroarc foreland basin of the Cordilleran fold-thrust belt of west-central Montana. The AMV complex preserves a 975 m thick succession of primary eruptive, intrusive and volcanoclastic rocks of mafic to intermediate alkalic composition, east of the Sevier fold-thrust belt near Craig and Wolf Creek, Montana (Figure 1). The AMV complex is an excellent location to document volcanoclastic facies architecture not presently accounted for in existing models of continental, mafic effusive volcanism because: 1) the volcanic rocks are well-exposed and little deformed; 2) relations between volcanoclastic apron deposits and deposits of adjacent environments are distinguishable; 3) the volcanic stratigraphy and petrology are reasonably well-defined; and 4) the unusual occurrence of volcanism within a foreland basin provides an opportunity to investigate effects of eruptive activity on adjacent foreland basin depositional systems.

Although the sedimentologic evolution of the Western Interior Cretaceous seaway and retroarc foreland basin are well-documented (Kauffman and Caldwell, 1993), the significance of AMV volcanoclastic sedimentation to foreland basin stratigraphy is largely unknown. Improved knowledge of sedimentation proximal to mafic volcanic centers will provide better tools for interpreting foreland basin-fill

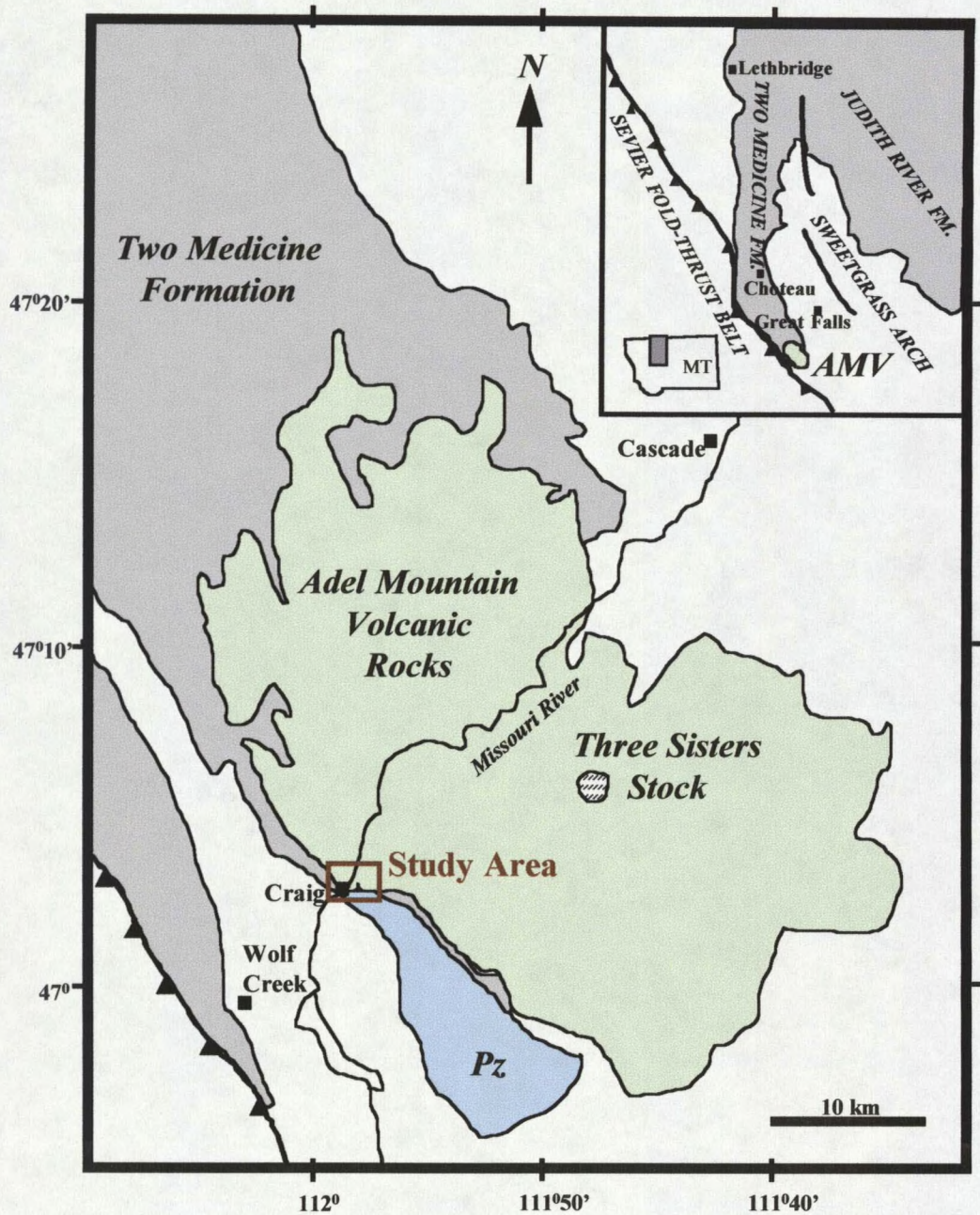


Figure 1: Generalized geologic map showing distribution of Upper Cretaceous rocks of the Adel Mountain Volcanic center (green) and the Two Medicine Formation (gray), and Paleozoic rocks (blue) (after Schmitt, unpublished map).

sequences influenced by eruptive activity. This is especially relevant to deciphering basin paleogeography in tectonically active basins where production of volcanoclastic sediment can complicate depositional patterns. Furthermore, understanding the regional significance of volcanoclastic processes and deposits will support improved interpretations of Late Cretaceous paleoenvironments in western Montana.

Purpose of Study

This thesis examines characteristic lithofacies architecture and depositional processes and environments of the AMV volcanoclastic apron and intertonguing foreland basin deposits. The specific research questions are:

1. What lithofacies characterize the sedimentary rocks of the volcanoclastic apron and intertonguing foreland basin deposits?
2. What sediment transport processes were active during deposition of the volcanoclastic apron and intertonguing foreland basin deposits? What types of lithofacies are produced by specific sediment transport processes?
3. What lithofacies, groups of lithofacies and sediment transport processes are indicative of depositional environments preserved in deposits of the volcanoclastic apron and adjacent foreland basin?
4. How do temporal and spatial changes in depositional environments influence the stratigraphy of the volcanoclastic apron and adjacent foreland basin?

GEOLOGIC SETTING

During Cretaceous time, the North American Cordillera comprised the following major tectonic elements: a western coastal-belt subduction zone complex; a broad calc-alkalic magmatic arc; an eastern fold-thrust belt; and a retroarc foreland basin occupied by the Western Interior seaway (Kauffman and Caldwell, 1993).

Tectonism induced prolonged episodes of magmatism, volcanism, eustatic sea-level fluctuations, including the highest post-Paleozoic stand from latest Albian through middle Maastrichtian time, and accelerated foreland-basin subsidence induced by progressive eastward propagation of the fold-thrust belt (Kauffman and Caldwell, 1993). Although more than 1300 volcanic ash and bentonite beds contained in Western Interior Basin sequences record explosive volcanism through approximately 38 m.y. of Albian-Maastrichtian time (Kauffman and Caldwell, 1993), some volcanoclastic successions in western Montana remain undefined in terms of their depositional sequences, geometry and facies distribution, and local stratigraphic relations.

Volcanic Setting

The geologic evolution of the Adel Mountain Volcanic complex reflects interactions between tectonism, volcanism and sedimentation. The AMV center is

characterized by polygenetic, mafic to intermediate volcanism centered within a retroarc foreland basin, depositing primary eruptive products and volcaniclastic sediments in coastal plain and marginal marine environments along the western margin of the Western Interior Cretaceous seaway (Figure 2). The southern and western margins of the AMV center are marked by zones of intense deformation. Thrust faults and folds extend beneath the complex along the southern margin, pre-dating volcanic activity (Schmidt, 1972; Schmidt, 1977; Schmidt, 1978; Sheriff and Gundersen, 1990).

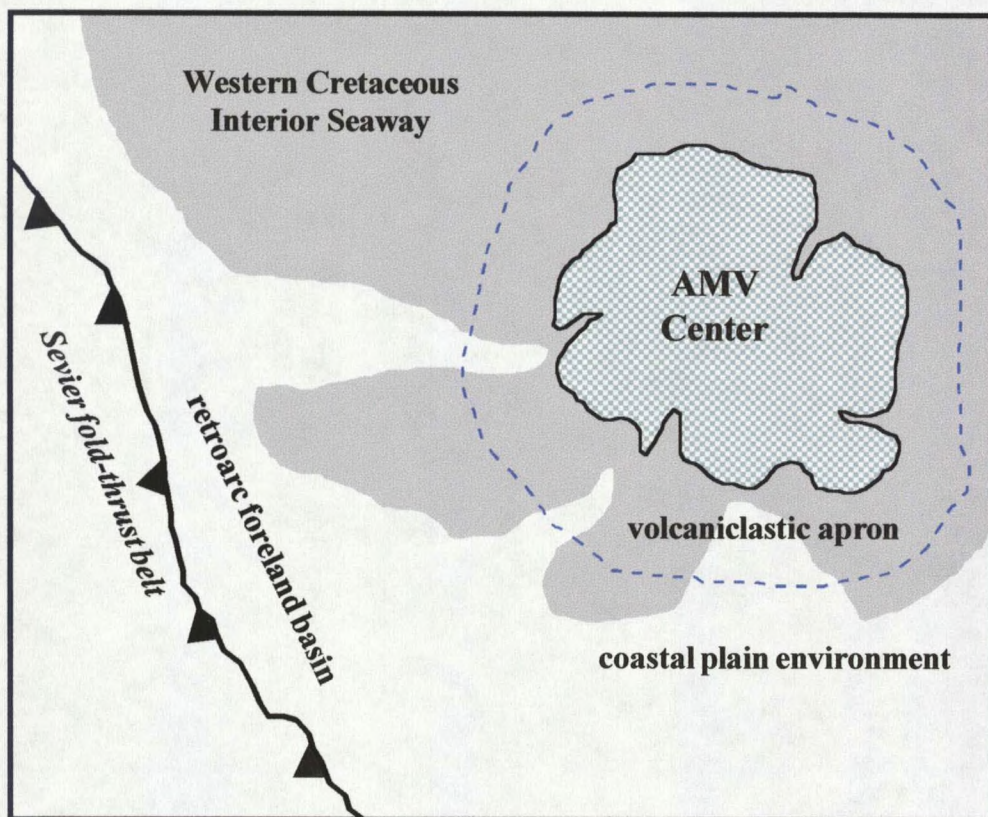


Figure 2: Diagrammatic illustration of the paleogeographic setting of the Adel Mountain Volcanic center during Late Cretaceous time.

Both the southern and western margins are cut by the Eldorado thrust which places Proterozoic Spokane Shale over AMV rocks (Lyons, 1944). Between the Eldorado thrust to the west and AMV center to the east, the Craig anticlinorium comprises complexly imbricated thrust faults placing Mississippian, Jurassic and Cretaceous units over AMV rocks and marks the eastern limit of Sevier thrusting (Schmidt, 1978). Due to pervasive homogeneity of individual rock units and the absence of distinct marker beds, few faults are identified within the AMV complex (Lyons, 1944).

Igneous activity in the AMV center produced large volumes of shonkinite, a mafic alkaline rock consisting of potassium feldspar and augite in approximately equal proportions with minor nepheline, olivine, biotite, magnetite and apatite and zeolites (Hyndman and Alt, 1987). Zeolites formed by alteration of potassium feldspar (Hyndman and Alt, 1987) or as primary minerals by the concentration of magmatic water as a result of crystallization of silicate minerals (Lyons, 1944). Extrusive rocks, including lava flows and flow breccias, are composed mainly of trachybasalt (analcime and augite varieties), latite and quartz latite (Lyons, 1944). Intrusive rocks, including dikes, sills and laccoliths, are composed of a wide range of mafic to intermediate rock types including diabase, syenogabbro, diorite, monzonite (hornblende, augite, sanidine and quartz varieties) and augite monzonite porphyry. Petrologic analyses indicate that the AMV alkalic series formed by crystal settling during differentiation showing a gradual and steady decrease in mafic minerals and calcic plagioclase and a corresponding increase in orthoclase (Lyons, 1944). Research by Cunningham (1999)

suggests two processes of magma petrogenesis; fractionation of shonkinitite to form syenite and generation of latite by some form of differentiation associated with partial melting of the crust associated with ascention of shonkinitic magma.

Intrusive bodies are prominent components of the volcanic succession which include radial dike swarms and arcuate laccoliths exposed in northern portions of the AMV center (Figure 3). The main dike swarm radiates approximately northward from an intrusion in Three Sisters Mountain (referred to as the Three Sisters Stock) near the center of the AMV succession. The dikes cross-cut shonkinitic extrusive rocks of the volcanic center indicating emplacement in the later stages of igneous activity (Beall, 1973; Whiting, 1974; Hyndman and Alt, 1987). The dikes range from a few m to a maximum of 20 m thick and stand in topographic relief to the less resistant Late Cretaceous sedimentary formations which they intrude (Hyndman and Alt, 1987). The radial distribution of the dikes result from load stresses produced by the the overlying central volcanic pile rather than stresses imposed by magma intrusion (Beall, 1973; Whiting, 1974; Hyndman and Alt, 1987).

The AMV complex represents a less than 10 m.y. period of magmatic activity during the later stages of Sevier fold-thrust belt contractile deformation in western Montana (Harlan et al., 1991). Several workers have reported various age dates from extrusive and intrusive rocks all of which support a Late Cretaceous age for the AMV center. Sheriff and Gunderson (1990) and Gunderson and Sheriff (1991) dated AMV rocks using whole-rock K-Ar analysis which yield age dates of 81.1 ± 3.5 Ma. from

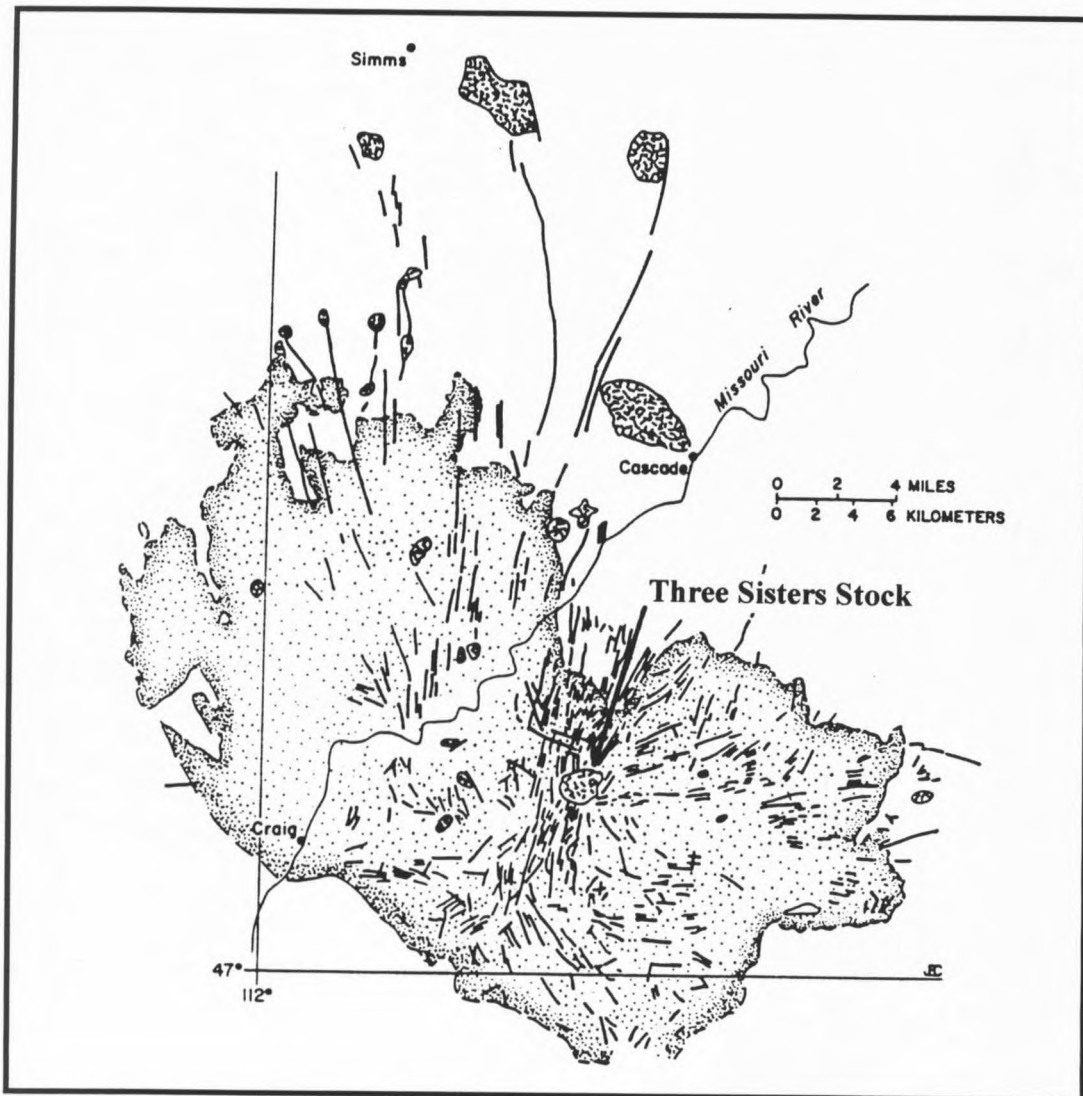


Figure 3: Dike swarms and arcuate laccoliths radiating from the Three Sisters Stock of the Adel Mountain Volcanic center (from Hyndman and Alt, 1987).

basaltic lava flows (representing early-stage volcanic activity) and 71.2 ± 2.7 Ma from shonkinite dikes that crosscut the volcanic center (representing late-stage intrusive activity). Harlan et al. (1991) dated basal volcanic rocks, using biotite and whole-rock age spectra analysis, which yield an approximate age of 75-76 Ma suggesting eruptive activity spanned a relatively short period (1-3 m.y. maximum). In addition, hornblende and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ dates from three radial dikes yield an average age of 73.6 ± 0.7 Ma. (Harlan et al., 1991).

In summary, petrologic characteristics, cross-cutting and structural relations and reported age dates of extrusive and intrusive igneous rocks suggest a two-stage magmatic evolution of the AMV center; early-stage mafic to intermediate volcanic activity followed by later-stage mafic to intermediate intrusive activity.

Study Area

The study area includes southwest portions of the Coburn Mountain Quadrangle (Schmidt, 1972) and west-central portions of the Craig Quadrangle (Schmidt, 1977) located in Lewis and Clark and Cascade Counties, Montana (Figure 4). The AMV center is highly dissected. Extensive erosion of proximal, near-vent areas has exposed much of the volcanic core region (proximal vent facies) and left only portions of the volcanoclastic apron intact along western and southwestern margins of the complex. The Missouri River roughly bisects the AMV center, revealing nearly

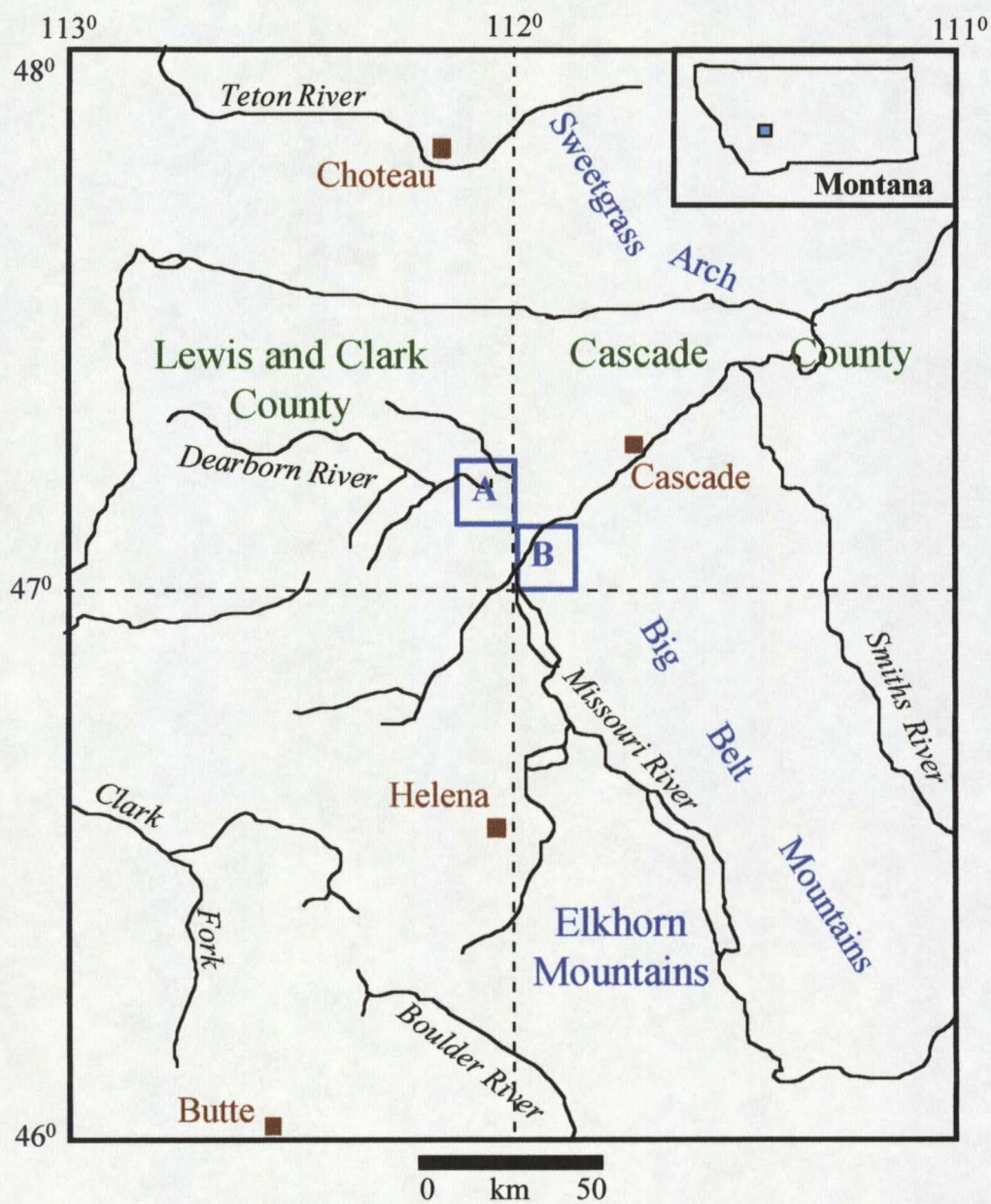


Figure 4: Locations of the Coburn Mountain Quadrangle (A) and Craig (B) Quadrangle (after Schmidt, 1977).

vertical exposures of intrusive, primary volcanic and volcanoclastic rocks. Primary volcanic rocks are concentrated in interior regions of the AMV center and comprise lava flows and flow breccia units crosscut by networks of radial dikes, sills and laccoliths. The AMV sedimentary succession comprises sequences of interbedded conglomerate, sandstone, mudrock and minor amounts of volcanic breccia that are well-exposed in field areas along the Missouri River near the town of Craig and Coburn Mountain. Outcrops of volcanoclastic rocks typically form isolated linear ridges and knobs east of the Missouri River and prominent topographic features west of the Missouri River including Coburn Mountain, Elephant Mountain and Gardipee Buttes. Bedding in structurally undeformed AMV rock units dips ($0-14^{\circ}$) quaquaversally from the volcanic core region (Schmidt, 1972; Schmidt, 1977). Throughout the study area, AMV rocks are overlain by discontinuous Pleistocene terrace gravels and glacial lake deposits and Holocene colluvial, landslide and stratified alluvium (Schmidt, 1972; Schmidt, 1977).

Previous Work

In the first comprehensive study of the AMV complex, Lyons (1944) made general observations of local structures and features and the stratigraphy and petrologic characteristics of the volcanic rocks of the northern Big Belt Mountains. Schmidt (1972, 1977, 1978) mapped generalized stratigraphic and structural relations and

reported detailed petrologic analysis and descriptions of AMV rocks. Subsequent research has focused on refined petrologic and geochemical analyses of igneous units and mechanics of intrusive features (Beall, 1973; Whiting, 1977; Hyndman and Alt, 1987; Swenson, 1987; Cunningham, 1999). The AMV complex was assigned a tenuous Late Cretaceous (Lyons, 1944) and, later, Early Paleocene age based on petrographic relations, and stratigraphic and paleontologic evidence (Schmidt, 1972; Schmidt, 1977; Schmidt, 1978). However, recent isotopic studies have produced ages of 73.6 (+/- 0.7) Ma by $^{40}\text{Ar}/^{39}\text{Ar}$ method (Harlan et al., 1988; Harlan et al., 1991) and 81.1 (+/- 3.5) – 71.2 (+/- 2.7) Ma by K-Ar method (Sheriff and Gunderson, 1990; Gunderson and Sheriff, 1991), unequivocally defining the AMV complex as Late Cretaceous (Campanian-Maastrichtian). Figure 5 shows regional age relations between western Montana stratigraphic units and AMV rocks, which are locally correlative with portions of the Two Medicine Formation, St. Mary River Formation and Elkhorn Mountain Volcanic rocks.

Stratigraphy

Chronostratigraphic relations of AMV rock units are not clearly defined and reflect the scope and focus of previous studies of the AMV complex. Geologic maps of the study area and previous geologic investigations (Lyons, 1944; Schmidt 1972; Schmidt, 1977) assign a Paleocene-Eocene age for the AMV complex and illustrate grossly generalized stratigraphic relations of rock units in cross-section.

