

THE INFLUENCE OF GROWING STRUCTURES ON CRETACEOUS
ALLUVIAL SYSTEMS ALONG THE CORDILLERAN THRUST BELT FRONT,
VALLEY OF FIRE, SOUTHERN NEVADA

by

Kelsey Caitlin McNamara

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

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

January 2010

©COPYRIGHT

by

Kelsey Caitlin McNamara

2010

All Rights Reserved

APPROVAL

of a thesis submitted by

Kelsey Caitlin McNamara

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

Dr. James G. Schmitt

Approved for the Department of Earth Sciences

Dr. Steven Custer

Approved for the Division of Graduate Education

Dr. Carl A. Fox

STATEMENT OF PERMISSION TO USE

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

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

Kelsey Caitlin McNamara

January 2010

ACKNOWLEDGEMENTS

First and foremost I would like to thank my advisor, Dr. Jim Schmitt. I came to MSU wanting to study sedimentation and tectonics and he set me up with a great project that I'm still super-passionate about! He was extremely straightforward, encouraging and very helpful. I am also thankful for a great committee, Dave Lageson and Dave Bowen, who scared the crap out of me during comps but provided valuable feedback and support during my time here. I would also like to thank the faculty of the MSU Earth Sciences Department, who introduced this girl from the midwest to the geologic wonders of the western U.S. Special thanks goes out to Todd Feeley, Kelli Heck and Gail Weidenaar. Many thanks to my fellow graduate students, especially Cathy Lash, Beth Helmke and Josh Bonde for help with fieldwork and Las Vegas adventures. I am also grateful to the Valley of Fire State Park staff—especially Jim Hammons, Thomas Fitzsimmons, Don Bolton and Amber Heman—for permission to conduct research in such a beautiful place, for sweet accommodations, and for checking on me everyday. I left the Valley of Fire with many new friends and great memories. Special thanks go to Marathon Oil Company, the Billings Geophysical Society and the MSU College of Letters and Science for their financial assistance. Finally, I would like to thank to Dee, Colin and Claire McNamara for their endless love and support and my doggie Jacko, who carried rocks for me in the field and was a great companion.

TABLE OF CONTENTS

1. INTRODUCTION	1
Statement of Problem.....	1
Purpose of Study.....	5
2. GEOLOGIC SETTING	8
Sevier Fold and Thrust Belt.....	8
Tectonics	8
Cretaceous Stratigraphy	8
Study Area	9
Tectonics	9
Cretaceous Stratigraphy	11
Timing of Deformation.....	16
Paleogeography.....	17
3. METHODS.....	19
Lithofacies Analyses	19
Composition	20
Willow Tank Formation Sandstone Point Counts	20
Red Member Conglomerate Clast Counts	20
Paleoflow	21
4. SEDIMENTOLOGY	22
Willow Tank Lithofacies Assemblages	22
Facies Assemblage A: Gravelly Braidplain System	23
Description	23
Interpretation	25
Facies Assemblage B: Anastomosed Stream System	26
Description	26
Interpretation	31
Facies Assemblage C: Sandy Braidplain System	33
Description	33
Interpretation	33
Willow Tank Provenance.....	37
Basal Conglomerates.....	37
Composition	37
Paleoflow.....	37

TABLE OF CONTENTS—CONTINUED

Source.....	38
Upper Mudstone and Sandstone-Dominated Sequence	39
Texture	39
Framework Grains.....	40
Discussion.....	43
Source.....	48
White Member Lithofacies Assemblages	50
Facies Assemblage A: Debris Flow-Dominated Alluvial Fan	50
Description	50
Interpretation	52
Facies Assemblage B: Sheetflood-Dominated Alluvial Fan	52
Description	52
Interpretation	54
White Member Provenance.....	54
Red Member Lithofacies Assemblages	56
Facies Assemblage A: Debris Flow-Dominated Alluvial Fan	58
Description	58
Interpretation	63
Facies Assemblage B: Sandy Braidplain System	68
Description	68
Interpretation	76
Facies Assemblage C: Interfingering Fan-Fluvial Systems.....	78
Description	78
Interpretation.....	80
Red Member Provenance	82
Composition	82
Paleoflow.....	88
Source and Discussion.....	88
 5. TECTONO-SEDIMENTARY EVOLUTION OF THE CRETACEOUS WEDGETOP-FOREDEEP TRANSITION ZONE.....	 97
Willow Tank Formation.....	97
Basal Conglomerate	97
Mud-Dominated Succession	99
White Member, Baseline Formation	100
Red Member, Baseline Formation.....	101
Lower Red Member	101
Upper Red Member	103

TABLE OF CONTENTS—CONTINUED

Overton Conglomerate Member, Baseline Formation	106
Interfingering Overton/Red Member.....	106
6. CONCLUSIONS.....	108
REFERENCES CITED.....	110
APPENDICES.....	123
APPENDIX A: Measured Section Location, Lithofacies Data, Legend for Measured Sections	123
APPENDIX B: Point and Clast Count Raw Data, Source Lithology Descriptions.....	128
APPENDIX C: Measured Section Legend, Willow Tank Formation and Red Member Measured Sections	134

LIST OF TABLES

Table	Page
4.1. Summary of Willow Tank lithofacies	22
4.2. Summary of Red Member lithofacies	57
A.1. Summary of Willow Tank and Red Member lithofacies	124
B.1. Willow Tank Formation point count data	129
B.2. Red Member clast description and source units.....	131
B.3. Red Member framework percentages	132
B.4. Paleoflow measurements	133

LIST OF FIGURES

Figure	Page
1.1. Tectogenic sediment provenance and dispersal.....	1
1.2. Thin-skinned terrane detritus sources and transport.....	2
1.3. Regional fold & thrust and field area maps	4
1.4. Generalized regional stratigraphic section	6
2.1. Cross-section of major southern Nevada thrust faults	10
2.2. Field area geologic map.....	12
2.3. Field area aerial view.....	13
2.4. Generalized Cretaceous stratigraphic section.....	14
2.5. Southwestern U.S. Cretaceous paleogeographic maps.....	18
4.1. Basal Willow Tank conglomerates/sandstone photographs.....	24
4.2. Willow Tank fine-grained strata photographs.....	27
4.3. Willow Tank sandstones photographs	29
4.4. Willow Tank sandstone package lateral variability	30
4.5. Willow Tank facies geometry, conglomerate organization	31
4.6. Willow Tank bed geometry and facies relationships	34
4.7. Willow Tank sandstones and contacts.....	35
4.8. Willow Tank sandstone geometry and contacts.....	36
4.9. Willow Tank sandstone thin section texture photographs	40
4.10. Willow Tank volcaniclastic thin section photographs.....	41
4.11. Willow Tank sandstone thin section framework grain photographs	42

LIST OF FIGURES—CONTINUED

Figure	Page
4.12. Willow Tank sandstone QmFLt diagrams	45
4.13. Willow Tank sandstone thin section photographs	46
4.14. Willow Tank conglomerate and sandstone composition	47
4.15. Willow Tank changes in sandstone composition upsection	49
4.16. Willow Tank fault propagation fold unroofing history	50
4.17. White Member facies assemblage A description/photographs	51
4.18. White Member facies assemblage B description/photographs	53
4.19. White Member growth strata	55
4.20. Red Member detailed 10 meter section of debris flow deposits	59
4.21. Red Member detailed 10 meter section of debris flow deposits	60
4.22. Red Member debris flow-dominated fan strata photographs	61
4.23. Red Member debris flow-dominated strata and contacts	62
4.24. Red Member debris flow-dominated fan strata photographs	64
4.25. Along-strike sequence of Red Member bioturbated strata	65
4.26. Red Member detailed 10 meter section of braided stream deposits	69
4.27. Red Member detailed 10 meter section of braided stream deposits	70
4.28. Red Member braided stream-dominated strata photographs	71
4.29. Lateral variation in Red Member braided stream deposits	72
4.30. Red Member braided stream-dominated strata photographs	74

LIST OF FIGURES—CONTINUED

Figure	Page
4.31. Mosaic of Red Member braided stream deposits.....	75
4.32. Textural inversion and strata of interfingering environments.....	79
4.33. Down-dip mosaic of interfingering strata.....	81
4.34. Willow Tank fault propagation fold unroofing history.....	82
4.35. Source strata, clast count location and histograms.....	83
4.36. Results and pictures of clast counts 1-5	85
4.37. Results and pictures of clast counts 6-10	86
4.38. Results and pictures of clast counts 11-15	87
4.39. Red Member paleocurrent data	89
4.40. Weiser Ridge 1:24,000 geologic map	90
4.41. Weiser ridge west-east cross-sections.....	91
4.42. Hanging wall anticline restoration from A – A'.....	94
4.43. Hanging wall anticline restoration from B – B'.....	95
5.1. Block diagram of Willow Tank basal conglomerate deposition.....	98
5.2. Block diagram of Upper Willow Tank deposition.....	100
5.3. Block diagram of White Member deposition.....	101
5.4. Block diagram of initial Red Member deposition	102
5.5. Block diagram of Upper Red/Overton Cgl. Member deposition.....	103
5.6. Block diagram of structural influences on sediment dispersal.....	105
A.1. Aerial view of measured section locations.....	125

LIST OF FIGURES—CONTINUED

Figure	Page
B.1. QmFLt sandstone classification and stratigraphic location.....	130
C.1. Legend for measured sections	135
C.2. Willow Tank Formation measured sections.....	136
C.3. Red Member measured sections 1-4	137
C.4. Red Member measured sections 5-7	138

ABSTRACT

Outstanding preservation and exposure of Cretaceous tectogenic deposits in the North Muddy Mountains of southern Nevada provide a rare opportunity to examine the influence of frontal structures on provenance and sediment dispersal to the Cordilleran foreland basin. Eastward migration of the Sevier wedge-top depozone into the contiguous foredeep depozone was facilitated by development of the Willow Tank thrust-cored fault-propagation fold. The resulting thrust-cored frontal ridge diverted pre-existing fluvial systems of the Willow Tank Formation and promoted proximal alluvial fan deposition of the Baseline Formation. The Albian Willow Tank Formation represents the earliest foreland basin sediments derived from large, integrated drainage basins of the thrust belt interior. Sandstone point counts reveal an up-section increase in quartz locally derived from erosion from the Jurassic Aztec Sandstone along the frontal anticlinal ridge in the proximal Willow Tank thrust hanging wall. Continued fold growth is documented by growth strata development in and provenance of the overlying White Member of the Baseline Formation. Conglomeratic clast counts and detailed lithofacies analyses in the Cenomanian Red Member of the Baseline Formation record sequential unroofing of the frontal anticline and interaction of adjacent alluvial fan and fluvial depositional environments, respectively. Clast counts of poorly-sorted, massive ungraded conglomerates indicate a reverse clast stratigraphy based on progressively increasing amounts of carbonate framework clasts up-section. This trend is attributed to exposure and erosion of Upper Paleozoic strata in the Willow Tank hanging-wall anticline. Evidence of interfingering depositional environments is shown by up-section trends including: 1) replacement of poorly-sorted and organized coarse-grained conglomerates by well-sorted stratified to normally-graded conglomerates, 2) an overall decrease in grain size, 3) a decrease in soft-sediment deformation and increase in bioturbation, and 4) an increase in lateral bed continuity. This up-section transformation represents a spatial and temporal transition from fold-proximal debris flow-dominated fans to an integrated braided stream system that transported detritus from the same source. Facies examination, clast composition and intertonguing relationships between the Red and Overton Conglomerate Members suggest contiguous braided stream networks that tapped separate, distinct source areas. These observations, as well as structural relationships, imply out-of-sequence movement on the Muddy Mountain thrust.

INTRODUCTION

Statement of Problem

Inherent difficulty exists in assigning tectogenic sediments to a particular source area in thin-skinned thrustured terrains due to: 1) an overall horizontal transport direction and associated basin detachment (Fig. 1.1a), 2) a lack of distinct lithologies in thrust sheet hanging walls, and 3) continued propagation and recycling of previous foreland basin detritus (Fig. 1.2; Steidtmann & Schmitt, 1988; Lageson & Schmitt, 1994). In addition, the majority of these strata are difficult to date and lack cross-cutting relations, further obscuring tectono-sedimentary evolution through time (Steidtmann & Schmitt, 1988).

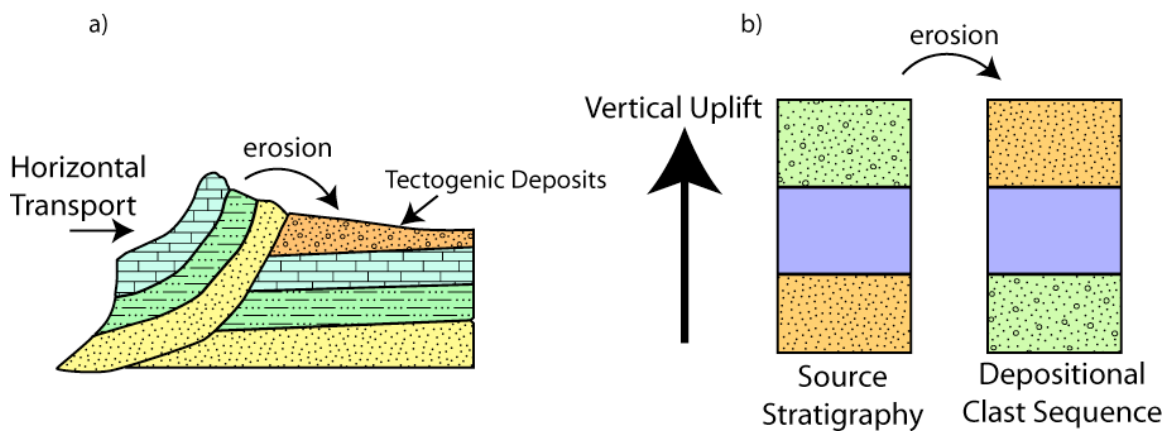


Figure 1.1: Diagram depicting provenance and dispersal of tectogenic sediments. a) Coeval erosion of more than one source unit, resulting in a blended clast composition. b) A classic unroofing sequence and resulting inverted stratigraphy. (after Steidtmann & Schmitt, 1988).

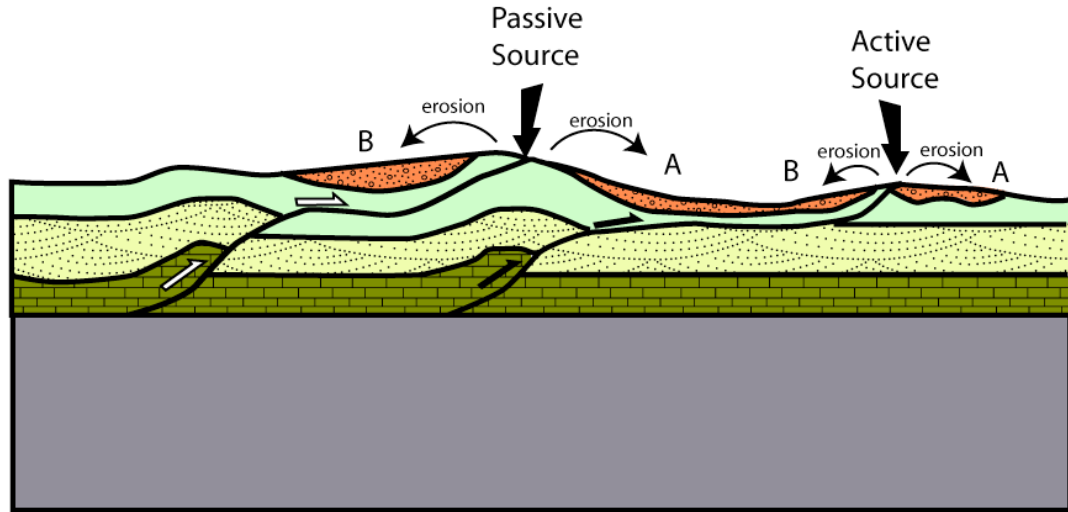


Figure 1.2: Diagram showing horizontal transport characteristic of thin-skinned thrust terranes. Sources of sediment and sediment dispersal synthetic (A) and antithetic (B) to thrust movement are depicted. Open and closed arrows indicate motion on inactive and active faults, respectively. As the orogenic wedge migrates, cannibalization of older thrust-derived deposits may result (after Steidtmann & Schmitt, 1988).

Most thrust-derived conglomerates are the result of distal fluvial systems that tapped large drainage basins of the thrust-belt interior (Lawton, 1986; Heller and Paola, 1989; Reese, 1989; Fillmore, 1991; Schmitt et al., 1991; Yingling and Heller, 1992; Goldstrand, 1992, 1994; Dougherty, 1997). Intermingling of sediment in channels from different sources and clast attrition due to substantial transport distances lead to blended clast compositions and masking of a distinct source area (Lageson & Schmitt, 1994).

On the contrary, proximal alluvial fan deposits reveal the most detail regarding provenance, but fall victim to continued deformation, cannibalization and recycling as thrust propagation ensues (Fig. 1.2; Graham et al., 1986; DeCelles, et al, 1987; Pivnik, 1990). Two types of coarse-grained alluvial

deposits have been recognized: 1) conglomerate wedges at the terminus of transverse structural zones (i.e. fluvial megafans; DeCelles & Cavazza, 1999; Horton & DeCelles, 2001), which are characterized by focused drainage transporting detritus from multiple sources within the interior thrust belt (Schmitt, 1992; Lawton et. al, 1994), and 2) localized alluvial fan assemblages representing small drainage basins at the thrust belt front that contain evidence of a reverse clast stratigraphy (Fig. 1.1b; Pivnik, 1990; Azevedo, 1993) and/or sediment derived from inactive older thrusts carried basinward by younger, frontal thrusts (i.e. ramp-supported uplifts; Steidtmann & Schmitt, 1988; DeCelles, 1988; Schmitt & Steidtmann, 1990; Lawton, 1986; DeCelles, 1994). The latter locally-derived synorogenic deposits are either shed synthetically directly into the foredeep or antithetically into wedgetop (piggyback basin) depozones (Fig. 1.2; Steidtmann & Schmitt, 1988; Lawton & Trexler, 1991) and often interfinger with gravelly transverse or longitudinal fluvial systems (Dougherty, 1997; Slaughter & Schmitt, 2000; Schmitt & Aschoff, 2005).

Outstanding preservation and exposure of Cretaceous tectogenic deposits in the southern Nevada segment of the Sevier fold and thrust belt provide a rare opportunity to examine the influence of frontal structures on provenance and sediment dispersal to the contiguous wedgetop and foredeep depozones. The North Muddy Mountains is a structurally diverse area comprising several thin-skinned thrust allochthons and related synorogenic deposits (Fig. 1.3; Longwell, 1949), with sediment dispersal controlled by hanging wall uplift and erosion.

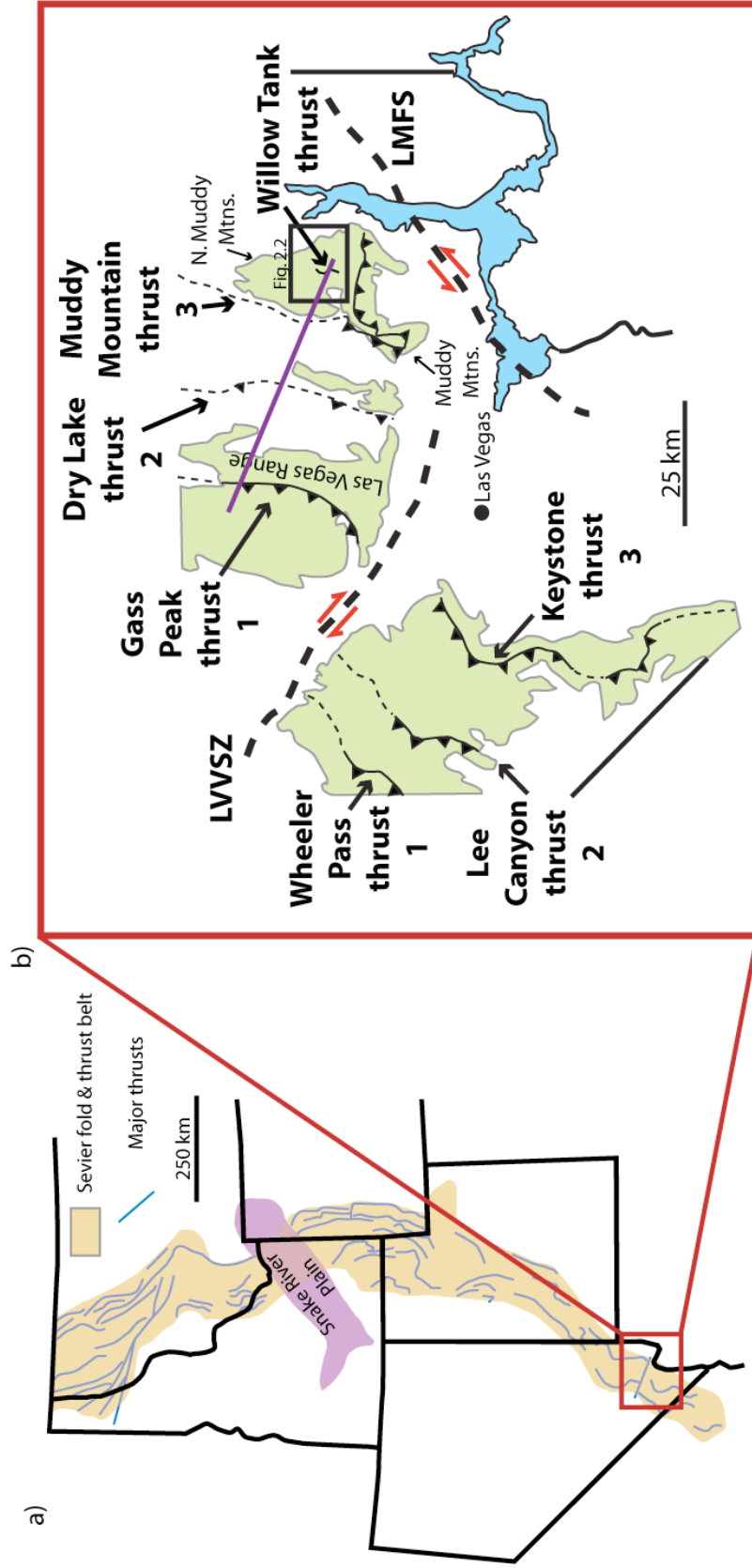


Figure 1.3: a) Extent of Sevier fold and thrust belt in western U.S. (after Decelles, 2004). b) Map of major Sevier thrusts and Basin and Range strike-slip faults (LVVZ=Las Vegas Valley Shear Zone, LMFS=Lake Mead Fault System) in study area. The numbered thrusts were offset via dextral movement on the LVVZ. The box outlines the field area and is represented by Figure 2.2 (after Aschoff & Schmitt, 2008). Cross-section through thrust belt from west to east is shown in Figure 2.1.

Siliciclastic Mesozoic strata in the frontal Willow Tank thrust hanging wall anticline and predominantly Paleozoic carbonate strata exposed to the west in the relatively distal Muddy Mountain thrust (Longwell, 1949; Armstrong, 1968) provide distinct sediment source areas in this region (Figs. 1.3 & 1.4).

Purpose of Study

Proximal alluvial fan deposits are the most valuable tools for determining source area information. Unfortunately, preservation potential of these deposits along the thrust-belt front is rare due to both active and passive uplift on thrusts and subsequent erosion (Lageson & Schmitt, 1994). The most favorable conditions exist when a source section that contains distinct stratigraphy is sequentially eroded and deposited in a proximal depositional setting. Given these specific conditions, inverted clast distributions (unroofing sequences) are extremely rare; exceptions to this are documented by the Upper Cretaceous Sphinx Conglomerate (DeCelles et al., 1987), the Upper Cretaceous Little Muddy Creek conglomerate (Pivnik, 1990), and the Oligocene Serra de La Llena conglomerate (Colombo, 1994) successions.

Where diverse strata is largely lacking, lithologic provenance modeling may be utilized to reveal potential sources (DeCelles, 1988). This method involves comparison of synthetic clast suites (based on source section thickness) and field-conducted clast counts to determine the most accurate erosional history of source area(s) (Graham et al., 1986). Conversely, this technique has been

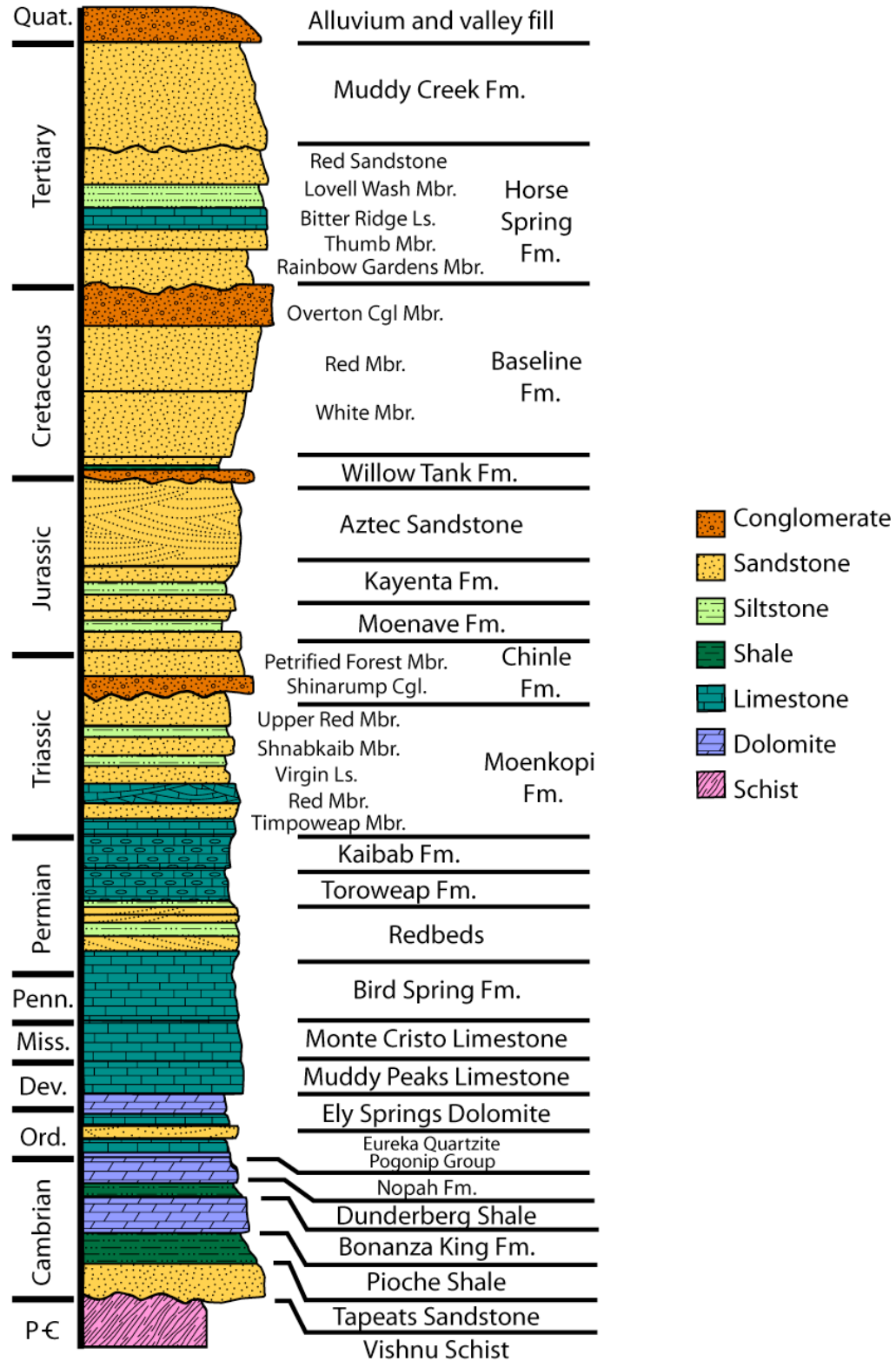


Figure 1.4: Generalized stratigraphic section of the North Muddy Mountains, southern Nevada (after Longwell, 1949).

used where source lithologies are well-known to evaluate both source strata and tectonic influences on sedimentation (Graham et al., 1986; Pivnik, 1990; DeCelles et al., 1991).

With this in mind, the significance of this project is supported by the: 1) non-cannibalization and preservation of a complete sequence of synorogenic strata, 2) presence of a potential, proximal inverted clast (unroofing) depositional sequence, and 3) distinct lithologies exposed on the hanging wall of regional thrusts, permitting delineation of source area(s). Given these unique characteristics, the following hypotheses will be tested: 1) an up-section increase in quartz content of sandstones in the Albian Willow Tank Formation is a product of local derivation of quartz sand from erosion of the proximal Willow Tank thrust allochthon and introduction into a braided fluvial system that had a large, well-integrated drainage basin in interior thrust sheets; and 2) Cenomanian-age Red Member conglomerates show an unroofing sequence based on progressively increasing amounts of carbonate framework clasts, derived from the hanging wall of the Willow Tank thrust.

GEOLOGIC SETTING

Sevier Fold and Thrust Belt

Tectonics:

The Cordilleran fold and thrust belt is a manifestation of the initiation of subduction at the U.S. western continental margin in early and late Triassic time (Dickinson, 2004), and is characterized by a distinct north-south trending zone comprised of numerous thin-skinned thrust faults spanning the western US and Canada (Fig. 1.3a; DeCelles & Giles, 1996; DeCelles, 2004; Dickinson, 2004). Major crustal shortening on these faults occurred from Late Jurassic to Tertiary time, with thrusts carrying Precambrian and Paleozoic miogeoclinal deposits over thinner Paleozoic and Mesozoic platform and nonmarine strata (Fig. 1.4; Longwell, 1949; Fleck, 1970; Burchfiel et al. 1974). Coeval foreland basin structural evolution is documented by Mesozoic synorogenic deposits derived from the eastward propagating thrust belt (Armstrong, 1968).

Cretaceous Stratigraphy:

Cretaceous syntectonic units crop out in proximal locales along strike of the Cordilleran fold and thrust belt. Units of the Montana-Wyoming-Idaho segment have been used to a) bracket movement on major thrusts (Armstrong & Oriel, 1965; Wiltschko & Dorr, 1983; Lawton & Trexler, 1991; DeCelles et al., 1993), b) record the sedimentary response to thrust-belt deformation (Yingling &

Heller, 1992; DeCelles & Burden, 1992; Horton et al., 2004), c) determine mechanisms responsible for subsidence (Jordan, 1981; Heller et al., 1988; Lawton, 1994), d) define contractional orogen and basin evolution between Sevier and Laramide deformation (Dickinson et al., 1986, Graham et al., 1986; Ingersoll et al., 1987; Pivnik, 1990; Schmitt et al., 1991; DeCelles et al., 1993; Azevedo, 1993) and e) reconstruct coeval thrust belt-foreland basin evolution (Currie, 2002; DeCelles, 2004; DeCelles & Coogan, 2006; Zahela, 2006). Much like correlative strata to the north and west, Cretaceous units of the southern Utah and Nevada portion also record the initiation and continuation of foreland basin development as a result of thrust-belt deformation (Carr, 1980; Reese, 1989; Goldstrand 1992; Goldstrand, 1994).