Upper Cretaceous Series			Wolf Creek area	Elkhorn Mountains	Livingston area	Central Montana
Maestrichtian	upper	my 74.5	*71.2 +/- 0.7 Ma Adel Mountain Volcanic Rocks *81.1 +/- 3.5 Ma	Willow Creek Formation	Fort Union Formation	Hell Creek Formation
	lower				Hoppers Formation	
					Billman Creek Formation	Fox Hills Sandstone
					Miner Creek Formation	Bearpaw Shale
Campanian	upper	84.0	Eastern and Western facies of Two Medicine Formation	Elkhorn Mountains Volcanic Rocks	Cokedale Formation	Judith River Formation
	lower				Eagle Sandstone	Claggett Shale
Santonian	upper	87.5	Virgelle Sandstone	Slim Sam Formation	Telegraph Creek Formation	Eagle Sandstone
	middle		Telegraph Creek Formation			Telegraph Creek Formation
	lower		Marias River Shale [Kevin Member]	Colorado Formation	Cody Shale	Niobrara Formation

Figure 5: Upper Cretaceous stratigraphy of western Montana. [Note: * Age dates for Adel Mountain Volcanic rocks from Sheriff and Gunderson (1991) and Gunderson and Sheriff (1990)]

Schmidt (1972, 1977, 1978) divided AMV rocks into four map units; volcanoclastic and lacustrine deposits (Tve, Tvd) and lava flows, volcanic breccias and intrusives (Tvc, Tvab) (Table 1). Field observations and rock unit descriptions indicate these divisions were based largely on petrologic characteristics of the rocks, not formal stratigraphic divisions. Because this thesis research is based on sedimentologic, stratigraphic and environmental interpretations, AMV rocks are subdivided into lithologic units (for discussion refer to LITHOFACIES section). Map units devised by Schmidt are used only to clarify the locations of measured sections on study area maps based on the Craig and Coburn Mountain Quadrangles (Schmidt, 1972; Schmidt, 1977).

Principal rock types in the study area include extrusive rocks composed of augite trachybasalt with lesser amounts of latite and quartz latite, and intrusive rocks composed of gabbro, monzonite (quartz, hornblende, augite, and sanidine varieties), monzonite porphyry and diorite (Lyons, 1944; Viele and Harris, 1965; Schmidt, 1972; Schmidt, 1977; Schmidt, 1978). Clasts contained in flow breccia and conglomerate lithofacies are composed mainly of augite trachybasalt and latite, with the exception of rare mudstone intraclasts. Many igneous clasts exhibit a notably consistent polygonal shape which is inferred to reflect the polygonal jointing pattern of igneous rocks upon cooling; hexagonal and columnar jointing were noted in intrusive rocks of the AMV center by Lyons (1944). Clasts showing spheroidal weathering patterns were also noted in flow breccia beds (lithofacies *Vb*) in the study area.

Table 1. Geologic map descriptions of AMV rock units Tve, Tvd, Tvc and Tvab from the Craig and Coburn Mountain Quadrangles, Lewis and Clark and Cascade Counties, Montana (from Schmidt, 1972, 1977).

Unit	Adel Mountain Volcanic Rock Units
Tve	<u>Volcanic Conglomerate</u> – Red, purplish red gray, and brownish gray; poorly sorted and indistinctly bedded; composed of rounded and subrounded clasts of trachybasalt, trachyandesite, latite, and quartz latite ranging from pebble size to as much as 2 ft (0.6m) across; a few thin interbeds of red, purplish-gray, gray, and brownish-gray volcanic sandstone, siltstone, and mudstone; maximum exposed thickness about 1,000 ft (304 m)
Tvd	<u>Lacustrine Deposits</u> – Gray, brownish-gray, and dark-brown volcanic sandstone, siltstone, and mudstone in thin beds; plant fragments and leaf impressions on some bedding surfaces; exposed thickness ranges from feather edge to about 20 ft (6 m); exposed only near east bank of Missouri River, 1.5 mi (2.5 km) north of Craig
Tvc	<u>Latitic Breccias and Lava Flows</u> – Chiefly brownish-gray and light-pinkish-gray volcanic breccias and brown, light-grayish-brown, light-pinkish-gray, and light-greenish-gray lava flows. Breccias composed of abundant angular clasts of latite and fewer clasts of trachyandesite in a matrix of coarse tuff; clasts as much as 10 ft (3 m) across; individual bodies of breccia as much as several hundred feet thick. Flows are massive, finely porphyritic latite with phenocrysts of augite in a groundmass of andesine, sanidine, augite, hornblende, magnetite, and apatite; tops of flows commonly brecciated; individual flows as much as 200 ft (60 m) thick
Tvab	<u>Trachybasaltic Breccias and Lava Flows</u> – Chiefly interfingering masses of dark-red, purplish-red, dark-grayish-green, and dark-gray volcanic breccia composed of abundant angular clasts of trachybasalt and fewer clasts of trachyandesite in a matrix of coarse tuff; lower breccias massive, unsorted, and coarse with clasts as much as 20 ft (6 m) across; upper breccias, beneath volcanic conglomerate unit, less coarse with thin lenses and interbeds of waterlaid volcanic sandstone, siltstone and mudstone. Thin lava flows of dark-gray, brown-weathered trachybasalt interlayered with the breccias at several different horizons, chiefly north and east of Stickney Creek; flows massive and coarsely porphyritic with large phenocrysts of augite in a fine-grained groundmass of labradorite, sanidine, augite, olivine, and magnetite; individual flows as much as 40 ft (12 m) thick. Maximum inferred thickness of unit about 1,500 ft (450 m) *Note: Unit Tvab is broken into two units on the Coburn Mountain Quadrangle, units Tva and Tvb.

Along the southern and western margins of the study area, portions of the volcanoclastic apron and marginal deposits are truncated by northwest-trending thrust faults and, thus, are not preserved in the AMV succession. Here, the upper portion of the eastern facies of the Upper Cretaceous Two Medicine unconformably overlies AMV rocks as a result of displacement by regional Paleocene thrust faults (Schmidt, 1972; Schmidt, 1977). Precambrian, Cambrian, Mississippian, Jurassic and Cretaceous stratified sedimentary rocks, of continental and marine origin, and intrusive and

extrusive volcanic rocks are included in these fault sequences (Schmidt, 1972; Schmidt, 1977).

The Two Medicine Formation is divided into two lithologically distinct sequences, the western and eastern facies, and is composed mainly of sedimentary and clastic volcanic rocks (Schmidt, 1978). The western facies comprises a lower sedimentary member and an upper volcanic member (Schmidt, 1978); eastern and northern exposures of the upper volcanic member are referred to as the Big Skunk Formation by Viele and Harris (1965). The eastern facies comprises a lower sedimentary member (equivalent to the lower sedimentary member of the western facies) and an upper clastic volcanic member including sandstone, siltstone, mudstone, limestone, bentonite and ash-fall tuff beds (Schmidt, 1978). The eastern facies of the Two Medicine Formation and AMV rocks are in conformable contact in the northern portion of the study area (Unit *Tva*, massive volcanic breccia, Coburn Mountain Quadrangle) (Schmidt, 1972; Smith, 1998) and are considered time-equivalent rock units. Near Elephant Mountain (directly north of Coburn Mountain field area), workers have observed conformable stratigraphic contacts and noted marine fossils in the Two Medicine Formation, indicating deposition in a shallow marine environment (Smith, 1998).

METHODS

Field Methods

The stratigraphic and sedimentologic framework for field study includes detailed section measurement and description, sample collection and reconnaissance of stratigraphic and structural relations of AMV rocks. Stratigraphic sections were measured using a Jacob staff and Brunton compass and detailed descriptions were noted. Stratigraphic sections were located based on the distribution and exposure of volcanoclastic rocks, outcrop accessibility, and location relative to the volcanoclastic apron region and environments adjacent to the AMV complex (refer to Appendix A for detailed descriptions of measured stratigraphic section locations). Stratigraphic sections were measured along transects radially from and tranverse to the AMV center at the following locations: Coburn Mountain sections include DB-1 (19 m), DB-2 (14.5 m), DB-3 (16.5 m), DB-4 (9 m) and DB-5 (Figure 6); Stirling Ranch sections include ST-1 (10 m), ST-2 (6.5 m), ST-3 (3 m), ST-4 (10 m), ST-6 (15.5), ST-7 (10.5) and ST-8 (6.5 m) (Figure 7); Craig sections include Hwy-N (eight, 3-3.5-m sections across the outcrop along Highway 15) and Tvd-1 (45 m), Tvd-2 (36.5 m), Tvd-3 (28 m), and Tvd-4 (8 m) along Frontage Road (Figure 7). These transect orientations were

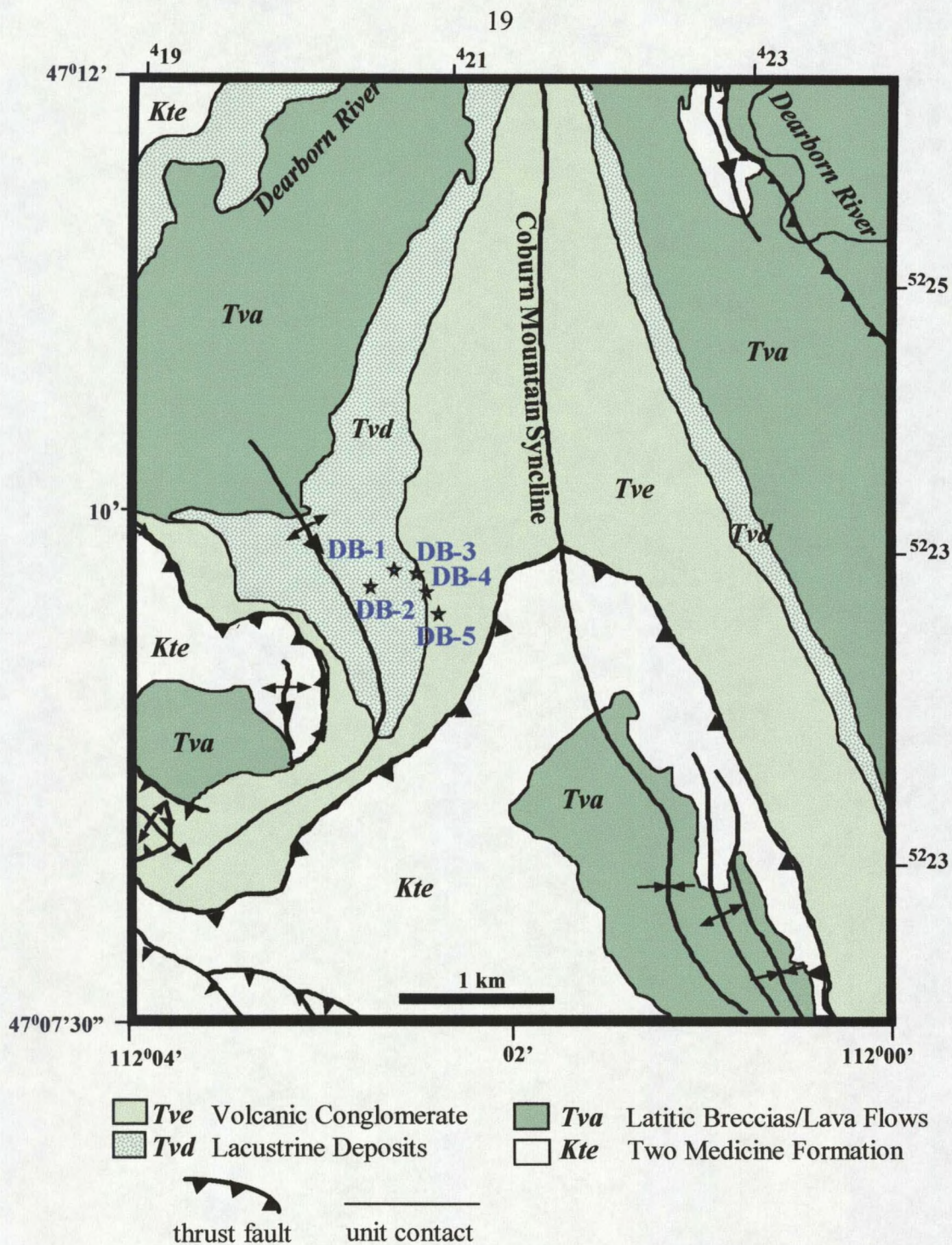


Figure 6: Locations of measured stratigraphic sections DB-1, DB-2, DB-3, DB-4 and DB-5 in the Coburn Mountain field area (after Schmidt, 1977).

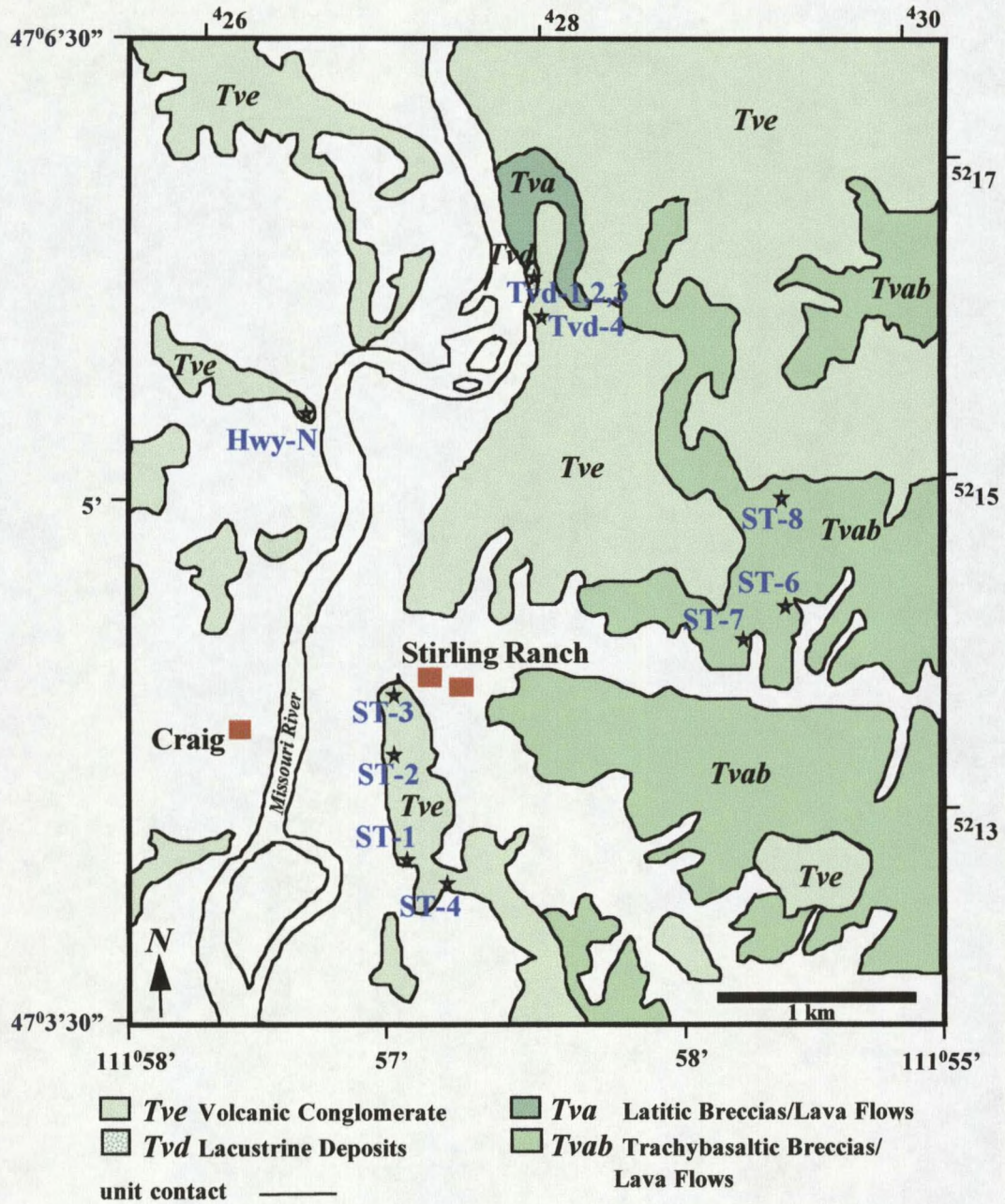


Figure 7: Locations of measured stratigraphic sections Tvd-1,2,3,4, ST-1,2,3,4,6,7,8 and Hwy-N in the Craig field area (after Schmidt, 1977).

selected to encompass the maximum range of lateral and vertical sequences, facies changes and depositional environments represented in the volcanoclastic apron and marginal deposits.

Samples were collected from rock units and lithofacies exhibiting specific lithologic and sedimentologic features and stratigraphic relations. Samples include representative conglomerate matrices, and conglomerate, sandstone and mudstone lithofacies.

Measured stratigraphic sections were not always obtainable due to the inaccessible nature of vertical exposures within the study area. In these instances, stratigraphic relations of extrusive and volcanoclastic rocks were noted during reconnaissance of southwestern portions of the AMV complex. Of particular interest were primary sedimentary structures, deformation features, and fabrics and textures that distinguish lithofacies and transport mechanisms indicative of depositional settings (subaqueous versus subaerial) and depositional environments.

Analytical Methods

Thin sections of rock samples were examined to determine: 1) lithology of mudstone lithofacies; 2) lithology of interbedded sandstone and mudstone sequences to determine provenance (i.e., AMV source area versus volcanic detritus from the Elkhorn Mountain Volcanic center to the west); 3) presence of interbedded lava flows;

and 4) presence of pyroclastic fragments in sandstone and mudrock units and conglomerate matrices. Petrologic analysis (including grain composition, grain sorting, grain shape, cement composition) facilitates interpretations of depositional environments represented in volcanoclastic apron and intertonguing marginal deposits.

Lithofacies Analysis

Lithofacies delineation was based on the facies classification scheme of Miall (1978) which was expanded to accommodate the range of volcanoclastic deposits in the study area. Stratigraphic sections were divided into lithofacies based on observed sedimentologic characteristics including fabric (preferred clast alignment or arrangement), texture (grain size and shape, degree of sorting), bed geometry, primary structures (grading, stratification, cross-bedding), secondary structures (deformation structures) and bounding surfaces. Most depositional units were distinguished by bedding surfaces marked either by sharp bedding planes or abrupt changes in clast size or concentration. Conglomerate lithofacies were further defined based on field estimates of matrix and framework clast ratios and matrix content. For this study, matrix is defined as granule size or smaller particles (<4 mm) and framework clasts are defined as pebble size or larger particles (> 4 mm).

Consideration of lithofacies relations and assemblages enables sediment transport mechanism, commonly independent of specific environmental settings, to be

determined. Lithofacies analysis requires definition of sedimentologic characteristics of individual lithofacies with respect to the (range of) rheologic properties active during sediment transport and deposition including grain-support mechanisms, flow type and flow characteristics (Pierson and Costa, 1987). Flow types and characteristics are inferred primarily from the particle-size distribution, particle composition, fabric, lateral relations and geometry of lithofacies (Pierson and Costa, 1987).

Lithofacies assemblages are lateral and vertical lithofacies groups delineated by stratigraphic and sedimentologic characteristics and flow mechanisms indicative of particular depositional environments. Lithofacies assemblages provide the basis for reconstruction of lithofacies architecture within the volcanoclastic apron and adjacent environments. Lithofacies architecture is based on architectural elements defined by sedimentologic attributes of lithofacies assemblages and their external geometry (Miall, 1985).

LITHOFACIES

Introduction and Terminology

Rheology, the study of the deformation and flow of materials, provides valuable information about the sediment transport mechanisms and flow types that produce sedimentary deposits. Rheologic classification of flow types facilitate interpretations of depositional processes represented in sedimentary deposits of modern and ancient geologic environments. The principal differences between flow types relate to variations in physical properties of the flow including yield strength, turbulence, clast interactions and the ratio of water and particle concentration (Schultz, 1984).

The three dominant flow types in the study area - debris flow, hyperconcentrated flow and normal or dilute stream flow - are linked genetically to form a flow continuum in which flow conditions reflect changes in physical properties over time and space (Figure 8). These flow types can occur in a continuum at a fixed depositional site, called a flow transformation, or as single depositional events (Smith and Lowe, 1991).

Debris flows are highly concentrated (> 80 weight percent), non-Newtonian dispersions with high apparent viscosity, high bulk density, and variable yield strength

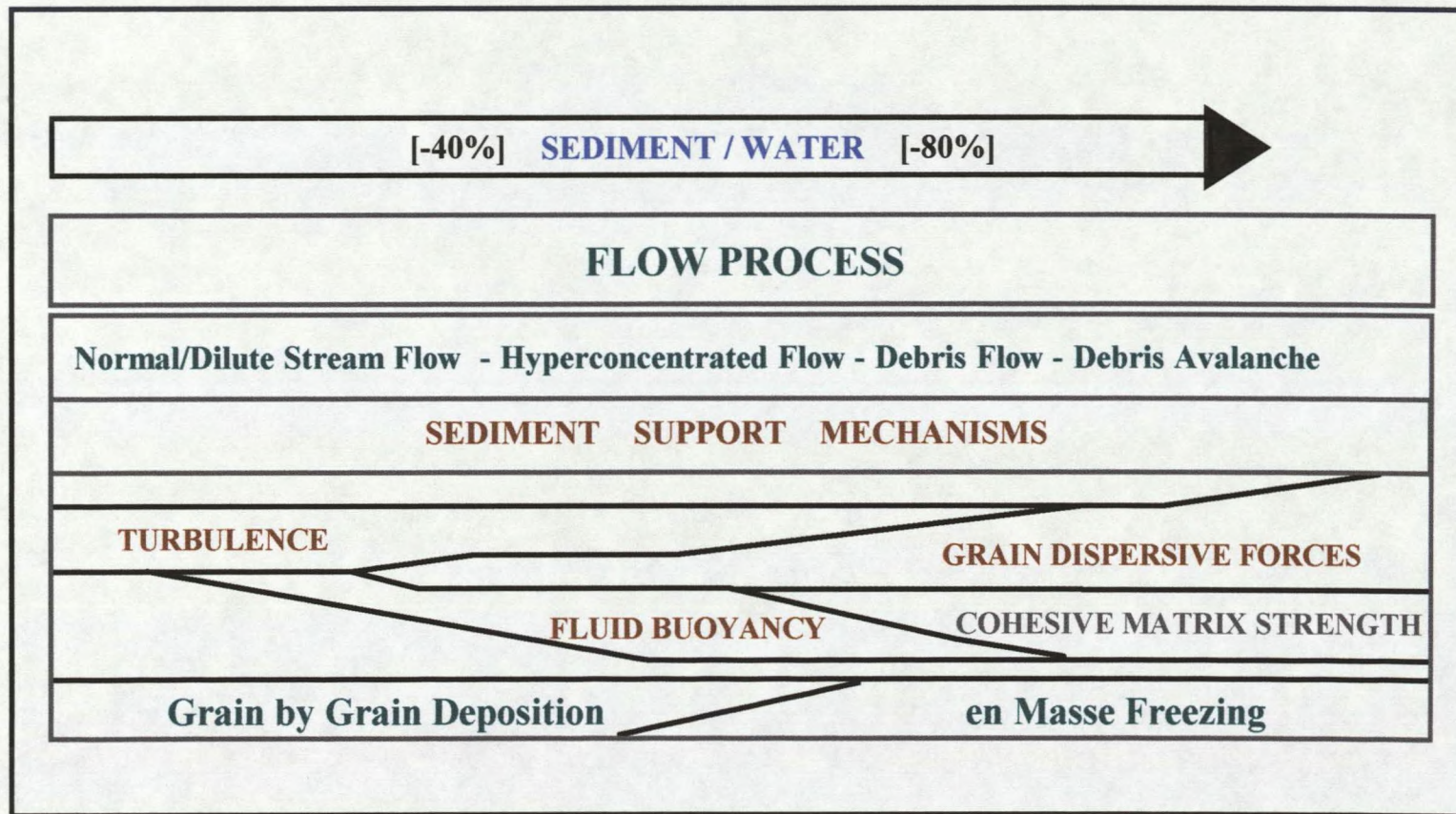


Figure 8: Flow processes and sediment support mechanisms that define tidal current, normal stream flow, hyperconcentrated flow and debris flow assemblages (after Smith and Lowe, 1991).

(Fisher, 1971; Schultz, 1984). Deposition from ideal, cohesive debris flows occurs by en masse freezing (immobilization of both solid particles and fluids when yield strength exceeds internal shear strength), which preserves internal structures present at the time of deposition and results in a poorly sorted deposit (Fisher, 1971; Enos, 1977; Pierson and Costa, 1987). Differences in the shear strength (cohesion and internal friction) of debris flows produce a range of sedimentologic features and deposit morphologies that can be diagnostic of different flow processes (Costa, 1988). Water saturated, non-cohesive debris flow deposits typically exhibit grading, clast imbrication and, in some instances, better sorting due to increased turbulence and particle interactions during flow (Smith, 1986). Most debris flow fabrics develop in the final stages of flow movement, as the flow velocity decreases, and it passes to a laminar phase before coming to rest (Lindsay, 1968). This occurs because as the load of dispersed grains increases turbulence is damped by the overall shear resistance, and laminar flow results (Bagnold, 1954). Surface flow transformations, resulting from addition of fluid (dilution) or addition of sediment (bulking), are important processes for producing debris flows and hyperconcentrated flows in the same depositional event (Smith, 1991).

Hyperconcentrated flow deposits are formed by flood events in which extremely high concentrations of sediment, with a wide range of grain size, are transported and deposited from suspension and as bed load (grain by grain) by traction (Smith, 1986; Smith, 1991). Sediment is supported by a combination of fluid buoyancy, grain-

dispersive pressure and dampened turbulence (Costa, 1988; Smith and Lowe, 1991).

Pierson and Costa (1987) further define hyperconcentrated flow as a mixture of water and sediment, exhibiting a measurable yield strength, that flows like a liquid but with dampened turbulence. Hyperconcentrated flood flows lack the strength and cohesion of debris flows but can carry high sediment loads (Pierson and Scott, 1985; Smith, 1986; Costa, 1988). The textures and stratification sequences of hyperconcentrated flood flow deposits vary due to differences in flow competency, depth, intensity of turbulence, sediment deposition rate, grain size (function of discharge and velocity), and degree of confinement (Blair, 1987).

Normal or dilute stream flow is characterized as a Newtonian fluid, containing less than 40 weight percent sediment concentration, in which flow is fully turbulent and where turbulence is the principal sediment support mechanism (Smith, 1986; Pierson and Costa, 1987; Smith and Lowe, 1991). Normal or dilute stream flow deposits form by sedimentation from suspension or grain-by-grain accretion of sediment on depositional surfaces (Schultz, 1984). Deposition of solid particles from the turbulent fluid suspension occurs "grain by grain", governed in large part by the settling velocity of particles as the competence of the stream decreases (Fisher, 1971). Normal or dilute streamflow includes: 1) continuous sediment transport over a wide range of discharge conditions; 2) flood-deposited material that is subsequently reworked into bedforms at lower flow stages; and 3) sediment transported and deposited only during high-discharge flood events (Smith and Lowe, 1991).

Descriptions and Interpretations

A code system for classifying lithofacies, rock units containing specific sedimentologic attributes, was established for fluvial deposits by Miall (1978). The lithofacies codes of Miall (1978) are assigned to equivalent lithofacies in the study area. Additional lithofacies codes were devised to accommodate the range of volcanoclastic lithofacies recognized in deposits of the AMV succession. The codes consist of a capital letter designating the dominant particle size (G for gravel, S for sand, F for fine-grained silt and clay) followed by one or two lower case letters designating the principal sedimentary components of each lithofacies. The lithofacies codes used in this study are listed in Table 2.

Conglomerate Lithofacies

Massive, Matrix-supported Conglomerate (*Gmm*)

Description. *Gmm*, a massive, ungraded, moderately to very poorly-sorted, pebble-boulder, matrix-supported conglomerate is the most abundant conglomerate lithofacies in the study area (Figure 9). Some beds contain gradational zones where matrix content decreases and framework clasts are more closely packed. Grain size of

Table 2. Summary of lithofacies codes and descriptions, sedimentary structures, flow types and flow characteristics.

Lithofacies Code	Lithofacies Description	Sedimentary Structures	Flow Type	Flow Characteristics
Gmm	clay to boulders matrix supported poorly-sorted rounded to subrounded clasts	massive	debris flow	clast-rich - low velocity, viscous, laminar flow, buoyancy, cohesion, matrix strength, clast-poor - high velocity, dilute, turbulent flow, dispersive and pore fluid pressure
Gmn	matrix-supported	normally graded	hyperconcentrated flow	dampened turbulence, grain-dispersive pressure, fluid buoyancy
Gmr	matrix-supported	reversely graded	debris flow (cold)	clast-rich, viscous, high-strength matrix, inertial particle interactions
			debris flow (hot)	non-cohesive, increased dispersive pressure
Gcm	clay to boulders clast-supported poorly-sorted, rounded to subrounded clasts	massive	debris flow	clast-rich, highly viscous, laminar flow, dispersive pressure, buoyancy, matrix strength
Gcn	clay to boulders clast-supported poorly sorted rounded to subrounded clasts	normally graded	hyperconcentrated flow	traction and suspension, turbulence, grain interaction,
			debris flow	dilute, high-competence, clast settling
Gcr	clay to boulders clast-supported poorly-sorted rounded to subrounded clasts	reverse grading	debris flow	dilute, low-viscosity, high sediment concentrations
				clast-rich, viscous, high-strength, inertial particle interactions

Table 2 (continued)

Gci	clay to boulders clast-supported poorly-sorted rounded to subrounded clasts	massive, weakly imbricated	hyperconcentrated flow debris flow	low viscosity, turbulence, high sediment concentrations low viscosity, laminar flow, basal shear
Sm	sand	massive or indistinctly bedded	hyperconcentrated flow	upper-flow regime, variable discharge flow
Smg	sand with gravel	massive	hyperconcentrated flow	upper-flow regime, variable discharge flow
Sgn	sand with gravel	normally graded	hyperconcentrated flow	upper-flow regime, variable discharge flow
Sgr	sand with gravel	reversely graded	hyperconcentrated flow	upper-flow regime, variable discharge flow
Smp	sand	massive, pedogenic features	unknown	post-depositional bioturbation
Sh	sand	horizontally stratified	hyperconcentrated flow	upper-flow regime, dampened turbulence, yield strength, traction or suspension
Shg	sand with gravel	horizontally stratified	hyperconcentrated flow	upper-flow regime, dampened turbulence, yield strength, traction or suspension
Sl	sand	low-angle, planar cross stratified	normal or dilute stream flow	lower-flow regime, scour/fill, high sediment concentrations
Sr	sand	ripple cross-lamination cosets	normal or dilute stream flow	low-flow regime, traction, turbulence, high sediment concentrations
Sd	sand	deformation structures	unknown	turbulence, remobilization/ mixing, slumping, loading
Fm	silt and clay	massive	flood flow	suspension
Fl	silt and clay	horizontally laminated	turbidity currents tidal currents	suspension, traction
Vb	volcanic breccia	massive	brecciated lava flow	mechanical brecciation, sediment mixing

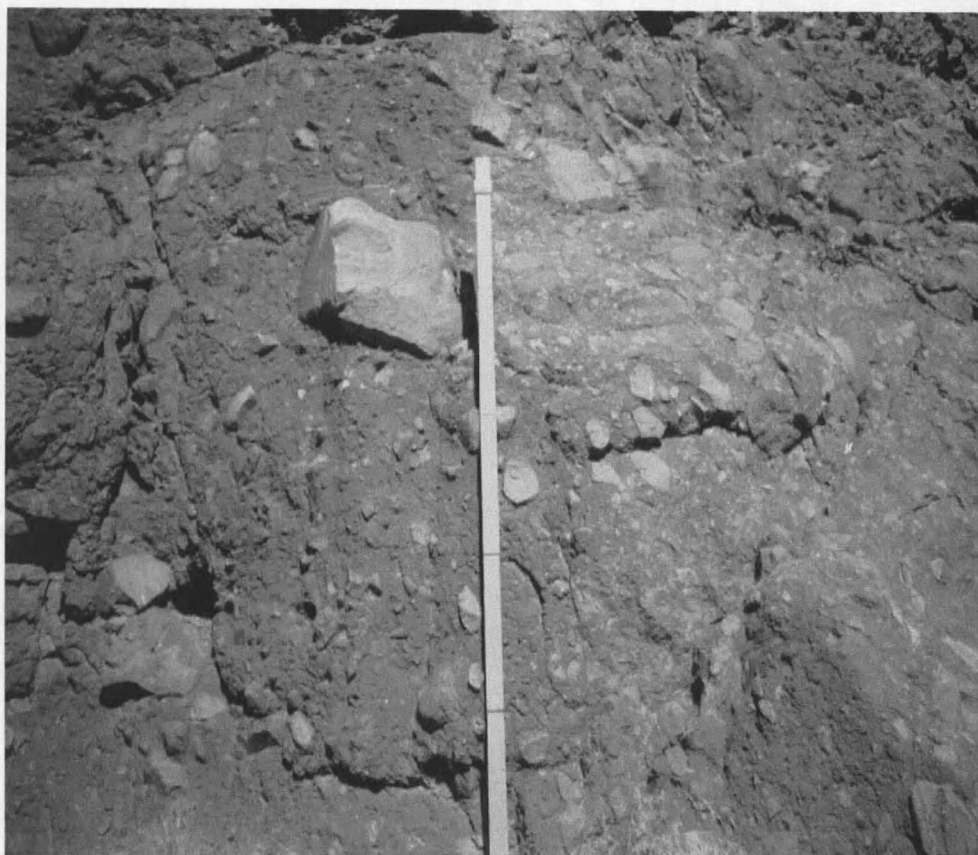


Figure 9: Massive matrix-supported conglomerate (*Gmm*) from measured section ST-7 (Jacob staff is 1.5 m in length). Note large boulder at center of outcrop

the matrix ranges from fine sand to granule size particles with small amounts of clay. Some *Gmm* beds contain a very coarse sand and granule matrix. Outsized clasts as large as 2.5 m are common at the top or base of individual beds but uncommon within beds. *Gmm* beds are 0.20-4.5 m thick with non-erosional, planar contacts and rare irregular bases. Tabular beds, both displaying clast-rich and clast-poor portions, extend laterally for tens of meters. Rarely, *Gmm* beds exhibit isolated horizons of poorly-developed, low-angle, cross-stratification up to 1 m thick near their bases. Lenticular and wedge shaped beds are laterally continuous for fewer than 8 m and most beds are composed of larger framework clasts (cobble-boulder size). *Gmm* beds are often interbedded with laterally continuous beds of horizontally laminated sandstone (*Sh*) and massive sandstone (*Sm*). Some *Gmm* beds contain deformed massive and laminated mudrock intraclasts (lithofacies *Fm* and *Fl*) (0.05-0.65 m in length) at their bases and load structures (lithofacies *Fm* and *Fl* are discussed later).

Interpretation. Lithofacies *Gmm* is interpreted as debris flow deposits due to their abundant matrix content, non-erosional and planar contacts, poor clast sorting, and, generally, lack of internal fabric, stratification or grading (Palmer et al., 1993). The geometry of *Gmm* beds is indicative of the degree of flow confinement; unconfined flow forms tabular beds with planar, non-erosional bases and channelized flow forms lenticular or wedge-shaped beds with erosive marginal contacts (Pierson et al., 1990; Palmer, 1991). Clast-rich, tabular deposits (high particle concentrations) are

deposited by low-velocity, viscous debris flows exhibiting laminar flow and buoyancy, cohesion and particle support mechanisms structural (high-strength matrix) (Fisher, 1971; Reading, 1986, p. 33; Costa, 1988; Fisher, 1991). Clast-poor tabular deposits (low particle concentrations) are deposited by high-velocity, dilute debris flows exhibiting turbulent flow and particle support mechanisms including dispersive pressure (particle interaction) and pore fluid pressure (Fisher, 1971; Reading, 1986, p. 33; Costa, 1988; Fisher, 1991). The presence of poorly-developed basal stratification indicates deposition by turbulent, hyperconcentrated flow derived from dilution at the front of a debris flow (Smith, 1988; Smith and Lowe, 1991). Hampton (1979) notes the presence of outsized clasts requires increased levels of dispersive pressure within the flow to remain suspended during flow movement.

Lenticular or wedge-shaped *Gmm* beds are similar to levee deposits from the Trollheim alluvial fan, California, described by Blair and McPherson (1998) but lack clast imbrication. These deposits form as a result of overtopping of channelized flows onto overbank areas and are deposited by laminar flow from moderately viscous, clast-rich, debris flows (Rodolfo, 1989; Palmer et al., 1993; Blair and McPherson, 1998). However, at Mayon Volcano in the Philippines, Rodolfo and Arguden (1991) observed the presence of turbulence and mixing at the center of channelized debris flows resulting in a chaotic arrangement of framework clasts in coarse-grained, clast-rich debris flow deposits.

Massive, Normally-graded, Matrix-supported Conglomerate (*Gmn*)

Description. Lithofacies *Gmn* comprises massive, normally graded, moderately to very poorly sorted, matrix-supported, pebble to boulder conglomerate. Matrix is composed of fine sand to granule size particles and framework clasts range from 1 cm to 2 m in size. *Gmn* beds are 0.65-1.7 m thick, laterally continuous across outcrops (maximum of 12 m) with upper and lower bounding surfaces commonly gradational with overlying and underlying sandstone lithofacies and often contain outsized clasts at their bases. This lithofacies exhibits well-defined planar contacts and, less commonly, crude horizontal stratification. Lithofacies *Gmn* is uncommon in the study area.

Interpretation. Due to the presence of normal grading and crude horizontal stratification, lithofacies *Gmn* represents deposition by hyperconcentrated flow (Smith, 1991). Although lacking the strength and cohesion of debris flows, hyperconcentrated flows can transport high sediment loads with particles supported by a combination of dampened turbulence, grain-dispersive pressure, and fluid buoyancy (Pierson and Scott, 1985; Smith, 1986, 1991). The resulting deposits are produced by high discharge flows intermediate in sediment to water ratio and gradational to those found in normal streamflow and debris flow deposits (Smith, 1991). Normal grading can indicate differential settling of larger clasts during deposition caused by matrix strength

insufficient to support clasts (Ballance and Gregory, 1991). The crude horizontal stratification observed in lithofacies *Gmn* could result from transition to hyperconcentrated flow at the margins of a debris flow. When debris flows, confined to channels, overtop channel margins, coarse particles can be deposited as linear clusters along channel margins (Palmer et al., 1993).

Massive, Reversely-graded, Matrix-supported Conglomerate (*Gmr*)

Description. Lithofacies *Gmr* comprises massive, reversely graded, moderately to very poorly sorted, matrix-supported, pebble to boulder conglomerate. Matrix is composed of fine sand to granule size particles, with small amounts of clay, and framework clasts range from 1 cm to 1.6 m in size. *Gmr* beds are 0.35-1.25 m thick, laterally continuous across outcrops (maximum of 12 m) with planar, non-erosional and gradational upper and lower bounding surfaces. These beds rarely exhibit crude stratification and poorly-developed clast imbrication that is usually discontinuous across outcrops. Moderately developed reverse, coarse-tail grading was observed rarely at the bases of beds, especially those with gradational lower bounding surfaces.

Interpretation. Lithofacies *Gmr* represents a clast-rich, viscous, high-strength matrix, debris flow similar to flows which produce lithofacies *Gmm* (massive, ungraded, matrix-supported conglomerate). This flow type can produce reverse grading

by two inertial particle support mechanisms: 1) kinetic sieving (clast shearing) causes continuous rearrangement of particles whereby smaller particles are displaced downward and larger grains are displaced upward within the flow (Middleton, 1970); and 2) dispersive pressure (produced by grain-grain collision) is disproportionately greater for larger clasts, forcing them away from zones of maximum shearing, such as near the base of the flow, and toward the top of the flow (Bagnold, 1954; Schultz, 1984). Schultz (1984), describes subaerial debris flow deposition in the upper Paleozoic Cutler Formation, Colorado and concludes reverse grading, produced by inertial particle interactions, develops during flow rather than during deposition. Reversely graded conglomerate lithofacies are similarly interpreted by other workers including Larsen and Steel (1978), Schultz (1984), Smith (1986) and Palmer (1991).

Alternately, one of the most significant characteristics of the deposits of hot debris flows is prominent reverse grading at their bases, which suggests a lack of cohesion and increased dispersive pressure within the flow (Arguden and Rodolfo, 1990). The reverse grading and non-erosional and gradational contacts of *Gmr* may indicate deposition by hot debris flows.

Massive, Clast-supported Conglomerate (*Gcm*)

Description. *Gcm*, a massive, ungraded, moderately to very poorly-sorted, pebble-boulder, clast-supported conglomerate is a common lithofacies in the study area

(Figure 10). Some beds contain gradational zones where matrix content increases and clasts are matrix-supported. Matrix is composed of fine sand to granule size particles, with small amounts of clay, and framework clasts range from 1 cm to 2 m in size. Some *Gcm* beds contain a very coarse sand and granule matrix. Some *Gcm* beds consist entirely of cobble to boulder size clasts in a closely-packed framework. Large outsize clasts are observed at the top and base of beds. *Gcm* beds are 0.1-0.5 m thick, forming laterally continuous sheet-like beds (tens of meters) or laterally discontinuous wedge-shaped beds (fewer than 10 meters). Upper and lower bounding surfaces are often sharp and non-erosional with rare outsized clasts protruding within overlying beds. Laterally discontinuous, extremely coarse-grained beds, composed primarily of cobbles and boulders (up to 1 m in size) and little matrix, are uncommon in the study area (measured sections Tvd-2, Tvd-3). Lenticular and wedge-shaped beds of massive (*Sm*) and cross-bedded sand (*Sl*) are interbedded with lithofacies *Gcm*.

Interpretation. Discontinuous wedge-shaped *Gcm* beds represent debris flow levees or surficial channel lag deposits. Debris flow levees form as a result of overtopping of channelized flows onto channel margins and are deposited by highly viscous, clast-rich, flows (Rodolfo, 1989; Blair and McPherson, 1998). Non-erosional bases of beds and outsized clasts at the top of beds indicate laminar flow at the time of deposition. Surface lag deposits (clasts at top of bed protruding into overlying bed) represent reworking of debris flow deposits which are infilled by well-sorted, stratified

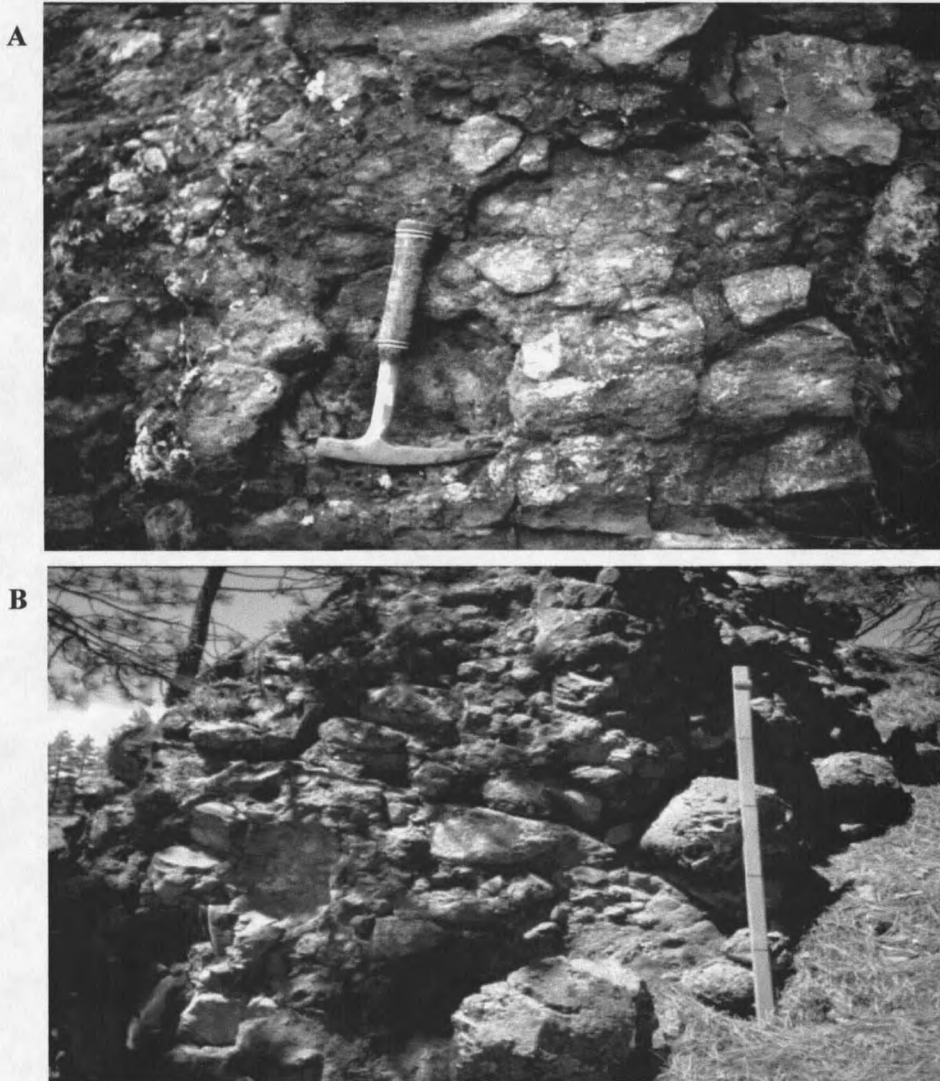


Figure 10: A. Poorly-sorted, massive clast-supported conglomerate (*Gcm*) with pebble to boulder size framework clasts from section DB-1 (hammer is 32 cm in length). B. Coarse-grained, poorly-sorted, massive, clast-supported conglomerate (*Gcm*) with cobble to boulder size clasts from measured section ST- 5 (Jaob staff os 1.5 m in length).

or cross-stratified sand (Palmer et al., 1993). Alternately, surficial winnowing of originally matrix-supported debris flow deposits by aeolian processes produce clast-supported gravel lag deposits into which subsequent channels are cut by fluvial activity (Blair, 1987; Blair and McPherson, 1998; Palmer et al., 1993). Discontinuous beds of massive (*Sm*) and cross-bedded sand (*Sl*) are commonly interbedded with *Gcm* beds and are formed by fluvial reworking of debris flow surfaces and subsequent deposition by sheetfloods, hyperconcentrated flow and normal stream flow (Hackett and Houghton, 1989; Palmer, et al., 1993).

Tabular *Gcm* beds, characterized by framework supported clasts, lack of stratification and poor-sorting, represent deposition from clast-rich, high-competence debris flows (Larsen and Steel, 1978; Palmer et al., 1993). Sediment support mechanisms of these flows include dispersive pressure (Bagnold, 1954; Pierson and Costa, 1987), buoyancy due to high clast concentrations (Hampton, 1979), and matrix strength. The presence of outsize clasts within beds is interpreted as due to: 1) considerable matrix strength within the flow allowing clasts to be carried passively on top of the flow (Larsen and Steel, 1978); and 2) increased levels of dispersive pressure within the flow causing clasts to stay suspended during flow movement (Hampton, 1979). Unusually coarse-grained *Gcm* beds, composed mostly of boulder size clasts, exhibit some sedimentary features of debris avalanche deposits including closely packed framework clasts and lack of pervasive fine-grained or muddy matrix (top of measured section ST-6) (Cas and Wright, 1988, p. 302). However, these deposits lack

specific features used to distinguish the deposits of debris avalanche versus debris flow including angular, brecciated or shattered framework clasts, megablocks (tens of meters or more in diameter), and hummocky upper bedding surfaces (Glicken, 1991; Palmer et al., 1991). Therefore, *Gcm* beds are interpreted as not having formed by debris avalanche.

Massive, Normally-graded, Clast-supported Conglomerate (*Gcn*)

Description. *Gcn*, a massive, normally graded, moderately to poorly-sorted, pebble-boulder, clast-supported conglomerate is a relatively uncommon lithofacies. Matrix consists of fine sand to granule size particles. *Gcn* beds are 0.65-1.5 m thick, laterally continuous over tens of meters with irregular, planar upper and lower bounding surfaces. Within discrete lenses of *Gcn* beds, preferentially arranged clasts form a weakly-developed fabric tangential to the lower bounding surface.

Interpretation. Lithofacies *Gcn* represents deposition by hyperconcentrated flow and dilute debris flow. The textures and fabrics exhibited by lithofacies *Gcn* are indicative of hyperconcentrated flow deposits, including poor-sorting, clast support, normal grading, clast imbrication, and coarse-grained matrix (Hackett and Houghton, 1989). These features of hyperconcentrated flow deposits suggest rapid traction and suspension deposition, characterized by high-sediment concentrations, with turbulent

grain interactions as the primary sediment support mechanisms (Smith, 1986).

Lithofacies *Gci* may represent deposits that formed by the transition to hyperconcentrated flow along the margins of debris flows (Palmer et al., 1993).

Normal grading can form by deposition from dilute, high-competence, debris flows by settling of clasts within the flow during transport (Smith, 1986). Pierson et al. (1990) describe channel-margin, longitudinal bars consisting of a reversely graded base and a normally graded top formed in modern debris flow deposits at Nevado del Ruiz, Colombia. These graded deposits suggest the presence of incomplete mixing and vertical density-segregation within debris flows (Pierson et al., 1990).

Massive, Ungraded, Imbricated, Clast-supported Conglomerate (*Gci*)

Description. *Gci* beds consist of massive, ungraded, weakly-imbricated, moderately to poorly-sorted, pebble-boulder, clast-supported conglomerate. Matrix is composed of fine sand to granule size particles, with small amounts of clay, and framework clasts are 1 cm to 0.5 m in size. *Gci* beds are 0.60-2.5 m thick and are laterally continuous across outcrops (maximum of 14 m) and most boundaries are planar and non-erosional. Clast imbrication is manifested as discontinuous particle trains aligned parallel to the bedding surfaces. The poor development of clast imbrication is attributed to the inherent rounded to sub-rounded shape of clasts available for transport.

Interpretation. Clast-supported conglomerates may result from turbulent suspension of a high volume, fine-grained load during subsequent deposition of larger particles from hyperconcentrated flows (Smith, 1986). Particles aligned parallel to bedding surfaces indicate that movement, at least immediately prior to deposition, was by laminar flow (Fisher, 1971). Mathisen and Vondra (1983) interpret similar clast-supported conglomerates as gravel sheets and longitudinal bars formed by deposition from normal stream flow in fluvial and pyroclastic deposits of the Cagayan Basin, Philippines. Pierson et al. (1990) interpret imbricated, clast-supported longitudinal bar deposits, at maximum channel depths, as having been transported by debris flows as bedload at the base of a zone of high shear at Nevado del Ruiz, Colombia. Lithofacies *Gci* could result from hyperconcentrated flows or low-viscosity debris flows.