Study Area

Tectonics:

The southern Nevada segment of the Sevier fold and thrust belt is made up of seven major NE-SW striking thrust systems (Armstrong, 1968; DeCelles, 2004). Numerous imbricate thrust plates and large-scale folds, with crustal shortening on the order of 35 to 72 km (Burchfiel et al., 1974), deform Precambrian to Mesozoic strata. However, subsequent extensional deformation in Neogene time created a structural overprint on previous tectonic episodes. Basin and Range extension was responsible for approximately 44 to 69 km of right lateral offset on the Las Vegas Valley Shear Zone (LVVSZ) (Longwell, 1960;

Burchfiel, 1965; Wernicke et al., 1982), approximately 65 km of left lateral slip on the Lake Mead Fault System (LMFS) (Anderson, 1973; Bohannon, 1979; Smith, 1981; Wernicke et al., 1982) and the formation of three distinct structural blocks north of the LVVSZ (Fig. 1.3b; Bohannon, 1983b). The North Muddy Mountain block includes two east-verging thrust faults: the Muddy Mountain and its frontal splay, the Willow Tank thrust (Figs. 1.3b & 2.1; Longwell, 1949). The Muddy Mountain thrust carried the Cambrian Bonanza King Formation over the Cretaceous Baseline Formation north of the study area and over the Jurassic

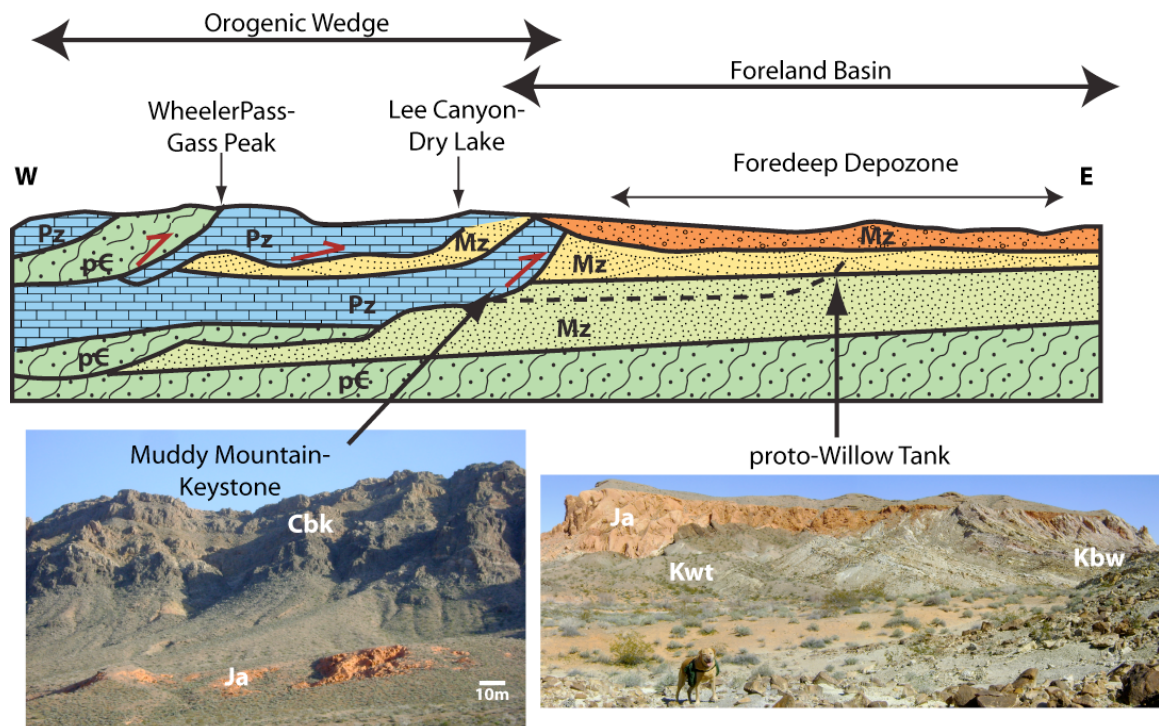
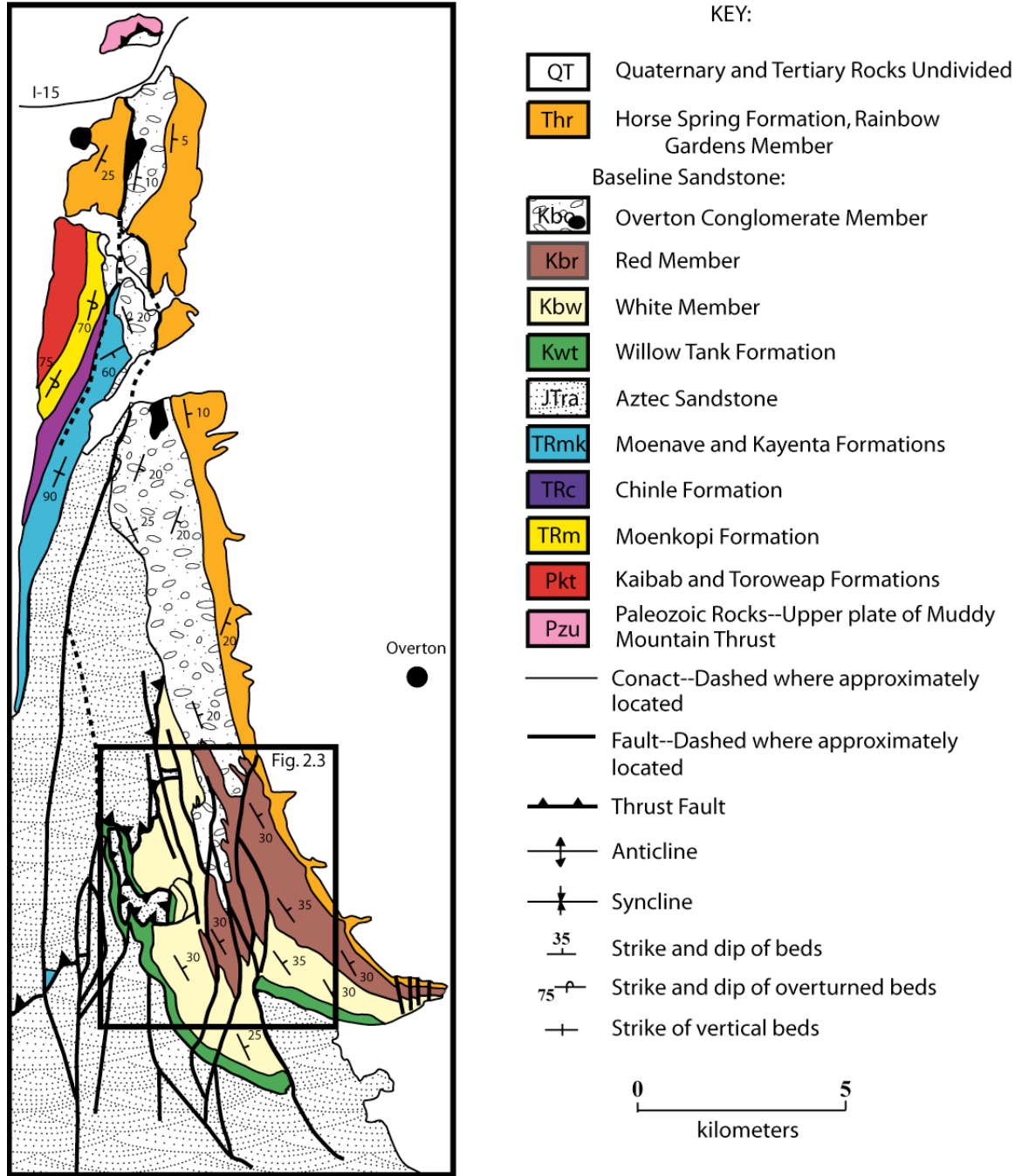


Figure 2.1: Cross-section from west to east showing major southern Nevada thrust faults and deformed strata. Mesozoic foreland basin deposits (basal Willow Tank conglomerate) are shown, before fault propagation fold growth of the Willow Tank thrust (after Steidtmann & Schmitt, 1988). Photos show major thrusts in field area: the Muddy Mountain thrust carries Cambrian Bonanza King (Cbk) over Jurassic Aztec Sandstone (Ja) (view looking to the south), and the Willow Tank thrust brings the Jurassic Aztec sandstone over the Cretaceous Willow Tank (Kwt) and White Member of the Baseline Formation (Kbw) (view looking north).

Aztec Sandstone in the field area (Longwell, 1921, 1949; Bohannon, 1983b; Carpenter, 1989). The Willow Tank thrust grew as a blind thrust-cored anticline and eventually placed the Jurassic Aztec sandstone over the Cretaceous Willow Tank and lower White Member of the Baseline Formation (Fig. 2.2; Bohannon, 1983b; Carpenter, 1989). The surface manifestation of this fault at Tearfault Mesa exhibits a horizontal attitude and associated high angle tear faults, which indicated an eastward direction of movement (Figs. 2.2 & 2.3; Longwell, 1949). Longwell (1949) proposed total displacement on the Willow Tank thrust to be approximately 1.6 km and suggested out-of-sequence movement on the Muddy Mountain thrust based on cross-cutting relationships and sedimentological evidence. In the field area, eastward fault propagation resulted in Cretaceous synorogenic deposits exhibiting evidence of both local fold growth and sequential unroofing (Fig. 2.3; Bohannon, 1983b; Schmitt & Aschoff, 2003; Aschoff & Schmitt, 2008).

Cretaceous Stratigraphy:

The fluvial Willow Tank Formation comprises a basal conglomerate and upper mudrock-dominated sequence recording the earliest thrust-derived sediments from the thrust belt interior (Fig. 2.4; Longwell, 1949; Bohannon, 1983b; Reese, 1989). An Albian age for the Cretaceous Willow Tank Formation is based on the presence of the fern *Tempskya* (Ash & Read, 1976), K-Ar ages



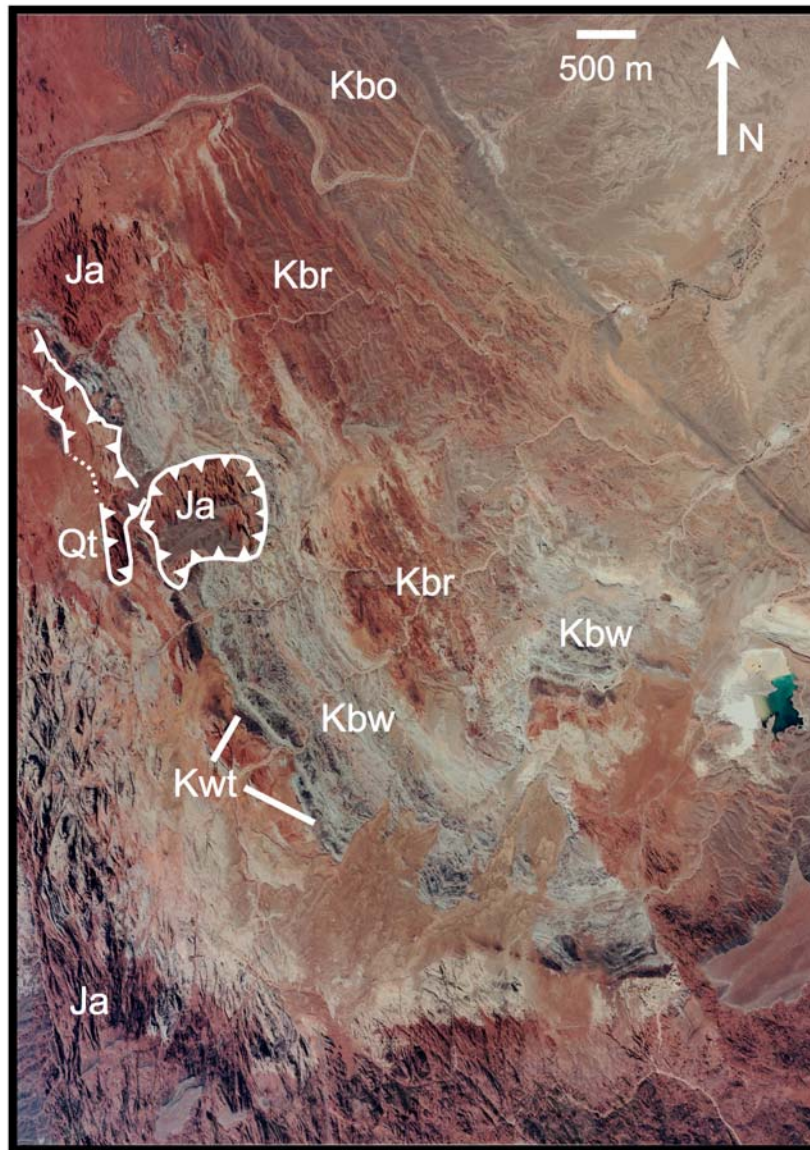


Figure 2.3: Aerial photograph of field area showing Mesozoic units: Ja=Jurassic Aztec Sandstone, Kwt=Cretaceous Willow Tank Fm., Kbw=White Mbr of Cretaceous Baseline Fm., Kbr=Red Member, Kbo=Overton Conglomerate Mbr. The Willow Tank thrust brings Ja over Kwt, deforms the lower Kbw, and is hypothesized to be the dominant sediment source for the White and Red Members of the Baseline Formation. Note the large-scale conjugate fractures in the Ja, which were a result of Sevier deformation.

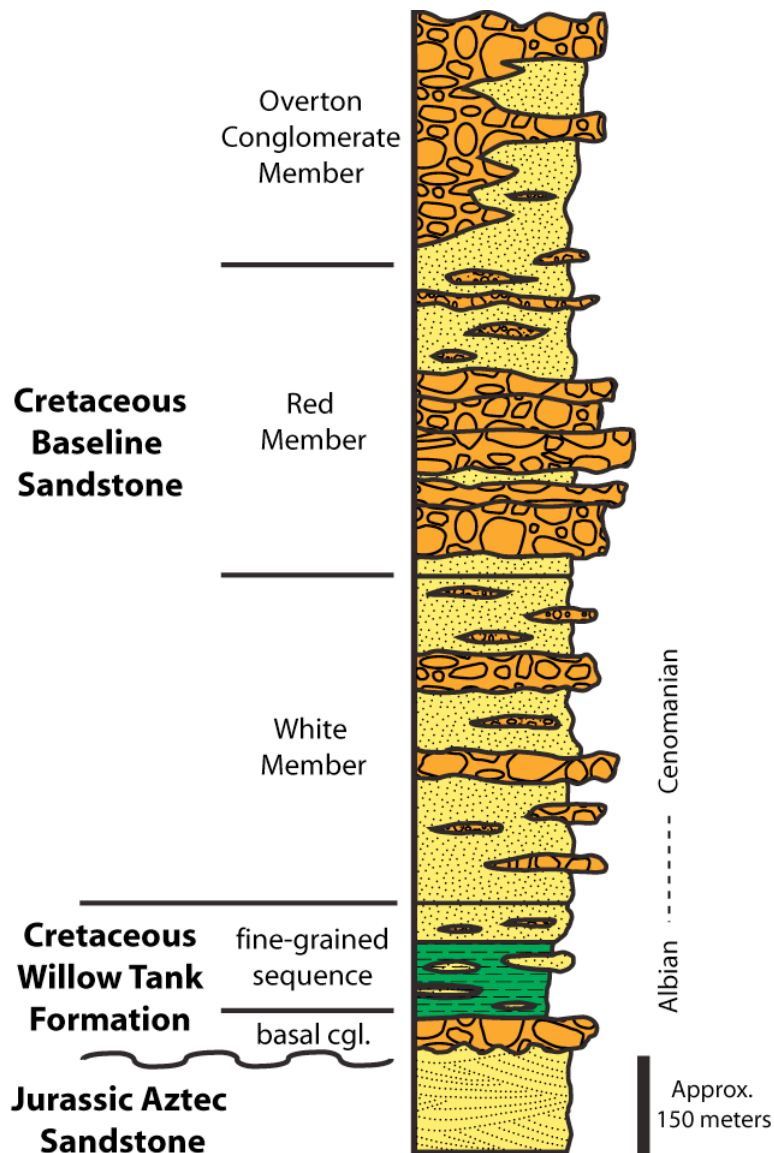


Figure 2.4: Generalized stratigraphic column showing Cretaceous units of southern Nevada.

of 98.4 and 98.6 m.y. (Fleck, 1970) and U-Pb zircon ages of 101.6 $\pm$ 1 and 99.9 $\pm$ 2 m.y. (Troyer, 2006) on volcanic beds.

Reese (1989) divided the basal conglomerate into a lower quartzite- and upper carbonate- dominated sequence, both of which contain a blended clast

composition (Fig. 1.1a; Steidtmann & Schmitt, 1988). The overlying mudrock-dominated sequence coarsens upward, with sandstones characterized by a progressive increase in quartz and decrease in chert and carbonate grains. Sandstone point count data described in Chapter 4 establish this trend and point toward an influence of local fold growth on fluvial sandstone composition.

The overlying Baseline Formation, formally divided into the White, Red and Overton Conglomerate Members (Figs. 2.4, 2.2 & 2.3; Bohannon, 1983b), was derived from thrust sheets to the west and deposited in adjacent alluvial fan and braided stream environments (Carpenter, 1989). The Cenomanian White Member of the Baseline Formation includes the fern *Microtaenia paucifolia* at its base (Hewett, 1936) and K-Ar ages of 95.8 $\pm$ 3.5 m.y. and 96.9 $\pm$ 3.6 m.y. (Carpenter & Carpenter, 1987) on volcanic units. Facies analyses, detrital zircon population ages, clast counts and syntectonic progressive unconformities indicate sequential unroofing and kinematic development of a frontal anticline in the frontal Willow Tank thrust hanging wall (Slaughenhop & Schmitt, 2000; Schmitt & Aschoff, 2003; Troyer et al., 2006; Aschoff & Schmitt, 2008).

The overlying Red Member is given a Cenomanian age based on a K-Ar date of 93.1 $\pm$ 3.4 m.y. (Carpenter & Carpenter, 1987). This member is composed of debris flow-dominated alluvial fan strata capped by braided stream deposits. This transition is documented by an overall decrease in grain size, increase in lateral bed continuity and upward changes in conglomerate framework clast size, organization and composition. These changes in

composition not only identify changing environments, but also indicate subsequent continued erosional unroofing of the frontal anticline. An upward decrease in sandstone clasts coupled with an increase in carbonate clasts suggest removal of siliclastic Mesozoic units and exposure, weathering and transport of Paleozoic carbonate strata from the hanging wall of the Willow Tank thrust allochthon. The Overton Conglomerate Member overlies/interfingers with the Red Member (Figs. 2.3 & 2.4) and shows a distinct clast suite proposed to be derived from the interior thrust belt transported eastward via transverse streams (Bohannon, 1983b; Fillmore, 1993).

Timing of Deformation:

Radiometric dating of volcanic units and plutons that cross-cut the southern portion of the Sevier fold and thrust belt bracket initial and continued movement as Late Jurassic and Late Cretaceous in age, respectively (Burchfiel et al, 1974; Carr, 1980; Fleck et al., 1994; Walker et al., 1995). Movement on the Willow Tank thrust, which deforms the White Member, folds the lowermost Red Member and is onlapped by the Red and Overton Conglomerate Members, is bracketed between 95.8 +/- 3.5 m.y. and 93.1 +/- 3.4 m.y. (Carpenter, 1989). The fact that both the Red and Overton Conglomerate Members of the Cenomanian Baseline Formation onlap the Willow Tank thrust and are truncated by the Muddy Mountain thrust implies out-of-sequence thrusting in this area (Longwell, 1949;

Bohannon, 1983b). This movement must have occurred after 93.1 ± 3.5 m.y. (Carpenter, 1989).

Paleogeography:

The regional paleoclimate during the Cretaceous was much more humid than the Jurassic, largely due to northward drift of North America into the midlatitude belt (Fig. 2.5; Blakey & Ranney, 2008). Widespread coal deposits and oncolites in correlative Lower Cretaceous strata of Utah indicates a proliferation of flora and fauna in a relatively wetter climate (Kirschbaum & McCabe, 2006; Shapiro et al., 2009). The presence of oncoid-bearing limestones a few meters above the Willow Tank basal conglomerate (Schmitt, pers. comm.) further documents periods of temperate conditions in the study area.



Figure 2.5: a) Paleogeographic reconstruction of North America during Late Early Cretaceous (100 Ma), box outlines the Colorado Plateau region in (b). b) Paleogeography of the Colorado Plateau region during the Albian (~105 Ma). The location of the North Muddy Mountains is outlined by a rectangle, WICS=Western Interior Cretaceous Seaway (from Blakey, 2009).

METHODS

Lithofacies Analyses

Data collection took place in the North Muddy Mountains, in the Valley of Fire State Park, Clark County, Nevada (Fig. 1.3b, Appendix A: Fig. A.1). Two sections were measured from the base of the Willow Tank conglomerate to the conformable contact with the overlying White Member of the Baseline Formation (Appendix A: Fig. A.1a, Appendix C). Lithostratigraphic correlation of beds was conducted by tracing lateral extent in the field as well as recognition of distinct volcanoclastic units. In addition, seven composite sections of the Red Member (Baseline Formation) span approximately 650 meters—from the White-Red Member contact to near the top of the Red Member (Appendix A: Fig. A.1b, Appendix C).

Each bed was measured in the field with a Jacob staff and strike and dip was determined with a Brunton compass. Detailed lithologic descriptions include: framework/matrix composition, grain size, sorting, textural inversion, sedimentary structures, lateral variability, contacts, paleoflow, colors of fresh and weathered surfaces, outcrop weathering patterns and lateral/vertical geometries and relationships.

Lithofacies codes in this study are similar to those of Miall (1978), but have been slightly modified to support the wide variety of lithofacies documented in the field area (Appendix A: Table A.1). Lithofacies descriptions and interpretations

were followed by grouping the data into assemblages to aid in the interpretation of depositional environment.

Composition

Willow Tank Formation Sandstone Point Counts:

From the Willow Tank section base to top, sandstone units were measured, described and sampled in the field. Sixteen samples were collected in 2 to 20 meter-intervals, cut into thin-sections and analyzed by point-counting over 350 framework grains per slide following the Gazzi-Dickinson method (Appendix B: Table B.1; Appendix C: Fig. C.2; Ingersoll et al., 1984; Dickinson, 1985). Based on composition, sandstones were classified according to Folk (1980) to distinguish vertical compositional trends and integrate compositional data into an interpretation of provenance (Appendix B: Fig. B.1).

Red Member Conglomerate Clast Counts:

Fifteen clast counts were performed every 15 to 60 meters on conglomerate beds throughout the Red Member section (Appendix A: Fig. A.1b, Appendix C: Figs. C.3 & C.4). Each count consists of a minimum of 450 clasts (Howard, 1993) counted in an expanding rectangle fashion in a defined bed, with clasts smaller than one centimeter considered matrix. This procedure provided accurate framework compositional data by avoiding compositional bias due to

grain size (Howard, 1993). Notes on each count were written to document changes in matrix or clasts failing to meet the size requirement.

Clast lithology was identified using basic terms (i.e. medium-grained, well-sorted sandstone) and formations were noted only if distinctive characteristics were observed (i.e. silicified wood clasts from the Petrified Forest Member of the Chinle Formation) (Appendix B: Table B.2). Given the distinct regional stratigraphy (Fig. 1.4), the lithology of clasts were determined and grouped into eight clast population categories (Appendix B: Tables B.2 & B.3).

Paleoflow

Paleocurrent measurements were taken on trough cross-stratification, trough axes, imbricated clasts, ripple cross-lamination, ripple marks, and scour axes. Fifty-one measurements were taken along the measured sections (Appendix B: Table B.4). This number is not enough to be statistically significant due to overall lack of: exposure, desired dimensions, and/or sedimentary structures. The orientation of many of these measurements were plotted on a stereonet and rotated to compensate for structural tilting (following methods of Tucker, 2003).

SEDIMENTOLOGY

Willow Tank Lithofacies Assemblages

The 67 to 80 meter-thick interval measured from the base to the top of the Willow Tank Formation includes 19 facies (Table 4.1) grouped into three facies

Table 4.1: Summary of Willow Tank lithofacies. Lithofacies codes similar to Miall (1978) and interpretations from Middleton (1965) and Lowe (1982).

<u>Facies</u>		
<u>Code</u>	<u>Description</u>	<u>Interpretation</u>
Gcu	clast-supported, massive ungraded, granule to boulder conglomerate	deposition by clay-poor, noncohesive debris flows
Gcn	clast-supported, normally graded, granule to boulder conglomerate	fluid turbulence and differential grain settling in noncohesive debris flows
Gci	clast-supported, inversely graded, granule to boulder conglomerate	buoyant forces and dispersive pressure in noncohesive debris flows
Gh	clast-supported, horizontally stratified, granule to pebble conglomerate	transport & deposition in shallow, high velocity flows
Gl	clast-supported, low-angle stratified, granule to pebble conglomerate	deposition in scours or bedforms with low-angle stratification
Sm	very fine to medium, poorly- to well-sorted massive ungraded sandstone	result of rapid deposition, liquefaction, or bioturbation
Sw	very fine to medium, moderately- to well-sorted wavy-laminated sandstone	result of fluctuating hydraulic conditions
Sh	very fine to medium, moderately- to well-sorted horizontally stratified sandstone	deposition of plane bed phase in upper flow regime
Sl	very fine to medium, moderately- to well-sorted low-angle stratified sandstone	deposition by plane beds in scours or bedforms with low-angle stratification
St	very fine to medium, moderately- to well-sorted trough cross-stratified sandstone	deposition by migrating 3D large ripples and/or dunes
Sp	very fine to medium, poorly- to well-sorted planar tabular cross-stratified sandstone	migration of large scale 2D ripples or dunes in lower flow regime
Sr	very fine to fine, well-sorted ripple cross-laminated sandstone	migration of unidirectional ripples under lower flow regime
Spb	massive, medium to coarse, pebbly sandstone	deposition by noncohesive debris flows or hyperconcentrated flows
Sd	very fine to medium, soft-sediment deformed sandstone with convolute lamination/bedding and dewatering structures common	plastic deformation of partially liquified sediment after deposition by tectonism and/or loading
Spbl	medium to coarse, moderately- to well-sorted, low-angle stratified pebbly sandstone	deposition by plane beds in scours or low-relief bedforms
Spbt	medium to coarse, moderately- to well-sorted, trough cross-stratified pebbly sandstone	deposition by migrating 3D large ripples and/or dunes
Sgl	medium to coarse, moderately- to well-sorted low-angle stratified granular sandstone	deposition by plane beds in scours or low-relief bedforms
Fh	stratified siltstone or mudstone	deposition by suspension settling of fines in decelerating flows
Fm	massive ungraded siltstone or mudstone	result of rapid deposition, liquefaction, or bioturbation

assemblages. Each assemblage is described separately below and interpreted in terms of depositional environment.

Facies Assemblage A: Gravelly Braidplain System

Description: An in-depth study of the basal conglomerates by Reese (1989) shows that clast-supported, massive ungraded (Gcu), normally graded (Gcn) and horizontally-stratified conglomerates (Gh) occur in vertically stacked sequences, approximately 12 to 45 meters thick. Two petrofacies were documented according to the dominant clast compositions: a basal quartzite-rich conglomerate and an overlying carbonate-dominated conglomerate, usually separated by a thin calcareous crust or horizon (Fig. 4.1a & 4.1b; Reese, 1989). In this study, a one cm-thick white crust is present between the conglomerates in Section WT2, and approximately six meters of laminated (FI) and massive mottled mudstone (Fm) with slickensides and plant material is stratigraphically equivalent in Section WT1 (Appendix C: Fig. C.2). The conglomerate matrix is composed of medium- to coarse-sized quartz, chert and carbonate sand and the framework contains subangular to rounded, dominantly pebble-sized clasts. Sporadic, large rounded cobble- to boulder-sized clasts of both chert pebble conglomerate and well-sorted medium-grained sandstone occur near the base of the formation (Fig. 4.1c). These 0.1 to 0.9 meter beds are lenticular to tabular and laterally continuous within channels scoured into the underlying Jurassic



Figure 4.1: Photos of basal Willow Tank conglomerates/sandstones: a) lower sandstone/quartzite-dominated, well-organized and sorted pebble conglomerate overlain by a granule conglomerate; b) upper carbonate-dominated conglomerate petrofacies, note preferred orientation of carbonate clasts; c) cobble- to boulder-sized clasts of Jurassic Aztec (Ja) and Triassic Shinarump conglomerate (Trc) near base; d) conglomerate occupying scour in Jurassic Aztec sandstone; e) conglomerate bed contacts marked by grain size changes; and f) horizontally-laminated sandstone unit located just above carbonate-rich upper conglomerate. Pencil is 15 cm and hammer is 32 cm for scale.

Aztec sandstone (Fig. 4.1d; Reese, 1989). Contacts between beds are marked by changes in grain size or aligned clasts (Fig. 4.1e). Discontinuous massive (Sm) and horizontally-stratified sandstone (Sh) lenses occur within and between conglomerates. Laterally continuous, medium-grained trough cross-stratified (St), horizontally (Sh) and ripple-cross laminated (Sr) beds commonly grade into one another laterally and are interbedded with conglomerate units (Fig. 4.1f; Reese, 1989).

Interpretation: The facies organization, bed geometry and sedimentary structures suggest deposition by braided stream processes (Rust, 1978). Gcu, Gcn and Gh represent aggrading longitudinal bars and migrating dunes (Miall, 1977). The thin calcareous crust and mudstone succession between the basal and upper conglomerate sequence represents an exposed surface and paleosol development, respectively (Reese, 1989). The presence of plant material and randomly oriented slickensides is consistent with this interpretation. The sandstone interbeds and lenses are a result of decreasing flow velocity causing sand-sized particles to be transported as bedload, resulting in the downstream migration of bars and dunes (Sh and St, respectively; Walker & Cant, 1979). Sr deposition occurs at a lower water depth and flow velocity (Middleton, 1965). The presence of the anomalously large clasts of chert pebble conglomerate (Triassic Chinle Shinarump Conglomerate Member) and well-sorted sandstone

(Jurassic Aztec Sandstone) suggests exposure and erosion of these units proximal to channels.

Alternating periods of flood and waning stages are interpreted to produce the vertical and horizontal arrangement of lithofacies (Reese, 1989). The overall lack of fine-grained units representing floodplain overbank deposition provides further proof of deposition by a gravelly braided stream system (Miall, 1977).

Facies Assemblage B: Anastomosed Stream System

Description: This assemblage is comprised of several lithologies (ranging in grain size from clay to pebble) and crops out from approximately 11 to 61 meters in Section WT1 and 9 to 72 meters in WT2 (Appendix C: Fig. C.2). 0.1 to 3.8 meter-thick, laminated (Fl) to massive (Fm) mudstone and siltstone units are dominantly gray in color with abundant green to red mottling (Fig. 4.2a). Biotite, slickensides, organic matter and plant material (Fig. 4.2b) are commonly found, with rare vertebrate fossils and chert pebbles. Siltstone units commonly contain 5 to 15% sand and rarely possess rip-up clasts. The majority of these beds are recessive, heavily weathered and had to be trenched. In Section WT1, Fl and Fm are dominantly laterally continuous (Fig. 4.2c), bounded by other fine-grained units and display sharp to gradational contacts. Conversely, these beds were interspersed with and commonly truncated by sandstones and displayed abrupt to erosive contacts in Section WT2 (Fig. 4.2d). Rare black and yellow-green mudstone beds are also present in both sections. Distinct 0.1 to 3.5 meter-thick,

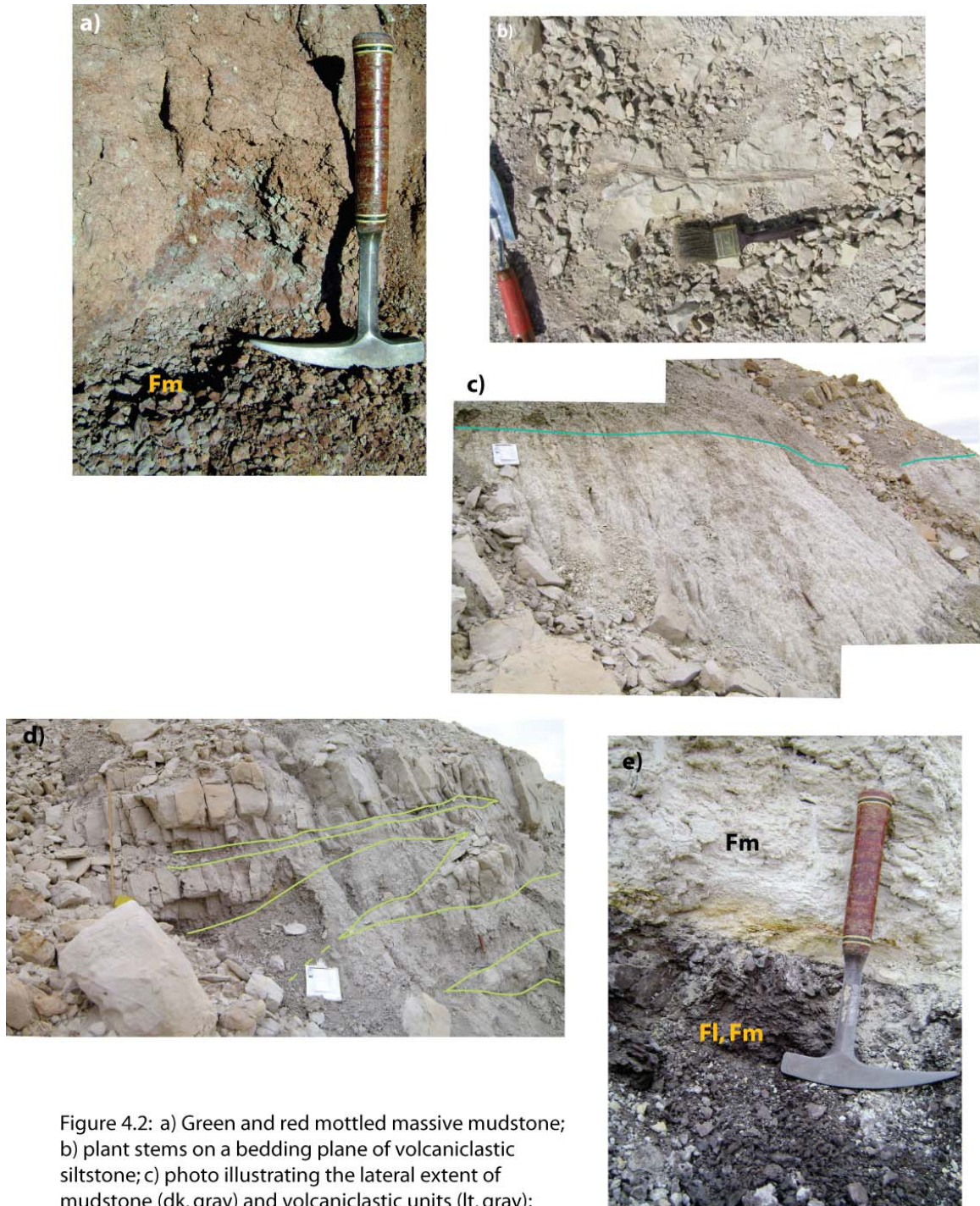


Figure 4.2: a) Green and red mottled massive mudstone; b) plant stems on a bedding plane of volcaniclastic siltstone; c) photo illustrating the lateral extent of mudstone (dk. gray) and volcaniclastic units (lt. gray); d) geometric relations between sandstone and mudstone beds of Section WT1, 56-59 m; and e) volcaniclastic siltstone (white) overlying an organic-rich massive to laminated mudstone. Hammer is 32 cm and jake staff is 1.5 m for scale.

white to light gray volcanoclastic mudstones and siltstones are present in both sections (Fig. 4.2e). These dominantly massive beds contain abundant biotite with rare plant material, pumice and ripple-cross laminae. Volcanoclastic units are usually incorporated into overlying beds as subangular rip-up clasts and are laterally continuous, making correlation less difficult.