Massive, Reversely-graded, Clast-supported Conglomerate (*Gcr*)

Description. Lithofacies *Gcr*, a massive, poorly-sorted, reversely graded, clast-supported conglomerate, is a common lithofacies in the study area. Matrix is composed of fine sand to granule size particles with small amounts of clay. *Gcr* lithofacies consists of tabular, sheet-like beds, 0.50-4.5 m thick, that are laterally continuous across outcrops (maximum of 20 m) with sharp and non-erosional boundaries. Framework clast size and bed thickness vary laterally across most exposures.

Interpretation. The presence of inverse grading suggests deposition from a dilute, low-viscosity debris flow with high sediment concentrations (Larsen and Steel, 1978; Smith, 1986). Studies of modern debris flow deposits have documented channel-margin longitudinal bars, with reversely graded bases and normally graded tops, formed by incomplete mixing and vertical density-segregation within debris flows (Pierson et al., 1990). Single, reversely graded *Gcr* beds may represent preservation of only the lower portion of this depositional sequence. Additional reversely graded longitudinal bar deposits, at maximum channel depths, were noted in broad channel sections and represent preferential clast deposition at the basal shear zone of a debris flow (Pierson et al, 1990). Lithofacies *Gcr* can also result from deposition by clast-rich, viscous, high-strength debris flows similar to flows that produce lithofacies *Gmr* and *Gmm*. Reverse grading is formed by inertial particle support mechanisms (kinetic sieving and dispersive pressure).

Sandstone Lithofacies

Massive Sandstone (*Sm*, *Smg*, *Sgn*, *Sgr*, *Smp*)

Description. *Sm* beds consist of massive, ungraded, moderately to poorly-sorted, fine to very coarse-grained sandstone and are common in the study area. Beds of *Sm* are 0.15-4.5 m thick. *Smg* beds consist of massive, moderately to poorly-sorted,

fine to very coarse-grained sandstone with granule size clasts. Beds of *Smg* are 0.04-1.5 m thick. Both *Sm* and *Smg* form laterally continuous, sheet-like beds and laterally discontinuous, lenticular or wedge-shaped beds which are often interbedded with lithofacies *Gmm*. Upper and lower bounding surfaces are planar and non-erosional or irregular and erosional. *Sm* and *Smg* beds are sometimes gradational with overlying and underlying lithofacies and often exhibit gradational contacts with laterally adjacent lithofacies, including low-angle cross-bedded sandstone (*Sl*) and massive mudrock (*Fm*) (Figure 11).

Lithofacies *Sgn* consist of massive, normally graded, moderately to poorly sorted, fine to coarse-grained, sandstone with granule to pebble size clasts and are common in the study area. *Sgn* beds are 0.20-1.15 m and exhibit gradational contacts with overlying and underlying conglomerate lithofacies and rare planar, non-erosional contacts. These beds are sheet-like, laterally continuous across outcrops (maximum of 8-10 m) or lenticular or wedge-shaped.

Lithofacies *Sgr* consists of massive, reversely graded, moderately to poorly sorted, fine to coarse-grained, sandstone with granule to pebble size clasts and are common in the study area. *Sgr* beds are 0.2-4.0 m thick with gradational or planar, non-erosional, upper and lower bounding surfaces. Some upper bounding surfaces have planar, irregular contacts with large out-sized clasts. *Sgr* beds are sheet-like and laterally continuous across outcrops (maximum of 8-10 m) or lenticular and wedge-

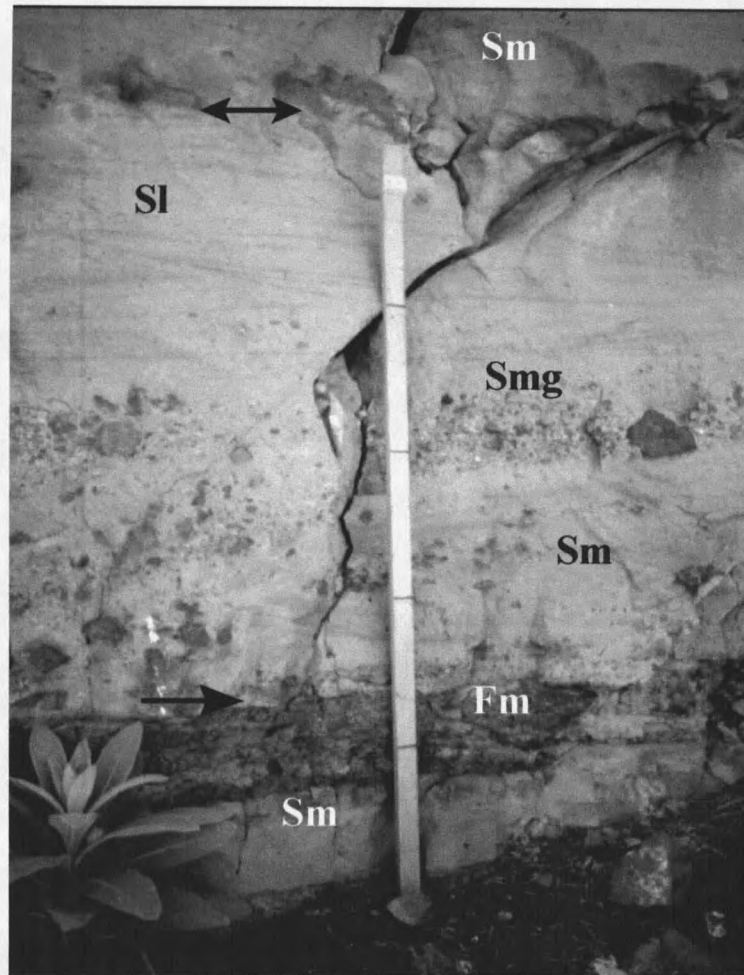


Figure 11: Interbedded massive sandstone (*Sm*), massive mudrock (*Fm*), massive sandstone with gravel (*Smg*) and low-angle cross-bedded sandstone (*Sl*) lithofacies from measured section Tvd-1 (Jacob staff is 1.5 m in length). Note deformed massive mudrock (*Fm*) intraclasts at contact between low-angle cross-bedded (*Sl*) and massive sandstone (*Sm*) bed in upper portion of photograph.

shaped. Lithofacies *Sgn* and *Sgr* commonly form interbedded sequences with gradational contacts and discontinuous, lenticular bedding.

Lithofacies *Smp* comprises 0.20-1.25 m thick beds of massive, muddy to coarse-grained sandstone with dense concentrations of root casts and patchy mottling throughout that exhibit sub-angular blocky, prismatic or columnar soil structures (Figure 12). Root casts are mostly vertical to sub-vertical relative to bedding surfaces and average less than 0.5 cm in width and 2-8 cm in length. Root casts appear densely concentrated near the tops of *Smp* beds (top 20-30 cm) and become fewer toward the base; a distinct horizon within each bed marking the lower extent of the root casts in each bed. *Smp* beds are rare in the study area, observed in three measured sections (section DB-1, DB-2 and DB-3). *Smp* beds are interbedded with mudrock lithofacies *Fm* and *Fl* and sandstone lithofacies *Sm*, *Sh* and *Sd* often with gradational upper and lower bounding surfaces.

Interpretation. Lithofacies *Sm*, *Smg*, *Sgn* and *Sgr*, characterized by normal or reverse grading, lack of stratification and gradational upper and lower bounding surfaces, are interpreted to have resulted from deposition by hyperconcentrated flow (Palmer, 1991; Smith, 1986; Smith, 1991). When flow velocities in hyperconcentrated unconfined flows decrease, but remain in the upper flow regime, massive, structureless deposits are formed (Cas and Wright, 1988, p. 316). Vertical sequences of interbedded, normally and reversely graded beds deposited from hyperconcentrated flows reflect changes in sediment influx to the flow and flow velocity over time. Normally graded

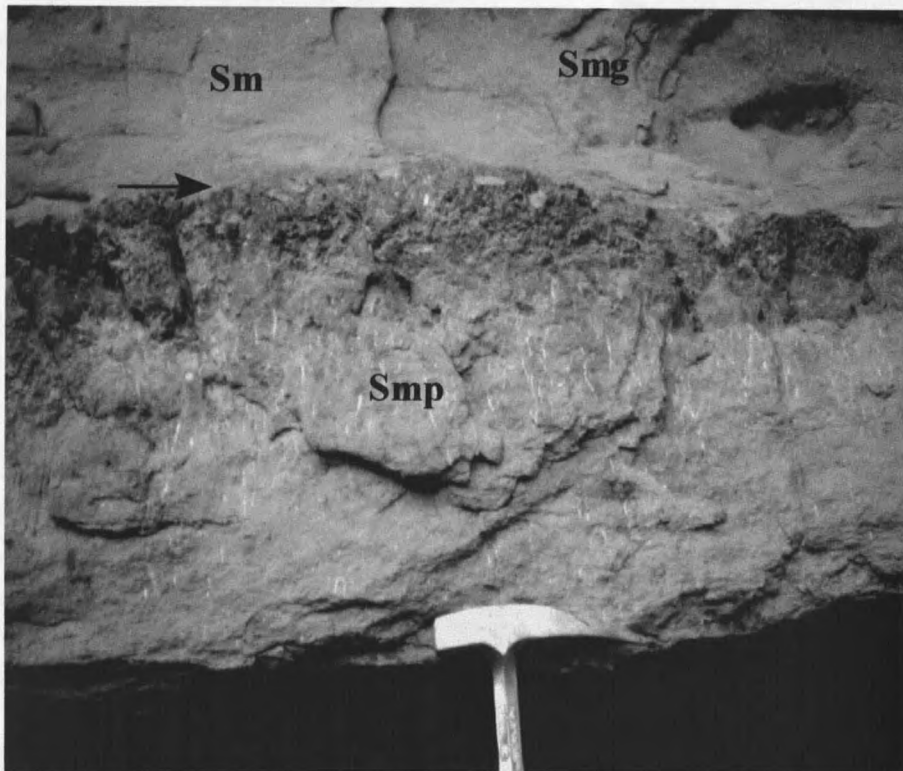


Figure 12: Massive sandstone with gravel (*Smg*), massive sandstone (*Sm*) and massive sandstone with pedogenic features (*Smp*) (from measured section DB-1). The top portion of the massive sandstone bed with pedogenic features (*Smp*) represents a paleosol horizon with dense concentrations of root casts preserved directly below (hammer is 32 cm. in length).

beds are deposited from high-discharge flows with initially high sediment concentrations from which sediment is continuously deposited as flow velocity is decreased, either from decreased slope or flow runout. Reversely graded beds are deposited from initially low-discharge flows (the dilute front of the main flow) that gradually increase in sediment concentration and flow velocity, by bulking (entrainment of sediment from channel floor and margins) or the progression of the main flow downslope. Massive sandstone beds exhibiting poorly-developed grading or patchy lamination can be produced by post-depositional modification through bioturbation or dewatering (Miall, 1996, p. 123).

Lithofacies *Smp* represents a paleosol horizon characterized by massive beds with specific soil structures and by dense root casts, a rarely well-preserved feature of ancient deposits. *Smp* beds do not contain well-developed soil profiles. Under most climatic regimes, thousands of years are required for development of mature soil horizons suggesting an environment marked by prolonged active deposition (Brackenridge, 1988). Primary sedimentary structures of underlying beds are often obscured or destroyed by root emplacement and bioturbation (Miall, 1996, p. 127) and the effects of diagenesis and lithification tend to obliterate many diagnostic features used to identify paleosols (Teruggi and Andreis, 1971). The absence of preserved plant material on bedding surfaces suggests erosion of the paleo-surface prior to deposition of overlying beds paleosols (Teruggi and Andreis, 1971). The pedomorphic root surface found in *Smp* beds is the distinct horizon below which few root casts are

present in each bed (approximately 20-30 cm from top) and may reflect the position of the water table during soil and plant formation (Samoylova, 1971). A locally shallow water table and erosional upper bedding surface support paleosol development in a fluvial environment such as floodplain or interchannel area of braided streams (Miall, 1996, p. 127).

Stratified or Laminated Sandstone (*Sh*, *Shg*, *Sl*, *Sr*)

Description. *Sh*, very poorly- to well-sorted, horizontally stratified sandstone, and *Shg*, horizontally stratified sandstone with granule-pebble size clasts, are the most common sandstone lithofacies in the study area. In combination, these lithofacies are 0.05-4.5 m thick and form lenticular or wedge-shaped beds, although rare tabular beds extend laterally for tens of meters. Three distinct types of lithofacies *Sh* include: 1) massive, up to 4.5 m thick, interbedded with isolated cosets, lenses or layers of *Sl*, low-angle, planar, cross-stratified sandstone ($<10^\circ$), and *Sr*, ripple cross-laminated sandstone (0.01-0.12 m thick) (Figure 13); 2) lenticular or wedge-shaped beds interbedded with conglomerate lithofacies (*Gmm*, *Gcm*, *Gmn*, *Gmr* and *Gci*); and 3) thinly interbedded with most conglomerate lithofacies and massive mudrock (*Fm*) and laminated mudrock (*Fl*) lithofacies.



Figure 13: Climbing ripples (Sr) in tidal current assemblage from measured section Tvd-1 (hammer head is 12 cm in width).

Interpretation. The association of lithofacies *Sh* and *Shg*, characterized by complexly interbedded sandstone lithofacies, horizontal stratification, lenses of coarse-grained material, isolated outsized clasts and generally poor to moderate sorting suggest deposition by hyperconcentrated flow (Larsen and Steel, 1978; Mathisen and Vondra, 1983; Smith, 1986; Costa, 1988; Smith, R., 1991a, 1991b). Interbedded *Sh* and *Shg* lithofacies represent sheetflood deposits formed by unconfined (tabular beds) and confined (lenticular or wedge-shaped beds) hyperconcentrated flow. This flow type is characterized by variable particle size, particle concentration, velocity and water depth during upper-flow regime conditions and marked by dampened turbulence (Blair, 1987; Pierson and Costa, 1987; Miall, 1996, p. 515, 520; Palmer, 1997). Horizontal stratification is produced by segregation of granule-rich and sand-rich horizons, commonly with outsized clasts up to 1 m, by suspended and tractional, bedload transport and reflects variable flow competency and yield strength due to high concentrations of suspended sand (Harms and Fahnstock, 1965; Smith, 1986; Blair, 1987).

Lithofacies *Sl* is produced by normal stream flow characterized by low-angle cross-bedding (Palmer, 1990; Smith, R., 1991a, 1991b; Palmer et al., 1993).

Lithofacies *Sl*, formed by scour and fill deposition, and lithofacies *Sh* and *Shg* were deposited from shallow, high-discharge stream flow (Palmer, 1991; Palmer, 1997).

Fritz and Howells (1991) describe sets of planar cross-beds in tabular beds of

moderately to well-sorted medium-grained sandstone from the Garth Tuff, North Wales and interpret these deposits as forming by migration of sandwaves during lower flow regime conditions. Cross-bedding can result from truncation of planar beds on dipping surfaces such as scour holes (Miall, 1996, p. 120-121). Interbedding of lithofacies *Sh* and *Sl* indicate deposition close to upper-flow regime, plane-bed conditions with formation of dune-like structures (Miall, 1996, p. 120-121; Palmer, 1997). Discontinuous wedges and stringers of lithofacies *Sh* and *Sl* in the top portions of debris flow deposits (commonly lithofacies *Gmm* and *Gcm*) indicate reworking of deposit surfaces by normal stream flow processes, infilling a matrix of poorly to moderately sorted sand (Palmer, 1991).

Isolated cosets of lithofacies *Sr* interbedded with lithofacies *Sh* represent deposition by traction currents from turbulent, low-discharge, dilute stream flow. Climbing ripples (Type B) form by ripple migration during lower flow regime conditions and often develop in coarse to fine sand (Miall, 1996, p. 215). Climbing ripple cross-lamination indicates a high rate of vertical bed accretion from flows with high sediment concentrations (Reading, 1986, p. 53; Miall, 1996, p. 115).

Massive, Deformed Sandstone (*Sd*)

Description. *Sd* lithofacies consist of massive sandstone often including deformation structures and irregular bedding. This lithofacies is 0.12-3.6 m thick and is

commonly interbedded with sandstone lithofacies *Sh*, *Sl* and *Sr* and *Fl*, horizontally laminated mudrock. Some *Sd* beds are laterally discontinuous, lenticular or wedge-shaped and have sharp, erosional contacts with adjacent conglomerate lithofacies. Characteristic features of this lithofacies include mudstone intraclasts, soft-sediment deformation structures (basal loading, squeeze ups) and convolute bedding.

Interpretation. As debris flows advance downslope they load the underlying deposits and can induce secondary failure in subaerial, saturated, semi- or unconsolidated sediments or subaqueous sediments on oversteepened slopes (Stow, 1978). Rip-up clasts (intraclasts) are evidence of turbulent flow, probably acquired during the period of accelerating flow or maximum flow velocity (Ballance and Gregory, 1991). Intraclasts are incorporated by mixing and remobilization of unstable (water saturated) deposits as the debris flow moves over sediment surfaces (Busby-Spera, 1988). Slumped horizons consist of recumbently folded or chaotically contorted bedded intervals, bounded above and below by undisturbed strata (Busby-Spera, 1988). The development of slumped horizons on relatively proximal part of the apron may have resulted from higher surface slopes due to rapid aggradation of coarse-grained debris, analogous to modern alluvial fans (Busby-Spera, 1988).

Mudrock Lithofacies

Massive Mudrock (*Fm*)

Description. Lithofacies *Fm* consists of 0.10-1.55 m thick beds of massive mudrock that are laterally continuous across outcrops (maximum of approximately 35 m) (Figure 14). Two distinct types of *Fm* lithofacies include: 1) *Fm* interbedded with rare horizons (0.20-1.2 m thick) of *Smp*, massive sandstone with pedogenic features; and 2) laterally continuous, 0.05-0.10 m thick couplets, interbedded with lithofacies *Sm*, that comprise 0.5-1.6 m thick beds, exhibiting sharp and nonerosional or lateral, gradational contacts with mudrock lithofacies *Fl* and sandstone lithofacies *Sm* and *Sh*.

Interpretation. Lithofacies *Fm*, and in association with lithofacies *Fl*, represents deposition from suspension during low-stage flood flow in overbank and floodplain areas (Mathisen and Vondra, 1983; Miall, 1996, p. 125). *Fm* beds also form mud drapes within gravel beds and are deposited from standing pools of water in distal floodplains or floodplain ponds (Miall, 1996, p. 125).

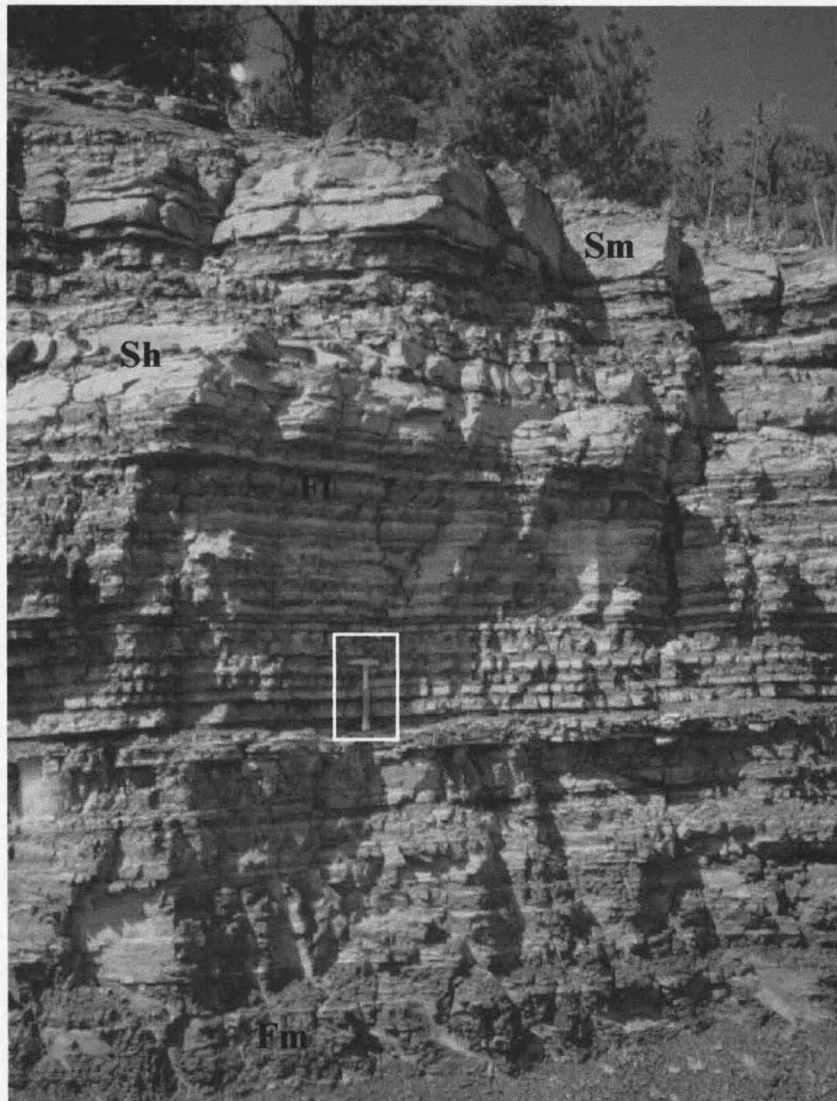


Figure 14: Massive mudrock (*Fm*), laminated mudrock (*Fl*), massive sandstone (*Sm*) and horizontally laminated sandstone (*Sh*) of the tidal flat assemblage from measured section Tvd-1 (hammer is 32 cm in length).

Laminated Mudrock (*Fl*)

Description. *Fl* beds comprise 0.15-1.5 m thick, horizontally laminated mudrock (Figure 14). These beds are tabular and laterally continuous with sharp, non-erosional upper and lower bounding surfaces or gradational with sandstone lithofacies *Sm*, *Smg*, *Sh*, and *Shg*. *Fl* beds interbedded with sandstone lithofacies *Sm*, *Sl*, *Sr* and *Sd*. Measured sections Tvd-1 and DB-2 contain the most extensive vertical exposure of interbedded sequences of lithofacies *Fl* and sandstone lithofacies observed in the study area. *Fl* beds, approximately 1 m thick with preserved plant fragments on bedding surfaces, were observed in measured section Tvd-1. Upper bounding surfaces of *Fl* beds commonly contain mudrock intraclasts (less than 1 cm in diameter), flaser bedding, lenticular bedding, and deformation features including flame structures (plumes of mud squeezed irregularly upward into an overlying bed), convolute bedding, and rare load structures; deformed *Fl* beds are usually overlain by sandstone and gravely sandstone lithofacies.

Interpretation. Lithofacies *Fl* indicates deposition from suspension, traction currents or turbidity currents. Interbedded massive mudrock lithofacies (*Fm*) and wavy or irregular *Fl* beds may represent sedimentation by low-density turbidity currents formed mainly by suspension deposition in lower shoreface water depths (Fritz and

Howells, 1991). Mud drapes represent deposition from suspension during waning flow where bed thickness is dependent on sediment supply and flow stage (Miall, 1996, p. 123). The presence of flaser bedding indicates tidal processes were active during deposition (Orton, 1995). Convolute bedding results from deformation caused by shear stress exerted on the sediment surface by currents (Blatt et al., 1972, p. 173). *Fl* beds containing flame and load structures indicate plastic deformation of the sediment surface during rapid deposition from suspension; deformation is facilitated by reduction of particle cohesion and internal friction or by increasing pore fluid pressure (Blatt et al., 1972, p. 173-174).

Lava Flow Lithofacies

Volcanic Breccia (*Vb*)

Description. Lithofacies *Vb* comprises an approximately 10 m vertical exposure of brecciated lava flow which was documented at only one location (measured section Tvd-3) in the study area (Figure 15). Lithofacies *Vb* is characterized by blocky, polygonal clasts, 0.10-0.8 m in diameter, composed of porphyritic trachybasalt with phenocrysts of augite enclosed in non-fragmented matrix of the same composition (Schmidt, 1972, 1977). *Vb* beds exhibit chaotic, lateral interfingering with lithofacies *Gcm* and *Gmm*, both of which contain a very coarse sand and pebble matrix.

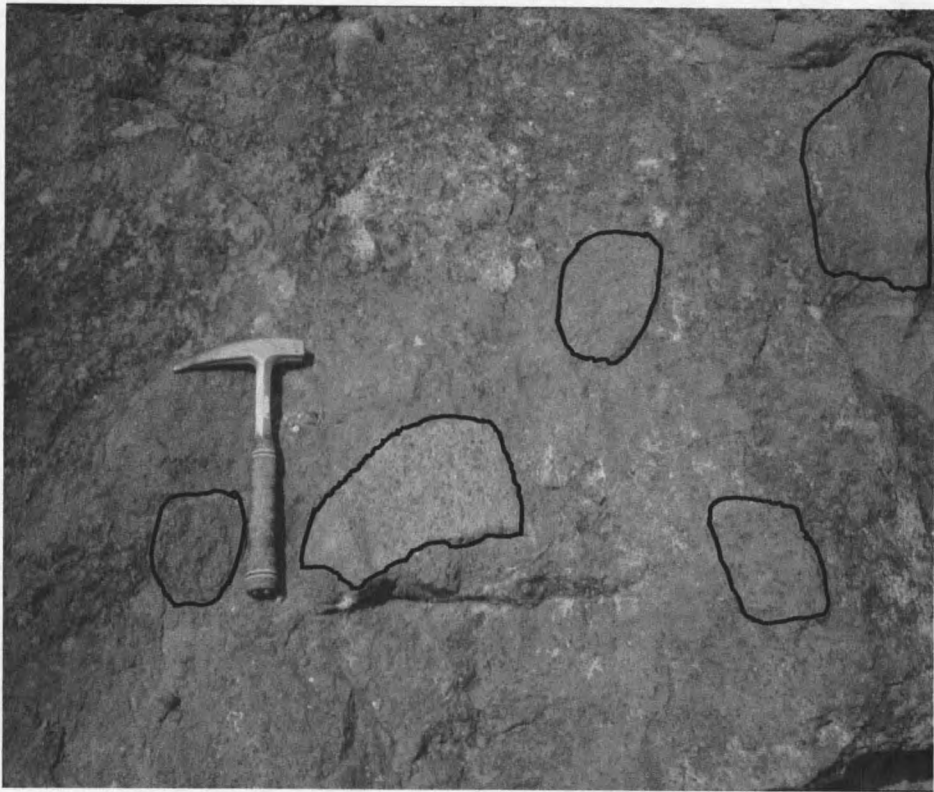


Figure 15: Brecciated lava flow (*Vb*) from measured section Tvd-3 (hammer is 32 cm in length). Several clasts (circled in black) are visible in the fine-grained groundmass.

Interpretation. Lithofacies *Vb* represents autoclastic flow breccia formed by mechanical brecciation or fragmentation of lava during flow (Fisher, 1960; Palmer and Walton, 1990). Lithofacies *Vb* is observed to grade laterally and become chaotically interfingered with lithofacies *Gcm* and *Gmm* (section Tvd-3) and both lithofacies contain identical monolithologic clasts. Hackett and Houghton (1989) describe similar autobreccia deposits at Ruapehu, an andesitic-basaltic stratovolcano in New Zealand. These deposits, commonly formed at flow margins, exhibit a transition from irregular, well-jointed lava flows to welded coarse breccia to matrix-rich breccia and often contain monolithologic clasts. Subaqueous, autobrecciated lava flows of a basaltic island arc succession are described by Mitchell (1970) as deposits that lack internal structure and are composed of a small proportion of matrix and clasts of homogeneous composition and texture. Given the similarity of these deposits to lithofacies *Vb* and the stratigraphic relations of lithofacies *Vb* with subaqueous mudrock and sandstone lithofacies in the study area, subaqueous deposition must be considered. Due to the absence of fractured clasts and matrix heterogeneity, described by Palmer and Walton (1990) and Smith (1991) as diagnostic features of debris avalanche deposits, formation of lithofacies *Vb* by debris avalanche is unlikely.

LITHOFACIES ASSEMBLAGES

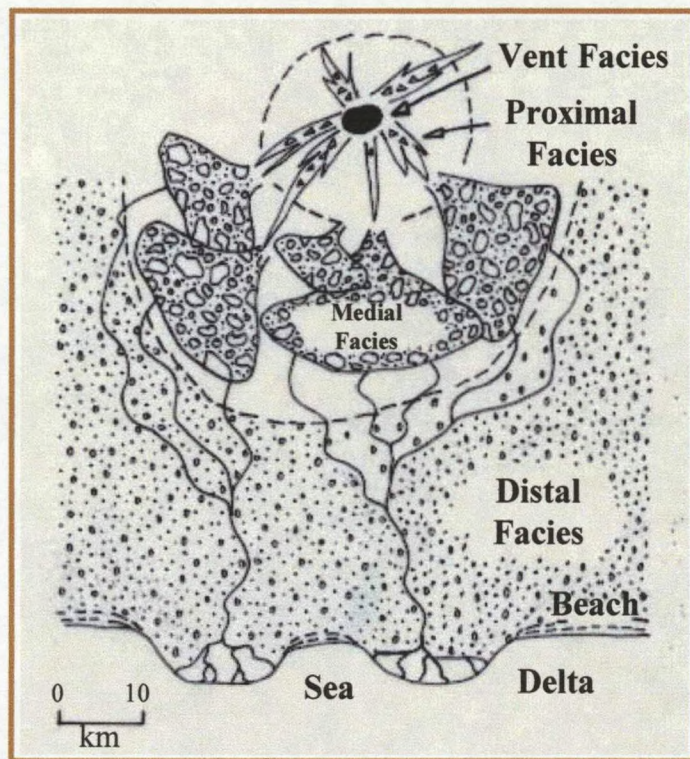
The genesis and spatial organization of volcanoclastic lithofacies can be used as a tool for deciphering deposits in modern and ancient volcanic successions (Palmer et al., 1991). Lithofacies assemblages are groups of lithofacies that occur together, vertically and laterally, and are genetically related by concomitant mechanisms of flow and sediment transport (Reading, 1986, p. 5). Five lithofacies assemblages are recognized in deposits of the AMV volcanoclastic apron and marginal environments. Lithofacies assemblages, codes and flow types are summarized in Table 3.

Table 3. Summary of constituent lithofacies present in each lithofacies assemblage, lithofacies assemblage codes and flow types. (Note: * indicates lithofacies assigned to multiple lithofacies assemblages.)

Lithofacies Assemblage Code	Flow Type	Lithofacies Present
LF	Lava flow, brecciated lava flow	<i>Vb</i> <i>Gmm*</i> , <i>Gcm*</i>
DF	Debris flow	<i>Gmm*</i> , <i>Gmr</i> <i>Gcm*</i> , <i>Gcr</i> , <i>Gci*</i> <i>Sd</i>
HF	Hyperconcentrated flow (transitional to debris flow)	<i>Gmn</i> , <i>Gcn</i> , <i>Gci*</i> <i>Sm</i> , <i>Smg</i> , <i>Smgn</i> , <i>Smgr</i> , <i>Sh*</i> , <i>Shg*</i>
SF TC	Normal or dilute stream flow (transitional to hyperconcentrated flow) Tidal currents	<i>Sh*</i> , <i>Shg*</i> , <i>Sl</i> , <i>Sr</i> , <i>Smp</i> <i>Fm</i> , <i>Fl</i>

Lithofacies assemblages define the range of lithofacies, flow types and sediment transport mechanisms that occur in particular depositional environments. Lithofacies assemblages are characterized by gradational successions of lithofacies that reflect changes in flow conditions and availability of sediment for transport. In some instances, individual lithofacies are formed by more than one flow type indicating that transitional phases (flow transformations) occur between specific flow types. Transitional flow phases occur spatially within flows and temporally as flow conditions vary during single depositional events. Lithofacies assemblages can also represent cyclic depositional processes where lithofacies are vertically repeated in a predicted order or as components of a single depositional event (Reading, 1986, p.5). Lithofacies assemblages are found in proximal, medial and distal settings progressively further away from the volcanic source area (Figure 16) (Vessel and Davies, 1981). Although this facies model refers to the volcanoclastic deposits of stratovolcanoes, the diagram clearly illustrates the spatial relations of proximal, medial and distal regions of the volcanoclastic apron.

In volcanic environments, periods of aggradation and degradation drastically alter the preservation potential of deposits produced by specific flow types in the geologic record. During periods of aggradation and degradation, controlled primarily by fluctuating sediment loads originating from the volcanic center, large volumes of volcanic detritus are reworked, transported and redeposited by a range of flow types and sediment transport mechanisms. Therefore, lithofacies analysis and delineation of



A

B

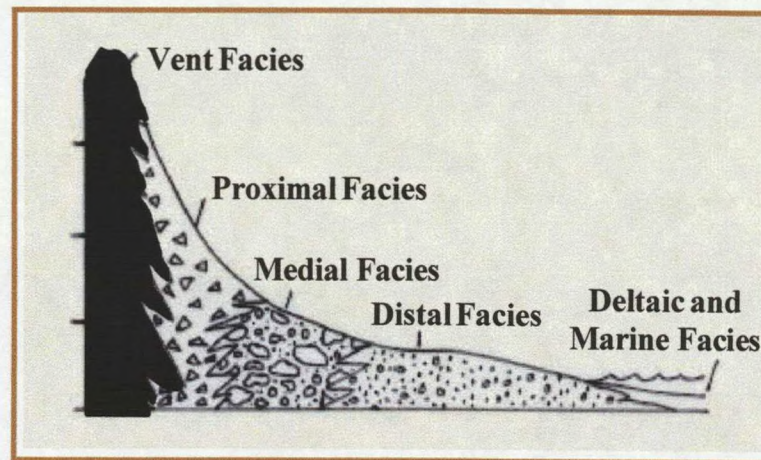


Figure 16: Generalized volcaniclastic fan facies model illustrating proximal, medial and distal facies:
A) plan view B) cross-sectional view (after Vessel and Davies, 1981).

lithofacies assemblages provide a basis for interpretations of volcanic sedimentary environments.

Lava Flow Assemblage (LF)

The lava flow (LF) lithofacies assemblage contains deposits formed by lava flow and brecciated lava flow. Lithofacies *Vb*, autoclastic flow breccia, is a rare flow type in the study area, although it is abundant in adjacent vent and proximal areas of the volcanic center. The chaotic, gradational contacts of lithofacies *Vb* with laterally adjacent conglomerate lithofacies (*Gmm*, *Gcn*) were not formed by the interfingering of separate lava flow and debris flow deposits. Rather, these deposits are interpreted as forming when wet, unconsolidated sediments (likely tidal flat deposits) were incorporated into lava flow margins during downslope transport (Figure 17). Similar deposits, documented by Riggs et al. (1997) in proximal areas of a volcanic dome field in central Arizona, are interpreted as "expansion breccias" formed by explosive release of vapor and sediment due to isobaric heating of water within the wet sediment. Deposits of the LF assemblage exhibit the complex contact relations associated with peperites but lack the angular, fragmented clasts commonly formed by hypabyssal intrusion of magma into wet, unconsolidated sediments (Fisher, 1960; Hanson and Schweickert, 1982; Busby-Spera and White, 1987; Hanson and White, 1993). Cas and Wright (1988, p. 361) use the term peperite to describe the various textures of rocks

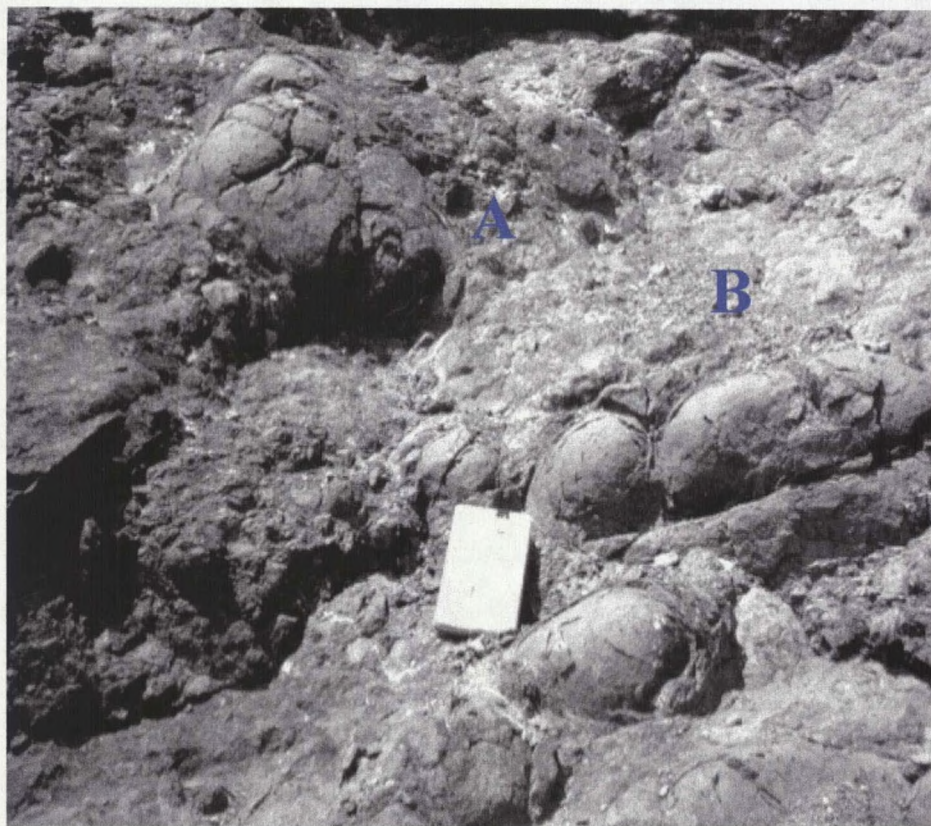


Figure 17: A) Boulder size clasts, exhibiting radial cooling joints in brecciated lava flow (Vb) in gradational contact with massive, poorly-sorted, clast-supported conglomerate (Gcm) and B) spheroidal weathering pattern of clasts from measured section Tvd- 3 (notebook is 19 cm in length).

composed of hyaloclastite (quenched, fragmented volcanic rock) and sediment formed either when magma intrudes or lava flows over wet, unconsolidated sediment and suggest that the term "peperite" be referenced in a non-genetic, descriptive sense because of the diverse origins of these types of deposits.

Debris Flow Assemblage (DF)

The debris flow (DF) lithofacies assemblage contains massive, reversely graded and imbricated conglomerate lithofacies. High-strength, low-velocity, viscous debris flows are characterized by: laminar flow in which particles are supported by cohesion, buoyancy and matrix strength; and deposition of material by en masse freezing of the entire flow. These deposits are massive, tabular, clast-rich, poorly-sorted and lack stratification and grading (lithofacies *Gmm* and *Gcm*). Discontinuous, wedge-shaped *Gcm* beds represent debris flow levees, deposited by viscous, clast rich debris flows, and surficial channel lag deposits, formed by reworking of debris flow surfaces by hyperconcentrated flow and normal stream flow.

Low-strength, high-velocity, dilute debris flows transport suspended material by turbulent or dampened turbulent flow in which particles are supported primarily by dispersive pressure and pore fluid pressure. These deposits are massive, inversely graded and exhibit poorly-developed clast imbrication (lithofacies *Gmr*, *Gcr* and *Gci*). In addition, reverse grading in lithofacies *Gmr* and *Gcr* may represent deposition by hot

debris flows. Interbeds of horizontally stratified sandstone (*Sh*, *Shg*), massive sandstone (*Sm*, *Smg*) and low-angle cross-bedded sandstone (*Sl*) between beds of *Gmm* and *Gcm* lithofacies indicate reworking of debris flow surfaces by hyperconcentrated flow and normal stream flow (Figure 18).

Debris flow assemblage (DF) constituent lithofacies are often associated with deformed sandstone lithofacies (*Sd*). Downslope movement of turbulent, dilute debris flows over saturated, unconsolidated sediment surfaces produces post-depositional deformation. Intraclasts, slump horizons and convolute bedding represent mixing and remobilization of sediment by turbulent basal flow (Figure 19). Load structures form in finer-grained deposits through compression by overlying coarser-grained deposits.

Hyperconcentrated Flow Assemblage (HF)

The hyperconcentrated flow (HF) lithofacies assemblage contains deposits formed by hyperconcentrated flow. Normal grading and clast imbrication in conglomerate lithofacies *Gmn*, *Gcn* and *Gci* result from traction and suspension deposition by differential settling of particles from hyperconcentrated flows in which particles are supported by dampened turbulence, dispersive pressure and fluid buoyancy.

Sandstone lithofacies *Sm*, *Smg*, *Smgn* and *Smgr*, characterized by normal or reverse grading and lack of stratification, represent deposition by hyperconcentrated

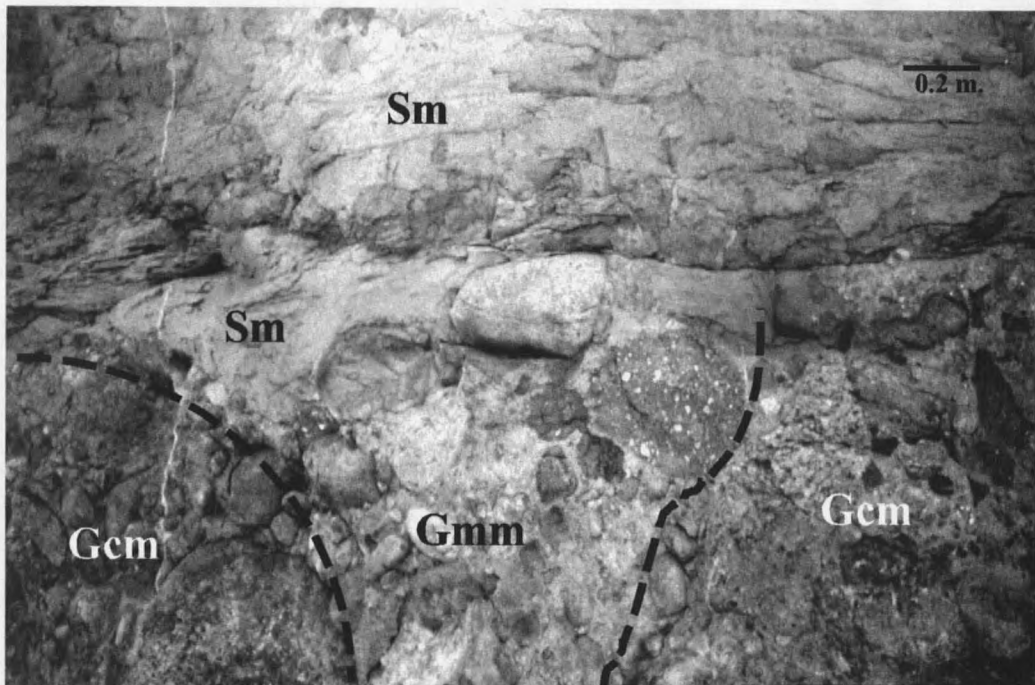


Figure 18: A) Massive matrix-supported conglomerate (*Gmm*) fills a channel incised into underlying massive clast-supported conglomerate (*Gcm*). B) Massive sandstone (*Sm*) wedge fills left side of channel (from highway outcrop Hwy-N). (Note scale in upper right corner of photograph.)



Figure 19: Sandstone lense chaotically interbedded with massive, clast-supported conglomerate (*Gcm*) from measured section St-6 (notebook at center of circle is 19 cm. in length).

flow. Decrease in flow velocity produces massive, ungraded sandstone deposits (*Sm*, *Smg*) and influx of suspended sediment, during early or late stages of flow, produce massive, graded sandstone deposits (*Smgn*, *Smgr*). Figure 20 shows horizontally stratified sandstone with gravel (*Shg*) overlain by massive, normally-graded conglomerate (*Gcn*). This sequence of hyperconcentrated flow assemblage (HF) lithofacies could be the result of a single depositional event, by the process of flow transformation (bulking), as indicated by the nonerosional, planar contact between lithofacies (*Shg*, *Gcn*).

Tabular and lenticular beds of horizontally stratified sandstone lithofacies (*Sh*, *Shg*) represent deposition by hyperconcentrated flow. These lithofacies are commonly interbedded with conglomerate lithofacies of the debris flow assemblage (DF), indicating reworking of debris flow surfaces by hyperconcentrated flood flow. Lateral interfingering of sandstone lithofacies and conglomerate lithofacies of the hyperconcentrated flow assemblage (HF) results from variable water depth, velocity and particle size and concentration at the margins of hyperconcentrated flows.

Normal or Dilute Stream Flow Assemblage (SF)

The normal stream flow (SF) lithofacies assemblage contains lithofacies formed by normal or dilute stream flow during upper- to lower-flow regime conditions (Figure 21). Sandstone lithofacies (*Sh*, *Shg* and *Sl*) contain sedimentary structures (horizontal



Figure 20: Horizontally stratified sandstone with gravel (*Shg*) overlain by massive, normally-graded conglomerate (*Gcn*) with sharp, slightly irregular contact from measured section DB-3 (Jacob staff is 1.5 m in length).



Figure 21: Stream flow and hyperconcentrated flow assemblage lithofacies including massive sandstone (*Sm*) and laminated and massive mudrock (*Fl*, *Fm*) lithofacies from measured section DB-1 (Jacob staff is 1.5 m in length).

stratification, low-angle cross-beds) formed by migration of channel bedforms or by channel scour and fill deposition during upper-flow regime conditions. Lithofacies *Sr* (ripple cross-laminated sandstone) forms by ripple migration (low-flow regime) and deposition by traction currents from turbulent, dilute stream flow. Lithofacies *Smp* (sandstone with pedogenic features) represents plant colonization and paleosol development in floodplain and interchannel areas of fluvial environments (Collinson, 1986). Gradational contacts with hyperconcentrated flow assemblage (HF) lithofacies indicate hyperconcentrated flows frequently inundated stream channels by the process of flow transformation, either from debris flow to hyperconcentrated flow (dilution) or normal stream flow to hyperconcentrated flow (bulking by increased discharge).

Tidal Current Assemblage (TC)

The tidal current (TC) assemblage contains lithofacies formed by tidal currents (Figure 22). Tidal flat facies, formed in intertidal zones, are dominated by interlaminated clays, silts and sands exhibiting well-developed flaser or wavy and lenticular bedding (Figure 23) (Elliott, 1978; Nichols et al., 1991). These facies reflect constantly fluctuating low energy conditions, with brief periods of bedload transport of sand and coarse silt by tidal currents and waves alternating with deposition from suspension of fine sediment during slack water tidal intervals (Reineck and Wunderlich, 1968). Similar vertical sequences of sandstone and mudrock lithofacies

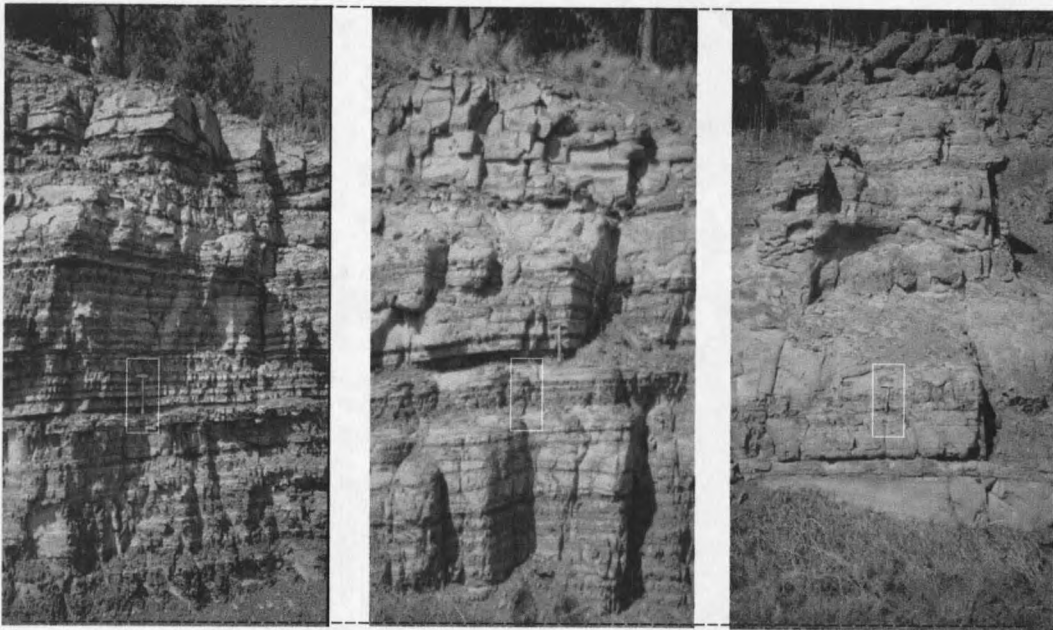


Figure 22: Outcrop of tidal current assemblage lithofacies including interbedded massive mudrock (*Fm*) and massive sandstone (*Sm*). The three photographs comprise a laterally continuous outcrop (from measured section Tvd-1). Hammer is 32 cm. in height.

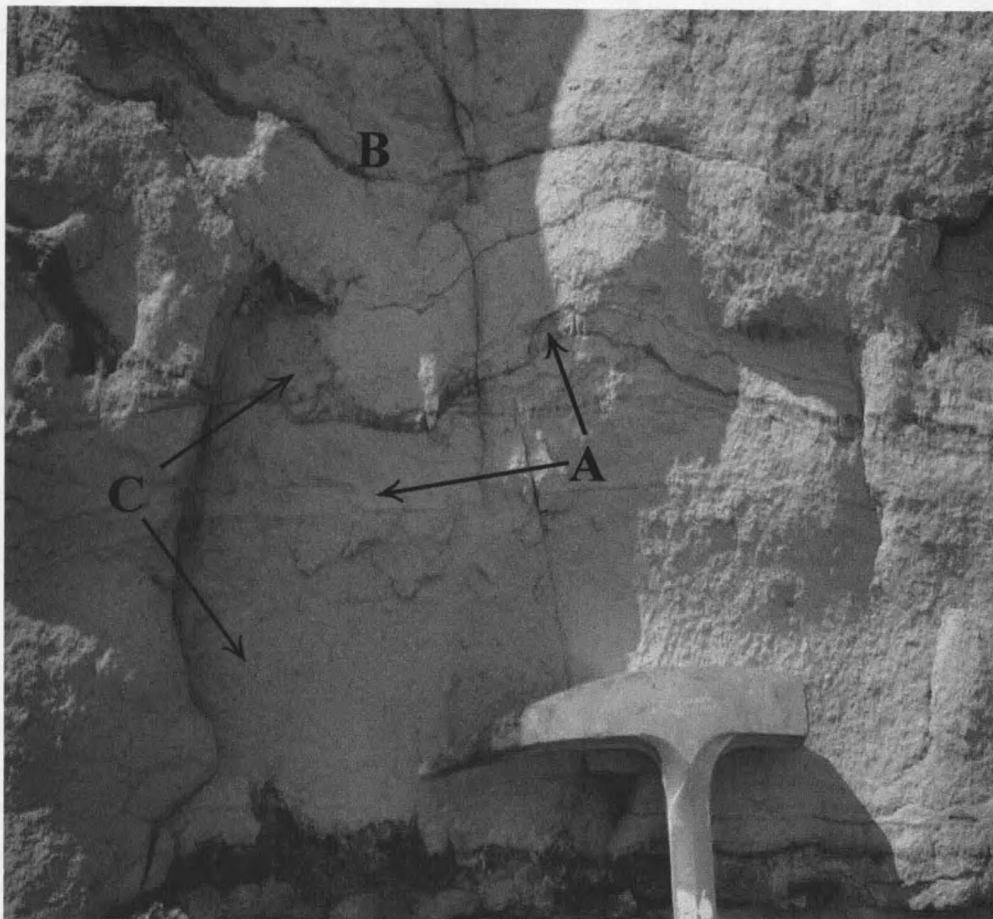


Figure 23: Tidal current assemblage lithofacies exhibiting wavy flaser bedding (A) , wavy bedding (B) and flame structures (C) from measured section Tvd-1 (hammer head is 12 cm in width).

from a modern microtidal coastal plain estuary in Virginia, were described by Nichols et al. (1991) in which tidal currents transported sand as bedload within tidal channels and deposited silt and clay from suspension during maximum tidal influx within marsh and interchannel areas. The presence of densely concentrated zones of quartz grains in tidal current assemblage massive and horizontally stratified sandstone lithofacies (*Sm*, *Sh*) suggests influx of sediment by long shore currents from sources outside the AMV center, characterized by dominantly quartz-poor lithologies (Appendix B).