Moderately well-sorted, 0.1 to 2.8 meter-thick massive (Sm), soft-sediment deformed (Sd), horizontally- (Sh), trough-cross (St) and low-angle (Sl) stratified sandstones make up the dominant lithofacies in Section WT2 (Fig. 4.3a-d). Planar-cross (Sp), ripple-cross (Sr) and wavy-(Sw) laminated units are rare (Fig. 4.3d & e). These stacked tabular to lenticular beds show gradational or sharp (commonly lined by pebbles or iron-stained) contacts, however evidence of major scouring is largely absent. Grain size is dominantly fine, with common chert pebbles, intraclasts (Fig. 4.3f) plant matter and rare mica. An increase in sandstone bed thickness, abundance, pebble pockets and pebble-aligned cross-bed laminae occur upsection (Fig. 4.4). Sandstones are thin and subordinate in Section WT1, except from 56 to 60 meters, where they are interbedded with and encase fine-grained lithologies (Fig. 4.5a).

Massive, ungraded (Gcu) to normally graded (Gcn) conglomerates, ranging in thickness from 0.1 to 0.7 meters, occur in conjunction with Sh and Sm in Section WT2. These units are dominantly well-organized and sorted, with subrounded to rounded pebble-sized chert framework grains (Fig. 4.5b). Gcu

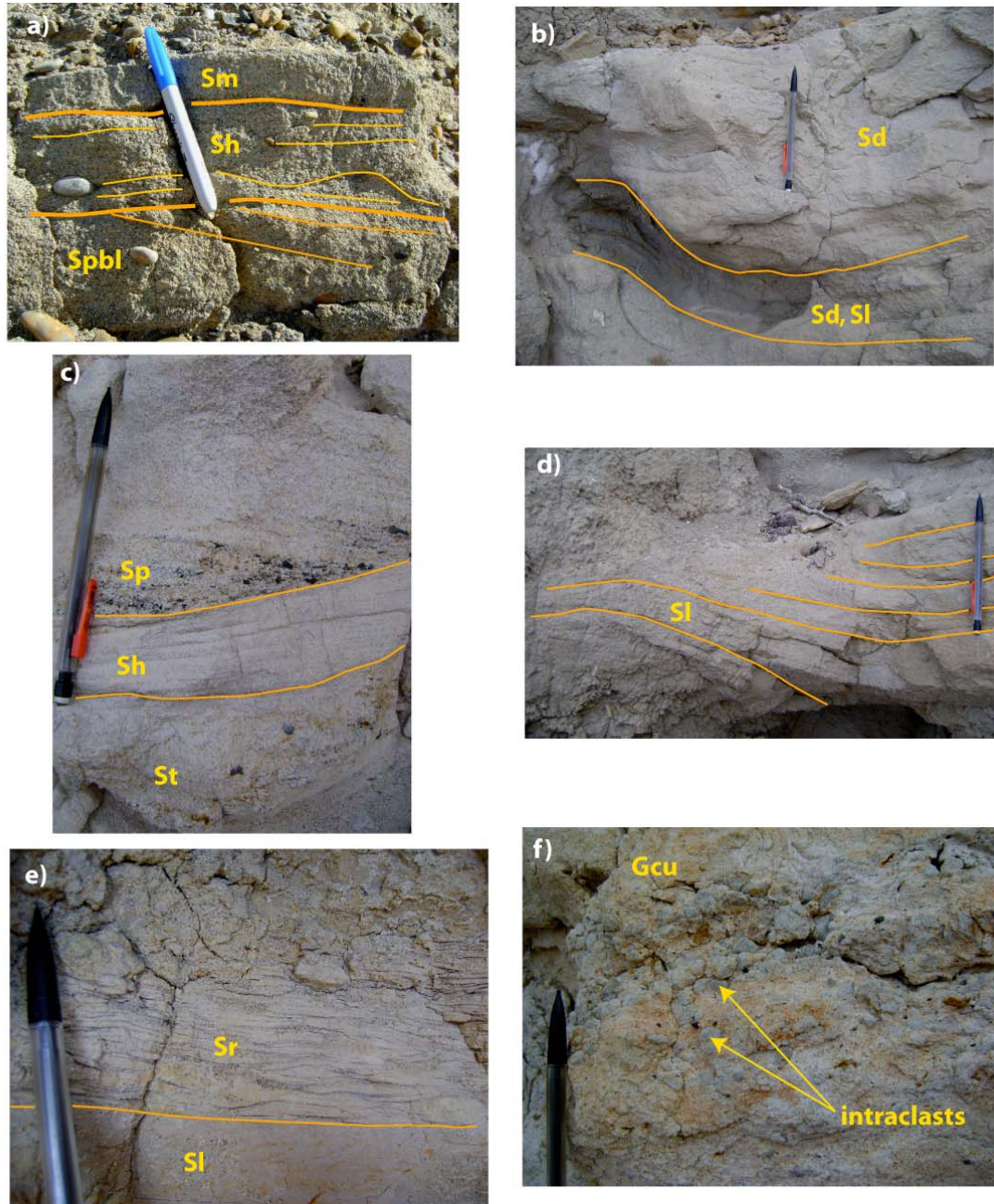


Figure 4.3: a) Pebbly, low-angle stratified sandstone overlain by parallel laminated and massive sandstone; b) soft-sediment deformed and low-angle stratified sandstones with undulatory laminae/bedding; c) trough cross-stratified, horizontally- and planar tabular cross-stratified sandstones; d) low-angle stratified sandstone; e) decrease in flow velocity shown by ripple cross-laminated sandstone overlying a horizontally laminated sandstone; f) laterally discontinuous, massive ungraded intraclast pebble conglomerate, framework is fine-grained, well-sorted sandstone with sporadic chert granules/pebbles. Pencil is 15 cm, sharpie is 14 cm for scale.

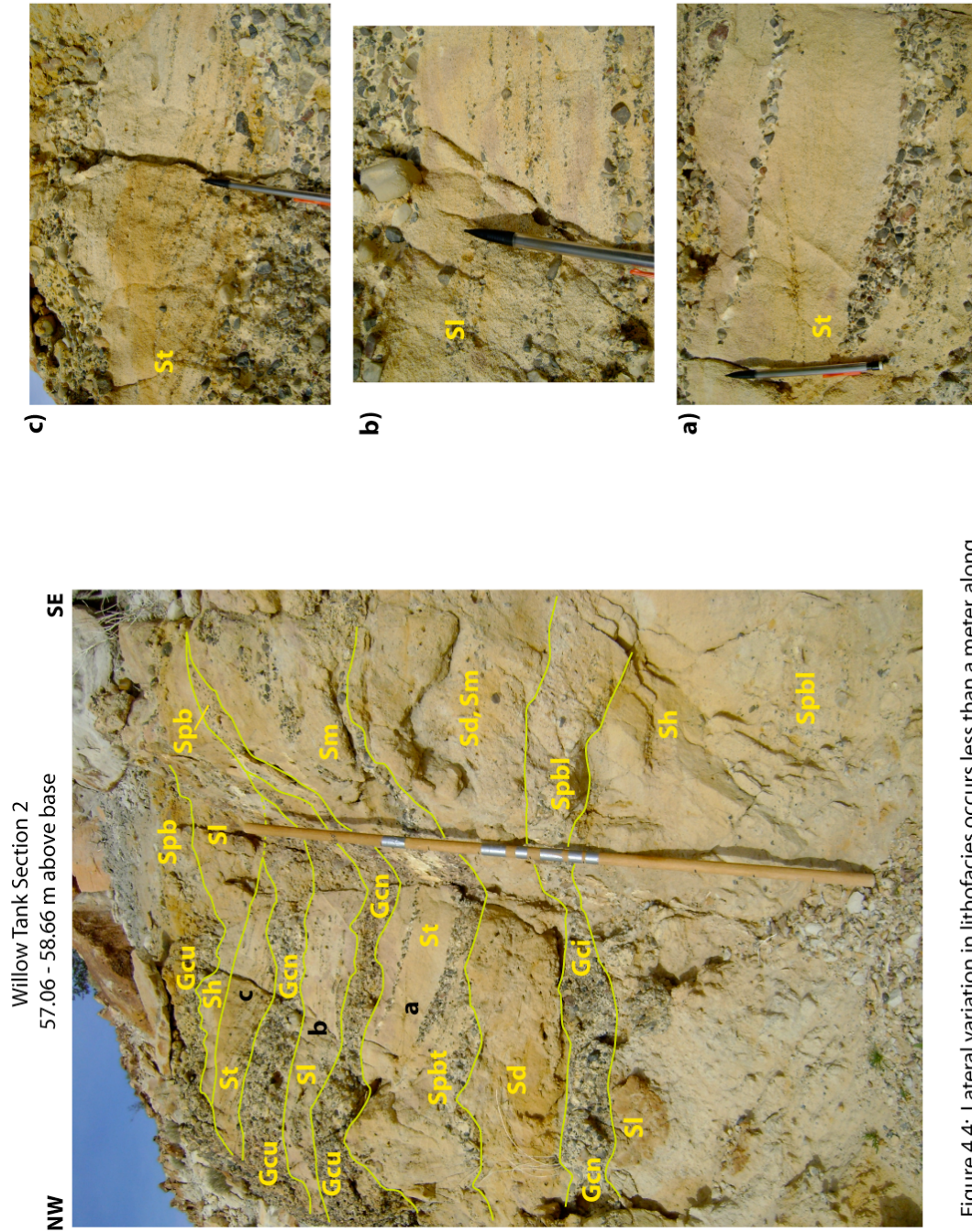


Figure 4.4: Lateral variation in lithofacies occurs less than a meter, along both strike and dip. Note stratigraphic pinchouts and thickening/thinning of beds. Beds are dipping approximately 30 degrees to the east. Jake staff is 1.5 m long. a & c) trough cross-stratified sandstone with granule and/or pebble-lined foresets b) low-angle stratified sandstone. Pencil is 15 cm.

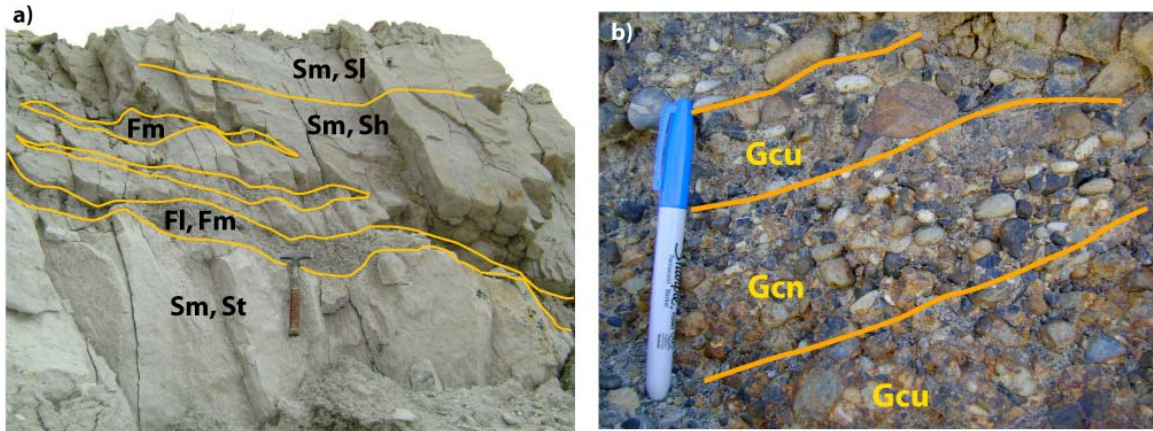


Figure 4.5: a) Relationships showing stratigraphic pinch-out of massive to stratified siltstones between dominantly massive, amalgamated sandstones (note extensive fracturing of outcrop); b) Massive and normally graded pebble conglomerates, note the abundance of black chert. Hammer is 32 cm and Sharpie is 14 cm for scale.

and Gcn display a tabular to lenticular geometry and are both laterally heterogeneous and discontinuous along strike.

Interpretation: The vertical and horizontal arrangement, bed geometry, fossil material and grain size/sorting of the previous spectrum of lithologies suggests deposition in the floodplain and channel environments of an anastomosing fluvial system (Smith, 1983). The lateral continuity and abundance of preserved fine-grained and volcanoclastic units point toward floodplain deposition (Miall, 1996). Grain size and sparse sedimentary structures signify gravity settling of fine material during decelerating fluid flow (Middleton, 1965). Subsequent soil formation and bioturbation of these deposits is shown by slickensides and fossil material (Retallack, 1988).

The geometry, stacking patterns and sedimentary structures of sandstone beds in this interval indicate anastomosing channel deposition (Nadon, 1994;

Miall, 1996). Tabular to lenticular sandstones lacking internal erosive surfaces with well-sorted gravel lenses interbedded with discontinuous fine-grained units are consistent with this interpretation (Makaske, 2001). Laterally discontinuous, lenticular sandstone bodies encased in mudstone exposed along strike (but not present in measured sections) most likely represent crevasse splay deposits (Nadon, 1994; Bonde, 2008). The presence of Sh, St, and Sl and a dearth of fine-grained strata in WT2 suggests bedload transport by fluid flow in a channel environment.

Substantial influence by fluid flow is further confirmed by the excellent organization and sorting in chert-pebble Gcu and Gcn lenses and beds (Pierson & Costa, 1987). Lack of both lateral accretion surfaces and fining upward sequences and the presence of extensive floodplain deposits provide evidence against meandering and braided stream deposition (Miall, 1996; Allen, 1997).

Even though a paucity of both lateral accretion foresets and lateral/vertical scouring exists, a meandering interpretation is not entirely untenable. In a study of Wabash River point bar deposits, Jackson (1976) recognized a transition zone in helical flow between meander bends. In these zones, resultant fluid flow deposits did not exhibit the characteristic vertical point bar facies and fining upward successions of conventional meandering stream facies models (Allen, 1970b; Walker & Cant, 1979). This information, as well as the presence of both crevasse splay and widespread floodplain deposits provides an alternative explanation for this portion of the Willow Tank Formation. However, further

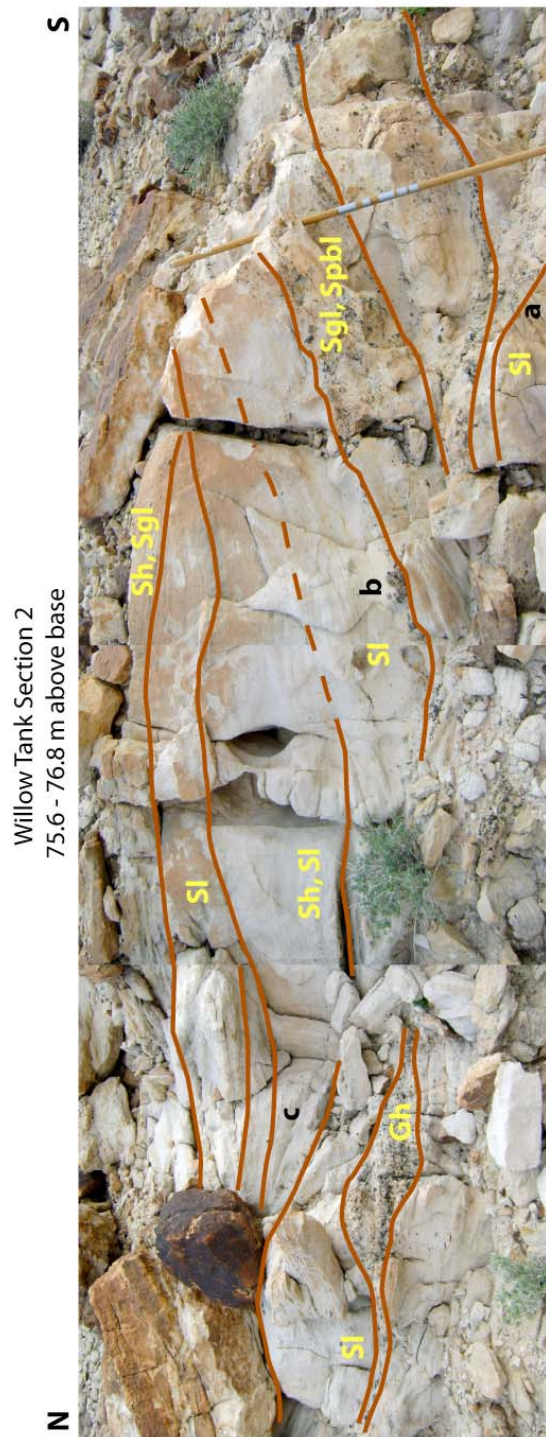
detailed facies mapping and architectural analyses along strike is necessary for accurate fluvial system identification.

Facies Assemblage C: Sandy Braidplain System

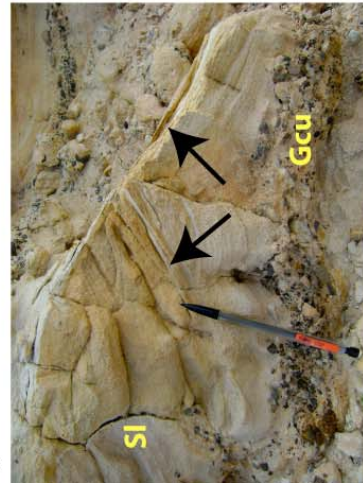
Description: The topmost six meters in Sections WT1 and WT2 is characterized by laterally continuous, tabular to lenticular stacked sandstone successions with a dearth of fine-grained beds (Fig. 4.6). Sh, Sl, Sm, Sd and St are present, with common discontinuous conglomerate lenses and stringers (Fig. 4.7a & b). Fl and Fm are laterally discontinuous where present (Fig. 4.8), and maybe represented by covered intervals near the top of Section WT2 (Appendix C: Fig. C.2).

Sandstone framework is quartz-rich, medium-grained, well-sorted and rounded. Gcu, Gcn and Gl are well-sorted and organized, chert pebble-dominated and laterally heterogeneous along strike (Fig. 4.6b). Scouring is pervasive in these packages (Fig. 4.8) and is usually accompanied by gravel lenses.

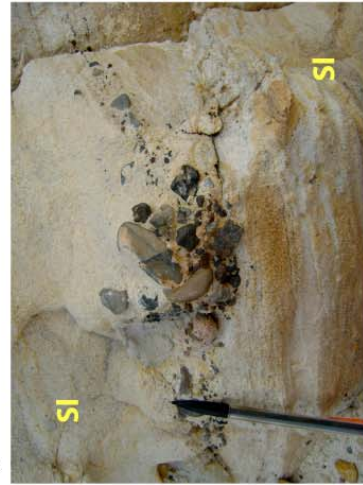
Interpretation: The characteristic sedimentary structures and bed geometry in the suite of facies previously described suggest deposition in a dominantly sandy braided fluvial system (Miall, 1977). Sh, Sl and St represent high flow regime deposition on and proximal to longitudinal sandbars (Walker & Cant, 1979).



a



b



c



Figure 4.6: Mosaic near top of WT 2 showing along-strike bed geometry and facies. a) Low-angle stratified sandstone overlying a massive ungraded pebble conglomerate lens. Arrows denote major scour surfaces that truncate laminae. b) Pebble pocket at the base of a low-angle stratified sandstone unit. Conglomeratic units at this stratigraphic level are dominantly composed of chert and quartzite from the uplift and cannabilization of the basal Willow Tank conglomerate on the growing frontal anticline. c) Low-angle granular stratified sandstone, a common facies filling pre-existing topography and/or scours. Jake staff is 1.5 m, pencil is 15 cm for scale.

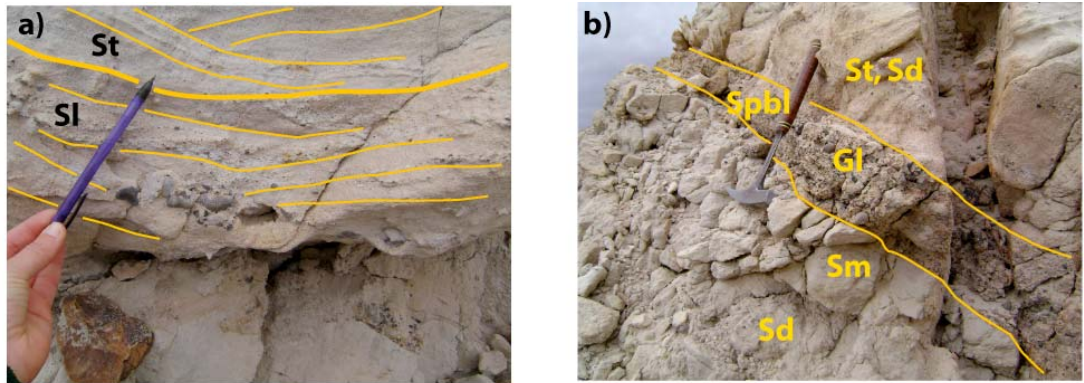


Figure 4.7: a) Low-angle stratified sandstone with granule-lined laminations and a granule/pebble pocket near the base, overlain by trough cross-stratified sandstone; b) erosive, iron-stained contact with a 5 - 15 cm low-angle stratified pebble-granule conglomerate to pebbly sandstone separating massive and trough-cross stratified sandstones. Hammer is 32 cm and pencil is 15 cm for scale.

Pebbles present at the base of cross-beds and bed surfaces represent the heaviest fraction of bedload material occupying troughs and topographic lows (Harms et al., 1975). Sm may result from large sediment loads unable to be hydraulically sorted, bioturbation, or liquefaction (Middleton, 1965). The regular presence of Sd units suggests post-depositional deformation by sediment loading and/or tectonic activity was common. Where present, Fl and Fm deposits signify accumulation on bar tops, overbank areas or abandoned channels during varying flood stages by suspension fallout (Cant & Walker, 1978).

The tabular to lenticular nature of sandstone bodies and discontinuity of fine-grained beds suggests deposition by upper flow regime conditions in shallow, shifting channels in a sand-dominated system (Miall, 1996). The sedimentary structures, geometry and vertical/lateral relationships of this facies assemblage point toward a sediment-laden fluvial system with varying discharge

Willow Tank Section 2
77.5 m - top

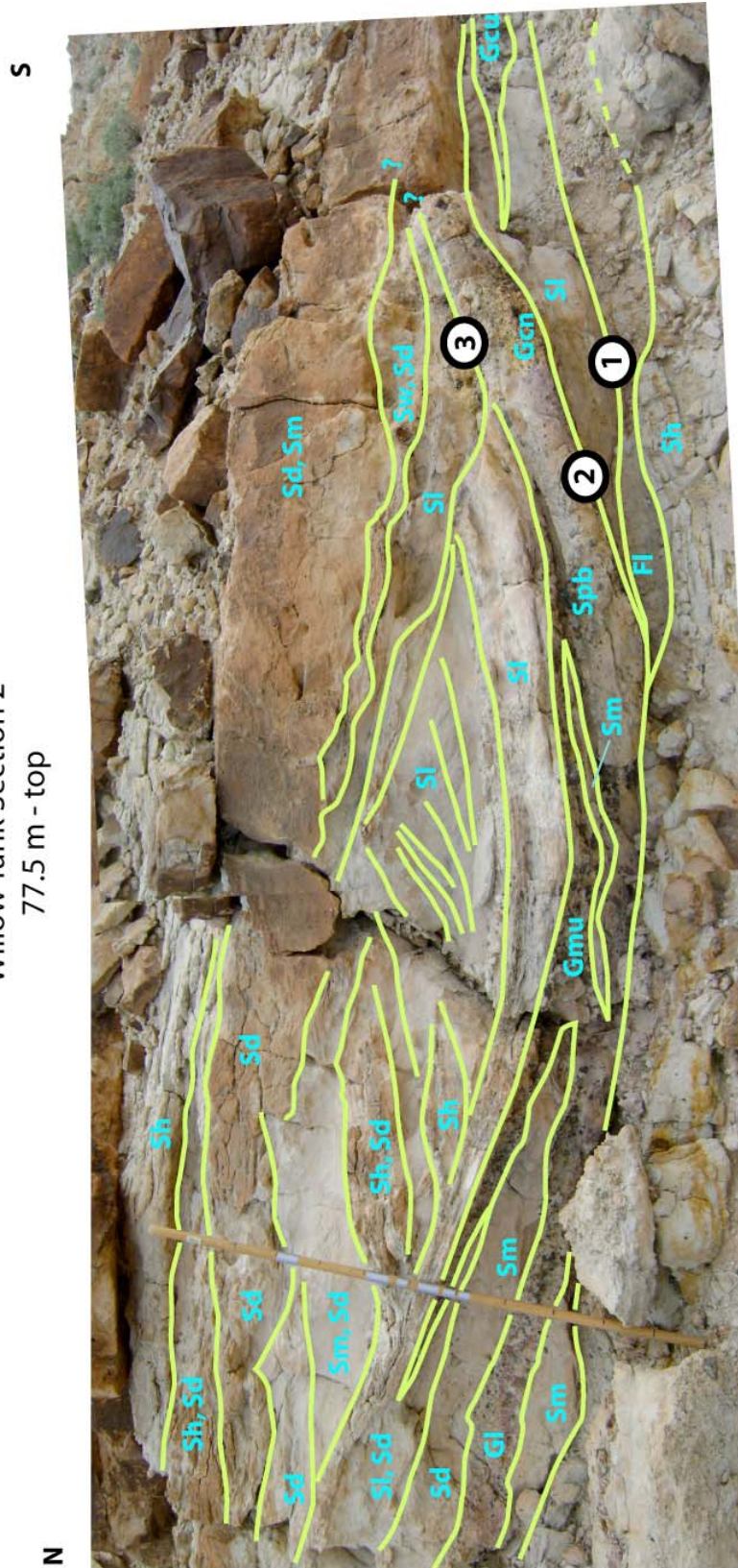


Figure 4.8: Mosaic near the top of WT 2 showing along-strike bed geometry and facies associated with multiple episodes of cut and fill. Crudely laminated, silty mudstone and horizontally-stratified sandstone were scoured and overlain by a low-angle stratified sandstone (1), which was truncated by conglomerate units that exhibit a heterogeneous fabric along strike (2). Subsequent to the conglomerate, deposition of low-angle stratified sandstone capped by massive and soft sediment deformed sandstone occurred. These units were then cut by a smaller scale scour (3), with a basal low-angle stratified sandstone overlain by a soft-sediment deformed/wavy laminated sandstone bed. A thick, continuous soft sediment-deformed/massive sandstone unit then filled in any existing topography. Convolute laminae and an overall undulatory nature in these beds is interpreted to be the result of rapid deposition or liquefaction resulting from tectonic activity. Horizontally stratified sandstone with local undulatory laminations makes up the topmost unit in this mosaic. Jake staff is 1.5 m for scale.

and frequent flooding events. The vertical transition from anastomosing to braided stream deposition was most likely influenced by tectonic uplift and an inundation of sand-sized material into the drainage system (Schumm & Lichty, 1963; Smith & Smith, 1984).

Willow Tank Provenance

Basal Conglomerates

Composition: Based on clast counts, the basal conglomerates of the Willow Tank Formation were divided by Reese (1989) into 2 petrofacies: a lower sandstone/quartzite-dominated succession overlain by a carbonate-dominated package (Figs. 4.1a & b). Point counts on interbedded sandstones and conglomerate matrix in both petrofacies confirms a recycled orogen provenance (Dickinson, 1985; Reese, 1989). In addition, point count compositions also show a tendency to correspond to the dominant framework clast types present in their respective conglomerate beds.

Paleoflow: In addition to clast composition, paleoflow measurements of imbricated pebbles and cobbles and subordinate trough cross-bed axes provide data on source area. Measurements from the lower conglomerate show an easterly transport direction (90° to 127°) and those from the upper conglomerate a northeast to southeast direction (81° to 212°) (Reese, 1989).

Source: The lower quartzite-dominated conglomerate exhibits a blended clast composition (as opposed to a reverse clast composition; Fig. 1.1; Steidtmann & Schmitt, 1988) of metaquartz-arenite from distal sources mixed with sandstone, chert and conglomerate from a proximal source. Based on known and exposed hanging wall strata, the Gass Peak and Willow Tank thrusts were proposed as the distal and proximal sources, respectively (Fig. 1.3b; Reese, 1989). The distal Gass Peak thrust is thought to have supplied durable Pre-Cambrian and Ordovician quartzites via trunk streams that mixed proximally with Mesozoic siliciclastics derived from the deformed footwall of the Muddy Mountain thrust. The upper carbonate-rich conglomerate is sourced from the Arrow Canyon, Dry Lake and/or Muddy Mountain thrust(s) (Reese, 1989). Delineation of an exact locality is difficult due to similar exposed Paleozoic carbonate strata in the hanging walls of thrusts to the west. Relative to the lower conglomerate, the abundance of limestone suggests a more proximal source area. Fillmore (1993) confirmed these western source areas by sedimentologic and compositional observations of equivalent strata in southwest Utah. Much like the basal Willow Tank, the distally equivalent Dakota Formation represents initial foreland deposition and exhibits similar upsection changes in conglomerate framework.

Upper Mudstone and Sandstone-Dominated Sequence

Sandstone samples were collected from an interval between the lower and upper conglomerates at 3.3 meters up to 67 meters above the base in WT1 and from 29 to 51 meters in WT2 (Appendix B: Table B.1; Appendix C: Fig. C.2). The counts show the following upsection trends: 1) a change from immature to mature composition and texture, and 2) an increase in quartz and decrease in chert and carbonate grains. Typical sandstone samples exhibited approximately 75% framework grains, 3% matrix, and 22% cement. Seven volcanoclastic units were also identified, with ~78% framework and 22% matrix.

Texture: Overall, Willow Tank sandstones are grain-supported, very poorly- to well-sorted, immature feldspathic litharenites to mature subarkoses. Framework grains are dominantly subangular to subrounded and range from upper fine to lower medium grain sizes (Fig. 4.9a). Cement includes combinations of clay, carbonate and lesser amounts of quartz and chalcedony (Fig. 4.9b). Contacts between framework grains are commonly concavo-convex to tangential, with rare floating grains (Fig. 4.9c). Intergranular porosity is most abundant, with rare moldic porosity (Fig. 4.9d). Alteration of feldspar by sericitization, the presence of quartz overgrowths, dissolved grains, oversized pores, and hematite cement are present but not common. Poorly- to moderately-sorted volcanoclastic units consist of silt- to fine sand-sized, angular to subangular grains of volcanic glass, feldspar, biotite, and quartz. These units

commonly show planar laminae and alignment of grains, with rare ripple cross-lamination (Fig. 4.10).

Framework Grains: Primary framework grains include monocrystalline quartz (Qm), polycrystalline quartz (Qp), lithic fragments (Lt) and feldspar (F).

Qm is the dominant framework grain with straight undulose extinction. These upper fine to medium grains are dominantly rounded and moderately well-sorted with rare authigenic overgrowths and vacuoles (Fig. 4.11a).