DEPOSITIONAL ENVIRONMENTS

Specific flow types, sediment transport mechanisms and lithofacies are not ubiquitous to certain areas of volcanic sedimentary systems but rather are found at variable distances from the volcanic source area depending on the magnitude of depositional events, duration of eruptive or dormant phases of volcanic activity (eruptive versus intereruptive, aggradational versus degradational) and developmental stage of the volcanic system. Therefore, lithofacies assemblages must be viewed as constituents of larger depositional environments.

Tidal Flat Environment.

Sedimentary and igneous volcanic rocks are associated with deposition in the tidal flat environment. Stratigraphic relations of brecciated lava flows (*Vb*), conglomerate lithofacies (*Gcm* and *Gmm*) and tidal current assemblage lithofacies (from measured sections Tvd-1, Tvd-2, Tvd-3) are diagrammatically illustrated in Figure 24. All stratigraphic contacts appear conformable with no evidence of faulting or erosional unconformity. Lithofacies *Vb* chaotically interbedded with conglomerate lithofacies (*Gcm* and *Gmm*) formed as a brecciated lava flow advanced across the tidal flat environment incorporating wet, unconsolidated sediments into the lava flow at

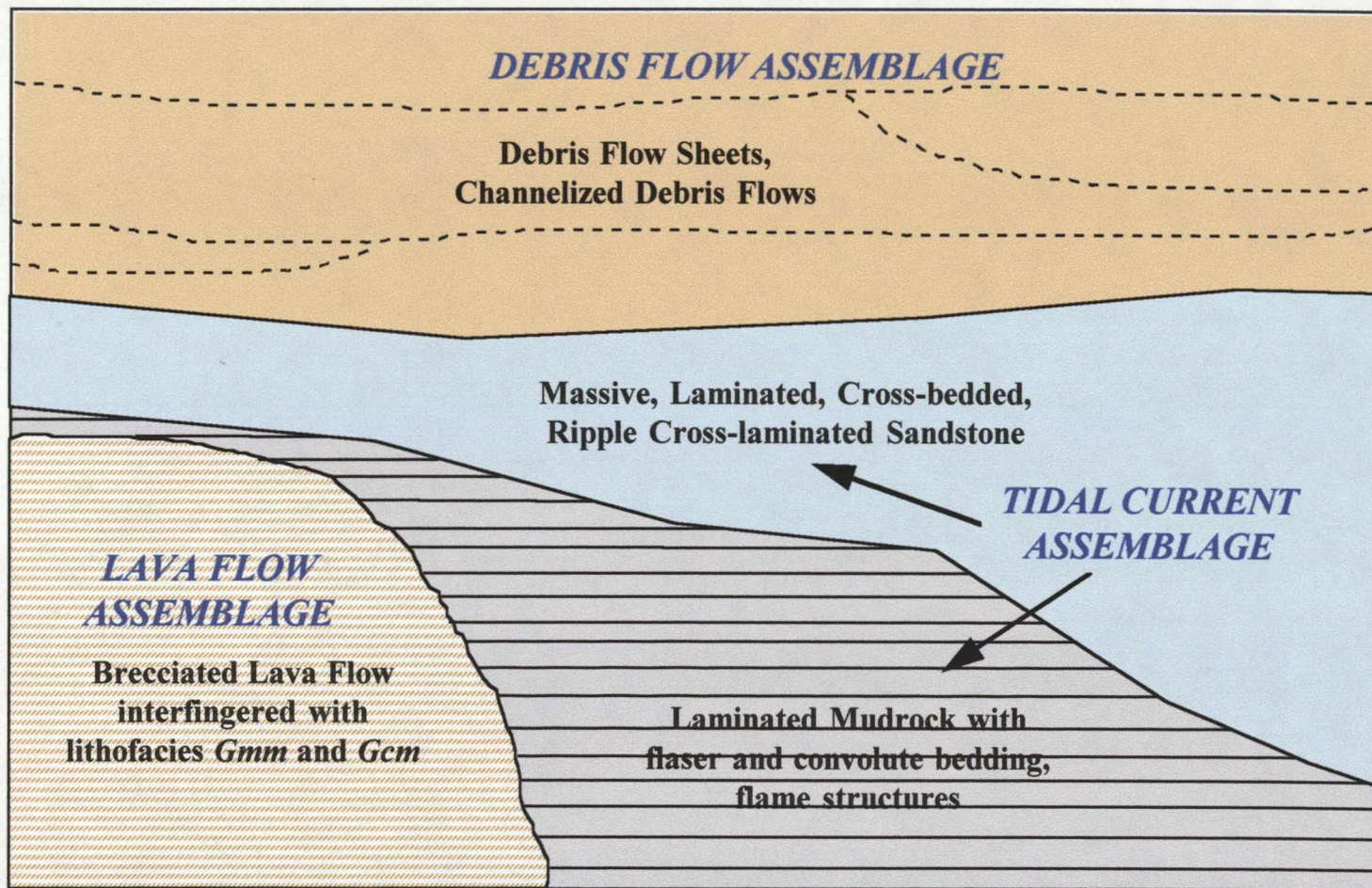


Figure 24: Illustration of an outcrop including measured sections Tvd-1, 2, 3 and 4 showing lateral and vertical stratigraphic relations of lava flow, tidal current and debris flow assemblages (outcrop width approx. 50 m).

flow margins. The contacts between lava flow and debris flow assemblages in the tidal flat environment are the only example of the presence of lava flows on the surface of the volcanoclastic fan within the study area; however, interbedded lava flows and debris flow deposits were noted during reconnaissance of proximal regions of the volcanic center.

The tidal current assemblage represents deposition in tidal flat areas of the shallow marine environment including supratidal and intertidal zones (Elliott, 1978). Tidal flat areas are highly dissected by complex networks of tidal channels and creeks (Elliott, 1978) in which vertical accumulations of interfingering mudrock and sandstone lithofacies are deposited. Lamination, small-scale bedforms, wavy or lenticular bedding, flaser bedding and rare grading are common features of the tidal flat deposits. The absence of fossils and rare preservation of organic layers suggest rapid deposition of sediment and aggradation in this tidal system (Nichols et al., 1991).

Tidal current assemblage lithofacies result from transgression of the Cretaceous seaway, decreased volcanic activity or reduced rates of weathering of volcanic source rock. These deposits exhibit onlap stratigraphic contacts with the adjacent lava flow assemblage lithofacies in which the tidal current assemblage aggraded to the top of the lava flow assemblage (LF) and is overlain by interbedded debris flow (DF) and hyperconcentrated flow (HF) assemblage lithofacies. Due to covered slopes and limited exposures, extensive lateral contacts are lacking precluding further

interpretation of interaction between the seaway and lava flow (LF) assemblage lithofacies

Braidplain Environment

The braidplain environment is dominated by all lithofacies of the normal or dilute stream flow assemblage (SF) with interbedded lithofacies of the hyperconcentrated flow assemblage (HF) (Figure 25). Braidplain deposits are characterized by: 1) laterally extensive, sheet-like geometries; 2) absence of scour and fill deposits; 3) pervasive horizontal stratification and ripple cross-lamination; and 4) lack of grading in sandstone lithofacies.

Fluvial deposits of the AMV braidplain environment exhibit sedimentologic features common to distal, sheetflood, sand-bed rivers (Model 11) and flashy, ephemeral, sheetflood, sand-bed rivers (Model 12) described by Miall (1996, p. 243-244). The presence of horizontally stratified, sheet-like sandstone beds (*Sh*, *Shg*) are characteristic of the deposits of distal, sheetflood, sand-bed river systems (Figure 26a). The presence of interbedded hyperconcentrated flow deposits (horizontally stratified sandstone lithofacies *Sh*, *Shg*), indicative of upper-flow regime deposition, are characteristic features of high-velocity, flashy discharge in shallow, poorly defined channels of sand-bed rivers (Figure 26b). Fluvial deposits of the braidplain environment are similar to distal volcanoclastic apron facies, of the Tornillo Flat area of

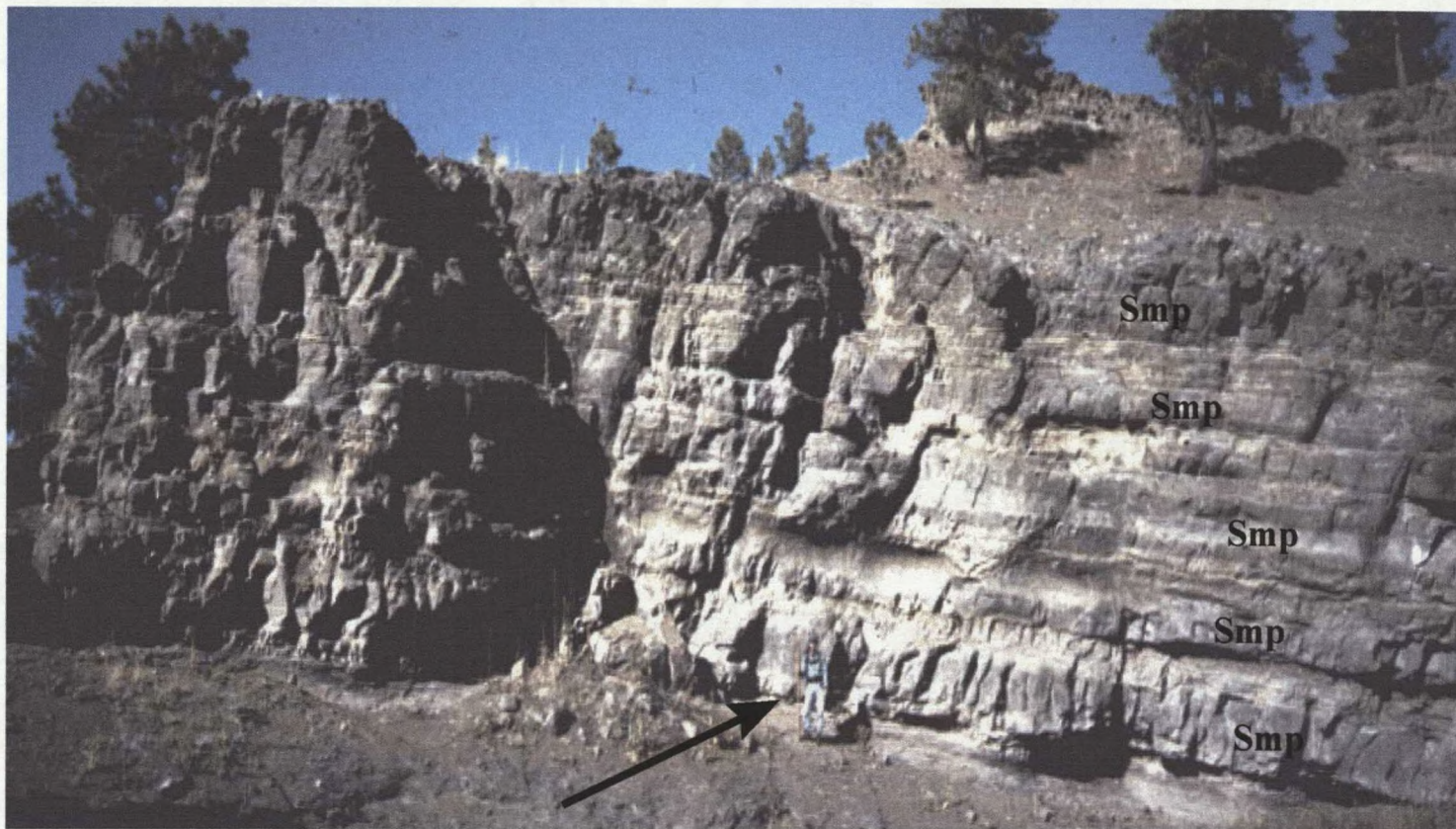


Figure 25: Laterally extensive hyperconcentrated flow and normal stream flow assemblage lithofacies interbedded with five paleosol horizons (lithofacies *Smp*) from measured section DB-1 (geologist in foreground for scale).

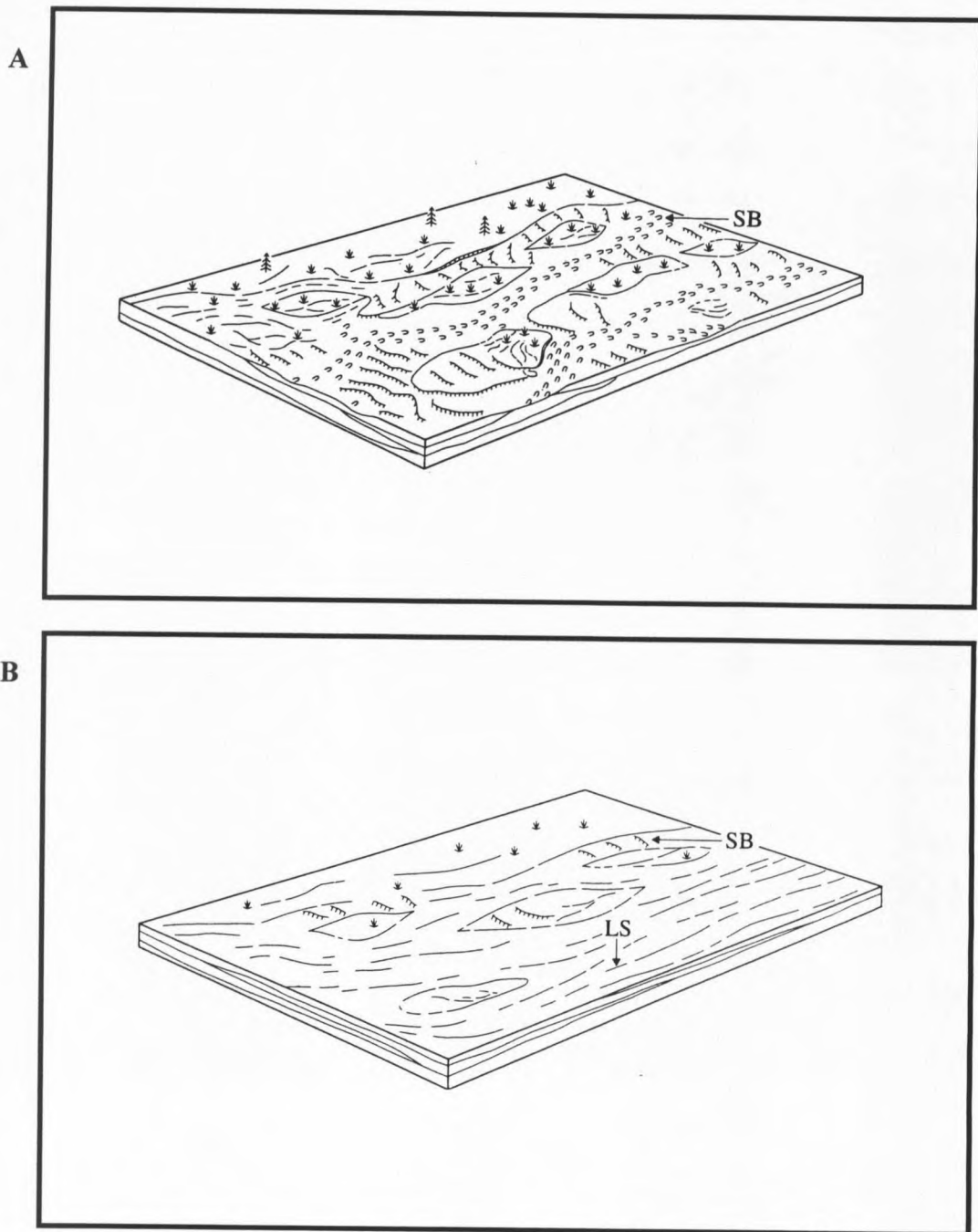


Figure 26: AMV braided stream deposits exhibit sedimentologic features common to: A) distal, sheetflood, sand-bed rivers and B) flashy, ephemeral, sheetflood, sand-bed rivers described by Miall (1996).

the Big Bend Region of Texas, documented by Runkel (1990). The tabular, laterally continuous lithofacies geometry suggest deposition in shallow, sand-dominated, channels that migrated across the floodplain in distal regions of the volcanoclastic apron. The overbank and interchannel deposits of the AMV braided stream system were likely modified by pedogenesis, indicated by prevalent root beds and paleosol horizons, suggesting prolonged periods of subaerial exposure (Collinson, 1986), perhaps due to seasonal fluctuations in discharge or frequent channel abandonment, and low sedimentation rates.

Interbedded normal stream flow assemblage (SF) and hyperconcentrated flow assemblage (HF) lithofacies suggest deposition under variable flow conditions dominated by upper-flow regime (Waresback and Turbeville, 1990). Sandy braided streams are characterized by shallow upper regime flow that can be flashy or ephemeral in nature (Rust, 1978). The common occurrence of pebble and cobble size intraclasts at the bases of massive and horizontally stratified sandstone beds (*Sm*, *Sh*, *Shg*) are interpreted as channel lag deposits and were likely deposited by hyperconcentrated flow during upper regime flow conditions. The presence of channel lag in sand-dominated hyperconcentrated flow deposits indicates the competency of the fluvial system to transport larger particles and that mostly sand size volcanic detritus was available for transport. Interbedded normal stream flow and hyperconcentrated flow deposits indicate periods of increased discharge that inundated the fluvial system of the braidplain environment represented by massive sandstone

(*Sm*) and horizontally stratified sandstone with and without gravel (*Sh*, *Shg*) lithofacies.

This cyclic repetition of stacked normal stream flow and hyperconcentrated flow deposits are similar to distal braided stream and sheetflood deposits associated with a rapidly aggrading volcanogenic-alluvial fan in the Puye Formation of the Jemez Mountains documented by Waresback and Turbeville (1990).

Braidplain assemblage lithofacies are illustrated by a representative stratigraphic column derived from measured section DB-1 (Figure 27). These deposits consist primarily of sandstone lithofacies, paleosol horizons and lesser mudrock lithofacies formed by normal or dilute stream flow and hyperconcentrated flow. The vertical thickness and cyclic repetition of lithofacies suggests prolonged occupation of distal regions of the volcanoclastic apron by a braided sand-bed river system. The braidplain assemblage grades upward into coarse-grained hyperconcentrated flow deposits and debris flow deposits. Massive matrix- and clast-supported conglomerate lithofacies (*Gmm*, *Gcm*) and massive, reversely-graded conglomerate lithofacies (*Gmr*) (at tops of measured sections DB-1) represent high volume debris flow events that reached beyond the volcanoclastic fan to distal environments (Palmer and Walton, 1990). These coarse-grained deposits are the initial stages of a generally coarsening upward sequence in the Coburn Mountain area which marks westward progradation of the developing volcanoclastic fan into the foreland basin (Mathisen and Vondra, 1983).

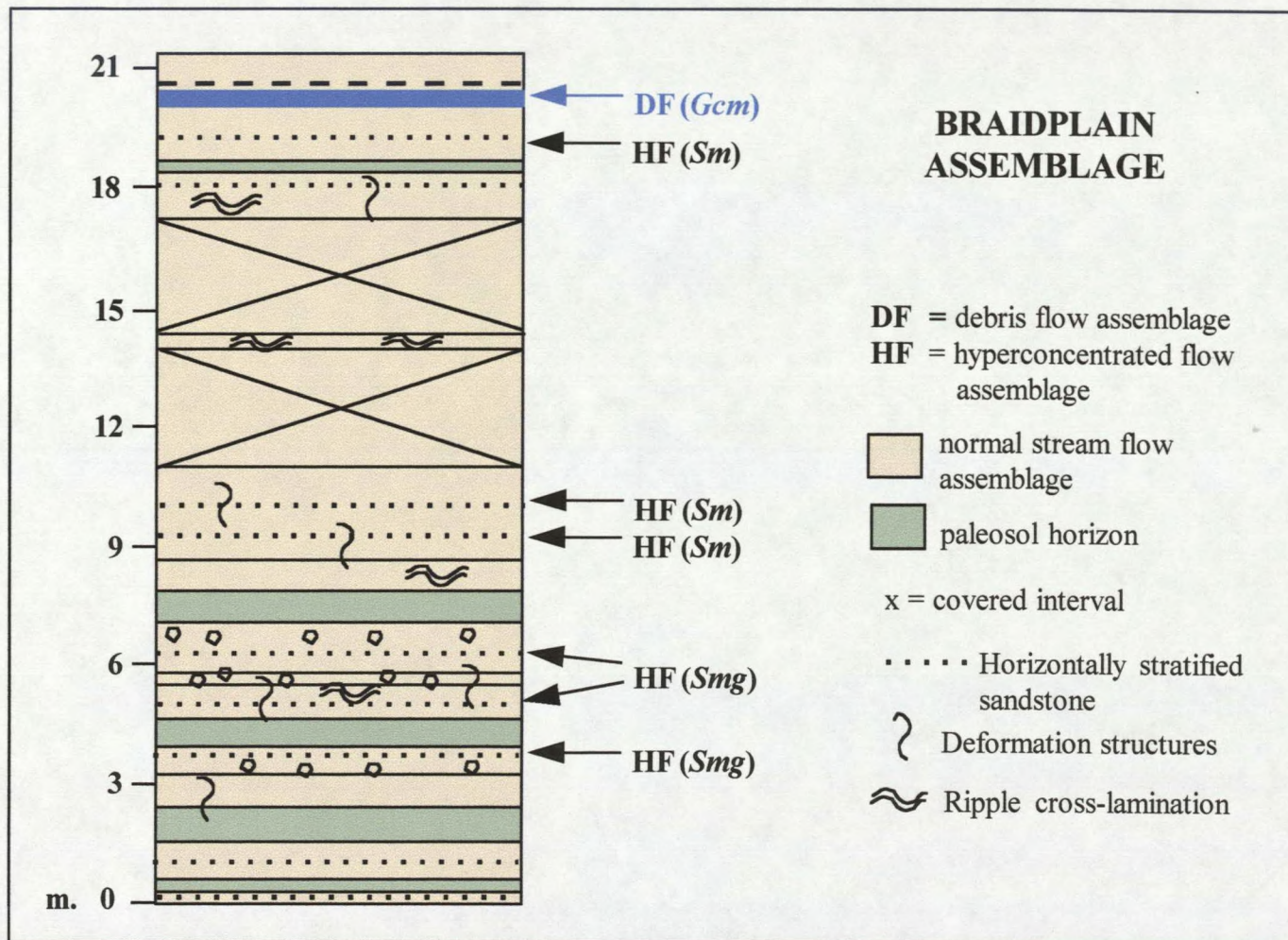


Figure 27: Generalized stratigraphic column of debris flow, hyperconcentrated flow and normal stream flow assemblages in the distal braidplain environment (from measured section DB-1).

Volcaniclastic Fan Environment

The volcaniclastic fan environment is dominated by massive, debris flow assemblage (DF) lithofacies. Although lesser in relative volume, hyperconcentrated flow assemblage (HF) lithofacies are significant components of the volcaniclastic fan stratigraphy. Debris flow and hyperconcentrated flow typify fan-building flow processes and sediment transport mechanisms in volcanic environments (Smith; 1986; Smith, 1988; Rodolfo, 1989; Palmer, 1989; Palmer and Walton, 1990; Smith and Lowe, 1991; Palmer et al., 1993). Debris flow deposits, interbedded with hyperconcentrated flow deposits, are commonly found in proximal and medial regions of volcanic environments and dominate the surrounding landscape, forming low-sloping, relatively flat-surfaced, volcanic aprons (Hackett and Houghton, 1989). Progradation of coalescing debris flow deposits form volcaniclastic fans, analogous in morphology and constructional processes to alluvial fans. Although stratigraphic contacts between lava flows and volcaniclastic fan deposits are limited to a small area in the tidal flat environment (discussed previously in Tidal Flat Environment) interbedded lava flows and debris flow deposits were frequently observed outside of the study area, in proximal regions of the volcanic center, indicating the lava flow assemblage was a significant component of the overall volcaniclastic fan stratigraphy.

The AMV volcanoclastic fan is characterized by coarsening-upward stacked, debris flow deposits that exhibit sheet-like geometries and lesser channel deposits (Figure 28). The presence of successive, laterally-extensive, sheet-like debris flow deposits and lack of erosional bounding surfaces represent distinct intervals of rapid aggradation within the overall volcanoclastic fan stratigraphy (Palmer and Walton, 1990). Sheet-like debris flow deposits mantle eroded surfaces of the volcanoclastic fan and subdue local topography by infilling depressions and channels and form vertical sequences, tens of meters thick (Tvd-1, Tvd-2, Tvd-3, Tvd-4, ST-1, ST-2, ST-3, ST-5, ST-6, ST-7). These deposits are typically finer grained than most channelized debris flow deposits (uniform pebble to cobble clast size) suggesting deposition by high-velocity, high-volume, clast-rich flows that spread laterally during downslope movement (Palmer and Walton, 1990; Palmer et al., 1993). Fine-grained debris flow deposits are prevalent at lower stratigraphic levels suggesting a limited supply of sediment was available for transport from the volcanic source area.

Channelized debris flows are generally coarser-grained (pebble to boulder size clasts) and more poorly-sorted than sheet-like debris flow deposits and display highly-irregular, erosional bounding surfaces. Channelized debris flows are more effective in eroding vertically by concentrating the weight of the flow in narrow channels (Arguden and Rodolfo, 1990). The extreme depths and densities of debris flows enable them to exert large shear stresses on their boundaries (Costa, 1988). When entering a wide stretch of channel, a debris flow spreads laterally and these portions of the flow often

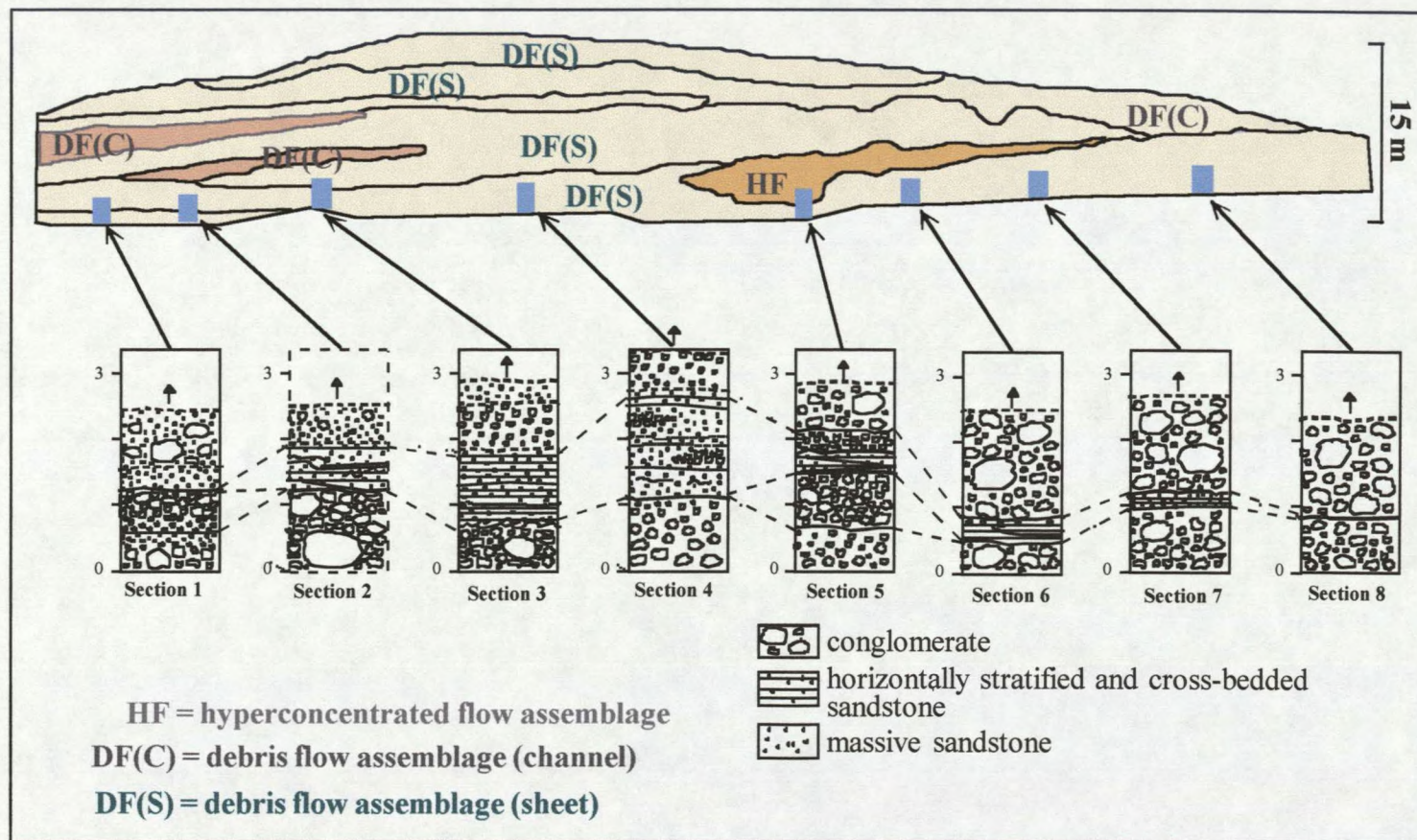


Figure 28: Lithofacies assemblages of the volcanoclastic fan environment including channelized (confined flow) debris flows and debris flow sheets (unconfined flow) with incised channels infilled with hyperconcentrated flow and debris flow deposits (top). Eight, 3-m measured sections from highway outcrop, Hwy-N (bottom). (Height of outcrop is 15 m.)

slow down or stop due to decreased depth and increased basal area friction (Arguden and Rodolfo, 1990). The thickest portions are likely to continue moving and eroding the channel, resulting in a narrow channel bounded by vertical walls or terraces composed of sequences of debris flow and hyperconcentrated flood flow deposits (Arguden and Rodolfo, 1990). Channelized debris flow deposits are lesser constituents of the overall stratigraphy of the volcanoclastic fan than unconfined debris flow deposits and are most common in proximal areas of the volcanoclastic apron (Palmer and Walton, 1990). Overall, coarse-grained debris flow deposits (cobble to boulder framework) are the dominant lithofacies in stratigraphic sequences higher in the overall fan stratigraphy and are interpreted to result from increased rates of weathering and mass-wasting from the volcanic edifice.

Repeated stratigraphic sequences of interbedded normal or dilute stream flow, hyperconcentrated flow and debris flow deposits indicate frequent degradation of the volcanoclastic fan surface. Reworking of mass flow deposits by normal stream flow and hyperconcentrated flood flow is pervasive in many volcanic environments (Palmer and Walton, 1990; Waresback and Turbeville, 1990). Debris flow deposits are commonly reworked by normal stream flow and hyperconcentrated flow in a braided pattern of shallow, shifting channels (less than 10 m wide and less than 1 m deep) produced by runoff during periods of heavy precipitation (Blair, 1987; Rodolfo, 1989). Associated debris flow assemblage (DF) and hyperconcentrated flow assemblage (HF) lithofacies are common in AMV sedimentary rocks in which hyperconcentrated flow erodes, and

subsequently infills, channels cut into debris flow sheets and channeled debris flow deposits (Figure 28).

A second association of gravel-dominated lithofacies (DF assemblage) with sand-dominated lithofacies (HF assemblage) is linked to the change from debris flow to hyperconcentrated flow by the process of flow transformation (Pierson and Scott, 1985; Smith, 1986). These bipartite depositional units are composed of a lower part displaying characteristics of hyperconcentrated flow deposits grading upward into a debris flow deposit (Pierson and Scott, 1985; Smith, 1986; Smith, 1991). Debris flows can be diluted by the addition of water during downslope movement, transforming them into hyperconcentrated flow at the flow front and flow margins (flow transformation) where deposition of the hyperconcentrated flow unit is followed by the cohesive portion of the original flow (Pierson and Scott, 1985; Smith, 1986; Smith, 1991). The association of interbedded debris flow assemblage (DF) and hyperconcentrated flow assemblage (HF) lithofacies are common throughout deposits of the volcanoclastic fan, especially at higher stratigraphic intervals within the study area.

DISCUSSION

The AMV succession comprises both primary eruptive products and associated volcanoclastic rocks that record deposition in coastal plain environments of the Western Interior Cretaceous seaway in a retroarc foreland basin setting. Thus, an appropriate lithofacies model for the AMV center must reflect the unusual paleogeographic and tectonic settings in which this volcanic system evolved.

Sediment Production

The sedimentary constituents of lithofacies include a wide range of volcanic detritus derived from the AMV center. The production of volcanic detritus is controlled by the availability and type of volcanic source rock, climatic conditions and post-depositional modification. Given the dominantly effusive nature of the AMV center, the bulk of sediment was inferred to be derived from physical and chemical weathering of volcanic source rocks.

Moderate climates that prevailed during Cretaceous time strongly influenced the sedimentary record of the AMV center (Gerard and Dols, 1990; Kauffman and Caldwell, 1993). The global climate of Late Cretaceous time was significantly warmer, approximately 6° to 12° warmer than today, and marked by an abrupt increase in

precipitation, resulting in a tropical to subtropical equatorial environment (Gerard and Dols, 1990; Kauffman and Caldwell, 1993). Warmer, wetter climates are conducive to rapid and sustained rates of climate-induced weathering of volcanic source rocks during which large volumes of volcanic detritus would be produced within the volcanic center. The presence of clay and detrital mineral grains within the matrix of both debris flow assemblage and hyperconcentrated flow assemblage lithofacies, as well as abundant detrital mineral grains in sandstones and mudrocks, indicates rapid rates of weathering of AMV rocks (Appendix A). The lack of large amounts of clay in AMV sedimentary rocks (refer to thin section analysis in Appendix B) may indicate that sediment was stored for short periods of time within the volcanic center prior to redistribution by various flow mechanisms; frequent precipitation events would initiate debris flows and hyperconcentrated flows that would facilitate deposition of available sediment in the volcanoclastic apron.

Sediment-producing processes characteristic of effusive volcanic settings must be considered in the context of: 1) variations in the proportions of specific lithofacies assemblages represented in volcanic successions (reflects preservation potential of specific types of deposits); 2) interpretations of depositional environments; and 3) development of lithofacies models that reflect different styles of volcanism.

Depositional Model

Specific depositional processes and deposits of volcanoclastic fan sequences are prevalent during interruptive periods, characterized by fan degradation, and syneruptive periods, characterized by fan aggradation (Smith, 1991). The lithofacies architecture of the AMV volcanoclastic apron and intertonguing foreland basin deposits record interruptive sedimentation marked by aggradation and progradation of the volcanoclastic fan into the adjacent retroarc foreland basin. In addition, volcanoclastic fans exhibit marked variations in lithofacies type and distribution as a function of proximity to source area and position in the vertical succession (Vessel and Davies, 1981; Waresback and Turbeville, 1990).

The lithofacies architecture of the AMV center is defined by vertical and lateral sedimentary sequences that record changes in depositional processes over time. Measured section data reveal well-established sedimentary environments - tidal flat and braidplain - that were periodically inundated by laterally extensive debris flow deposition and lava flows. Figure 29 illustrates generalized stratigraphic columns representing the depositional sequences that characterize tidal flat, braidplain and volcanoclastic fan environments of the AMV center. Evidence of progradation of the volcanoclastic fan is represented by debris flow deposits that cap stratigraphic sections of tidal flat and braidplain environments. Absence of channel incision and degradation

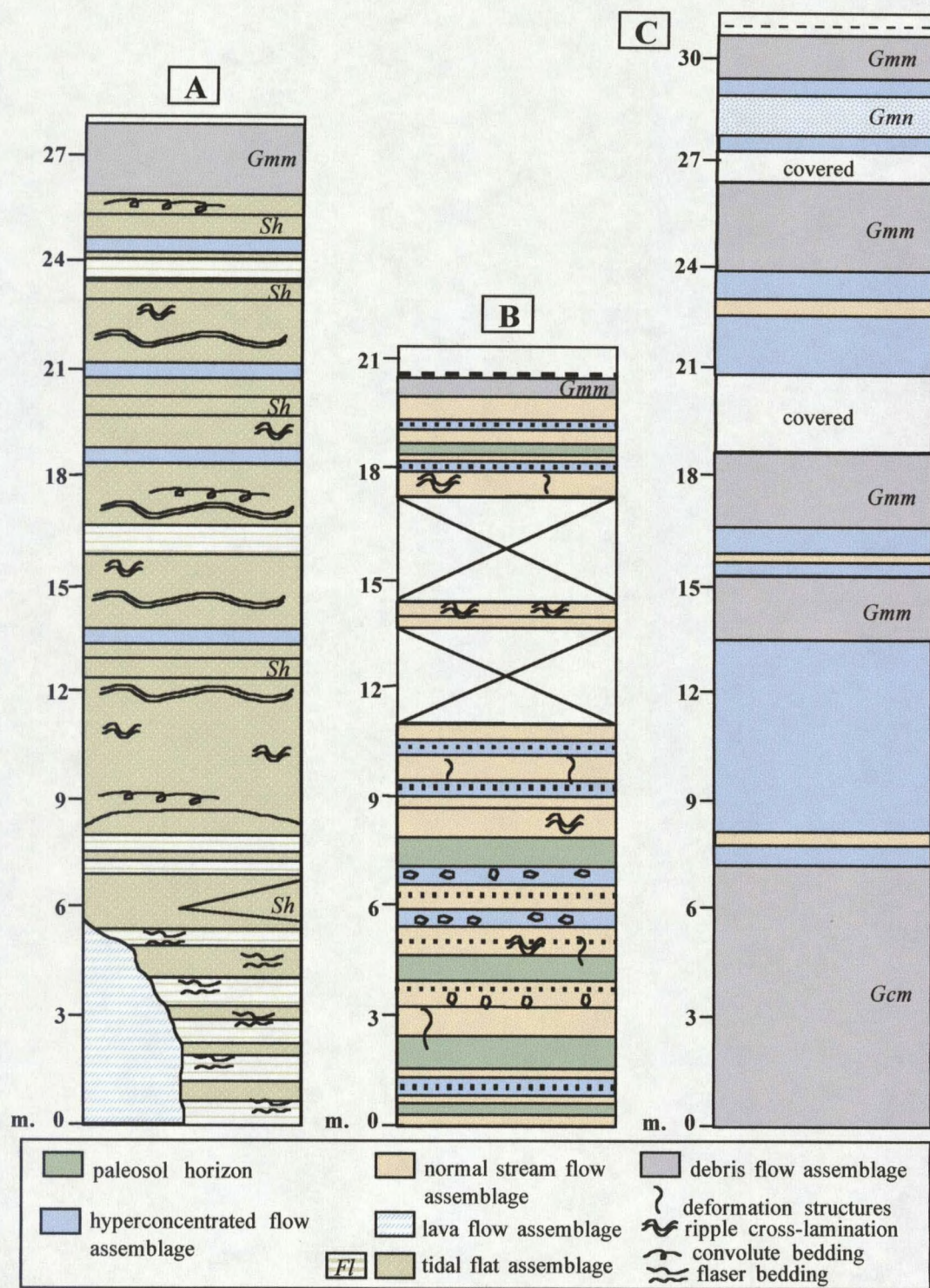


Figure 29: Generalized stratigraphic columns of sequences of lithofacies assemblages which define: A) tidal flat environment; B) braidplain environment; and C) volcanoclastic fan environment.

in many stacked debris flow deposits of the volcanoclastic fan environment suggests rapid aggradation induced by increased sediment production and increasing relief of proximal regions of the volcanic center by eruptive activity. Large volumes of sediment produced by denudation of proximal regions greatly increase the competency and capacity of debris flows and hyperconcentrated flows as the volcanoclastic fan prograded over distal braidplain deposits into the retroarc foreland basin (Waresback and Turbeville, 1990).

Sedimentary sequences recorded in measured sections compiled for this study suggest that the stratigraphic interval sampled represents early stages of development of the AMV volcanoclastic apron. This interpretation is based on specific sedimentologic features of volcanoclastic fan deposits including: 1) abundance of coarse-grained debris flow deposits (pebble-boulder size clasts) at higher stratigraphic intervals in measured sections (capping Coburn Mountain, which is the local topographic high); 2) a generally coarsening-upward depositional sequence; 3) paucity of degradational features including erosive bounding surfaces, deeply incised channels, paleosol horizons, interbedded normal stream flow and volcanoclastic fan deposits; and 4) laterally extensive deposition of debris flow sheets. Within the study area, stratigraphic sequences lower in the volcanoclastic apron stratigraphy contain a variety of deposits indicative of environments occupying distal regions of the volcanic center including braidplain deposits and tidal flat deposits (coastal plain environment).

The proposed model of lithofacies architecture of the AMV center stresses lateral variation in depositional environments and depositional events over time. Figure 30 diagrammatically illustrates the paleogeography of proximal, medial and distal regions of the AMV volcanoclastic apron and marginal foreland basin environments. Although tidal flat and braidplain lithofacies assemblages are restricted to their respective environments, lava flow, debris flow and hyperconcentrated flow assemblages can be transitory within all environments of the AMV center, creating lateral variability in depositional sequences that do not require extensive lateral shifting of depositional environments. For example, lava flow, debris flow and hyperconcentrated flow assemblage lithofacies could occur simultaneously in the volcanoclastic fan, braidplain or tidal flat environments at a given time or periodically over time. These spatial and temporal variations in depositional events, as well as the gross aggradation and progradation of the volcanoclastic fan, produce the vertical variations in depositional sequences of the AMV stratigraphic record.

Comparison of Effusive and Explosive Volcanic Systems

Examples of continental, mafic, effusive volcanism and associated sedimentation are limited to a few studies of monogenetic dome fields (White, 1991; Riggs et al., 1997) which show few similarities to the proposed depositional model of the AMV center. Riggs et al. (1997) documents the interaction of volcanism and

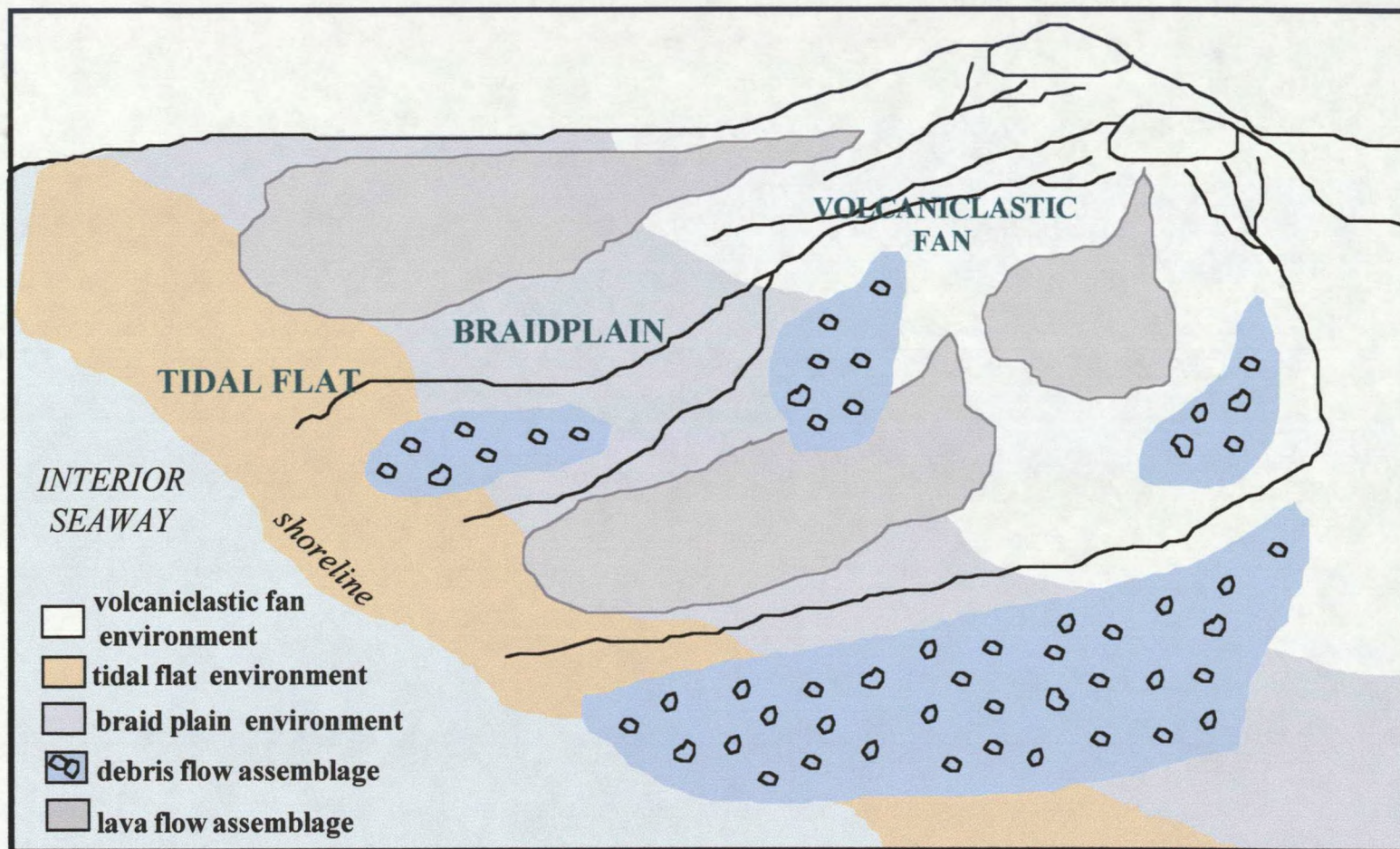


Figure 30: Volcaniclastic facies model for the AMV center illustrating lateral variation of depositional processes and deposits of the tidal flat, braidplain and volcaniclastic fan environments.

sedimentation in proximal areas of a mafic, mid-Tertiary dome field in central Arizona characterized by effusive volcanic activity punctuated by episodic explosive events.

White (1991) summarizes previous studies of the lithofacies types and landforms produced by monogenetic dome complexes including: hydrovolcanic fields (tuff rings, tuff cones, maars) characterized by syneruptive pyroclastic deposits and interuptive, reworked pyroclastic and hydroclastic deposits; and scoria dome fields (scoria cones, lava flows) characterized by syneruptive lava flows and pyroclastic deposits.

Comparison of the AMV volcanoclastic sequences with those documented by White (1991) and Riggs et al. (1997) reveals similarities in sedimentary processes but vastly different overall volcanic stratigraphy. Similarities between these volcanic systems and the AMV center include: 1) large volumes of epiclastic sediment produced by weathering of primary eruptive products; 2) epiclastic sediment transported and distributed primarily by debris flow, hyperconcentrated flow and normal stream flow; and 3) stratigraphy strongly influenced by intereruption redistribution of epiclastic deposits. Monogenetic dome fields differ from the AMV center in that: 1) most epiclastic sediment is preserved in areas proximal to the volcanic center, mainly low topographic areas between lava flow lobes; 2) regional fluvial systems surrounding the volcanic center transport large volumes of sediment away from the volcanic center; 3) effusive activity is punctuated by episodic explosive volcanic activity which contributes pyroclastic deposits; 4) sedimentary records of hydrovolcanic fields and scoria dome fields are dominated by deposits produced by normal stream flow processes; and 5)

dome fields have low topographic relief and therefore small volcanic source areas and volumetrically less epiclastic sediment.

Deposits of the AMV volcanoclastic apron and intertonguing foreland basin contain lithofacies assemblages common to volcanoclastic deposits of explosive stratovolcanoes (described previously in LITHOFACIES AND LITHOFACIES ASSEMBLAGES) indicating these volcanic systems contain deposits produced by similar flow types and sediment transport mechanisms, mainly debris flow, hyperconcentrated flow and normal stream flow. However, explosive volcanic systems produce large volumes of volcanoclastic sediment (pyroclastic, epiclastic) during eruptive periods and therefore syneruptive sediment production is dominant. In comparison, the AMV center is characterized by intereruptive sedimentation based on: 1) absence of lava flows interbedded with sedimentary deposits; 2) presence of early-stage extrusive rocks and late-stage intrusive rocks in sedimentary deposits; and 3) aggradation of the volcanoclastic apron induced by rapid rates of sediment production and deposition.

Deposits associated with stratovolcanoes contain large volumes of particles formed by explosive processes including bombs, pumice, welded tuff, lapilli, volcanic glass and ash. These types of explosively produced particles, and associated deposits, are not preserved in the AMV study area. AMV volcanoclastic rocks contain mostly lithic clasts, detrital mineral grains and clay derived from weathering of volcanic source rocks including intrusive and extrusive igneous rocks.

In summary, this research expands existing lithofacies models by: 1) contributing detailed sedimentologic analysis of the range of lithofacies, flow types, sediment transport mechanisms, and lithofacies architecture that characterize a previously unrecognized style of continental, mafic, effusive volcanism; 2) documenting that volcanoclastic deposits can be a significant component of the stratigraphic record of mafic, effusive volcanic centers; and 3) documenting that particular sedimentary processes, and resulting deposits, are characteristic of both effusive and explosive volcanic systems.

CONCLUSIONS

This study applies principals of sedimentology, stratigraphy and rheology to expand existing volcanoclastic facies models of continental, mafic, effusive volcanic systems. Interpretations of flow types, sediment transport mechanisms and volcanic fan-building processes provide valuable information regarding the paleogeography, depositional processes and depositional environments preserved in volcanoclastic apron and foreland basin deposits of the Late Cretaceous Adel Mountain Volcanic center.