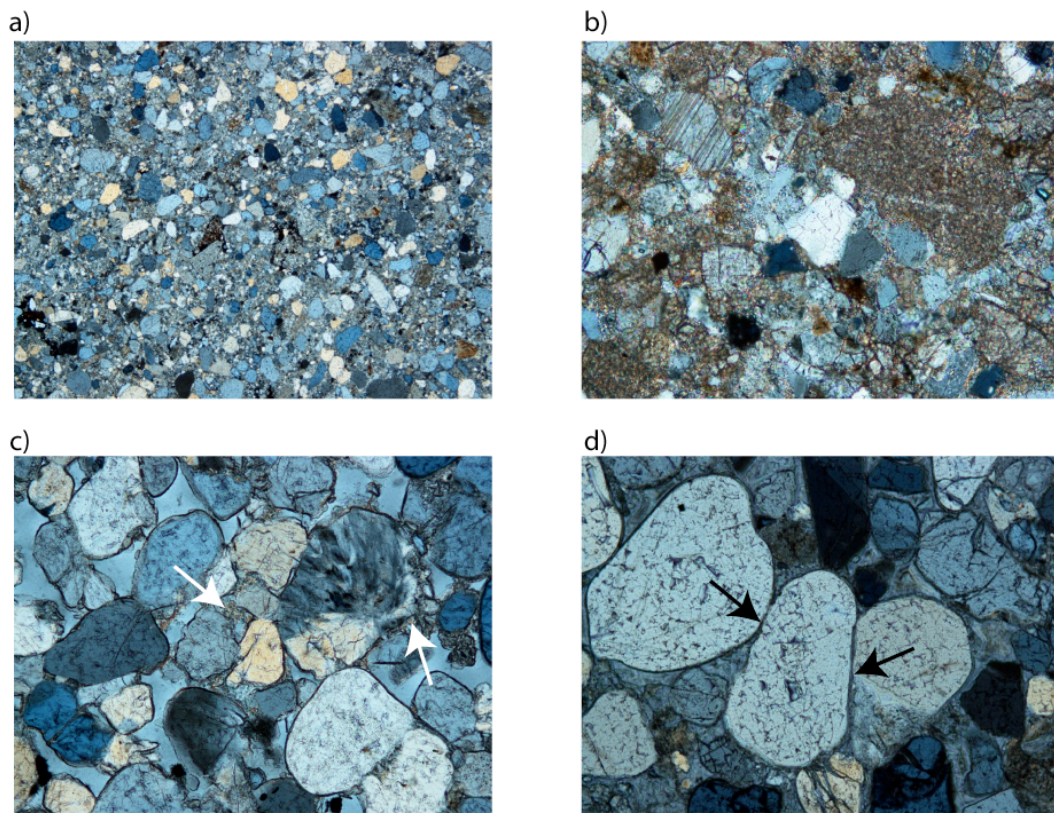
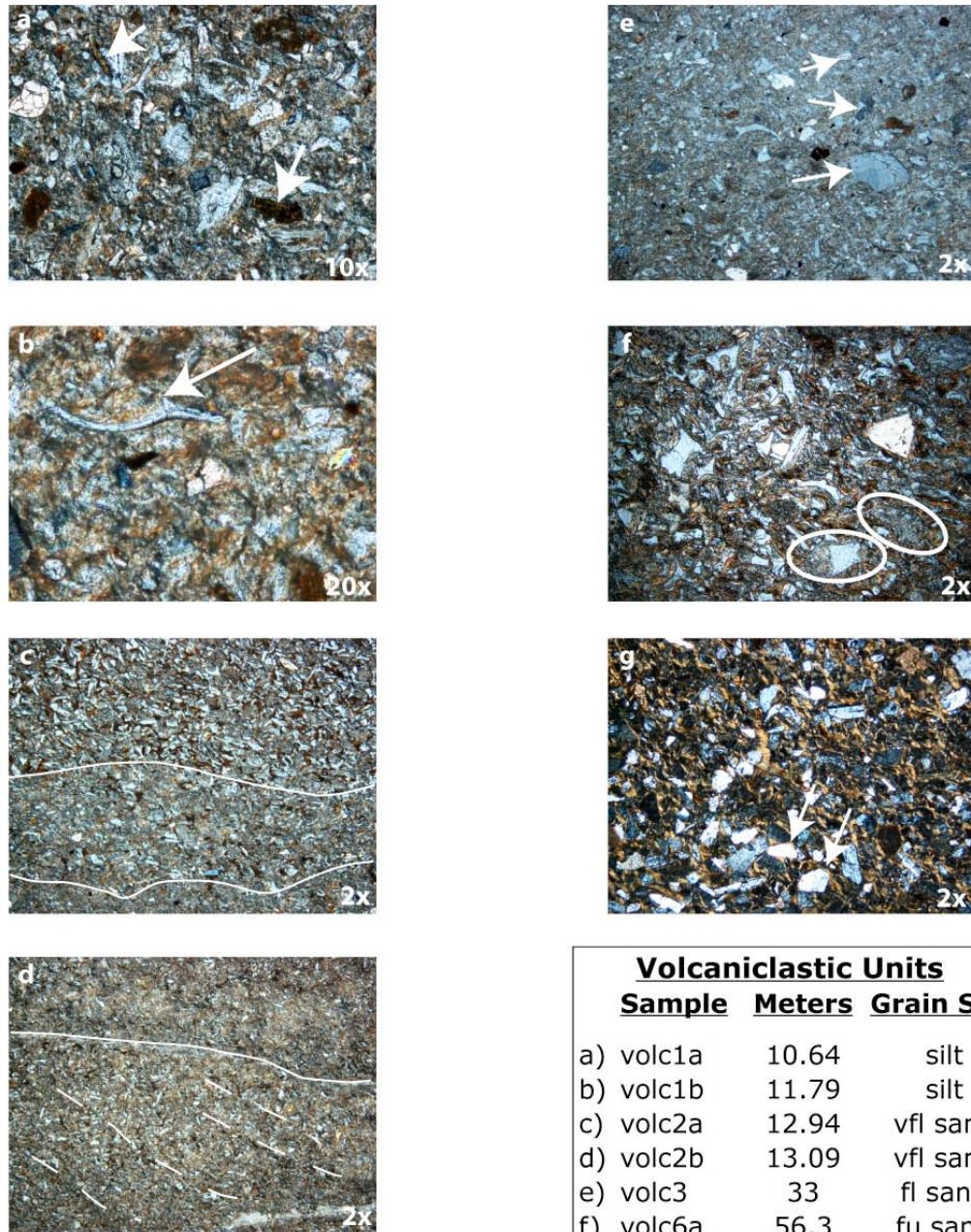


Figure 4.9: Willow Tank sandstone thin section photos showing textural characteristics: a) feldspathic litharenite, 3.9 m, 2x, framework grains are dominantly subangular to subrounded; b) feldspathic litharenite, 45 m, 20x, shows framework grains encased in carbonate cement and iron-stained alteration of minerals; c) lithic arkose, 59.8 m, 10x, photo showing intergranular porosity with arrows pointing to subordinate carbonate cement coating framework grains; d) feldspathic litharenite, 56.88 m, 10x, arrows point to tangential and concavo-convex grain-to-grain contacts.



Volcaniclastic Units		
Sample	Meters	Grain Size
a) volc1a	10.64	silt
b) volc1b	11.79	silt
c) volc2a	12.94	vfl sand
d) volc2b	13.09	vfl sand
e) volc3	33	fl sand
f) volc6a	56.3	fu sand
g) volc4a*	18.92	fu sand

*Located in Section WT2

Figure 4.10: Volcaniclastic siltstones and sandstones of the Willow Tank Formation.

a) Arrows pointing toward biotite grains; b) arrow pointing at volcanic glass that has been fractured; c) laminated volcaniclastic sandstone, note grain size differences and alignment of glass shards; d) crudely ripple cross-laminated (?) volcaniclastic unit; e) Arrows pointing toward orthoclase feldspar grains; f) unit with abundant volcanic glass and minerals altered to clays, denoted by circles.; g) arrows pointing toward quartz grains in a feldspar-dominated unit.

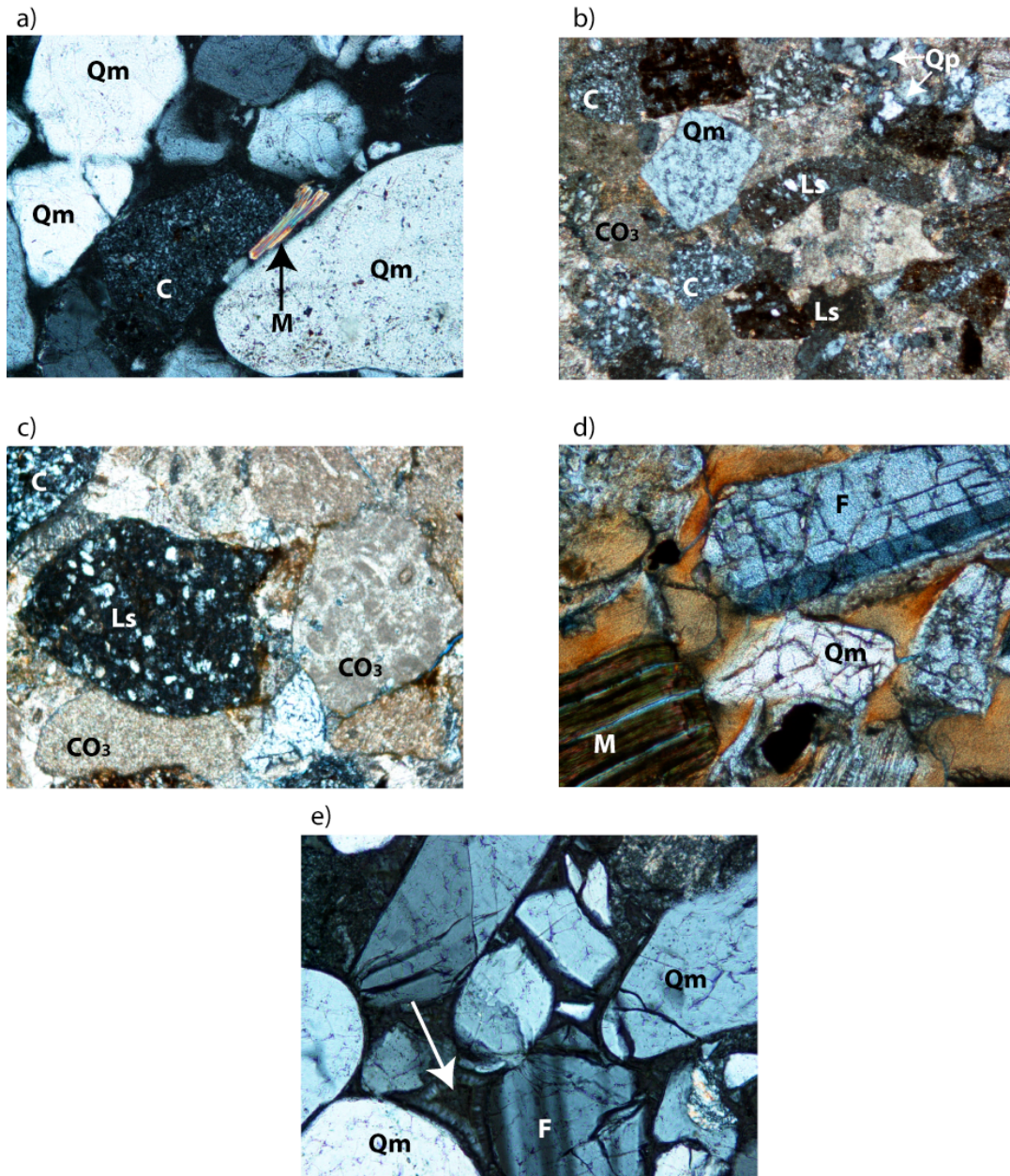


Figure 4.11: Photos of Willow Tank sandstones showing major framework grains. a) Subarkose, 62.83 m, 10x; b) litharenite, 10.64 m, 10x, note carbonate matrix; c) litharenite, 29.2 m, 10x; d) volcaniclastic sandstone, 18.92 m, 20x, note clay matrix; e) feldspathic litharenite, 56.88 m, 10x, note chalcedony matrix. Qm=monocrystalline quartz, Qp=polycrystalline quartz, C=chert, F=feldspar, M=mica, Ls=sedimentary lithics, CO₃=carbonate.

Qp is rare and comprised of two or more crystals of quartz within the grain. These grains are usually lower fine to upper fine in size and subangular (Fig. 4.11b).

Lt fragments range in size from very fine to lower medium and include carbonates, chert, volcanic fragments, siltstone, mudstone, and micas (Fig. 4.11c). Carbonates are generally micritic, homogenous and contain rare quartz grains and fossil fragments. Chert is cryptocrystalline and typically angular to subrounded. Volcanic fragments are felsic, fine-grained and commonly include glass, biotite, and feldspar laths. Volcanic grains are commonly altered and are usually encased by clay minerals (Fig. 4.11d). Siltstone and mudstone are generally subangular and commonly contain quartz grains. Micas are angular to subangular and are dominantly biotite with rare muscovite (Fig. 4.11a & d). Isotropic heavy minerals are rare and usually finer-grained than the majority of framework grains.

F grains are mostly subangular to subrounded, fine-grained and exhibit alteration, sericitization and straight extinction. Untwinned orthoclase is dominant, with rare occurrences of albite, microcline and plagioclase feldspar (Fig. 4.11d & e).

Discussion: Composition ranges from litharenite to subarkose based on QmFLt ternary diagrams (Appendix B, Fig. B.1) from Folk's classification scheme (1980). The following observations can be made from the point count numbers:

1) Point count data collected in this study verify a recycled orogen provenance (Dickinson, 1985) and demonstrate a trend from dominantly lithic-rich beds at the base of the section to dominantly subarkose near the top (Fig. 4.12).

2) Also of significance is the vertical change in textural and compositional maturity, with decreasing amounts of angular to subrounded carbonate, chert and fine-grained fragments concurrent with an increase of rounded to well-rounded quartz grains (Fig. 4.13). No significant change in grain size was documented upsection.

3) Samples KM1 and 2b were sampled between the two conglomerate petrofacies recognized by Reese (1989) and display a high quartz content. KM0, sampled just above the upper conglomerate, is comprised of an anomalous amount of carbonate grains (Fig. 4.14; Appendix B: Table B.1). These observations are corollary to those of Reese (1989): that conglomerate matrix and sandstone interbed point counts reflect the conglomerate framework modal composition.

4) An abundance of feldspar in point counts can be explained due to incorporation via: a) reworking and recycling of grains from previously deposited volcanic strata, b) direct fallout from the atmosphere, and c) formation of authigenic feldspar as a diagenetic product. The high values of K-feldspar, siltstone and biotite in sample KM4 favor the first explanation of reworking previously deposited volcanic or volcanoclastic beds (Appendix B: Table B.1).

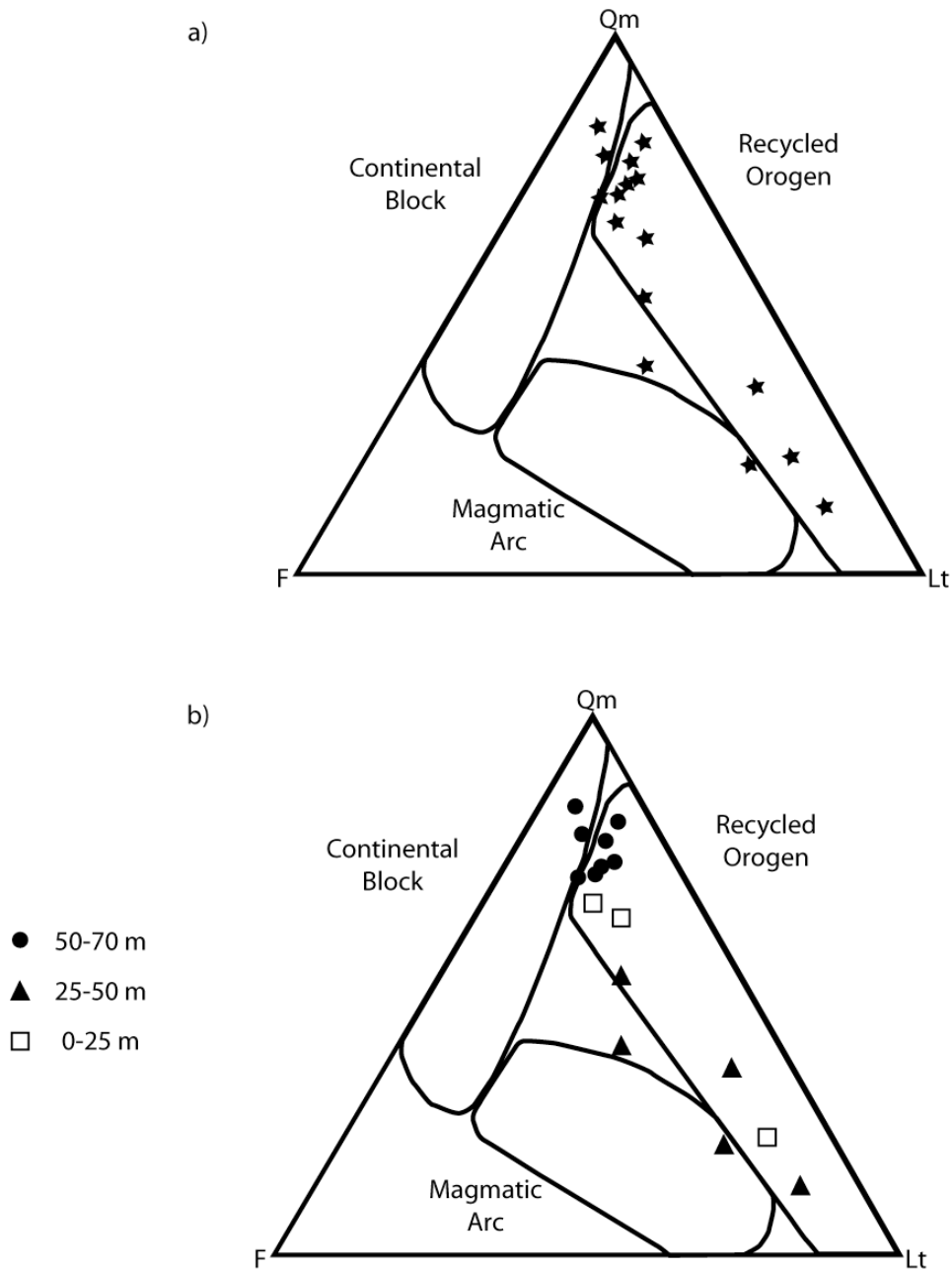


Figure 4.12: QmFLt diagrams from sandstones of the Willow Tank measured section. a) Sandstone detrital modes indicate a dominantly recycled orogen provenance. The sweep of points to the left is attributed to the feldspar influx due to volcanism. b) Modal percentages shown moving up-section from the Willow Tank Formation base toward the conformable contact with the overlying White Member of the Baseline Formation. The overall increase in quartz moving upsection provides evidence of erosion of the Jurassic Aztec sandstone from the hanging wall of the Willow Tank thrust.

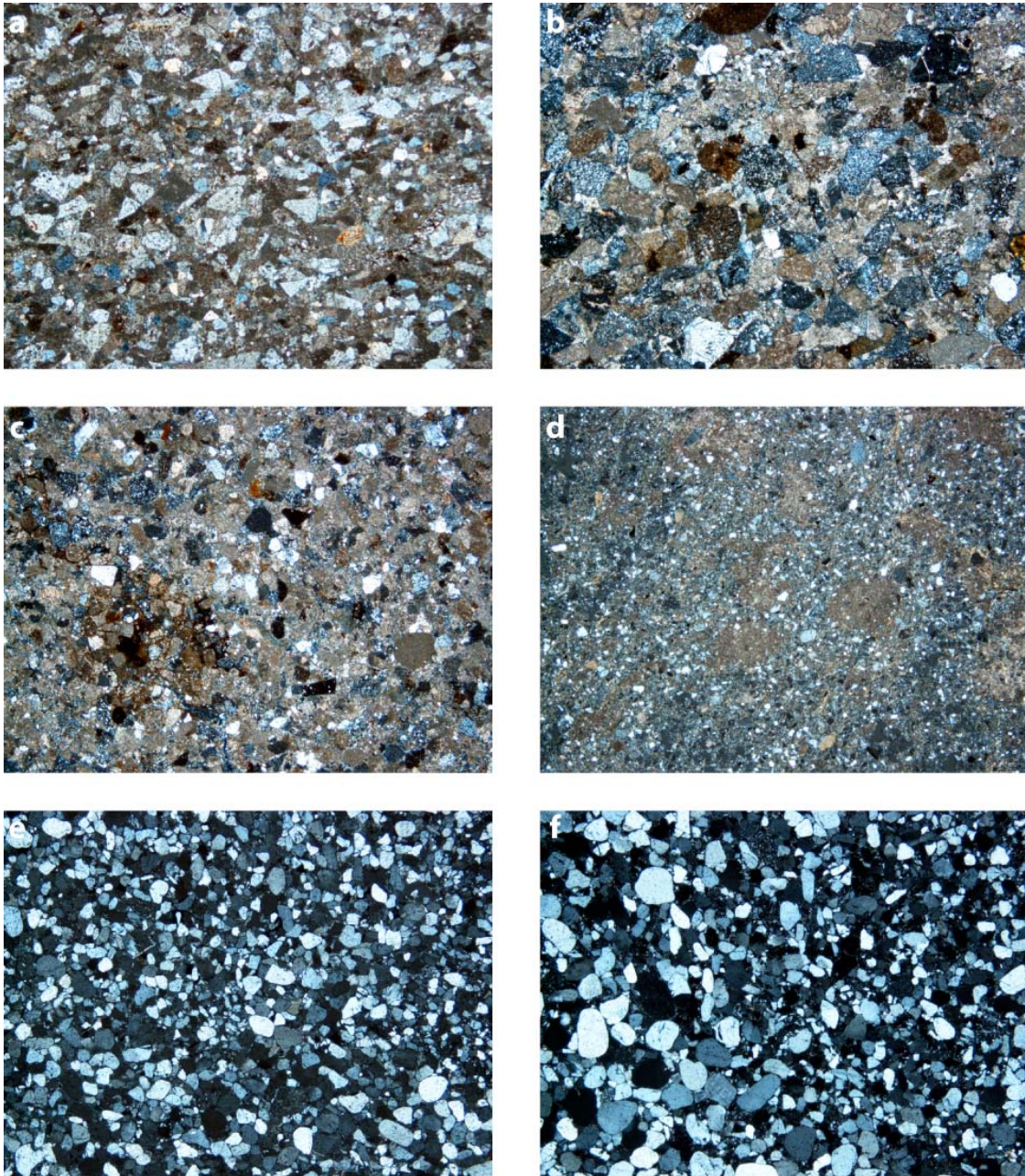


Figure 4.13: Photos of Willow Tank Formation sandstone thin sections (2x) showing upsection increase in quartz content. a) Litharenite, 10.64 m; b) litharenite, 29.2 m; c) litharenite, 39.00 m; d) feldspathic litharenite, 49.00 m; e) lithic arkose, 59.83 m; f) subarkose, 67.78 m. Sandstone classifications are based on Folk (1980).

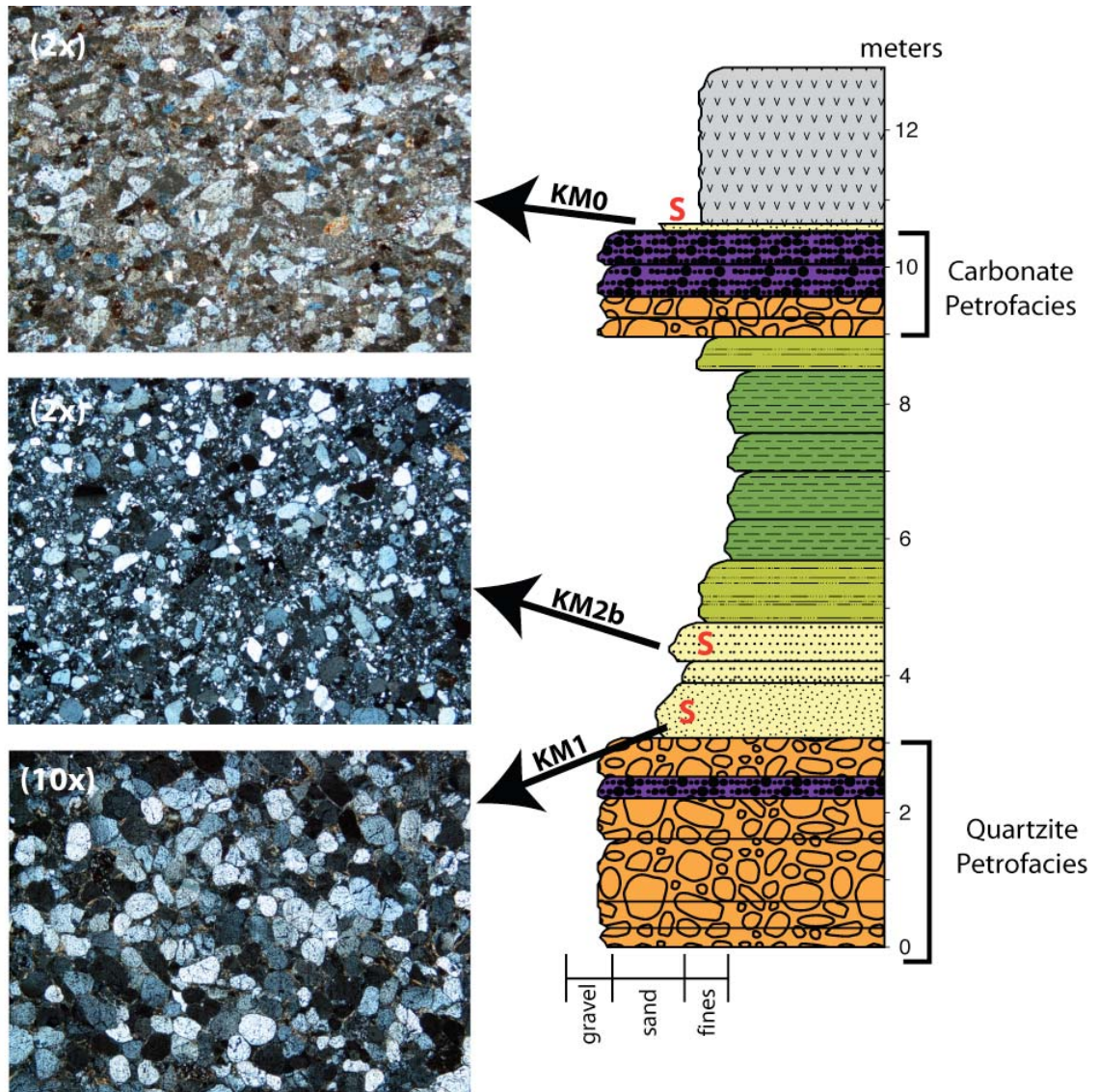


Figure 4.14: Diagram showing location of sandstone samples relative to basal conglomerate petrofacies of Reese (1989). Samples KM1 and 2b are feldspathic litharenites and show a higher percentage of quartz relative to KM0, a litharenite with a preponderance of carbonate grains and cement.

The presence of seven volcanoclastic beds also supports these interpretations (Fig. 4.10).

Source: The overall increase in monocrystalline quartz and corresponding decrease of lithic fragments moving upsection (Fig. 4.15), coupled with an east to southeast paleoflow direction (Reese, 1989) point toward the unroofing and erosion of the Aztec Sandstone from the hanging wall of the Willow Tank blind thrust-cored anticline (Fig. 4.16). Further evidence of this is shown by inheritance of eolian texture (well-sorted, well-rounded) moving stratigraphically upward. The abundance of rounded, pebble-size chert clasts in sandstones and subordinate conglomerates represents the recycling of the basal Willow Tank conglomerates from this fold.

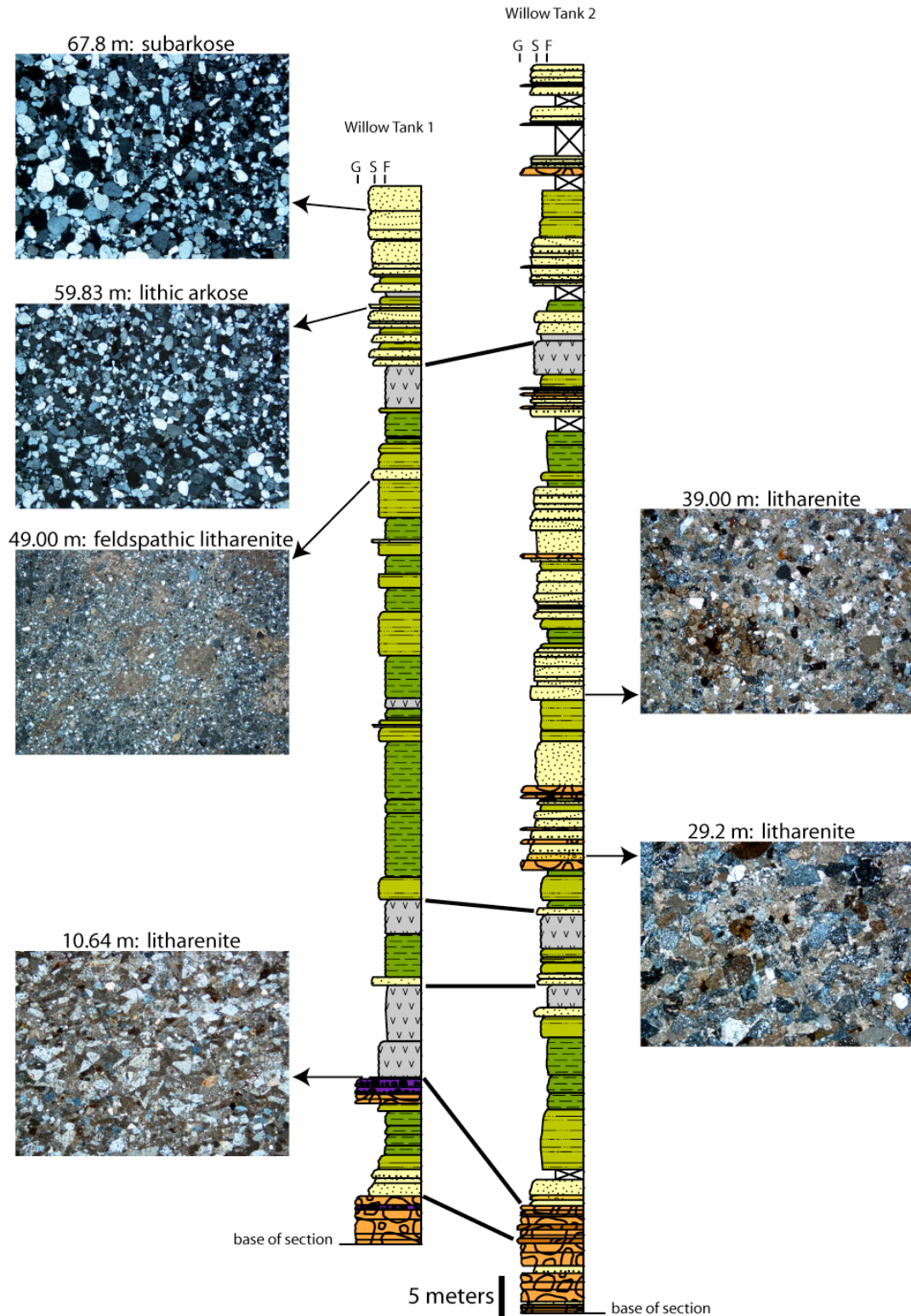


Figure 4.15: Willow Tank sections with sandstone thin section (2x) photos showing changes in grain composition upsection. Note the increase in rounded, fine- to medium-grained quartz sand and decrease in lithics moving upsection. F=fines, S=sand, G=gravel.

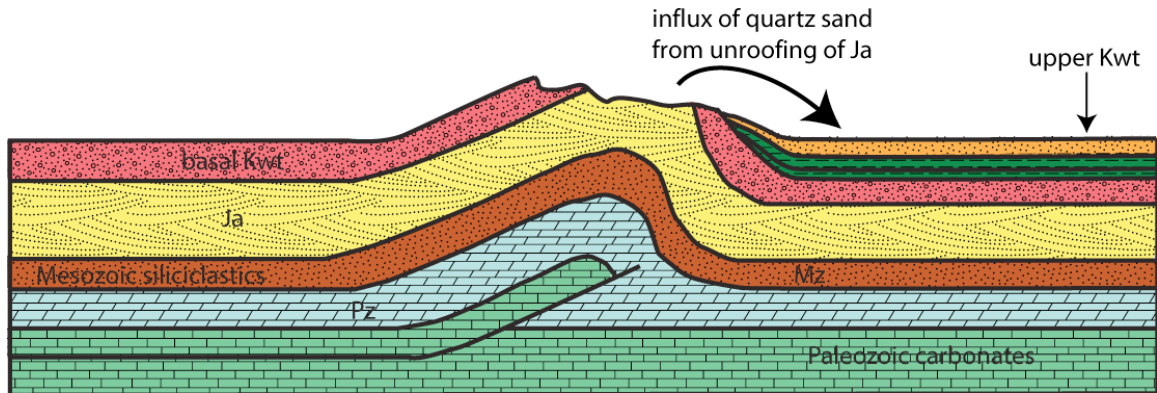


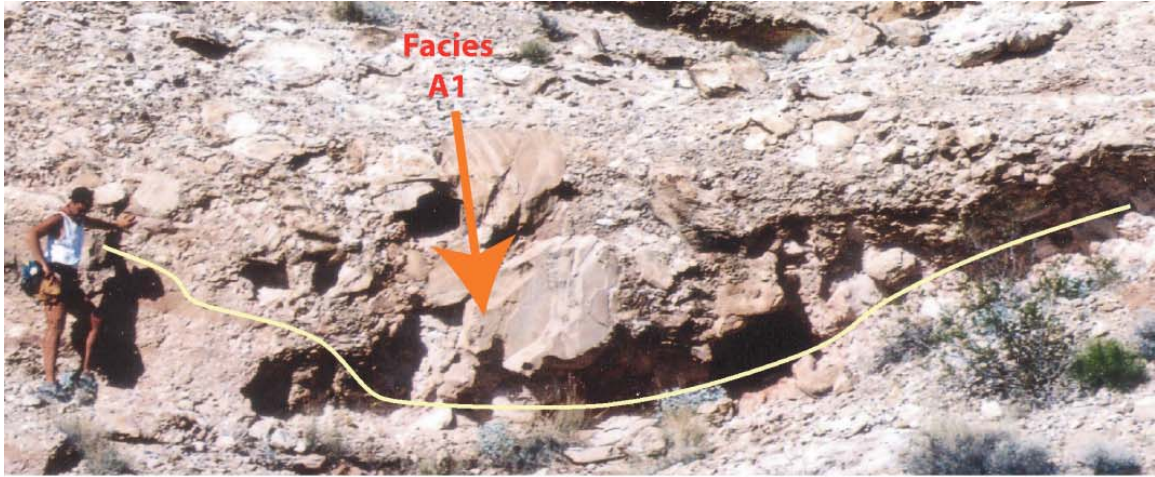
Figure 4.16: Diagram of the Willow Tank blind thrust-cored fault propagation fold. The increasing amount of quartz sand upsection in the Willow Tank Formation (Kwt) is proposed to be a result of the unroofing and exposure of the Jurassic Aztec Sandstone (Ja) on this fold.

White Member Lithofacies Assemblages

According to sedimentological and stratigraphic analyses by Aschoff and Schmitt (2008), the White Member of the Baseline Formation is made up of a 130 meter thick sheetflood-dominated alluvial fan sequence overlain by a 20 to 30 meter thick debris flow alluvial fan assemblage.

Facies Assemblage A: Debris Flow-Dominated Alluvial Fan

Description: This assemblage consists of clast supported, massive ungraded to inversely graded cobble to boulder conglomerates in vertically stacked successions with matrix-supported, massive ungraded to normally graded pebble to cobble conglomerates (Fig. 4.17). These deposits exhibit lenticular geometries and commonly incise underlying strata. A generally fining-



White Member Facies Assemblage A

	Description	Illustration	Interpretation
1	Very thick-bedded (1-3 m), lenticular beds of poorly-sorted, clast-supported, massive, ungraded to inversely graded, cobble to boulder conglomerate with angular to subangular clasts and a disorganized internal fabric. Poorly sorted, mud-poor matrix with granules and pebbles. Typically fills large gully-like features.	 50 cm	Clast-rich, debris-flow "plug" deposits
2	Very thick-bedded (1-2 m), lenticular beds of poorly-sorted, matrix-supported, massive ungraded to normally graded, subangular cobble conglomerate. Poorly sorted, mud-poor matrix with granules and pebbles. Typically fills large gully-like features.	 50 cm	Clast-poor, debris-flow "tail" deposits
3	Medium-bedded (10-25 cm), continuous, lenticular beds of low-angle stratified pebble conglomerate and pebbly sandstone. Typically adjacent to, and interfinger with Facies A1 and A2.	 25cm	"Winnowed" debris-flow deposits

Figure 4.17: Typical debris flow-dominated facies of the White Member. Arrows point to lithologies described in the table above. Hammer is 32 cm for scale, (from Aschoff & Schmitt, 2008).

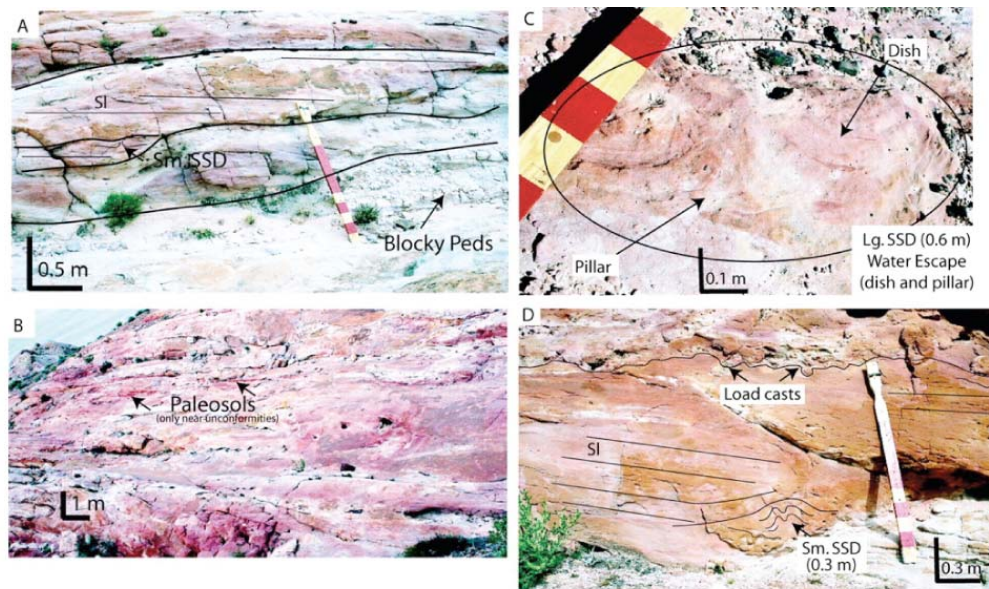
upward, clast-supported low-angle stratified pebble to cobble conglomerate also occasionally interfingers with the previous two deposits. The framework and matrix of these units are dominated by well-sorted, friable sandstone with abundant randomly-oriented conjugate fractures and well-sorted and rounded, frosted sand-sized quartz grains, respectively.

Interpretation: The grain size, sorting and organization of the conglomerate framework clasts point toward deposition by single en masse flows (Nemec & Steel, 1984). The lack of mud in the matrix indicates deposition by cohesionless debris flows (Gloppen & Steel, 1981; Blair, 2000). The lenticular geometry is attributed to the debris from these events filling pre-existing scours. The low-angle laminated beds represent the debris flow tail and/or winnowed remnants of the debris flows.

Facies Assemblage B: Sheetflood-Dominated Alluvial Fan

Description: Five sand-rich facies characterize this succession: 1) low-angle and trough cross-stratified sandstones with clast-supported conglomerate lenses; 2) low-angle to horizontally-stratified sandstone with subordinate conglomerate stringers and soft-sediment deformation; 3) chalky massive mudstone interbedded with ripple cross- and horizontally-laminated sandstones; 4) fine- to medium-grained horizontally laminated sandstone with soft-sediment deformation structures; and 5) pervasively discolored low-angle and trough-cross

stratified sandstones occupying scours (Fig. 4.18). All of the units, with the exception of the mudstone, exhibit undulatory and slightly erosive basal contacts and form lenticular to planar stacks. The distinct mudstone facies includes a



White Member Facies Assemblage B

	Description	Illustration	Interpretation
1	Thick-bedded, low-angle and trough cross-stratified medium- to coarse-grained sandstone with thick lenses of clast-supported, poorly- to moderately-sorted monomictic pebble to cobble conglomerate. Lenses are unstratified near the base of low-relief scours but become organized upward.	 50 cm	Interbedded sheetflood & gully-fill/lag deposits
2	Thick to very thick, flat bedded, low-angle stratified, fine- to medium-grained sandstone with non-erosive, undulatory bases and pebble stringers. Beds have lenticular geometry, oversteepened foresets, water escape structures and small scale soft sediment deformation.	 50 cm	Sheetflood deposits
3	Thin- to medium-bedded, chalky, white massive mudstone with subordinate blocky peds, interbedded with horizontally and ripple cross-laminated very fine-grained sandstone. Locally bleached or oxidized.	 10 cm	Pedogenically-modified/ winnowed sheetflood deposits
4	Thick- to very thick, flat-bedded, internally deformed, fine- to medium-grained sandstone with relict, oversteepened laminae. Sharp, erosional to undulatory bases with local preferential clay cementation and rip-up clasts. Large-scale soft-sediment deformation features are common.	 50 cm	Deformed sheetflood deposits
5	Thick-bedded, locally intensely burrowed, medium-grained sandstone with relict, low-angle stratification and cross-bedding in scours. Pervasive, red-purple oxidation, iron banding and bleaching.	 50 cm	Bioturbated and diagenetically altered sheetflood deposits

Figure 4.18: Typical sheetflood dominated facies of the White Member. a) Facies B2 overlying facies B3; b) vertical succession showing undulatory contacts, flat bedding and paleosols; c) close up view of a dish and pillar structure; and d) soft sediment deformed unit overlain by low-angle stratified sandstone, which was subsequently loaded. Jake staff is 1.5 meters (from Aschoff & Schmitt, 2008).

locally blocky texture, root traces and relict ripple cross-lamination. Deep scours and lateral heterogeneity in grain size and sorting are rare in these conglomerates and sandstones.

Interpretation: The lenticular to planar geometries, interbedded nature of conglomerate and sandstone units at low angles, and absence of pervasive scouring suggest deposition by sheetfloods with sediment-rich, unchannelized fluid gravity flows (Sohn et al., 1999; Blair, 2000). Alternating grain sizes may suggest hyperconcentrated flows with periodic influxes of granules to pebbles followed by a more fluid-rich phase, consistent with sheetflood couplets proposed by Blair and McPherson (1994b). Mudstones are the product of suspension settling of fine grains in lower flow regime sheetfloods. Slaugenhooft and Schmitt (2000) documented 400 meters of fluvial sandstone and conglomerate overlain by 200 meters of debris flow- and sheetflood-dominated alluvial fan deposits in the White Member. These authors noted that the influx of quartz sand delivered to the following depositional environments produced noncohesive sediment transport processes, resulting in comparable lithofacies associations and thereby causing complexity distinguishing between adjacent environments.

White Member Provenance

Longwell (1949) was the first to propose that the White Member of the Baseline Formation was most likely derived from the Jurassic Aztec Sandstone to

the west. Bohannon (1983b) further noted that coarse conglomerate outcrops north of Tearfault Mesa are adjacent to the trace of the Willow Tank thrust and indicate contemporaneous thrusting and sedimentation. This observation was confirmed from detailed analyses of growth strata by Aschoff & Schmitt (2008) (Fig. 4.19).

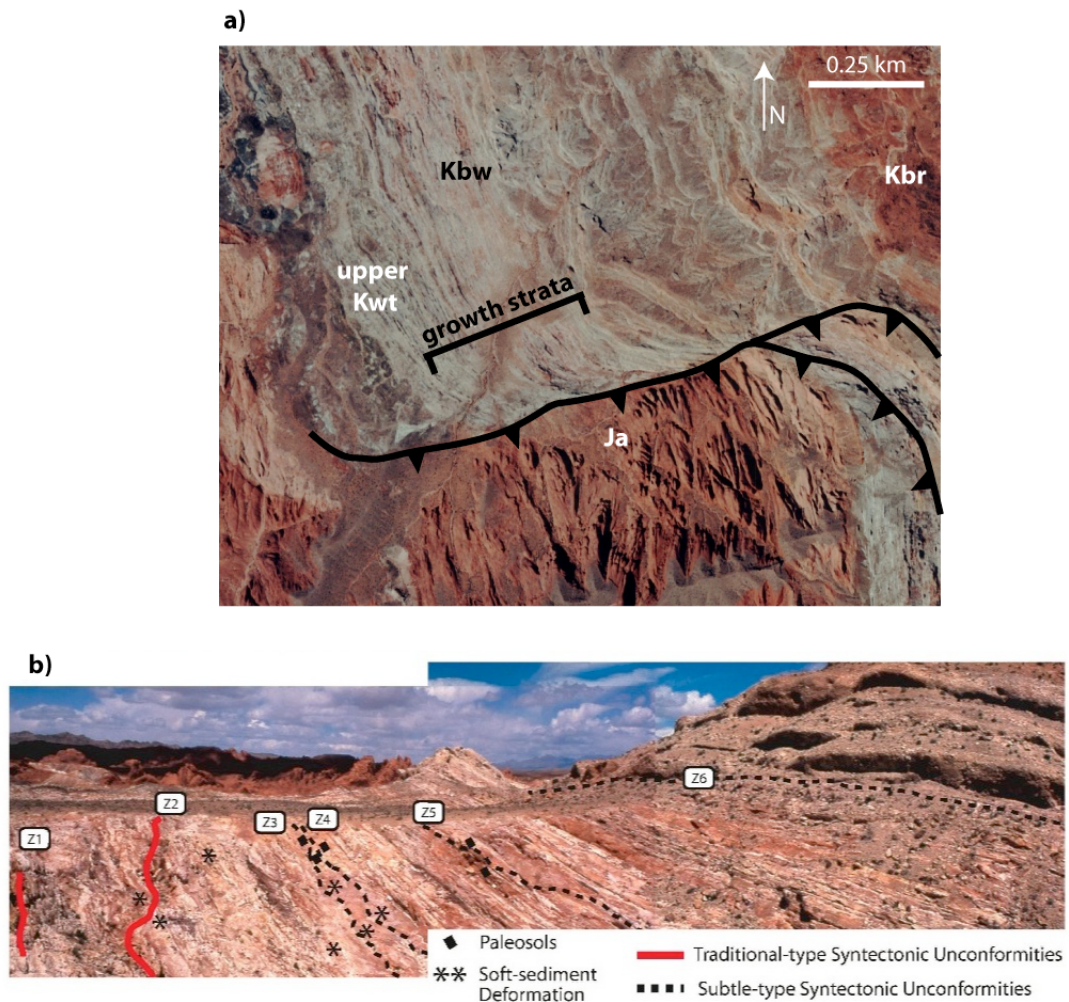


Figure 4.19: Growth strata of White Member. a) Aerial photo of northern flank of Tearfault Mesa showing location of growth strata in the upper Willow Tank (Kwt) and White Member (Kbw). b) Photomosaic of Kbw growth strata, showing upsection decrease in bedding dips and major traditional type (6-90°) and subtle-type (2-5°) unconformities (from Aschoff & Schmitt, 2008).

In contrast to these interpretations, Carpenter (1989) proposed that this member was derived and transported eastward from the thrust-belt interior. Evidence for this interpretation includes: 1) well-rounded conglomerate framework clasts, 2) an absence of a reverse clast stratigraphy, and 3) “exotic” quartzite and chert clasts. Due to these observations, the Willow Tank frontal anticline was discounted as a possible source area.

According to Aschoff and Schmitt (2008), a proximal sediment source is suggested due to the interpretation of deposition by noncohesive debris flows coupled with conglomerate clast composition. The framework clasts include friable, well-sorted sandstones with randomly oriented conjugate fractures and the matrix consists of well-sorted and rounded fine- to medium-grained frosted quartz sand, both corresponding to the eolian Jurassic Aztec sandstone. The “exotic” clasts of Carpenter (1989) are interpreted to represent recycled detritus from the uplift and erosion of the basal Willow Tank conglomerate on the frontal anticline.

Red Member Lithofacies Assemblages

The 642 meter-thick interval measured from the base of the Red Member includes 26 facies (Table 4.2) grouped into three facies assemblages. Each assemblage is described separately below and interpreted in terms of depositional environment.

Table 4.2: Summary of Red Member lithofacies. Lithofacies codes similar to Miall (1978) and interpretations from Middleton (1965) and Lowe (1982).

Facies		
Code	Description	Interpretation
Gcu	clast-supported, massive ungraded, granule to boulder conglomerate	deposition by clay-poor, noncohesive debris flows
Gcn	clast-supported, normally graded, granule to boulder conglomerate	fluid turbulence and differential grain settling in noncohesive debris flows
Gci	clast-supported, inversely graded, granule to boulder conglomerate	buoyant forces and dispersive pressure in noncohesive debris flows
Gmu	matrix-supported, massive ungraded granule to pebble conglomerate	clast-poor debris flow with high matrix strength
Gh	clast-supported, horizontally stratified, granule to pebble conglomerate	transport & deposition in shallow, high velocity flows
Gt	clast-supported, trough cross-stratified, granule to pebble conglomerate	deposition by migrating 3D large ripples and/or dunes
Gl	clast-supported, low-angle stratified, granule to pebble conglomerate	deposition in scours or bedforms with low-angle stratification
Sm	very fine to medium, poorly- to well-sorted massive ungraded sandstone	result of rapid deposition, liquefaction, or bioturbation
Sn	very fine to medium, moderately- to well-sorted normally-graded sandstone	deposition under decelerating flow conditions
Si	very fine to medium, moderately- to well-sorted inversely-graded sandstone	dispersive pressure and/or kinetic sieving during sediment transport
Sh	very fine to medium, moderately- to well-sorted horizontally stratified sandstone	deposition of plane bed phase in upper flow regime
Sl	very fine to medium, moderately- to well-sorted low-angle stratified sandstone	deposition by plane beds in scours or bedforms with low-angle stratification
St	very fine to medium, moderately- to well-sorted trough cross-stratified sandstone	deposition by migrating 3D large ripples and/or dunes
Sp	very fine to medium, poorly- to well-sorted planar tabular cross-stratified sandstone	migration of large scale 2D ripples or dunes in lower flow regime
Sr	very fine to fine, well-sorted ripple cross-laminated sandstone	migration of unidirectional ripples under lower flow regime
Sg	massive, medium to coarse, granular sandstone	result of rapid deposition, liquefaction or bioturbation
Spb	massive, medium to coarse, pebbly sandstone	deposition by noncohesive debris flows or hyperconcentrated flows
Sd	very fine to medium, soft-sediment deformed sandstone with convolute lamination/bedding and dewatering structures common	plastic deformation of partially liquified sediment after deposition by tectonism and/or loading
Sb	very fine to medium, bioturbated sandstone, root traces, burrows and mottling common, rare wood fragments	original structure destroyed due to biogenic processes
Spbl	medium to coarse, moderately- to well-sorted, low-angle stratified pebbly sandstone	deposition by plane beds in scours or low-relief bedforms
Spbt	medium to coarse, moderately- to well-sorted, trough cross-stratified pebbly sandstone	deposition by migrating 3D large ripples and/or dunes
Spbh	medium to coarse, moderately- to well-sorted horizontally stratified pebbly sandstone	deposition of plane bed phase in upper flow regime
Sgh	medium to coarse, moderately- to well-sorted horizontally stratified granular sandstone	deposition of plane bed phase in upper flow regime
Sgl	medium to coarse, moderately- to well-sorted low-angle stratified granular sandstone	deposition by plane beds in scours or low-relief bedforms
Fh	stratified siltstone or mudstone	deposition by suspension settling of fines in decelerating flows
Fm	massive ungraded siltstone or mudstone	result of rapid deposition, liquefaction, or bioturbation

Facies Assemblage A: Debris Flow-Dominated Alluvial Fan

Description: Deposits that comprise this facies assemblage occur from the base of the section to approximately 360 meters (Appendix C: Fig. C.3). This assemblage is dominated by thin- to very thick-bedded, clast-supported, poorly organized, massive ungraded pebble- to boulder conglomerates (Gcu) (Figs. 4.20 & 4.21). The framework is dominantly pebble-sized, poorly sorted, subangular to subrounded clasts. These units are commonly laterally discontinuous and display a lenticular to lobate geometry. Lateral changes from pebbly sandstone (Spb) to inverse and/or normal grading (Gci and Gcn, respectively) often occur within a few meters along both strike and dip (Fig. 4.22a). Thin, discontinuous massive (Sm), low angle laminated (Sl), and horizontally-stratified sandstone (Sh) lenses usually occur within and between conglomerate beds (Fig. 4.22b). Conglomerate beds often pinch between or are truncated by overlying conglomerate or sandstone beds (Fig. 4.23). Basal and upper contacts with conglomerates are marked by a change in grain size or aligned clasts and those with sandstones are erosive to depositional. An abundance of boulder-dominated conglomerates appear in two intervals: from 218 to 260 and 308 to 354 meters, with pebble- to cobble-dominated beds uniform throughout this assemblage (Appendix C: Fig. C.3).

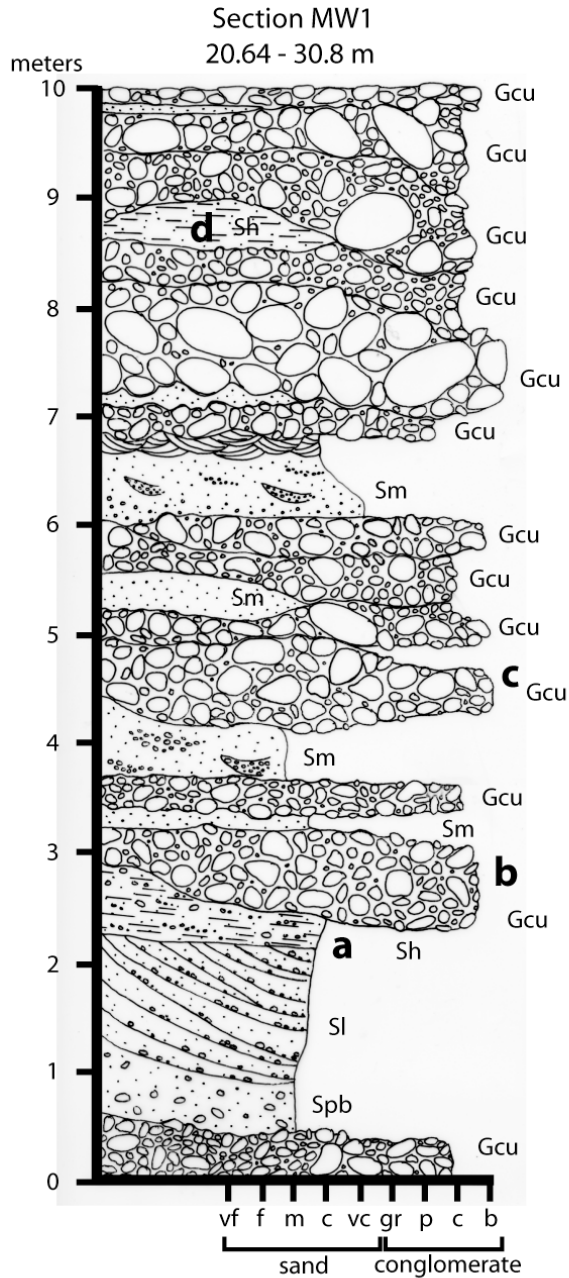


Figure 4.20: Detailed 10 meter section showing characteristic vertical succession of debris flow-dominated alluvial fan deposits. Letters in section correspond to pictures on right. Facies codes are included in Table 4.2. Location of detailed section is outlined in Figure A.1b. Pencil is 15 cm, hammer is 32 cm, and jake staff is 1.5 m for scale.

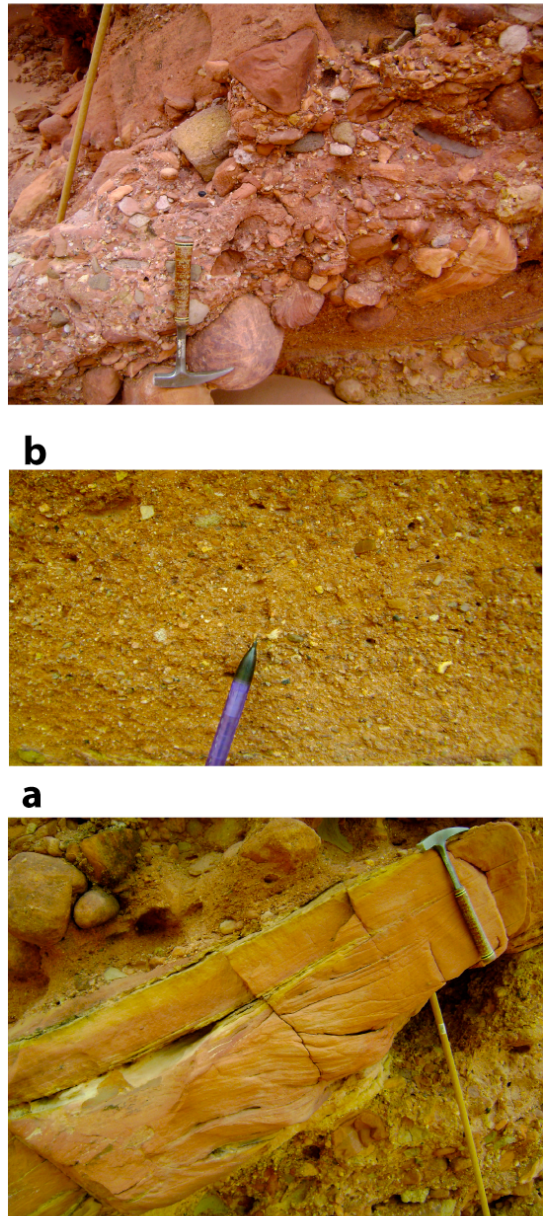
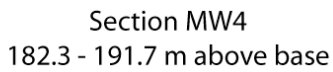


Figure 4.21: Detailed 10 meter section showing characteristic vertical succession of debris flow-dominated alluvial fan deposits. Letters in section correspond to pictures on right. Facies codes are included in Table 4.2. Location of detailed section is outlined in Figure A.1b. Pencil is 15 cm, hammer is 32 cm, and jake staff is 1.5 m for scale.

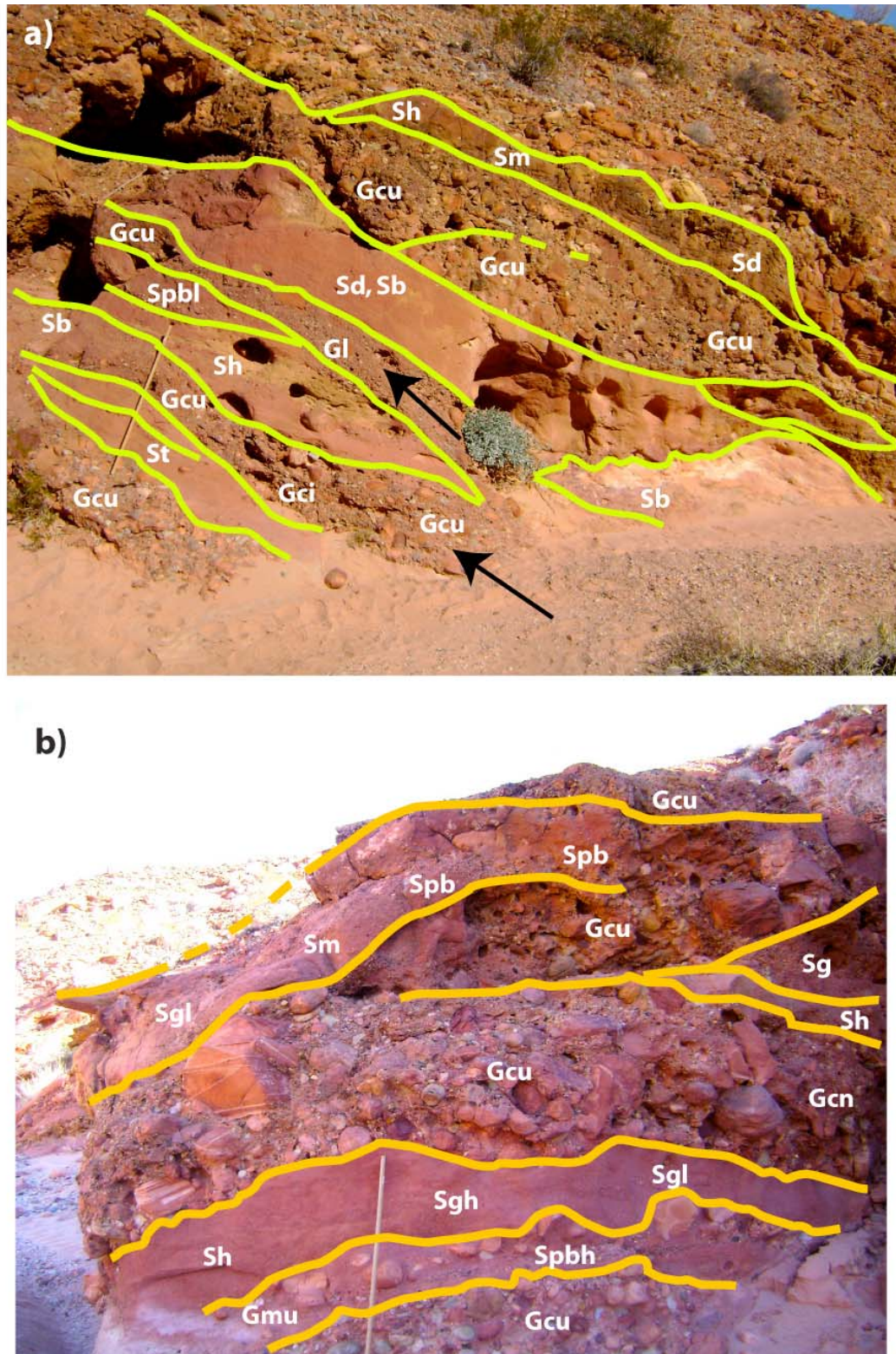


Figure 4.22: Photos of debris flow-dominated alluvial fan deposits, dominated by massive, ungraded conglomerates. a) Arrows point to beds exhibiting lateral facies changes over just a few meters. b) Along-strike view showing interbedded conglomerates and sandstones. Note variations in bed thickness and geometry. Jake staff is 1.5 m.

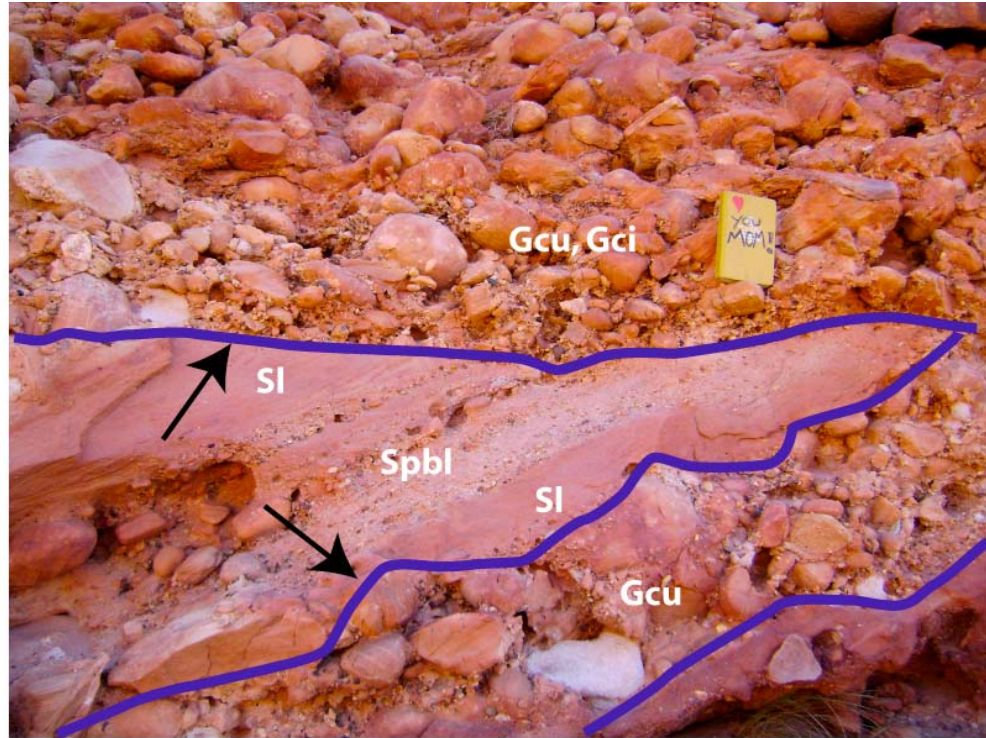


Figure 4.23: Photo showing debris flow-dominated deposits, with arrows pointing toward depositional and erosive contacts. Beds are commonly truncated and thus laterally discontinuous along both strike and dip. Fieldbook is 19 cm in length.

The poorly organized conglomerates are often associated with massive (Sm), soft-sediment deformed (Sd), low-angle (Sl) and/or horizontally stratified sandstones (Sh), ranging from 0.1 to 6 m thick (Figs. 4.20 & 4.21). These planar to lenticular units are upper fine- to medium grained, moderately- to well-sorted and commonly exhibit granule to small pebble alignments and lenses (4.24a). Lateral discontinuity by stratigraphic pinchout or truncation by bounding conglomerate and/or sandstone units is common (Fig. 4.23). Like the conglomerates in this assemblage, sandstone beds display lateral heterogeneity along both strike and dip (4.24b). Sd beds contain abundant convolute lamination with common dewatering pipes, dish and pillar structures and mottling

(Fig. 4.24c). Contacts between sandstones are dominantly erosive with cut-and-fill structures (Fig. 4.24d) occupied by granular to pebbly low-angle laminated sandstones (Sgl/Spbl) or normally graded conglomerates (Gcn). Those with conglomerates are often depositional to abrupt and occasionally show evidence of loading (Fig. 4.24e).

Sd and Sm often possess an iron-stained surface with rare burrows, rootlets and organic matter (Fig. 4.25). All of the above mentioned facies are deficient in silt- and clay-sized particles in the matrix. However, subordinate, thin Sh, Sm, and ripple cross-laminated (Sr), very fine-grained sandstones occur between thick Sm, Sd and Sh beds (Fig. 4.24f). These fine-grained beds are: 1) characterized by a flakey weathered profile, 2) commonly recessive and mottled, and 3) replaced by a surface when thickness changes laterally. Mudstone units are extremely rare, thin and laterally discontinuous.