Lithofacies represent the basic depositional units that comprise the volcanoclastic apron and intertonguing foreland basin deposits. Twenty lithofacies are delineated on the basis of sedimentologic characteristics, bed geometry and internal structures observed from field data and compiled in measured stratigraphic sections. Lithofacies were grouped based on particle size and include conglomerate lithofacies (gravel), sandstone lithofacies (sand and granules) and mudrock lithofacies (silt and clay). Five lithofacies assemblages were recognized in the AMV succession - lava flow, debris flow, hyperconcentrated flow, normal stream flow and tidal current assemblages. These assemblages are defined as groups of lithofacies that form by similar flow types and sediment transport mechanisms. Deposits of one or several associated assemblages are characteristic of particular depositional environments: lava

flow and tidal current assemblages comprise tidal flat deposits of the shallow marine environment; normal or dilute stream flow and hyperconcentrated flow assemblages comprise the braidplain environment; and debris flow and associated hyperconcentrated flow assemblages comprise the volcanoclastic fan environment.

Sedimentary and primary igneous rocks of the AMV volcanoclastic apron were deposited in tidal flat, braidplain and volcanoclastic fan environments that record aggradation and westward progradation of the volcanoclastic fan into the retroarc foreland basin. The lateral and vertical distribution of lithofacies assemblages record transitory depositional events occurring in proximal, medial and distal regions of the volcanic center and distinctive lateral changes in sedimentation that correspond to distance from the volcanic source area. The lithofacies architecture of the Adel Mountain volcanoclastic apron and intertonguing foreland basin deposits is distinguished by widespread interruptive sedimentation, dominated by debris flow deposition, in response to local precipitation events and denudation of the volcanic center.

Further research of the AMV center should include: 1) additional sedimentologic investigation of volcanoclastic deposits located north and west of the study area; 2) development of a stratigraphic chronology of the AMV succession; 3) clarification of regional structural and stratigraphic relations of AMV rock units.

REFERENCES CITED

- Arguden, A.T., and Rodolfo, K.S., 1990, Sedimentologic and dynamic differences between hot and cold laharic debris flows of Mayon Volcano, Philippines: Geological Society of America Bulletin, v. 102, p. 865-876.
- Bagnold, R.A., 1954, Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear: Proceedings Royal Society of London, v. 225, p. 49-63.
- Ballance, P.F., and Gregory, M.R., 1991, Parnell Grits - large subaqueous volcanoclastic gravity flows with multiple particle-support mechanisms, *in*: Fisher, R.V. and Smith, G.A., eds., Sedimentation in volcanic settings: Society of Economic Paleontologists and Mineralogists Special Publication 45, p. 189-200.
- Beall, J.J., 1973, Mechanics of intrusion and petrochemical evolution of the Adel Mountain Volcanics: unpublished Ph.D. dissertation, University of Montana, Missoula, 101p.
- Blair, T.C., 1987, Sedimentary processes, vertical stratification sequences, and geomorphology of the Roaring River alluvial fan, Rocky Mountain National Park, Colorado: Journal of Sedimentary Petrology, v. 57, n. 1, p. 1-18.
- Blair, T.C., and McPherson, J.G., 1998, Recent debris-flow processes and resultant form and facies of the Dolomite alluvial fan, Owens Valley, California: Journal of Sedimentary Research, 68, 5, p. 800-818.
- Blatt, H., Middleton, G., and Murray, R., 1972, Origin of sedimentary rocks. New York, Prentice-Hall, 634 p.
- Brackenridge, G. R., 1988, River flood regime and floodplain stratigraphy, *in*: Baker, V.R., Kochel, R.C., Patton, P.C., eds., Flood geomorphology, New York, John Wiley & Sons, p. 139-156.
- Busby-Spera, C.J., and White, J.L., 1987, Variation in peperite textures associated with differing host-sediment properties: Bulletin of Volcanology, 49, p. 765-775.

- Busby-Spera, C.J., 1988, Evolution of a Middle Jurassic back-arc basin, Cedros Island, Baja California: evidence from a marine volcanoclastic apron: *Geological Society of America Bulletin*, v. 100, p. 218-233.
- Cas, R.A.F., Wright, J.V., 1988, Volcanic successions modern and ancient: a geological approach to processes, products and successions, New York, Chapman & Hall, 528 p.
- Collinson, J.D., 1986, Alluvial sediments, *in*: Reading, H.G., eds., *Sedimentary environments and facies*, London, Blackwell Scientific Publications, p. 20-62.
- Costa, J.E., 1988, Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows, *in*: Baker, V.R., Kochel, R.C., Patton, P.C., eds, *Flood geomorphology*, John Wiley & Sons, New York, p. 113-122.
- Cunningham, B., 1999, Petrogenesis of the Adel Mountains, central Montana: evidence for magma mingling: *Geological Society of America, Rocky Mountain Section Meeting, Abstracts with Programs*, p. A-9.
- Elliott, T., 1978, Siliciclastic shorelines, *in*: Reading, H.G., ed., *Sedimentary Environments and Facies*, London, Blackwell Scientific Publications, p. 155-188.
- Enos, P., 1977, Flow regimes in debris flow: *Sedimentology*, v. 24, p. 133-142.
- Fisher, R.V., 1960, Classification of volcanic breccias: *Geological Society of America Bulletin*, v. 71, n. 7, p. 973-982.
- Fisher, R.V., 1971, Features of coarse-grained high-concentration fluids and their deposits: *Journal of Sedimentary Petrology*, 41, 4, p. 916-927.
- Fisher, R.V., and Smith, G.A., 1991, Volcanism, tectonics and sedimentation, *in*: Fisher, R.V., and Smith, G.A., eds., *Sedimentation in volcanic settings: Society of Economic Paleontologists and Mineralogists Special Publication 45*, p. 1-5.
- Fritz, W.J., and Howells, M.F., 1991, A shallow marine volcanoclastic facies model: an example from sedimentary rocks bounding the subaqueously welded Ordovician Garth Tuff, North Wales, U.K.: *Sedimentary Geology*, v. 74, p. 217-240.
- Gerard, J.C., and Dols, V., 1990, The warm Cretaceous climate: role of the long-term carbon cycle: *Geophysical Research letters*, v. 7, n. 14, p. 1561-1564.
- Glicken, H., 1991, Facies architecture of large volcanic-debris avalanches, *in*: Fisher, R.V. and Smith, G.A. eds., *Sedimentation in volcanic settings: Society of Economic Paleontologists and Mineralogists Special Publication 45*, p. 99-108.

- Gunderson, J.A., and Sheriff, S.D., 1991, A new Late Cretaceous paleomagnetic pole from the Adel Mountains, west central Montana: *Journal of Geophysical Research*, v. 96, p. 317-326.
- Hackett, W.R., and Houghton, B.F., 1989, A facies model for Quaternary andesitic composite volcano: Ruapehu, New Zealand: *Bulletin of Volcanology*, v. 51, p. 51-68.
- Hampton, M.A., 1979, Buoyancy in debris flows: *Journal of Sedimentary Petrology*, v. 49, n. 3, p. 753-758.
- Hanson, R.E., and Schweickert, R.A., 1982, Chilling and brecciation of a Devonian rhyolite sill intruded into wet sediments, Northern Sierra Nevada, California: *Journal of Geology*, v. 90, p. 717-724.
- Hanson, R.E., and White, T.J., 1993, Large-scale rhyolite peperites (Jurassic, southern Chile): *Journal of Volcanology and Geothermal Research*, v. 54, p. 247-264.
- Harlan, S.S., Geissman, J.W., Lageson, D.R., and Snee, L.W., 1988, Paleomagnetic and isotopic dating of thrust-belt deformation along the eastern edge of the Helena salient, northern Crazy Mountains Basin, Montana: *Geological Society of America Bulletin*, v. 100, p. 492-499.
- Harlan, S.S., Mehnert, H.H., Snee, L.W., Sheriff, S., and Schmidt, R.G., 1991, New ^{40}Ar - ^{39}Ar isotopic dates from the Adel Mountain Volcanics: implications for the relationship between deformation and magmatism in the Montana disturbed belt, western Montana (abstract): *Geological Society of America Abstracts with Programs*, v. 23, p. A136.
- Harms, J.C., and Fahnestock, R.K., 1965, Stratification, bed forms, and flow phenomena (with an example from the Rio Grande: *Society of Economic Paleontologists and Mineralogists Special Publication 12*, p. 84-115.
- Hyndman, D.W., and Alt, D., 1987, Radial dikes, laccoliths and gelatin models: *Journal of Geology*, v. 95, p. 763-774.
- Kauffman, E.G., and Caldwell, W.G.E., 1993, The western interior basin in space and time, In Caldwell, W.G.E. and Kauffman, E.G., eds., *Evolution of the Western Interior Basin: Geological Association of Canada, Special Paper 39*, p. 1-30.
- Larsen, V., and Steel, R.J., 1978, The sedimentary history of a debris-flow dominated Devonian alluvial fan - a study of textural inversion: *Sedimentology*, 25, p. 37-59.

- Lindsay, J.F., 1968, The development of clast fabric in mudflows: *Journal of Sedimentary Petrology*, v. 38, n. 4, p. 1242-1253.
- Lyons, J.B., 1944, Igneous rocks of the northern Big Belt Range, Montana: *Geological Society of America Bulletin*, v. 55, p. 445-472.
- Mathisen, M.E., and Vondra, C.F., 1983, The fluvial and pyroclastic deposits of the Cagayan basin, Northern Luzon, Philippines - an example of nonmarine volcanoclastic sedimentation in an interarc basin: *Sedimentology*, v. 30, p. 369-392.
- Mathisen, M.E., and McPherson, J.G., 1991, Volcanoclastic deposits: implications for hydrocarbon exploration, *in*: Fisher, R.V. and Smith, G.A. eds., *Sedimentation in volcanic settings*: Society of Economic Paleontologists and Mineralogists Special Publication 45, p. 27-36.
- Miall, A.D., 1978, Lithofacies types and vertical profile models in braided river deposits: a summary, *in*: Miall, A.D., ed., *Fluvial Sedimentology*, Canadian Society of Petroleum Geologists Memoir 5, p. 597-604.
- Miall, A.D., 1985, Architectural-element analysis: a new method of facies analysis applied to fluvial deposits: *Earth-Science Reviews*, v. 22, p. 261-308.
- Miall, A.D., 1996, *The geology of fluvial deposits: sedimentary facies, basin analysis, and petroleum geology*: New York, Springer, 582 p.
- Middleton, G.V., 1970, Experimental studies related to problem of flysch sedimentation, *in*: Lajoie, J., ed., *Flysch sedimentology in North America*: Geological Society of Canada Special Paper 7, p. 253-272.
- Mitchell, A.H.G., 1970, Facies of an Early Miocene volcanic arc, Malekula Island, New Hebrides: *Sedimentology*, v. 14, p. 201-243.
- Newhall, C.G., and Punongbayan, R.S., 1996, *Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines*: University of Washington Press, Seattle, 1125p.
- Nichols, M.M., Johnson, G.H., and Peebles, P.C., 1991, Modern sediments and facies model for a microtidal coastal estuary, the James Estuary, Virginia: *Journal of Sedimentary Petrology*, v. 61, p. 883-899.
- Orton, G.J., 1995, Facies models in volcanic terranes: time's arrow versus time's cycle, *in*: Plint, A.G., ed., *Sedimentary facies analysis*: International Association of Sedimentologists Special Publication 22, p. 157-193.

- Palmer, B.A., 1991, Holocene lahar deposits in the Whakapapa catchment, northwestern ring plain, Ruapehu volcano (North Island, New Zealand): *New Zealand Journal of Geology and Geophysics*, v. 34, p. 177-190.
- Palmer, B.A., 1997, Sedimentary record of caldera-forming eruptions, Eocene Challis volcanic field, Idaho: *Geological Society of America Bulletin*, v. 109, p. 242-252.
- Palmer, B.A., and Walton, A.W., 1990, Accumulation of volcanoclastic aprons in the Mount Dutton Formation (Oligocene-Miocene), Marysvale volcanic field, Utah: *Geological Society of America Bulletin*, v. 102, p. 734-748.
- Palmer, B.A., Alloway, B.V., and Neall, V.E., 1991, Volcanic debris-avalanche deposits in New Zealand - lithofacies organization in unconfined wet avalanche flows, *in*: Fisher, R.V., and Smith, G.A., eds., *Sedimentation in volcanic settings: Society of Economic Paleontologists and Mineralogists Special Publication 45*, p. 89-98.
- Palmer, B.A., Purves, A.M., and Donoghue, S.L., 1993, Controls on accumulation of a volcanoclastic fan, Ruapehu composite volcano, New Zealand: *Bulletin of Volcanology*, v. 55, p. 176-189.
- Pierson, T.C., and Scott, K.M., 1985, Downstream dilution of a lahar: transition from debris flow to hyperconcentrated streamflow: *Water Resources Research*, v. 21, n. 10, p. 1511-1524.
- Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, *in*: Costa, J.E., and Wieczorek, G.F., eds., *Debris flows/avalanches: process, recognition, and mitigation: Geological Society of America Reviews in Engineering Geology*, n. 7, p. 1-12.
- Pierson, T.C., Janda, R.J., Thouret, J.C., and Borrero, C.A., 1990, Perturbation of melting snow and ice by the 13 November eruption of Nevado del Ruiz, Columbia, and consequent mobilization, flow and deposition of lahars: *Journal of Volcanology and Geothermal Research*, v. 41, p. 17-66.
- Reading, H.G., 1986, Facies, *in*: Reading, H.G., ed., *Sedimentary environments and facies*, London, Blackwell Scientific Publications, p.4-19, 33.
- Reineck, H.E., and Wunderlich, F., 1968, Classification and origin of flaser and lenticular bedding: *Sedimentology*, v. 11, p. 99-104.
- Riggs, N.R., Hurlbert, J.C., Schroeder, T.J., and Ward, S.A., 1997, The interaction of volcanism and sedimentation in the proximal areas of a mid-Tertiary volcanic dome field, central Arizona, U.S.A.: *Journal of Sedimentary Research*, v. 67, p. 142-153.

- Rodolfo, K.S., 1989, Origin and early evolution of lahar channel at Mabinit, Mayon Volcano, Philippines: Geological Society of America Bulletin, v. 101, p. 414-426.
- Rodolfo, K.S., and Arguden, A.T., 1991, Rain-lahar generation and sedimentary delivery systems at Mayon volcano, *in*: Fisher, R.V. and Smith, G.A., eds., Sedimentation in volcanic settings: Society of Economic Paleontologists and Mineralogists Special Publication 45, p. 71-78.
- Rowley, P.D., MacLeod, N.S., Kuntz, M.A., and Kaplan, A.M., 1985, Proximal bedded deposits related to pyroclastic flows of May 18, 1980, Mount St. Helens, Washington: Geological Society of America Bulletin, v. 96, p. 1373-1383.
- Runkel, A.C., 1990, Lateral and temporal changes in volcaogenic sedimentation: analyses of two eocene sedimentary aprons, Big Bend region, Texas: Journal of Sedimentary Petrology, v. 60, p. 747-760.
- Rust, B.R., 1978, Depositional models for braided alluvium, *in*: Miall, A.D., ed., Fluvial sedimentology, Canadian Society of Petroleum Geologists Memoir 5, p. 605-625.
- Samoylova, E.M., 1971, Some relict signs in contemporary soils of the Tambov Lowland, U.S.S.R. *in*: D.H. Yaalon, ed., Paleopedology: origin, nature and dating of paleosols: Jerusalem, Israel Universities Press, p. 173-180.
- Schmidt, R.G., 1972, Geologic map of the Coburn Mountain quadrangle, Lewis and Clark and Cascade Counties, Montana: United States Geological Survey Geological Quadrangle Map GQ-975.
- Schmidt, R.G., 1977, Geologic map of the Craig quadrangle, Lewis and Clark and Cascade Counties, Montana: United States Geological Survey Geological Quadrangle Map GQ-1411.
- Schmidt, R.G., 1978, Rocks and mineral resources of the Wolf Creek area, Lewis and Clark and Cascade Counties, Montana: United States Geological Survey Bulletin 1441, 91p.
- Schultz, A.W., 1984, Subaerial debris-flow deposition in the Upper Paleozoic Cutler Formation, Western Colorado: Journal of Sedimentary Petrology, v. 54, no. 3, p. 759-772.
- Sheriff, S.D., and Gunderson, J.A., 1990, Age of the Adel Mountain volcanic field, west-central Montana: Isochron/West, n. 56, p. 21-23.

- Singer, B.S., Thompson, R.A., Dungan, M.A., Feeley, T.C., Pickens, J., Brown, L.L., Nelson, S.T., Wulff, A.W., Davidson, J.P., and Metzger, J., 1997, Volcanism and erosion during the past 930 k.y. at the Tatara-San Pedro complex, Chilean Andes: Geological Society of America Bulletin, v. 109, p. 127-142.
- Smith, A., 1998, Volcanism and associated sedimentation in a retroarc foreland basin: the Upper Cretaceous Two Medicine Formation of west-central Montana: unpublished Master's thesis, Montana State University, Bozeman, p. 170.
- Smith, G.A., 1988, Sedimentology in proximal to distal volcanoclastics dispersed across an active foldbelt: Elensburg Formation (late Miocene), central Washington: Sedimentology, v. 35, p. 953-977.
- Smith, G.A., 1991, Facies sequences and geometries in continental volcanoclastic sediments, *in*: Fisher, R.V., and Smith, G.A., eds., Sedimentation in volcanic settings: Society of Economic Paleontologists and Mineralogists Special Publication 45, p. 109-121.
- Smith, R.C.M., 1991a, Landscape response to a major ignimbrite eruption, Taupo Volcanic Center, New Zealand, *in*: Fisher, R.V., and Smith, G.A., eds., Sedimentation in volcanic settings: Society of Economic Paleontologists and Mineralogists Special Publication 45, p. 123-137.
- Smith, R.C.M., 1991b, Post-eruption sedimentation on the margin of a caldera lake, Taupo Volcanic centre, New Zealand: Sedimentary Geology, v. 74, p. 89-138.
- Smith, G.A., and Lowe, D.R., 1991, Lahars: volcano-hydrologic events and deposition in the debris flow-hyperconcentrated flow continuum, *in*: Fisher, R.V., and Smith, G.A., eds., Sedimentation in volcanic settings: Society of Economic Paleontologists and Mineralogists Special Publication 45, p. 59-70.
- Stow, D.A.V., 1978, Deep clastic seas, *in*: Reading, H.G., ed., Sedimentary Environments and Facies, London, Blackwell Scientific Publications, p. 399-443.
- Swenson, R.F., 1987, Adel Mountain Volcanics: a trip through geo-fantasyland: unpublished senior thesis, University of Montana, Missoula, 45p.
- Teruggi, M.E., and Andreis, R.R., 1971, Micromorphological recognition of paleosolic features in sediments and sedimentary rocks, *in*: Yaalon, D.H., ed., Paleopedology: origin, nature and dating of paleosols: Jerusalem, Israel Universities Press, p. 161-172.

- Turbeville, B.N., Waresback, D.B., and Self, S., 1989, Lava-dome growth and explosive volcanism in the Jemez Mountains, New Mexico: Evidence from the Plio-Pleistocene Puye alluvial fan: *Journal of Volcanology and Geothermal Research*, v. 36, p. 267-291.
- Vessell, R.K., and Davies, D.K., 1981, Nonmarine sedimentation in an active fore arc basin, *in*: Ethridge, F.G., and Flores, R.M., eds., Recent and ancient nonmarine depositional environments: models for exploration: Society of Economic Paleontologists and Mineralogists Special Publication 31, p. 31-45.
- Viele, G.W., and Harris, F.G., 1965, Montana Group stratigraphy, Lewis and Clark County, Montana: *American Association of Petroleum Geologists Bulletin*, v. 49, p. 379-417.
- Walton, A.W., 1986, Effect of Oligocene volcanism on sedimentation in the Trans-Pecos volcanic field of Texas: *Geological Society of America Bulletin*, v. 97, p. 1192-1207.
- Walton, A.W., and Palmer, B.A., 1988, Lahar facies of the Mount Dutton Formation (Oligocene-Miocene) in the Marysvale volcanic field of Utah: *Geological Society of America Bulletin* v. 100, p. 1078-1091.
- 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.
- White, J.D.L., 1991, The depositional record of small, monogenetic volcanoes within terrestrial basins, *in*: Fisher, R.V., and Smith, G.A., eds., Sedimentation in volcanic settings: Society of Economic Paleontologists and Mineralogists Special Publication 45, p. 155-171.
- Whiting, C.K., 1977, Small laccoliths and feeder dikes of the northern Adel Mountain volcanics: unpublished Master's thesis, University of Montana, Missoula, 74p.

APPENDICES

APPENDIX A

LOCATIONS OF MEASURED STRATIGRAPHIC SECTIONS

Craig Field Area: From the center of Craig, Montana travel east over the Missouri River bridge and turn left onto Frontage Road. Continue for 2.4 kilometers. Stratigraphic sections Tvd-1, Tvd-2, Tvd-3 and Tvd-4 were measured in units Tvab, Tvd and Tve from roadside to vertical outcrop exposures upslope. (Reference the Craig Quadrangle for landmarks and rock units, Schmidt, 1972)

Stirling Ranch Field Area: The Stirling Ranch is privately owned and access must be requested in advance of field work by contacting the Blackman family in Craig, Montana. From the center of Craig, Montana travel east over the Missouri River bridge and turn right onto Frontage Road. Stratigraphic sections ST-1, ST-2, ST-3 and ST-4 were measured from outcrops along Frontage Road (immediately after right turn from bridge) from roadside upslope to top of ridge. Stratigraphic section ST-6, ST-7 and ST-8 were measured in interior areas of the Stirling Ranch. (Reference the Craig Quadrangle for landmarks and rock units, Schmidt, 1977.)

From private driveway opposite Missouri River bridge, follow dirt access road, turn left at first fork and continue to end of road (near corral). These sections were measured near top of ridge upslope from corral (approximately 1/2 way upslope to top of ridge). (Reference the Craig Quadrangle for landmarks and rock units, Schmidt, 1977.)

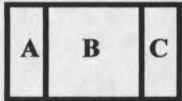
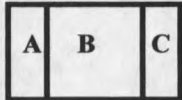
Highway 15 Field Area: Stratigraphic section Hwy-N was measured along the south-bound side of Highway 15. From the town of Craig, Montana, travel west out of town and turn onto Highway 15 north. Travel for approximately 6 kilometers on Highway 15 north to the town of Dearborn, take exit and return back to Highway 15 heading south. Hwy-N outcrop is approximately 0.5 kilometers from the Craig exit. Eight 3-m sections were measured near the base of the outcrop (from southern end to northern end). (Reference the Craig Quadrangle for landmarks and rock units, Schmidt, 1977.)

Dearborn Ranch Field Area: The Dearborn Ranch is privately owned and access must be requested from the Ranch Manager (Rock Creek Office in Wolf Creek, Montana) in advance of field work. From the center of Craig, Montana travel west out of town, under Highway 15 overpass to Seven Mile Road. Continue on Seven Mile Road approximately 5.85 kilometers (west) to Dearborn Ranch access gate on right side of road. (Four-wheel drive vehicles are recommended on this ranch access road.) Travel approximately 3 kilometers taking left at fork in road. Stratigraphic sections DB-1, DB-2, DB-3, DB-4 and DB-5 were measured in units Tvab and Tvd which crop out along drainages in low-lying areas west of Coburn Mountain.). (Reference the Coburn Mountain Quadrangle for landmarks and rock units, Schmidt, 1972.)

APPENDIX B

SUMMARY OF PETROGRAPHIC ANALYSIS OF THIN SECTIONS

Table 4. Summary of petrologic analysis of thin sections of AMV sedimentary rocks.

Slide/Rock Name	Petrologic Description
Tvd-1 Volcanic Litharenite (fine-grained mudrock)	30% detrital minerals 30% magnetite and clay 4% volcanic rock fragments 2% labradorite Cement - quartz (reprecipitated), kaolinite
Tvd-2 Volcanic Litharenite (fine-medium sandstone)	<u>Zone A</u> Fine-medium grained sandstone 60% quartz (angular grains, overgrowth, rare cement) 15% volcanic rock fragments 15% detrital minerals 10% magnetite and clay Slide Tvd-2  <u>Zone B</u> 70% detrital minerals 20% quartz (angular grains, overgrowths) 10% magnetite and clay <u>Zone C</u> 90% quartz (sub-angular grains, overgrowths) 5% rock fragment 5% detrital minerals
Tvd-3 Volcanic Litharenite (medium-coarse sandstone)	<u>Zone A</u> 80% volcanic rock fragments 10% detrital minerals 5% magnetite and clay 5% quartz (reprecipitated cement) Slide Tvd-3  <u>Zone B</u> 60% volcanic rock fragments 30% detrital minerals 10% magnetite and clay <u>Zone C</u> 50% volcanic rock fragment 40% quartz (reprecipitated) 5% detrital minerals 5% magnetite and clay
Tvd-4 Volcanic Litharenite (very coarse sandstone)	75% volcanic rock fragments 10% detrital minerals 10% magnetite and clay 5% quartz (reprecipitated)
Hwy-2, Hwy-3, Hwy-4 Conglomerate Matrices	coarse-very coarse grained Composed of volcanic rock fragments and detrital minerals

* Detrital minerals consist mostly of augite (phenocrysts) with lesser labradorite, sanidine, olivine and magnetite (from Schmidt 1972, 1977, 1978).

MONTANA STATE UNIVERSITY - BOZEMAN



3 1762 10422656 6