Interpretation: The facies relationships in this assemblage exhibit characteristics of debris flow alluvial fan deposits (Bull, 1972; Blair & McPherson, 1994a). The poorly organized nature and pebble- to boulder-sized framework of Gcu, Gci and rare Gcn units suggests deposition by clast-rich debris flows (Nemec & Steel, 1984). A lack of clay-sized particles in the matrix is attributed to the lack of mud in the source area and suggests the absence of cohesion in flow behavior (Gloppen & Steel, 1981; Shultz, 1984; Blair, 2000). Clast support was

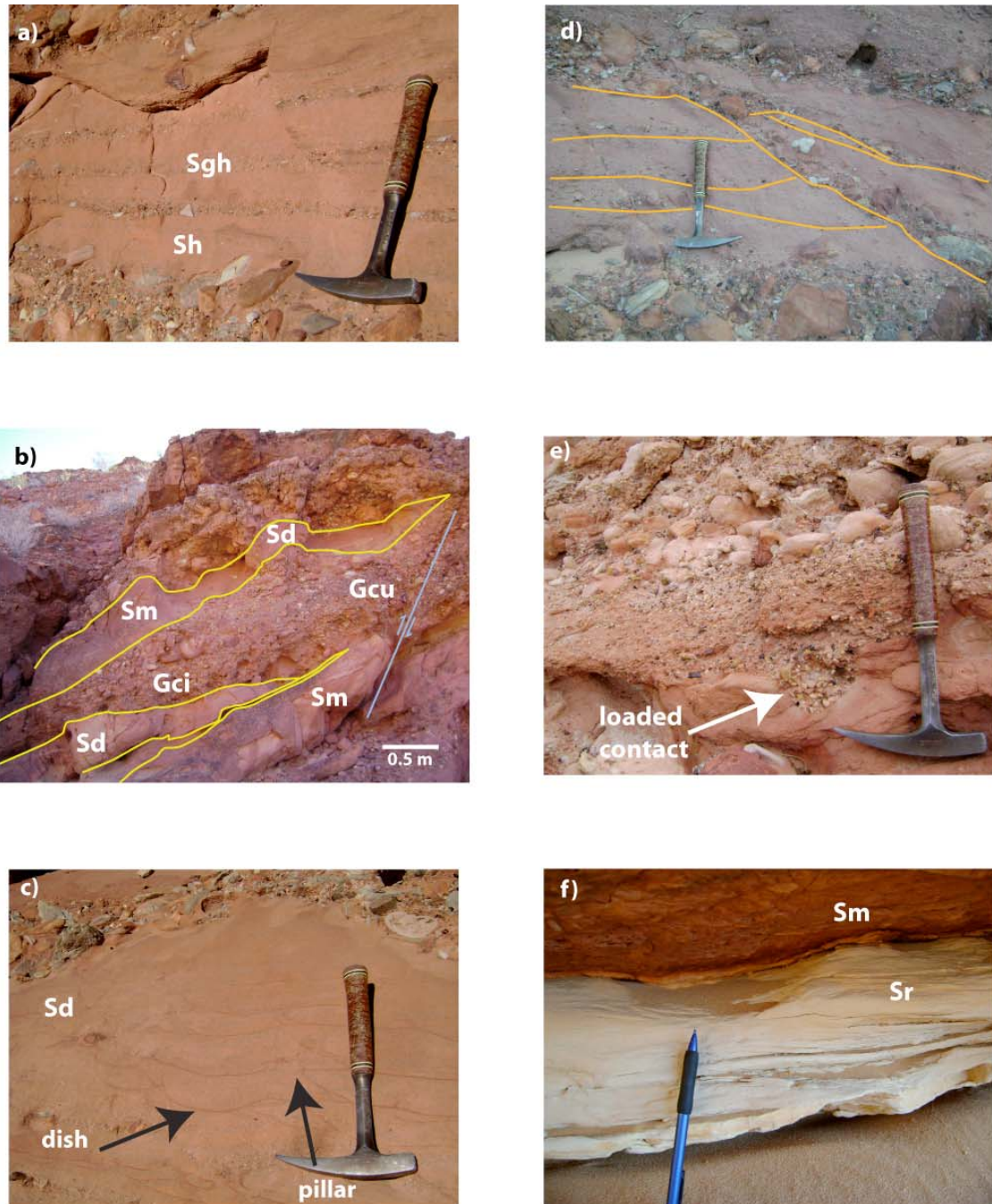


Figure 4.24: Photos showing: a) aligned granules/small pebbles between beds; b) dip view of lateral facies changes and bed discontinuity; c) dish and pillar features; d) pebble-aligned cut and fill structures; e) loaded contact between small pebble conglomerate and massive sandstone; and f) recessive, very fine-grained ripple laminated sandstone. Hammer is 32 cm and pencil is 15 cm for scale.

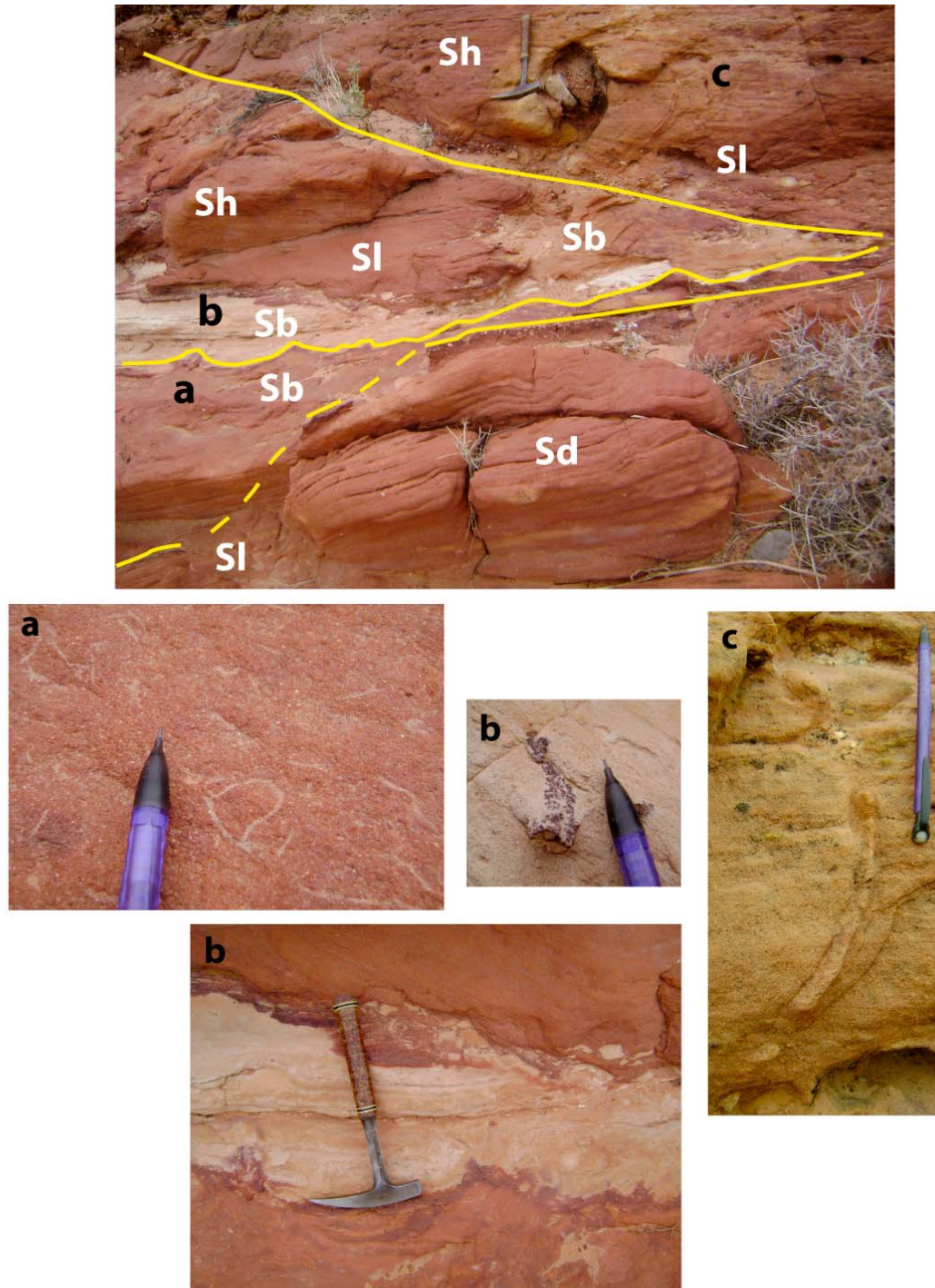


Figure 4.25: Photos showing along-strike sequence of characteristic bioturbated sandstones: a) strange, stringy patterns of discoloration; b) mottled horizon bounded by iron-rich banding and a burrow or root replaced by iron oxide; and c) burrow in horizontally stratified sandstone. Hammer is 32 cm and pencil is 15 cm for scale.

most likely attained by turbulence, dispersive pressure, grain-to-grain contact and buoyancy (Nemec & Steel, 1984; Blair, 1987a; Costa, 1988). Grain sliding and interlocking caused internal friction, which controlled yield strength in these heterogeneous, poorly-sorted cohesionless masses of material (Nemec & Steel, 1984). Alternatively, Gcu deposition could be the result of hyperconcentrated flow, possessing sediment concentration from 40 to 80 weight percent and measurable yield strength (Beverage & Culbertson, 1964; Pierson & Costa, 1987). However, the abundance of Gcu and dearth of Gcn deposits suggests that gravity settling due to dampened turbulence was minimal (Shultz, 1984; Pierson & Costa, 1987).

Lobate and lenticular geometries in these units are interpreted as levees built by flow spilling over channel banks and deposition within active channels, respectively (Hooke, 1967; Blair & McPherson, 1994a). The heterogeneity in texture within the same bed points toward flow transition over time. For example, inverse grading results from buoyancy and dispersive pressure that keeps large particles near the top of the flow (Bagnold, 1954; Fisher, 1971). Normal grading in the same bed maybe the result of gravity settling of the larger clasts due to decreasing velocity over time.

Sm units show a lack of internal stratification and are interpreted as a result of four possible processes: 1) The destruction of primary sedimentary structures by bioturbation, which is shown by the presence of patchy cross-bedding and lamination in the same bed as well as rare roots and burrows

(DeCelles et. al, 1987). 2) Liquefaction is another possibility given that deposition occurred in a tectonically active area and Sm is commonly associated with Sd units. 3) A large amount of detritus (from the friable Aztec Sandstone) incorporated in sediment-laden flows and rapid deposition due to gravity settling. 4) Uniform grain size due to: homogeneity in the source area, selective deposition, and/or breakdown or alteration of different size material could also prevent the formation of sedimentary structures.

Sg and Spb units are interpreted to be deposited by sandy debris flows (Nemec & Steel, 1984), while coarser grains bundled in stringers are interpreted to be the result of traction transport (Todd, 1989). These observations suggest that neither deposition by sediment nor fluid gravity flow can be ruled out. Sh and Sl beds result from deposition by lower or upper plane bed conditions by fluid gravity flows (Harms et al., 1982). The presence of aligned granules/pebbles and the association of trough cross-stratified sandstone (St) favor upper flow regime conditions. Furthermore, deposition by lower flow regime is ruled out because a coarser grain size is needed to fulfill those conditions. Sl beds exhibit laminae that lie less than the angle of repose ($\sim 34^\circ$) and are not always associated with a scoured base and fill pre-existing topography. Sl can form by sand sheet deposition under plane bed conditions (Rust, 1978; Miall, 1996) and/or antidune formation (Harms & Fahnestock, 1965).

Sd beds exhibit abundant convolute laminae/bedding, dewatering pipes, and dish and pillar structures. The fact that the convolute laminae/bedding is still

intact indicates that the sediment was semi-consolidated at the time of deformation. Fluid escape pipes and dish and pillar are attributed to the upward migration of water due to loading by sediment or tectonically-associated movement. Sediment loading is favorable due to the presence of loaded upper contacts. Thin, discontinuous very fine-grained sandstones are the product of gravity settling of fine material during waning water flow (Harms & Fahnestock, 1965) and/or sediment that was exposed and reworked by organisms, water and/or wind (Aschoff & Schmitt, 2008).

Facies Assemblage B: Sandy Braidplain System

Description: Deposits of this assemblage crop out from approximately 500 to 652 meters (Appendix C: Fig. C.4) and are principally sandstones with minor conglomerates (Figs. 4.26 & 4.27). The sandstones are primarily massive (Sm), horizontally-stratified (Sh) and bioturbated (Sb) with occasional low-angle laminated (Sl), trough cross-stratified (St) and soft-sediment deformed units (Sd) (Fig. 4.28a). These lenticular to tabular beds range in thickness from 0.08 to 2.18 meters, are moderately well- to well-sorted and show upper fine to lower medium grain sizes. Sandstones are laterally continuous along both strike and dip with rare truncation due to stratigraphic pinchout or scouring (Fig. 4.28b). Lateral variation is common, but not as pronounced as in Assemblage A (Fig. 4.29). Contacts are either erosive with low-amplitude scours, rip-up clasts and

cut-and-fill structures, or are depositional and undulatory with no evidence of major loading seen.

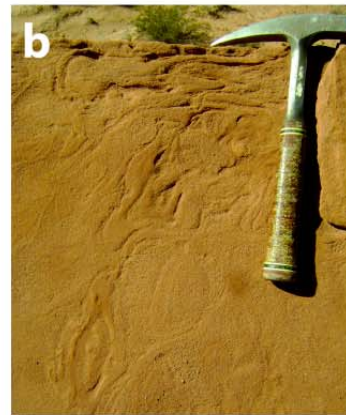
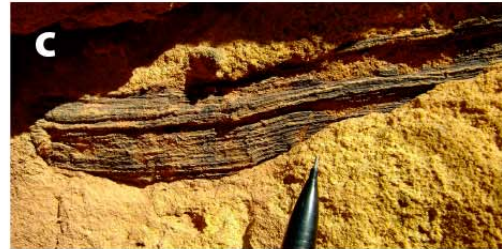
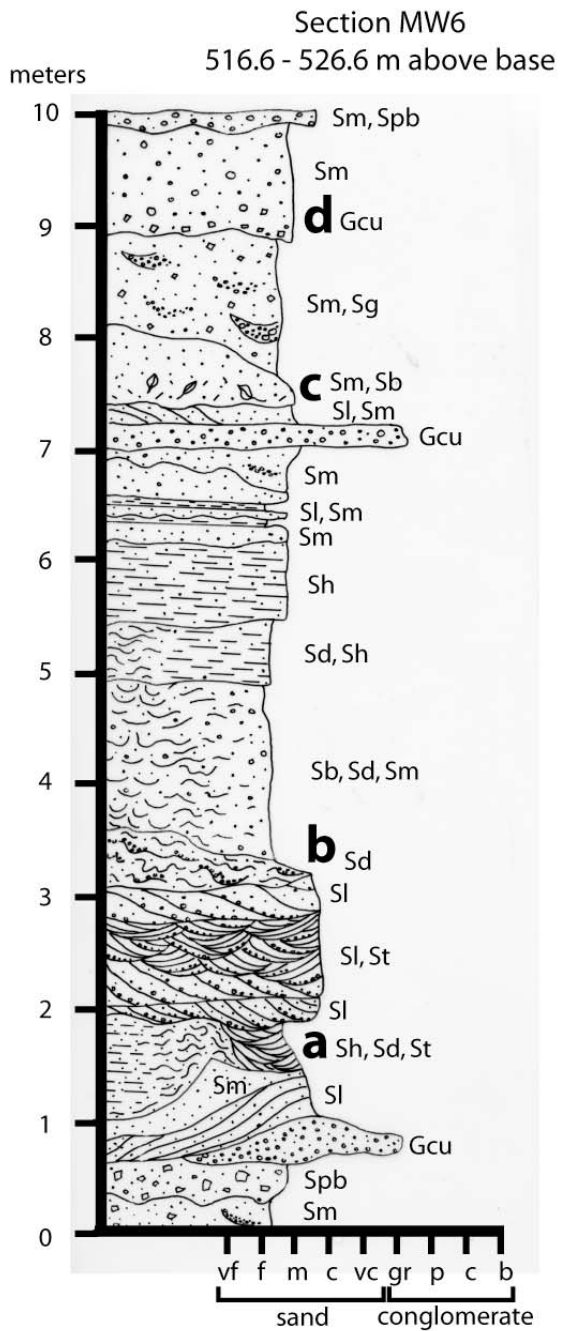


Figure 4.26: Detailed 10 meter section showing a vertical succession of braided stream-dominated deposits. Letters in the section correspond to pictures on the right. Facies codes are included in Table 4.2. Location of detailed sections are outlined in Fig. A.1b. Hammer is 32 cm and pencil is 15 cm long for scale.

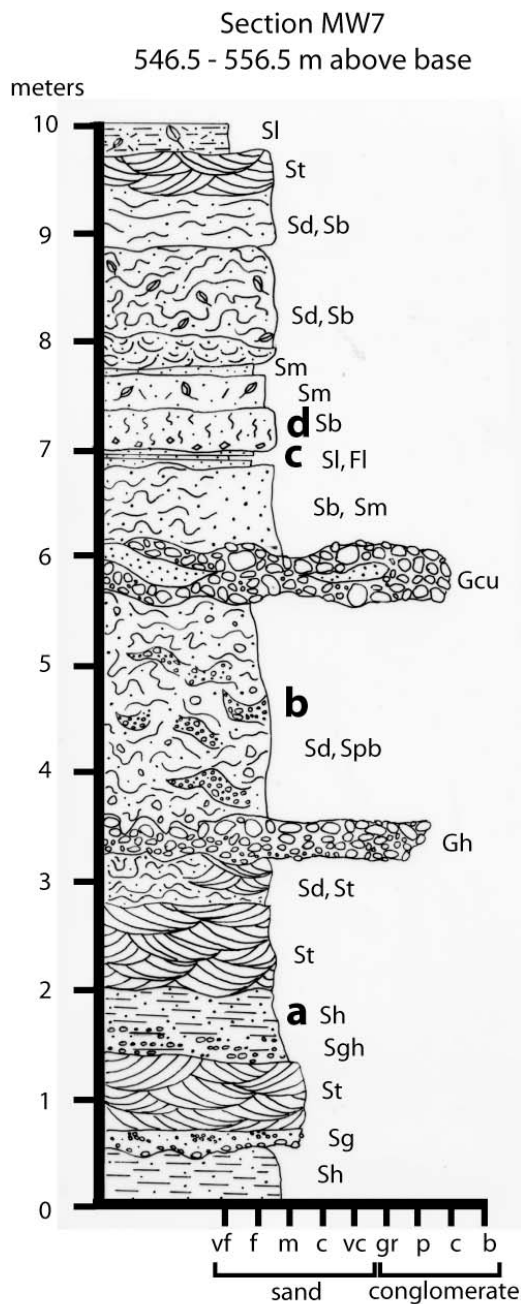


Figure 4.27: Detailed 10 meter section showing a vertical succession of braided stream-dominated deposits. Letters in the section correspond to pictures on the right. Facies codes are included in Table 4.2. Location of detailed sections are outlined in Fig. A.1b. Hammer is 32 cm and pencil is 15 cm long for scale.

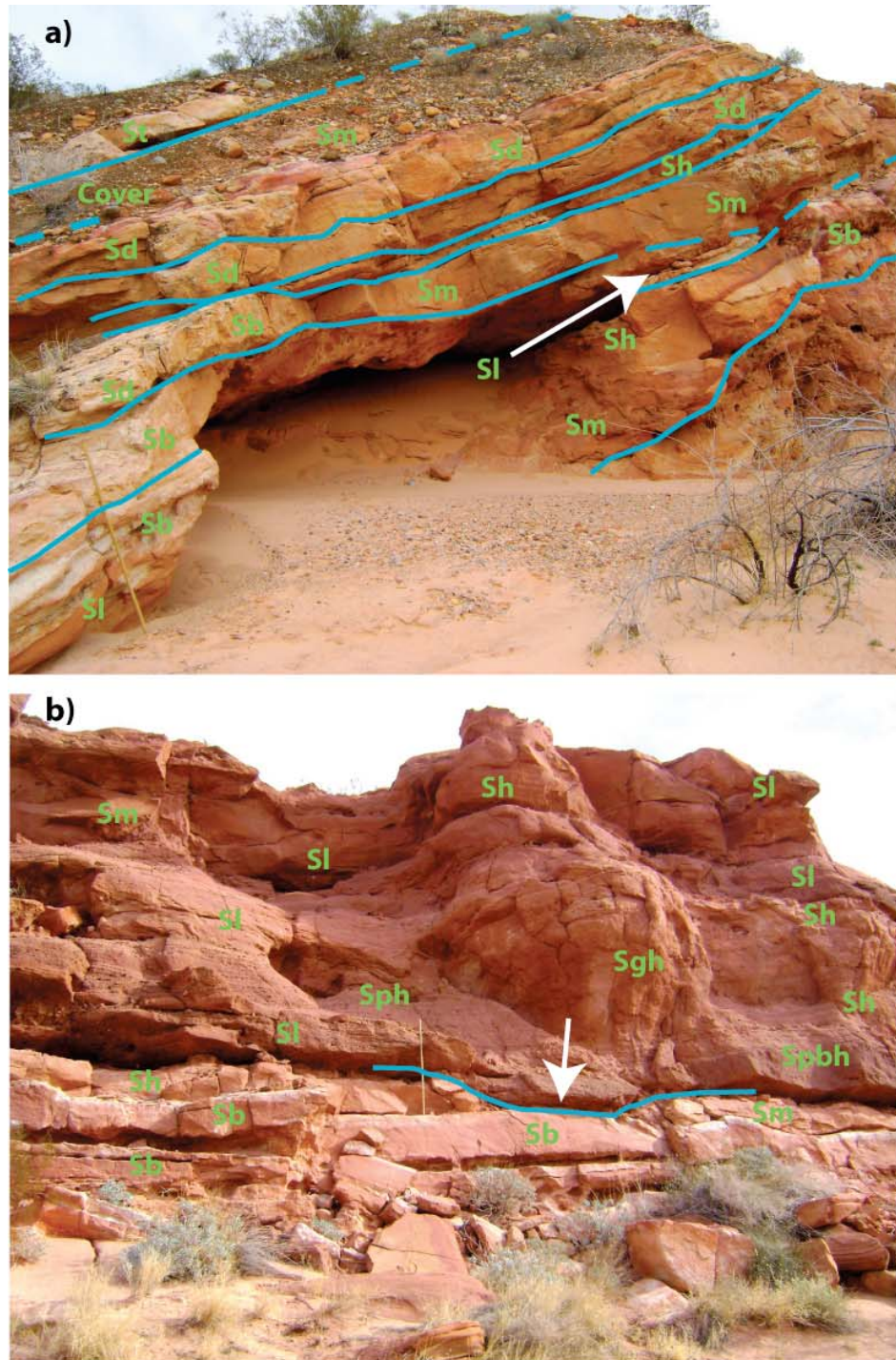


Figure 4.28: Photos showing typical vertical sequences of braided stream sandstones. Note lateral continuity in views oblique to dip (a) and along-strike (b). Contacts are usually undulatory and occasionally show evidence of scouring (arrow in (b)). Jake staff is 1.5 meters.

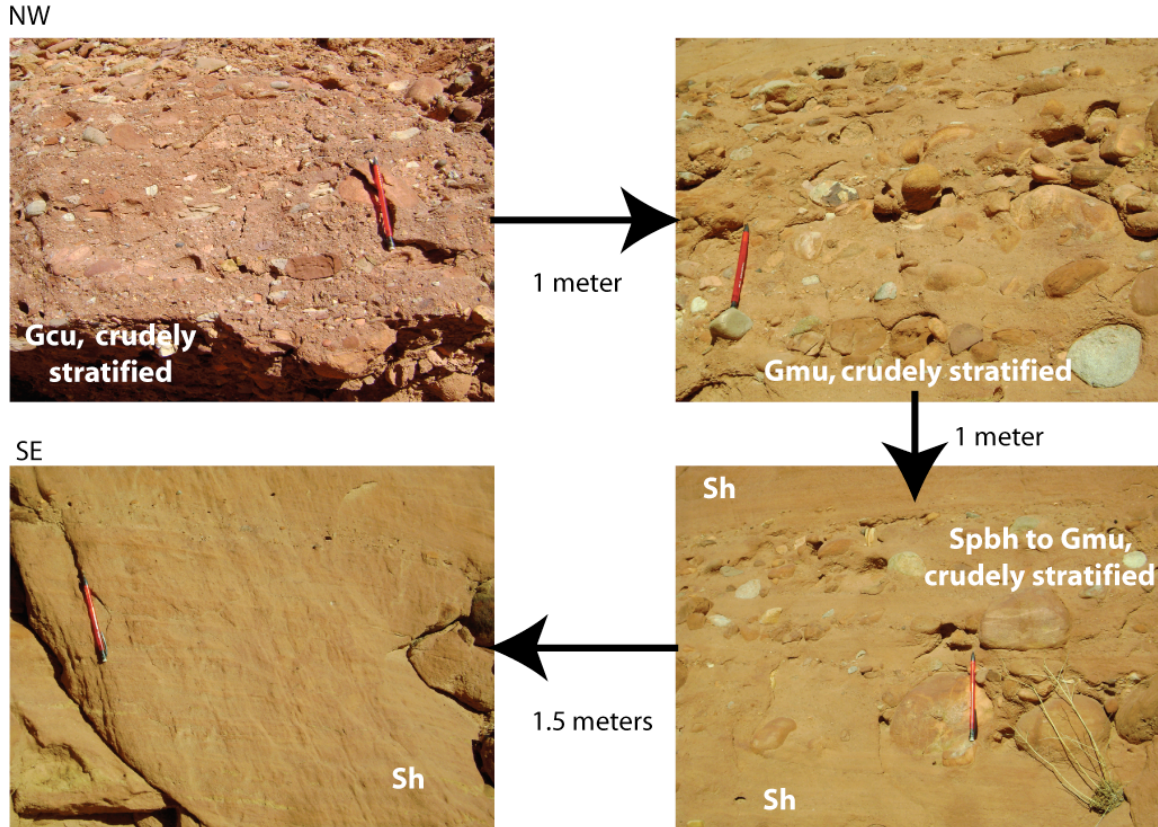


Figure 4.29: Lateral variation observed down dip in the same bed over 3.5 meters. Bed is approx. 0.54 m thick, thins to a pebble stringer to NW and is laterally continuous to SE before pinching between conglomerates.

Granular (Sgl) to pebbly (Spbl) low-angle stratified sandstones commonly occupy the bases of scours. Iron-staining is profuse between units and commonly is accompanied by small clasts, burrows, and wood and plant fragments (Fig. 4.30a & b). Sandstones usually fine upward and occasionally contain rip-up clasts, wood fragments and organic matter (Fig. 4.30b & c). Many Sb beds display purple to yellow mottling, burrows and rootlets.

Clast-supported conglomerates (Gcu) occur mostly as 0.12 to 0.79 meter thick lenticular pockets encased in sandstone units or thin-bedded tabular to lenticular bodies. These moderately well-sorted deposits display a bimodal

framework of granules and pebbles and are dominantly stratified (Gh), normally-graded (Gcn) or ungraded (Gcu) with a uniform framework size and lack cobble- to boulder-sized clasts (Fig. 4.31). Conglomerate units that are laterally continuous commonly change in the amount and size of framework clasts along both strike and dip (Fig. 4.29). Occasional low-angle laminated (Gl) and trough cross-stratified (Gt) conglomerates are associated with Gh, Sh, Sgh, and Spbh beds (Fig. 4.30d). Contact surfaces are usually abrupt and straight, with rare evidence of scouring. A dearth of both large framework clasts and poor organization is accompanied by an increase in: clast imbrication, the presence of intraclasts (Fig. 4.30e), and matrix-supported conglomerates (Gmu).

Relative to facies assemblage A, an increasing amount of fine-grained units is seen and are usually recessive and enclosed between sandstone units. These 0.1 to 0.6 meter thick mudstones and siltstones are massive (Fm) or horizontally-stratified (Fh) and are commonly mottled (Fig. 4.30f). Rare organic matter, slickensides, burrows and casts are present. These beds either pinch laterally or are scoured down to just a surface between thicker, coarser beds. Often rip-up clasts of these fine-grained units occur at the base of overlying sandstones or conglomerates.

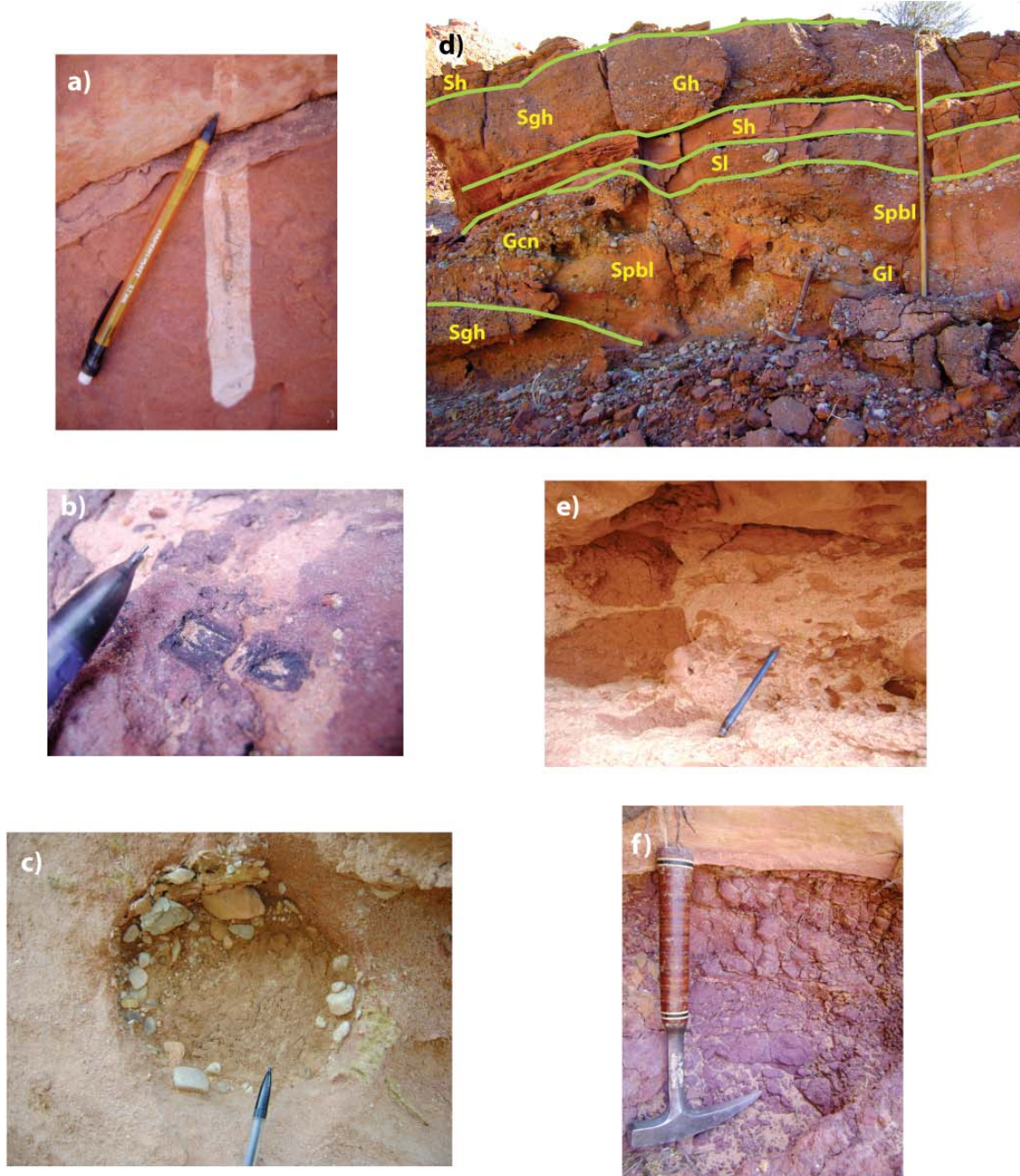


Figure 4.30: a) Burrow just below an iron-stained bedding plane; b) wood fragment exposed on an iron-stained surface; c) muddy intraclast encased in low-angle laminated sandstone. Pebbles on the outer surface indicate that this clast wasn't fully lithified and was probably rolling along as bedload. d) Succession of pebbly sandstones and well-organized conglomerates; e) matrix-supported intraclast conglomerate with fine-grained, angular sandstone framework clasts with a very fine-grained, moderately sorted matrix; and f) massive mudstone overlain by a massive sandstone. Hammer is 32 cm and pencil is 15 cm for scale.

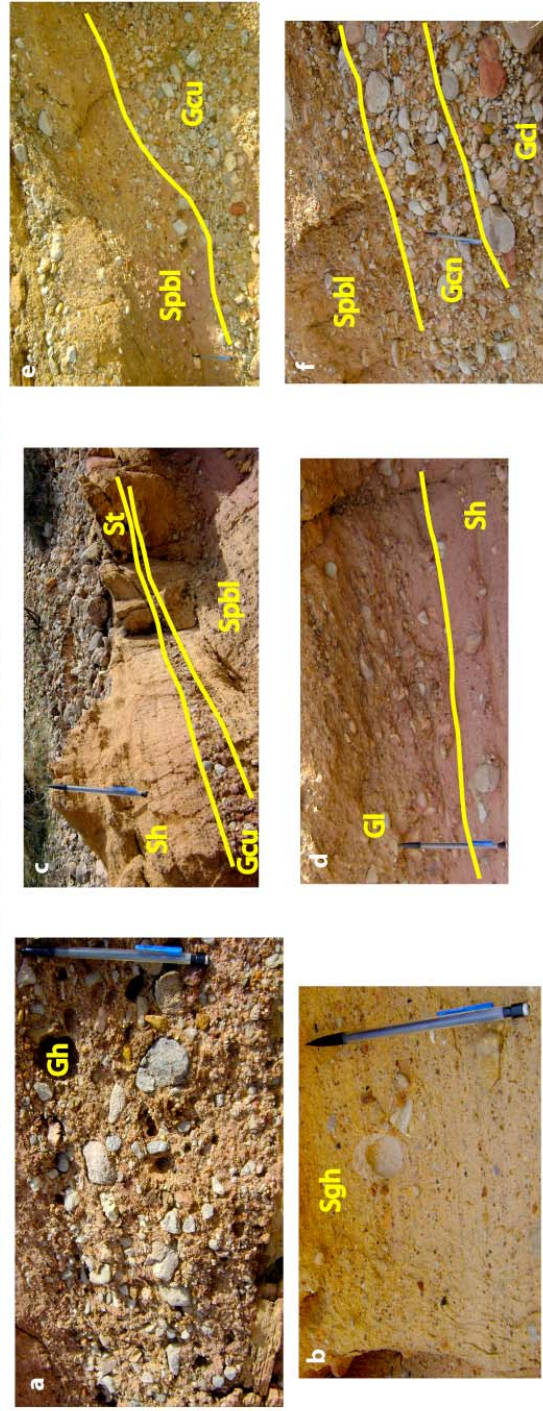
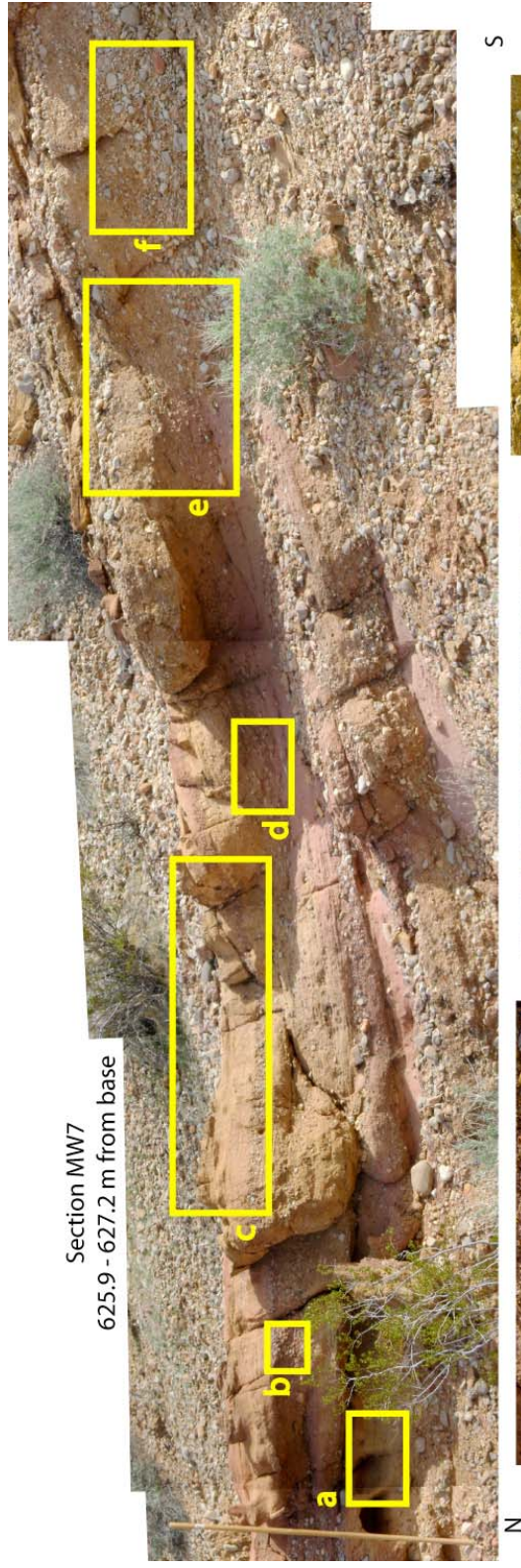


Figure 4.31: Mosaic showing braided stream interbedded sandstones and well-sorted and organized conglomerates. Note the uniform framework clast sizes of granule to pebbles and the continuity of beds relative to facies assemblage A. Jake staff is 1.5 meters and pencil is 15 cm for scale.

Interpretation: The texture, sedimentary structures, geometry and horizontal and vertical facies successions in assemblage B record deposition within a high-energy sandy braided fluvial system (Rust, 1978; Miall, 1978). The fact that Sh units typically contain aligned granules and pebbles (Sgh and Spb) and bound Gh beds favors an interpretation of deposition by upper flow regime fluid gravity flow (Harms & Fahnestock, 1965; Smith, 1986). St units, interpreted to be the result of 3D dune deposition in an active channel (Miall, 1978; Walker & Cant, 1979) also occur in concert with Sh, providing further evidence of upper flow regime conditions. The alternating vertical sequence of these units with both Gh and well-organized Gcu /Gcn units suggests sand accumulation around and above gravelly longitudinal bars due to a decrease in water depth and/or flow velocity (Rust, 1978).

Sm beds are often considered to be the result of high sediment concentration and rapid deposition, bioturbation, and/or liquefaction. Therefore, deposition by fluid or sediment gravity flows is often ambiguous. In this assemblage however, Sm deposits often grade both vertically and horizontally to Sh, contain granule to pebble pockets, and are associated with Gcn and Gh, suggesting traction transport by fluid gravity flows (Nemec & Steel, 1984). With major iron-stained surfaces, burrows, and organic matter, Sb show that conditions in this environment were suitable for life.

Gcu units with a lack of outsized clasts are interpreted to be the result of rapid deposition and suppressed turbulence in hyperconcentrated flows (Smith,

1986). The lack of grading in these beds indicate grain-to-grain interaction was minimal (Pierson & Costa, 1987). Given that these deposits are much coarser-grained than the encasing sandstones, they were probably in motion during maximum flow stages (Hein & Walker, 1977). The occurrence of Gh and Gcn point toward fluid gravity flow processes building gravelly longitudinal bars in braided streams (Smith, 1970; Rust, 1972; Boothroyd & Ashley, 1975; Miall, 1977). The horizontal size sorting indicates selective particle deposition by flow velocity (Pierson & Costa, 1987), with gravel deposited during supercritical flow and subsequent sand infiltration during waning stages (Miall, 1978; Rust, 1978, Nemec & Steel, 1984). Less common Gt and Gl also indicate upper flow regime conditions with actively migrating dunes and the filling of channel lows, respectively. Gcu, Gcn, Gcu and Gh occupying stringers and lenses near the base of sandstone units are interpreted as lag deposits occupying scours during maximum flow velocity (Harms & Fahnestock, 1965). The occurrence of intraclast conglomerates indicate erosion, mobilization and proximal deposition before disintegration of semi-consolidated particles.

Siltstone and mudstone (Fm, Fb and Fl) beds are interpreted to represent deposition of fine material by suspension during waning fluid flow on floodplains, bar crests or inactive channels (Miall, 1977). The dearth of these deposits is most likely due to the lack of mud in the source area. However, the association of these deposits with bioturbated units, occasional trace fossils and randomly

oriented slickensides indicates prolonged exposure and reworking by biogenic and pedogenic processes.

The vertical and horizontal arrangement of lithofacies, sedimentary structures and fossils indicate deposition processes of a braided fluvial system. Sheetflood-dominated alluvial fan deposition, which does occur in the White Member (Slaugenhoe & Schmitt, 2000; Aschoff & Schmitt, 2008), is ruled out for this sequence on the basis of: 1) abundant angle of repose cross-bedding and bedsets, 2) evidence of scouring, and 3) the lack of vertically stacked, alternating successions of well-sorted conglomerates overlain/interstratified with laminated granular sandstone beds. These “sheetflood couplets” are prevalent in both modern (Blair, 2000; Blair & McPherson, 1994b) and ancient (Nichols & Hirst, 1998; Aschoff & Schmitt, 2008) sheetflood-dominated fan sequences, but do not occur in Red Member assemblages of this study.

Facies Assemblage C: Interfingering Alluvial Fan-Fluvial Systems

Description: Facies assemblage C spans approximately 140 meters between assemblages A and B (Appendix C: Fig. C.4). This association is composed of predominately 0.1 to 2.6 meter thick sandstones and well-organized conglomerate beds that very much resemble those of assemblage B. However, sporadic clast-supported, massive ungraded, cobble- to boulder-dominated conglomerates (Gcu) are present. These poorly-sorted and organized beds range from 0.2 to 0.7 meters thick and display textural inversion—with friable

subrounded to rounded sandstone cobbles and boulders interspersed with granule to pebble-sized, subangular to subrounded carbonate clasts (Fig. 4.32). Contacts with underlying and overlying units are generally depositional and abrupt, respectively. These anomalous beds are mostly wedge-shaped and tend to thicken and thin abruptly along strike and dip.

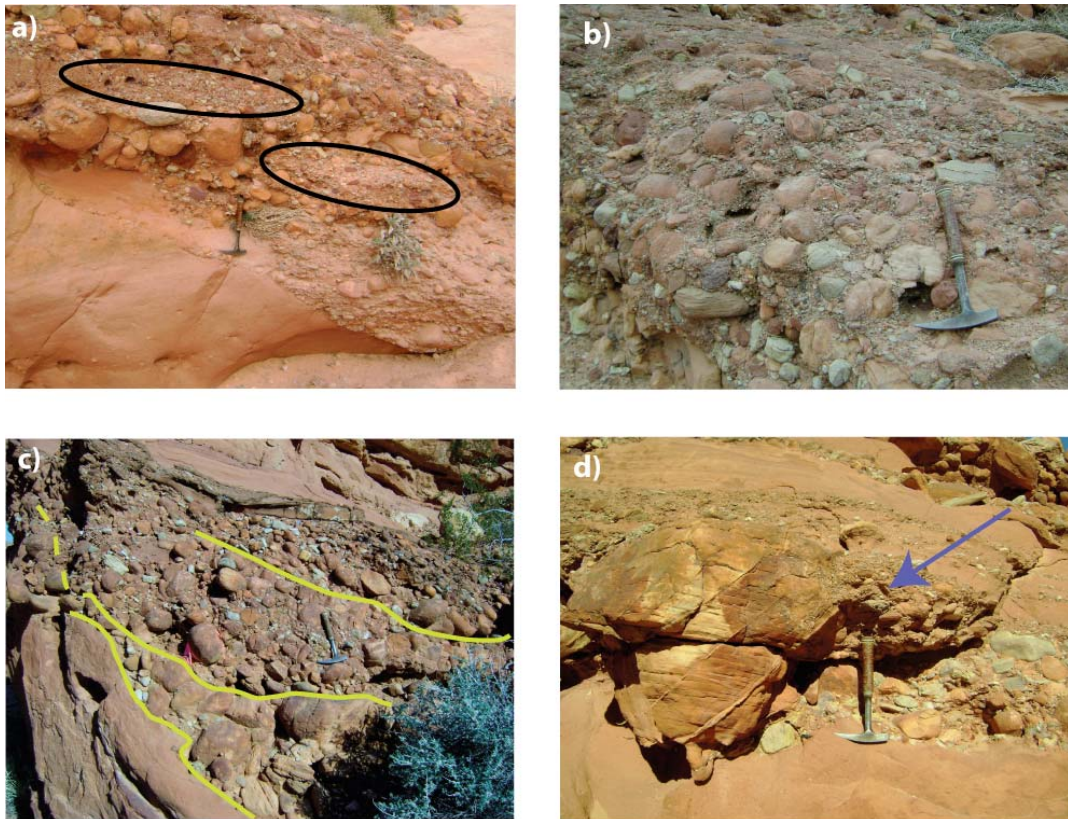


Figure 4.32: Cobble to boulder, massive ungraded conglomerates showing textural inversion. a) Massive, ungraded to inversely graded conglomerates with pebble- to cobble-sized sandstone framework clasts surrounded by granule- to small pebble-sized carbonate clasts. Ovals outline pockets of well-organized small pebble conglomerate. b) Cobble to pebble, massive ungraded conglomerate with ~30% granules surrounding framework grains. This unit exhibits both cobble-sized subrounded sandstone and subangular carbonate clasts, suggesting that both were derived from a proximal source. c) Pebble to cobble massive ungraded bed with abundant carbonate pebbles overlying a massive, ungraded boulder conglomerate that largely lacks carbonate clasts. d) Sandstone boulder from a debris flow deposit, overlying soft sediment deformed sandstone and bounded above by horizontally stratified granule conglomerate and granular sandstone. Arrow is pointing toward pocket of crudely stratified pebble conglomerate, a result of sediment and water diversion around the boulder. Hammer is 32 cm for scale.

Interpretation: As stated earlier, poorly organized coarse-grained strata (Gcu) suggests en masse deposition by sediment gravity flows (Nemec & Steel, 1984). However, the profuse textural inversion and better sorting of granule- to pebble-sized clasts in these coarse-grained units points toward winnowing by fluid gravity flows. The presence of anomalous cobble- to boulder-, poorly sorted, laterally discontinuous conglomerates within finer-grained, well-sorted, laterally continuous sandstones points toward the interaction of neighboring depositional environments (Fig. 4.33).

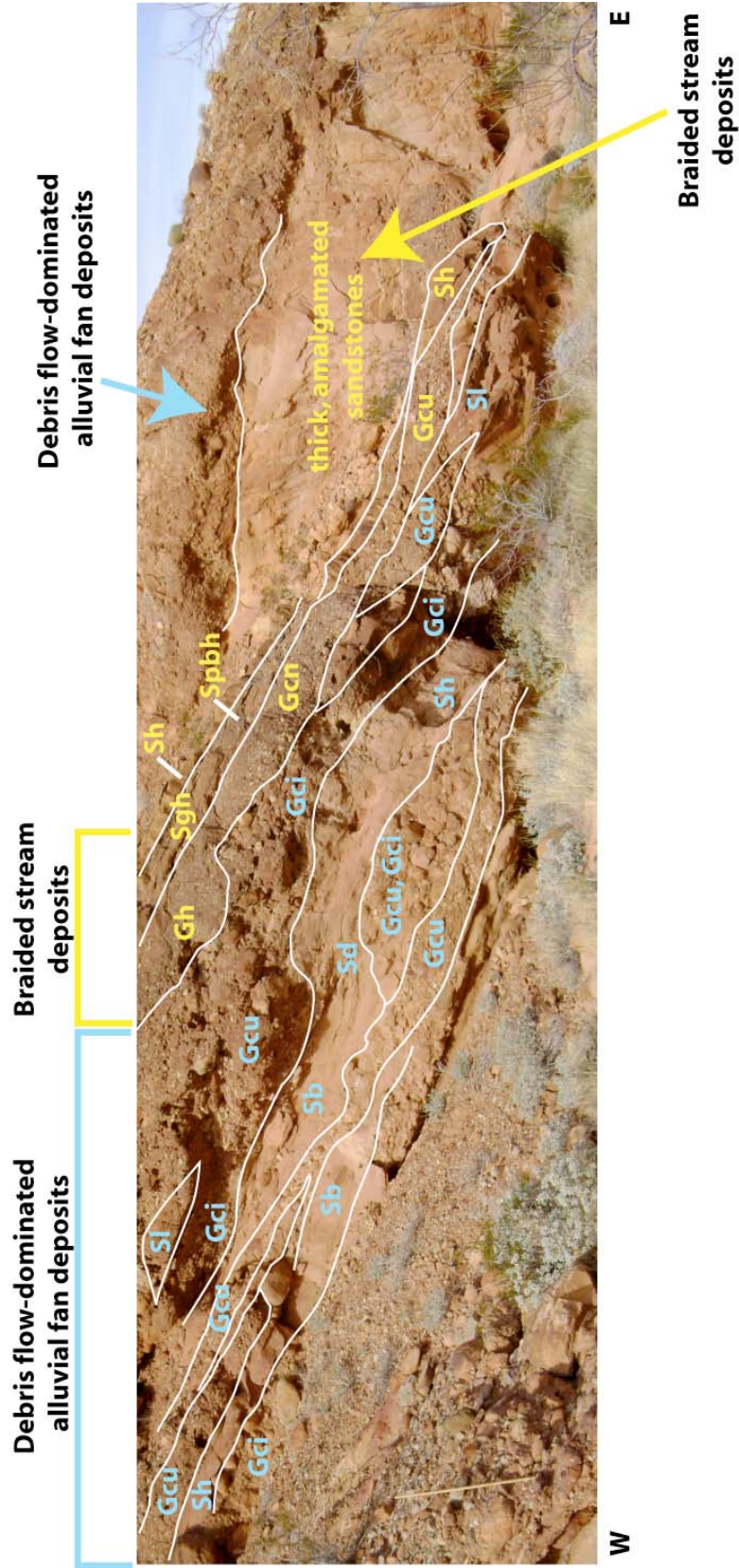


Figure 4.33: Dip view of transition zone between contiguous alluvial fan and braided stream depositional environments. Debris flow-dominated alluvial fan deposits are more coarse-grained, unorganized and laterally variable relative to fluvial deposits. Jake staff is 1.5 meters for scale.

Red Member Provenance

Composition:

Conglomerates of the Red Member are composed of detritus derived from Pennsylvanian to Cretaceous units exposed in the hanging wall anticline of the Willow Tank thrust. A trend of progressively decreasing siliciclastic and increasing carbonate framework clasts upsection represents a reverse depositional sequence created by the sequential unroofing and erosion of the frontal anticline (Fig. 4.34). This reverse depositional sequence is attributed to the identification of distinct strata in the source section—namely the dominantly Mesozoic siliciclastic and Paleozoic carbonate units (Fig. 4.35).

Clasts in clast count (CC) 1 through 5 are dominantly: 1) well-sorted, well-rounded, medium-grained sandstones of the Jurassic Aztec, 2) laminated siltstones to fine sandstones of the Jurassic Kayenta and Moenave Formations,

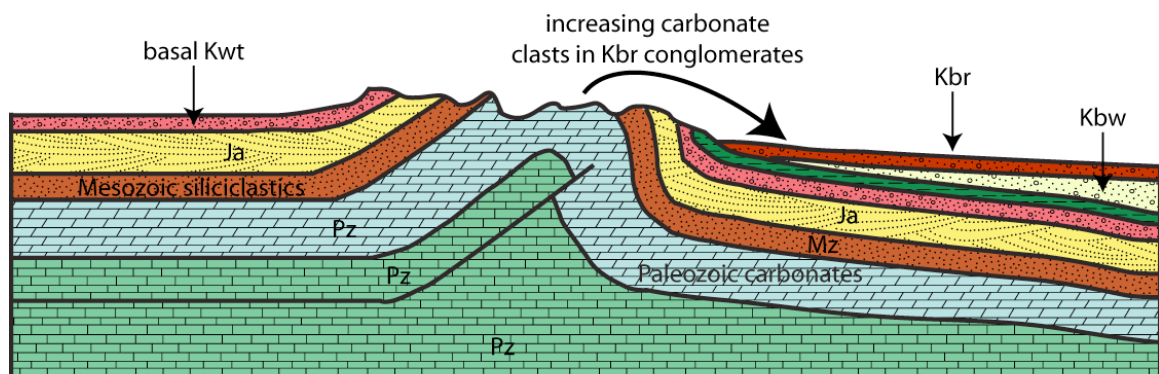


Figure 4.34: Diagram of the Willow Tank blind thrust-cored fault propagation fold. The increasing amount of carbonate framework clasts upsection in the Red Member of the Baseline Formation (Kbr) is proposed to be a result of erosion through the Mesozoic section and exposure of Paleozoic carbonate strata.

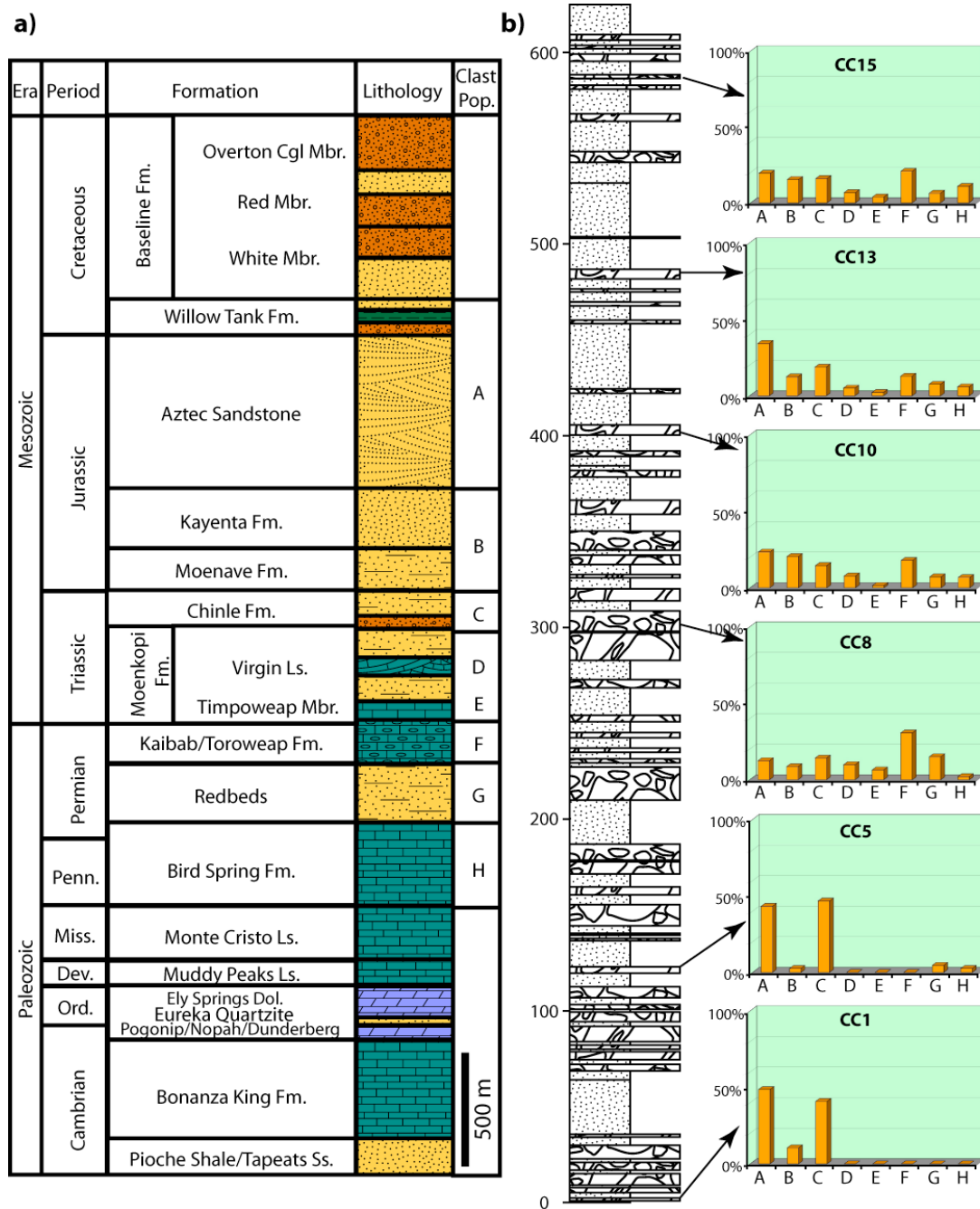


Figure 4.35: a) Stratigraphic section showing source units and clast populations assigned to point counts. b) Red Member stratigraphic section and locations of conglomerate framework clast counts (letters A - H correspond to units shown in part (a)). Note the decrease in abundance of Mesozoic siliciclastics and increase in Paleozoic carbonates clasts upsection.

and 3) sandstones, petrified wood and chert pebble conglomerate of the Triassic Chinle Formation (Fig. 4.36).

CC 6 through 10 show an overall decrease in Mesozoic strata, with the exception of cross-bedded to laminated silty limestones and granular limestone conglomerates of the Triassic Moenkopi Formation, and an increase in: 1) cherty limestone of the Permian Kaibab and Toroweap Formations, 2) carbonate-cemented siltstones of the Permian redbeds, and 3) fossiliferous wackestone to packstones of the Pennsylvanian Bird Spring Formation (Fig. 4.37).

An influx of Jurassic Aztec sandstone in CC 12-14 can be attributed to exposure and recycling of White Member conglomerate units and/or another episode of Jurassic Aztec exposure and erosion in the catchment. These conglomerates occur in the zone of intermingling between adjacent depositional environments and exhibit textural inversion between siliciclastic and carbonate clasts. An even distribution of Paleozoic and Mesozoic clasts is seen in CC 15, which is interpreted to be fluvial in origin (Fig. 4.38).

Siliciclastic clasts are generally subrounded to rounded, equidimensional, and range in size from pebble to boulder. Carbonate clasts are dominantly subangular to subrounded, oblate to prolate and are usually granule to cobble in size. Rounded to well-rounded quartzite and chert pebbles are common in conglomerates throughout the stratigraphic section. The matrix of the

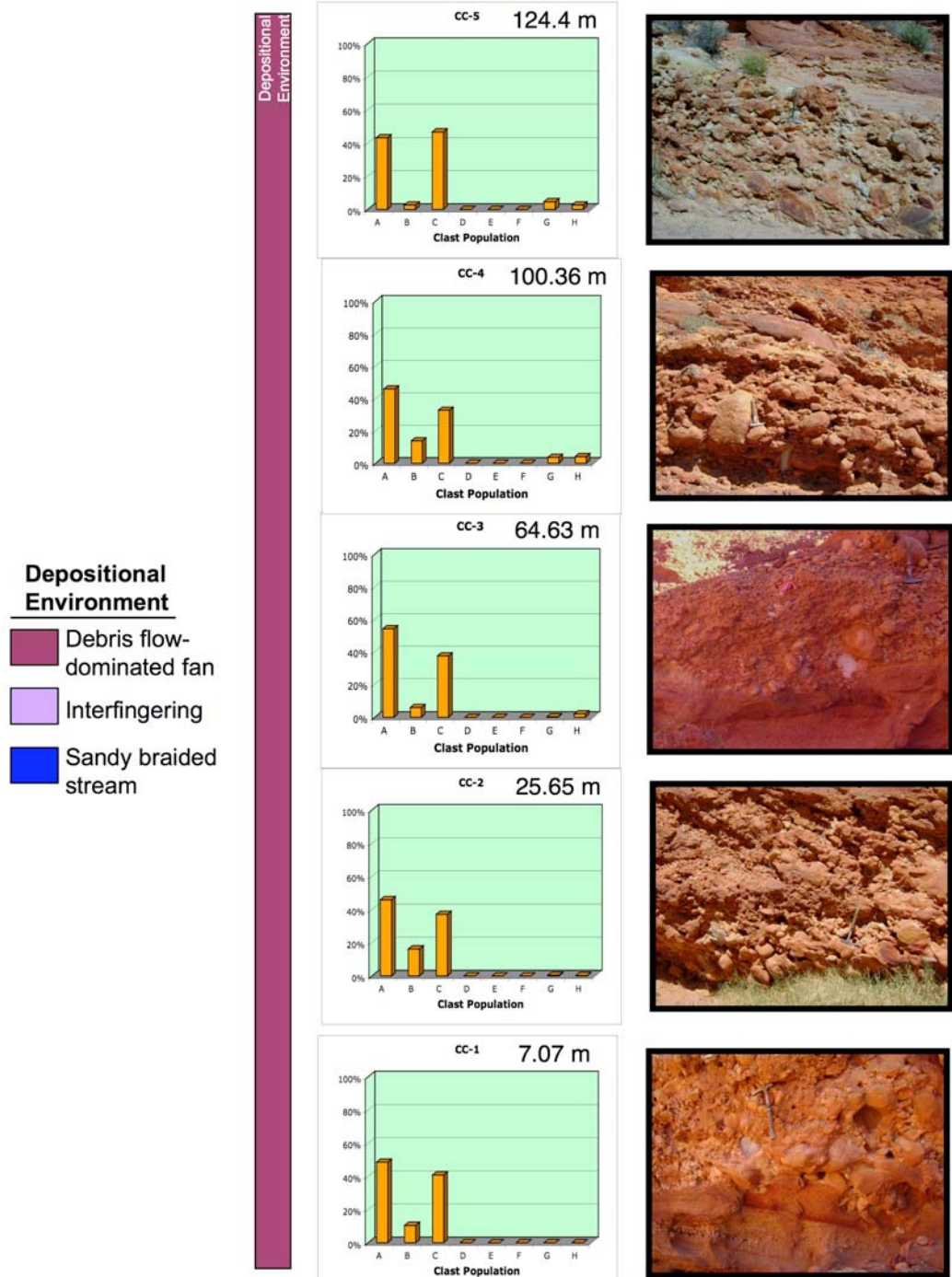


Figure 4.36: Clast counts on Red Member conglomerates. These counts show dominantly Mesozoic siliciclastic framework clasts. Clast population letters on the x-axis of the histograms are explained in Figure 4.35 and Table B.2.

Depositional Environment

- Debris flow-dominated fan
- Interfingering
- Sandy braided stream

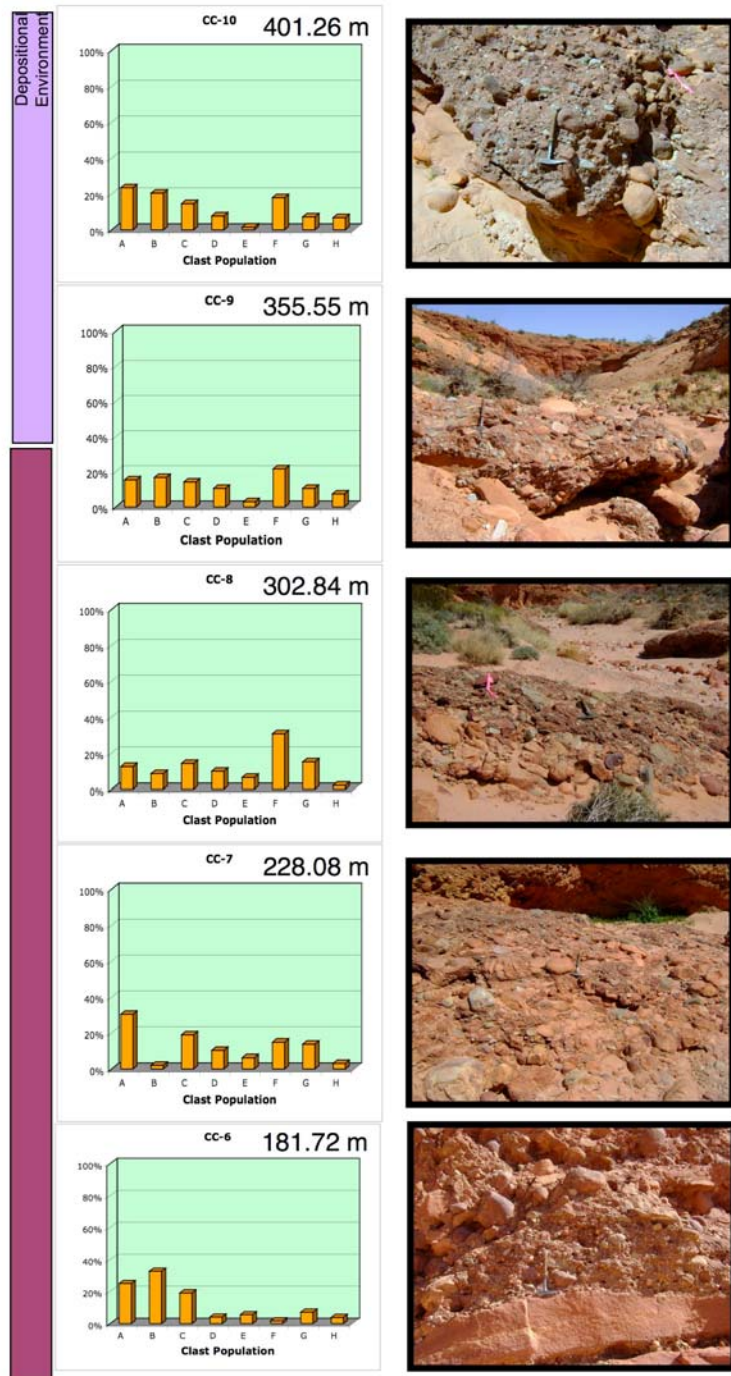


Figure 4.37: Clast counts on Red Member conglomerates. These counts show decreasing amounts of Mesozoic siliciclastics and increasing carbonates upsection. Clast population letters on the x-axis of the histograms are explained in Figure 4.35 and Table B.2.

Depositional Environment

- Debris flow-dominated fan
- Interfingering
- Sandy braided stream

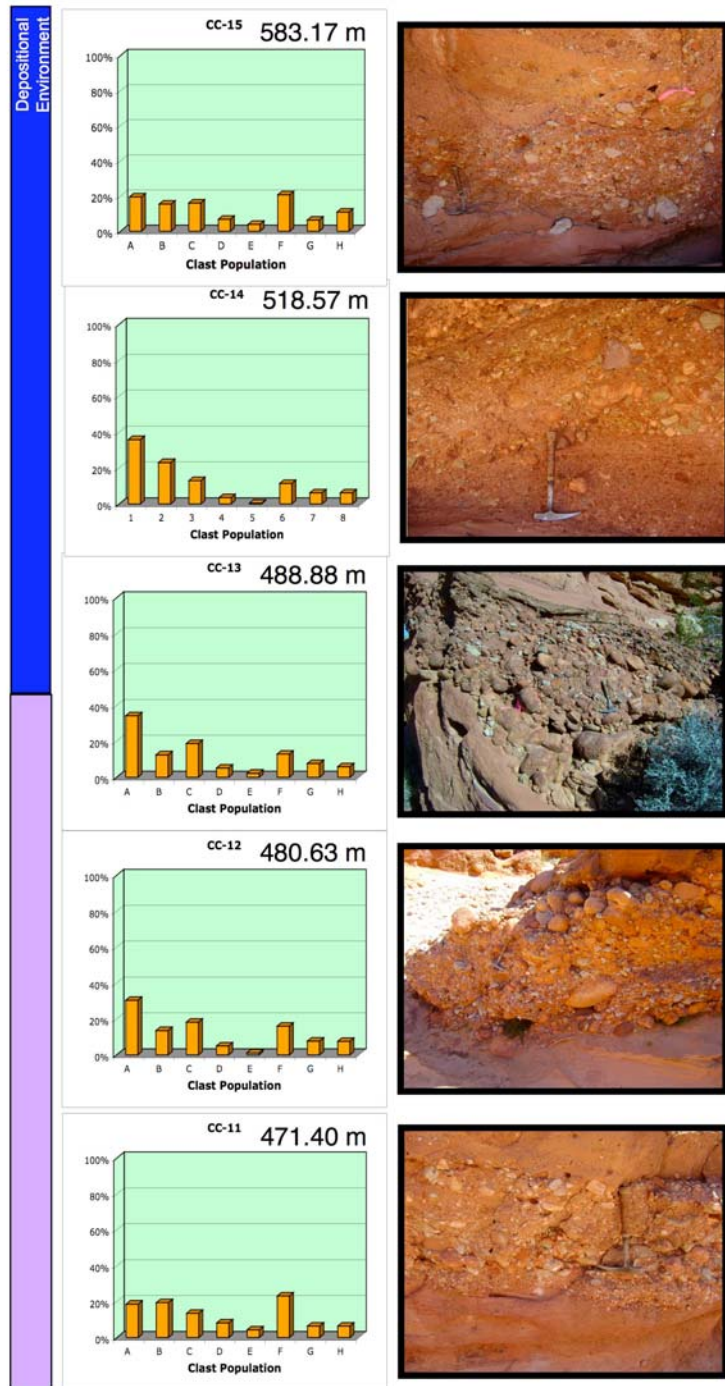


Figure 4.38: Clast counts on Red Member conglomerates. These counts still show a significant amount of Paleozoic carbonates, with an anomalous influx of Jurassic Aztec sandstone seen in CC 12-14 (discussed in text). Clast population letters on the x-axis of the histograms are explained in Figure 4.35 and Table B.2.

conglomerate and sandstones of the Red Member is composed of upper fine to medium sand-sized, well-rounded, well-sorted monocrystalline quartz derived from the Jurassic Aztec sandstone. The matrix completely lacks silt- and clay-sized particles.

Paleoflow:

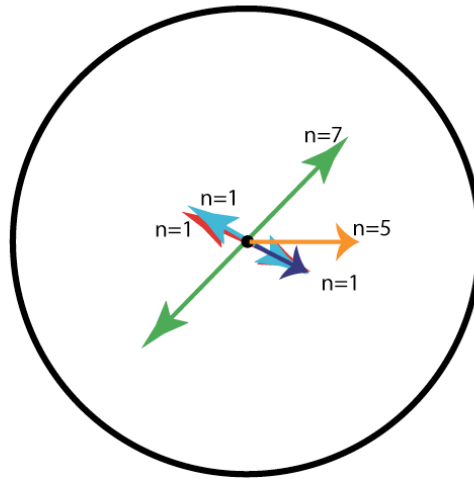
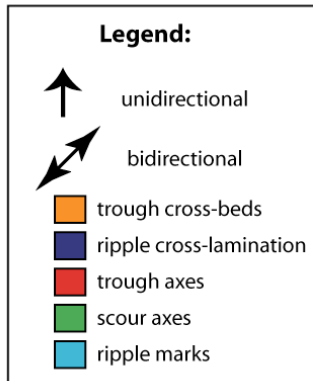
A total of 51 paleoflow measurements were collected on both unidirectional (trough cross-bedding, ripple cross-lamination and imbricated clasts) and bidirectional (trough cross-bed axes, scour axes, and ripple marks) structures (Fig. 4.39, Appendix B: Table B.4). Although the number of paleoflow measurements is not statistically significant, they do provide a general flow direction for this member that is important in provenance interpretation.

Unidirectional paleoflow averages an eastward direction for both alluvial fan and braided stream environments, while bidirectional structures exhibit a NE-SW trend for the alluvial fan environment and NW-SE direction for braided stream system (Fig. 4.39). Fillmore (1991, 1993) proposed mean vectors of 65° and 42° for the Baseline Sandstone and correlative Iron Springs Formation in Utah, respectively. In addition to framework clast composition, these transport directions support a western source area.

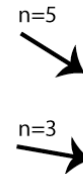
Source and Discussion:

The Red Member conglomerates of the Baseline Formation were derived from source rocks exposed in the hanging wall of the Willow Tank blind thrust-

a) Debris flow-dominated alluvial fan



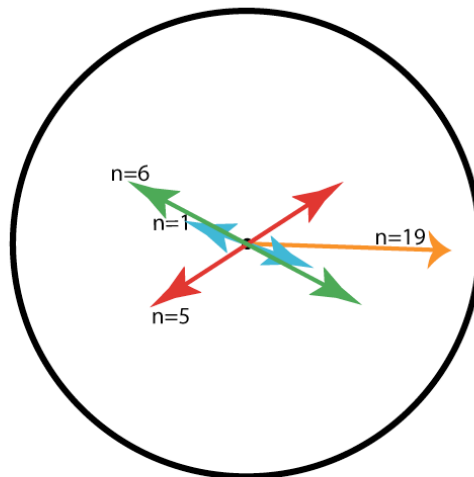
IMBRICATION:



**b) Sandy braided fluvial system
(includes interfingering zone)**

c)

Weighted Averages	
Unidirectional:	
Alluvial fan	98.63°
Braided stream	99.32°
Bidirectional:	
Alluvial fan	61°/241°
Braided stream	93°/273°



IMBRICATION:

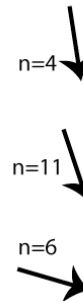


Figure 4.39: Paleocurrent data for debris flow-dominated fan (a) and sandy braided stream (b) environments. (c) shows the weighted averages of both unidirectional and bidirectional data. Even though these data are not statistically significant, the numbers show a general east to southeast paleoflow trend.

cored anticline (Figs. 4.40 & 4.41). Evidence supporting this is the: 1) framework clast composition, 2) organization, grain size and clast types, 3) presence of an unroofing sequence, 4) interpreted Red Member depositional environments and paleoflow measurements from both this study and correlative units in

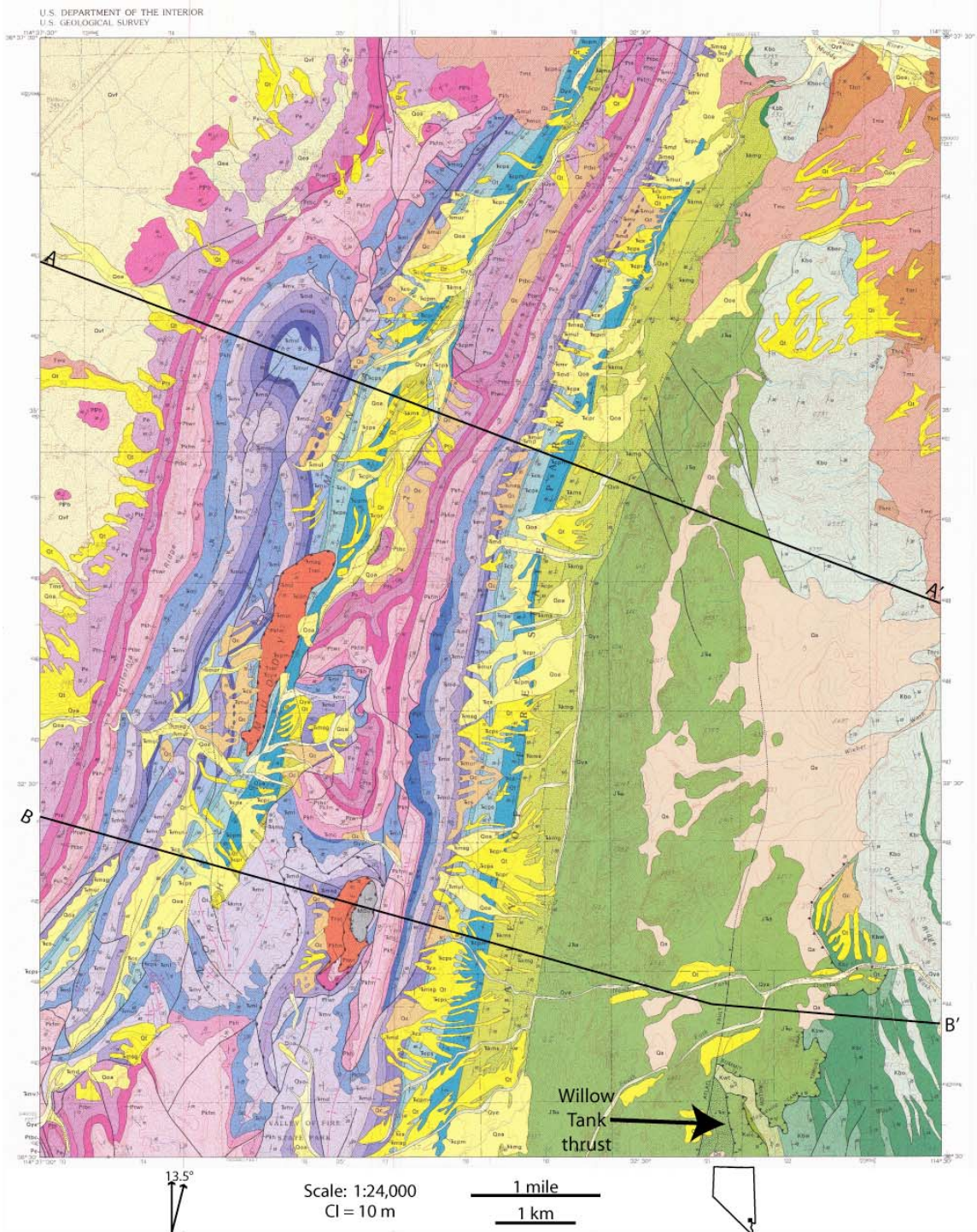


Figure 4.40: Geologic map of Weiser Ridge (Bohannon, 1992), a prominent feature in the North Muddy Mountains northwest of the field area. The Weiser syncline formed as a result of Muddy Mountain thrust propagation, which overrode the syncline. The strata that outcrop on this structure represent the Willow Tank hanging wall source area that contributed detritus to alluvial systems of the Cretaceous Willow Tank and Baseline Formations. Green=Jurassic/Cretaceous, Blue/Purple=Triassic, Pink=Permian/Pennsylvanian. Cross sections A-A' and B-B' are shown in Figure 4.41.

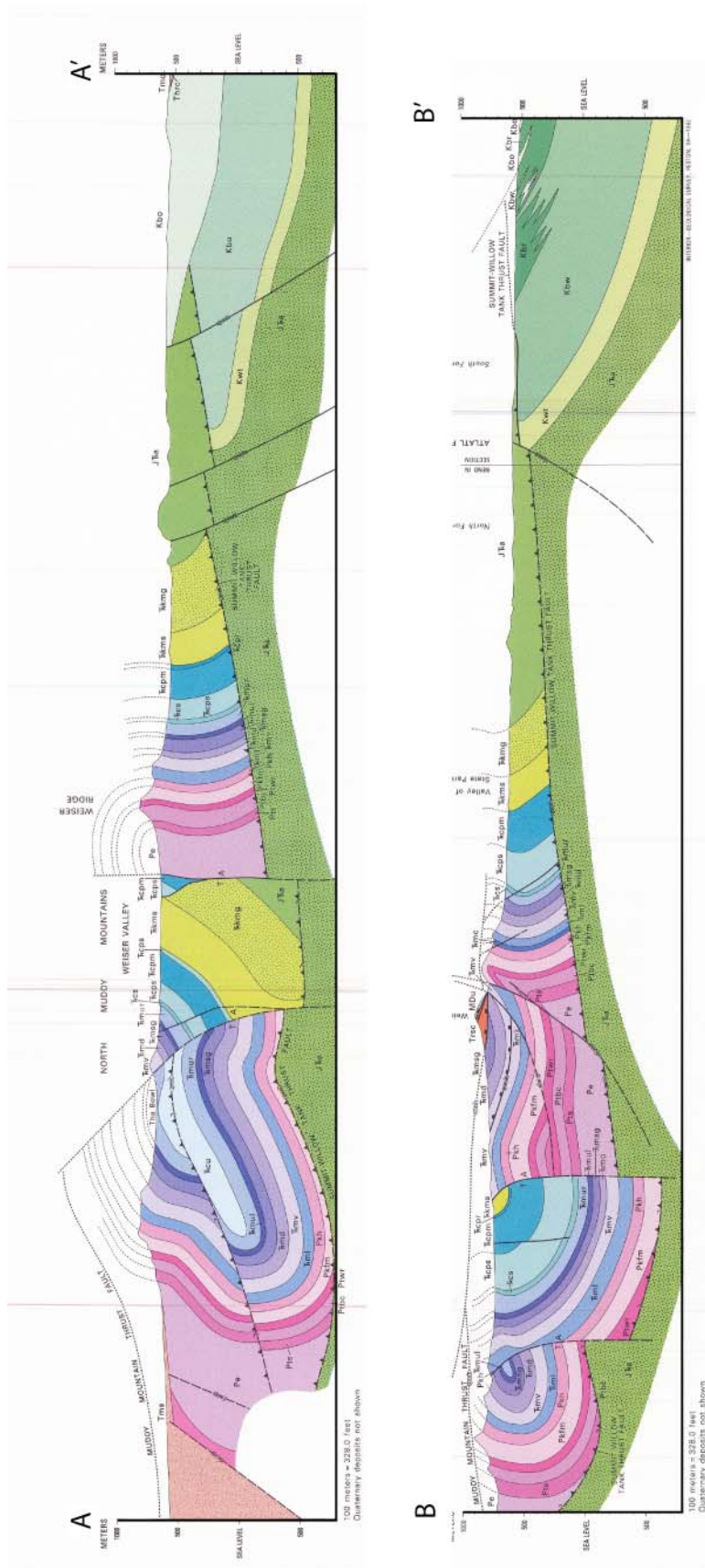


Figure 4.41: Cross-sections from Fig. 4.40. The oldest unit that is exposed in these sections is the Esplanade sandstone of the Permian Toroweap Formation. These cross-sections represent the hanging wall of the Willow Tank thrust, which was overridden by out-of-sequence movement on the Muddy Mountain thrust, post 93.1 $\pm$ 3.4 Ma (Carpenter, 1989). Green=Jurassic/Cretaceous, Blue/Purple=Triassic, Pink=Permian/Pennsylvanian. Weiser Ridge Quadrangle by Bohannon, 1992.

southwestern Utah (Fillmore, 1991,1993), and 5) supporting evidence from previous studies on the Willow Tank Formation (Reese, 1989) and White Member (Schmitt & Aschoff, 2003; Aschoff & Schmitt, 2008).

1) The composition of framework clasts closely matches strata exposed to the west of the field area location. Strata from the Pennsylvanian Bird Spring limestone to the Jurassic Aztec sandstone are exposed in the Weiser Ridge syncline, a fold comprising the hanging wall of the Willow Tank thrust (Figs. 4.40 & 4.41).

2) The abundance of poorly-organized and sorted, massive ungraded, pebble to boulder conglomerates dominated by subrounded to rounded friable sandstone clasts point toward a proximal source area. These medium-grained, well-rounded and sorted sandstone clasts contain annealed, conjugate fractures that do not extend into the surrounding matrix, proof of a Jurassic Aztec sandstone origin. The clast suite in conglomerates of fluvial origin contain no clasts older than Pennsylvanian, also suggesting a nearby source. Finally, the correlative Iron Springs Formation of southern Utah exhibits comparable strata and compositional trends proposed to be derived from the same source (Fillmore, 1991, 1993).

3) Excellent preservation and distinct source strata have contributed to an exceptional unroofing sequence. The increase in carbonates and decrease in siliciclastics upsection in these proximal conglomerates suggest continued erosion through the Mesozoic section and exposure of Paleozoic units on the

hanging wall of the Willow Tank thrust allochthon (Figs. 4.42 & 4.43). The anomalous occurrence of quartzite clasts, which are not present in the proposed source section, is interpreted to be due to recycling of the Willow Tank conglomerates and White Member conglomerates.

4) The change from poorly-organized, massive ungraded, pebble to boulder, siliciclastic-dominated conglomerates to well-organized, graded to stratified, pebble to granule conglomerates with increasing amount of carbonates upsection records the transition from debris flow-dominated alluvial fan deposition to that of a braided stream (Figs. 4.20 & 4.26). Interfingering of these adjacent environments is supported by: a) coarse, poorly-organized conglomerates in well-sorted, well-rounded, laterally continuous sandstone packages interpreted to be deposited in a fluvial system (Fig. 4.33), and b) textural inversion of framework clasts (i.e. sandstone boulders intermixed with carbonate pebbles)(Fig. 4.32). Paleoflow measurements, although not statistically significant, suggest a general eastward transport direction (Fig. 4.39). East to northeast paleoflow of the Baseline Sandstone and the correlative Iron Springs Formation in southern Utah was noted by Fillmore (1993).

5) Previous structural, sedimentologic and stratigraphic studies (Longwell, 1949; Bohannon, 1983b, Schmitt & Kohout, 1986; Carpenter, 1989; Reese, 1989; Schmitt & Aschoff, 2003; Aschoff & Schmitt, 2008), outline the sequence of thrusting and confirm the significance of the growth of the frontal blind thrust-

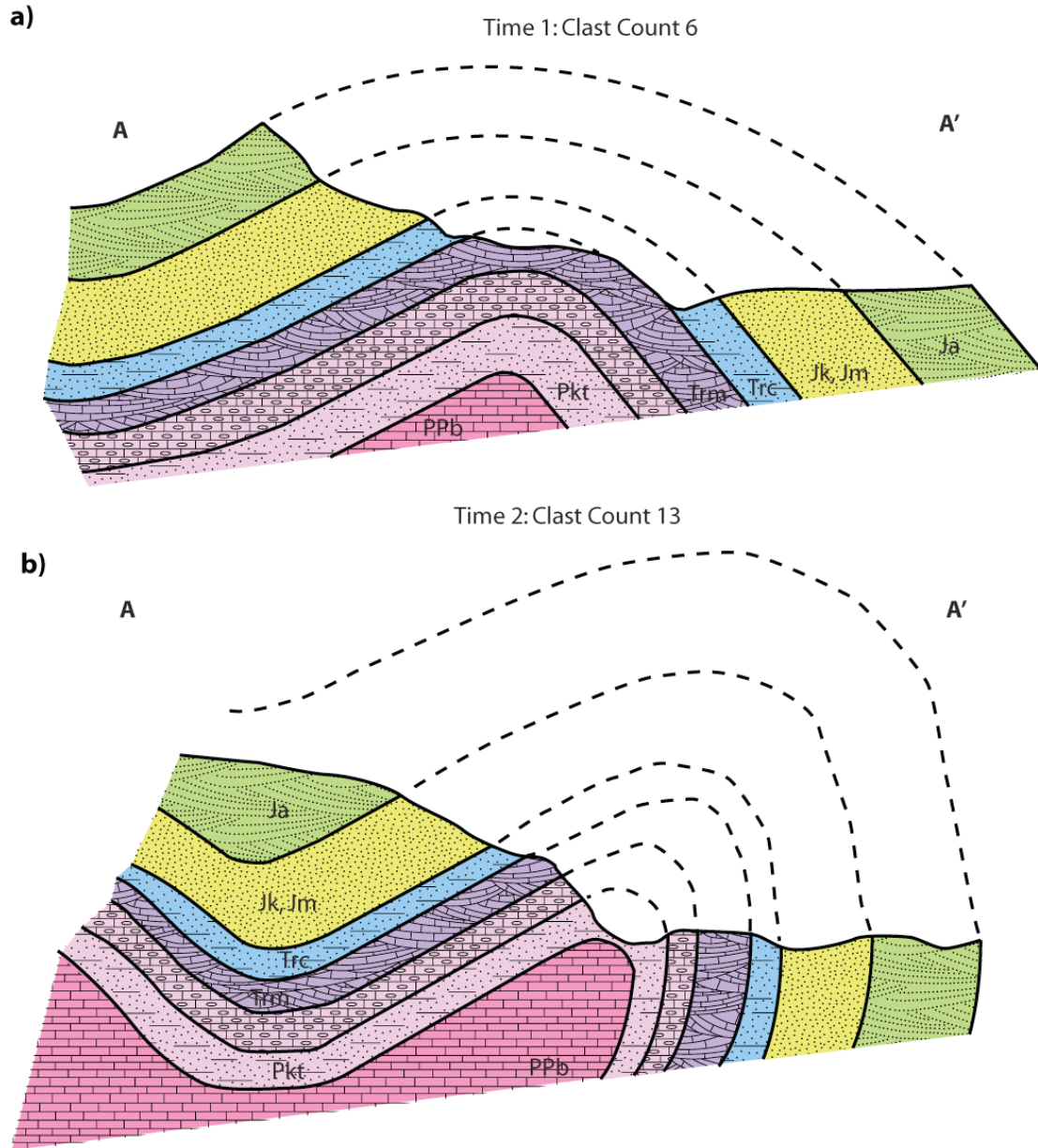


Figure 4.42: Willow Tank thrust hanging wall anticline restoration based on cross section A-A' (Fig. 4.41, Bohannon, 1992). Due to structural complexity by normal and strike-slip faulting, folds are not drawn to scale. a) Reconstruction showing what units were exposed and eroded at the time of clast count 6 (CC6). b) Reconstruction showing what units were exposed and eroded at the time of CC13. Clast count histograms are shown in Figs. 4.37 & 4.38. Note that PPb is present as clasts in CC13, but is not shown in outcrop from A-A'. Also, the Permian Redbeds are not included in this map, but crop out to the south in the Muddy Mountains. Ja=Jurassic Aztec Sandstone; Jk, Jm=Jurassic Kayenta & Moenave; Trc=Triassic Chinle; Trm=Triassic Moenkopi; Pkt=Permian Kaibab/Toroweap, PPb=Pennsylvanian Bird Spring.

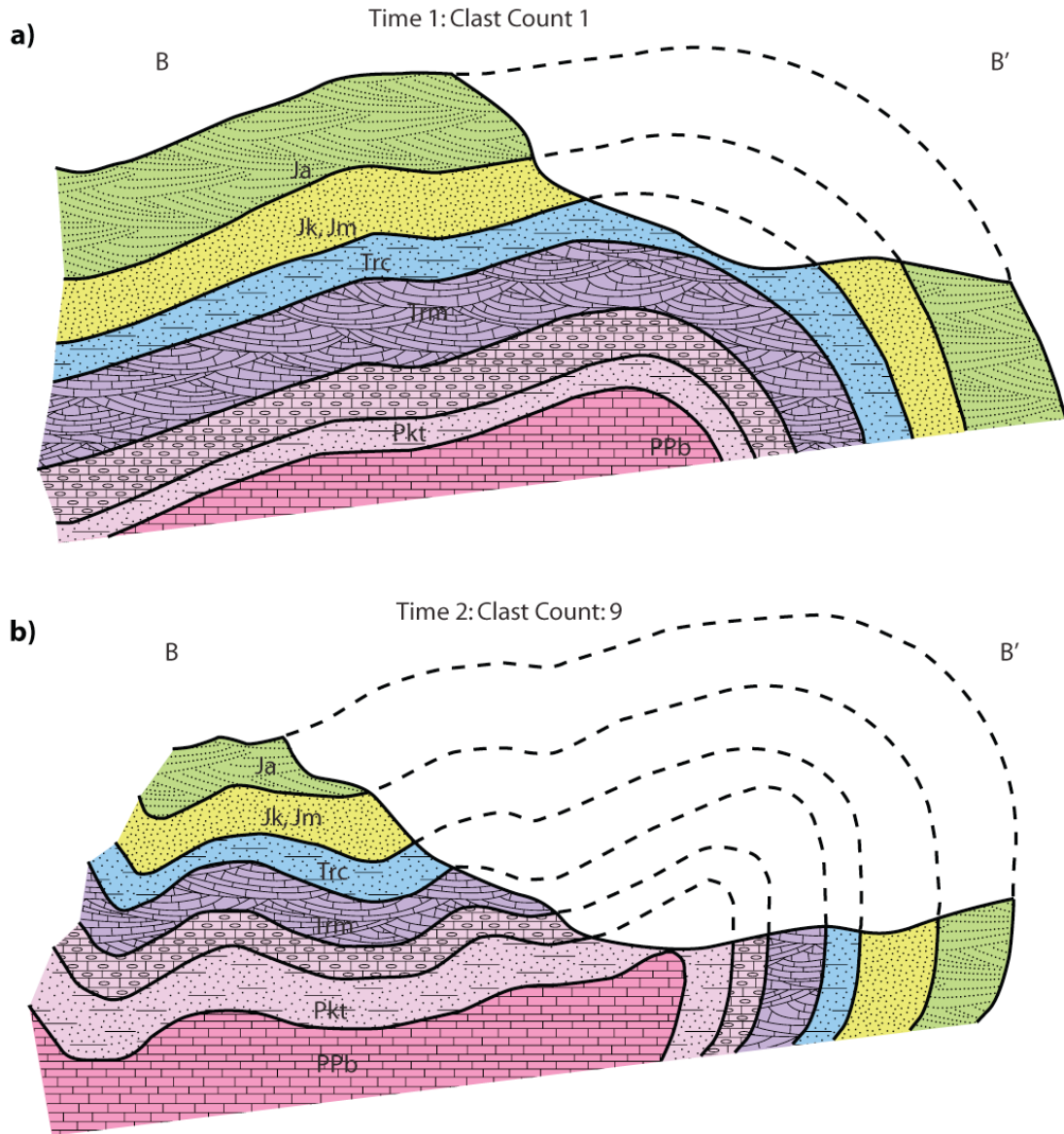


Figure 4.43: Willow Tank thrust hanging wall anticline restoration based on cross section B-B' (Fig. 4.41, Bohannon, 1992). Due to structural complexity by normal and strike-slip faulting, folds are not drawn to scale. a) Reconstruction showing what units were exposed and eroded at the time of clast count 1 (CC1). b) Reconstruction showing what units were exposed and eroded at the time of CC9. Clast count histograms are shown in Figs. 4.36 & 4.37. Note that PPb is present as clasts in CC9, but is not shown in outcrop from B-B'. Also, the Permian Redbeds are not included in this map, but crop out to the south in the Muddy Mountains. Ja=Jurassic Aztec Sandstone; Jk, Jm=Jurassic Kayenta & Moenave; Trc=Triassic Chinle; Trm=Triassic Moenkopi; Pkt=Permian Kaibab/Toroweap, PPb=Pennsylvanian Bird Spring.

cored fault propagation fold on proximal alluvial systems in the field area. A detailed synthesis is presented in the following chapter.

Given all of this supporting evidence, the most straightforward explanation is that Red Member sediment was shed synthetically from small drainage basins sourced in the Willow Tank thrust hanging wall toward the foredeep via alluvial fan and subsequent fluvial systems.

TECTONO-SEDIMENTARY EVOLUTION OF THE CRETACEOUS WEDGETOP-FOREDEEP TRANSITION ZONE

Willow Tank Formation

Basal Conglomerate

Willow Tank basal conglomerates record the beginning of foreland basin sedimentation before deformation on the frontal Willow Tank thrust in the field area (Longwell, 1949; Bohannon, 1983b; Schmitt & Kohout, 1986; Reese, 1989). The thin, sheetlike geometry, lateral extent and unconformable relationship with the Jurassic Aztec Sandstone suggest deposition before substantial subsidence occurred (Reese, 1989).

This sequence exhibits a blended clast composition and was shed synthetically via a gravelly braid-plain system draining the thrust-belt to the west (Fig. 5.1; Schmitt & Kohout, 1986; Reese, 1989). Two conglomerate petrofacies include the basal quartzite-sandstone conglomerate package from the Gass Peak allochthon and Muddy Mountain footwall, and the overlying carbonate-rich conglomerates sourced from the Arrow Canyon, Dry Lake and/or Muddy Mountain allochthon(s) (Reese, 1989; Fillmore, 1993).

The fact that this stratal package is vertical to overturned in the footwall of the Willow Tank thrust north of and in the study area indicates deposition before eastward propagation. The along-strike extent of the anticline is also outlined by this unit, which exhibits a decrease in bedding dip moving toward the south.

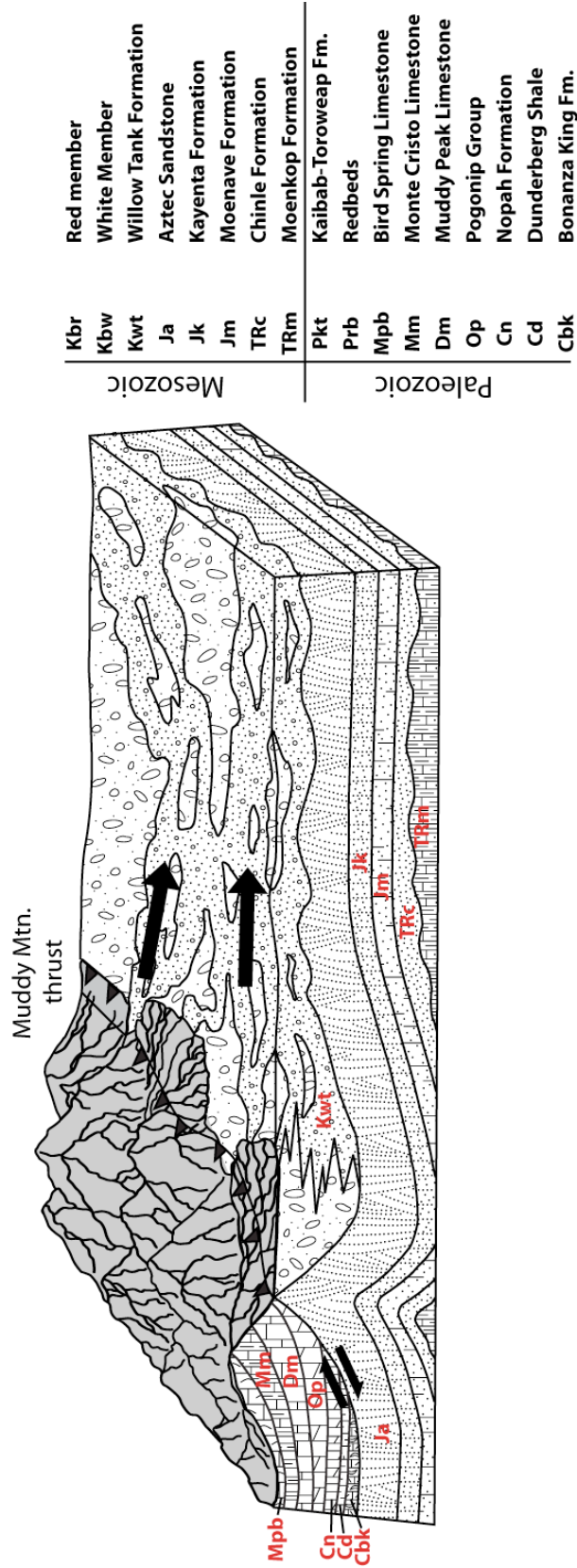


Figure 5.1: Block diagram showing Willow Tank basal conglomerate deposition, which occurred before growth of the frontal Willow Tank blind thrust-cored anticline. Detritus was transported east to southeast in gravely braided streams that tapped the thrust-belt interior. Diagram is not to scale. Stratigraphic abbreviations are listed above to the right.

Mud-dominated Succession

A dramatic change in grain size from gravel to mud marks a transition in depositional environments (from a gravelly-braided to an anastomosing fluvial system) that reflects an increase in basin subsidence (Reese, 1989; Bonde, 2008). This fine-grained sequence is given an Albian age, based on the presence of *Tempskya minor* (Ash & Read, 1976), K-Ar age dates of 98.4 and 98.6 m.y. (Fleck, 1970), and U-Pb zircon ages of 101.6 +/- 1 and 99.9 +/-2 m.y. (Troyer, 2006).

At the time this sequence was being deposited, movement on the Muddy Mountain thrust ceased and propagation of the frontal Willow Tank fault propagation fold-cored anticline initiated. An upward influx of quartz sand and appearance of well-rounded quartzite and chert pebbles in the mud-rich succession are attributed to the erosion of the Jurassic Aztec sandstone and Willow Tank basal conglomerate on the frontal fold (Fig. 4.15). This structure was responsible for the arrival of a significant amount of detritus and an increase in gradient, which caused a transition from an anastomosing to a sandy-braidplain environment. Furthermore, the growth of the anticlinal ridge caused: 1) piggyback basin formation, 2) deformation of pre-existing Willow Tank deposits, and 3) diversion of fluvial systems around the ridge (Fig. 5.2).

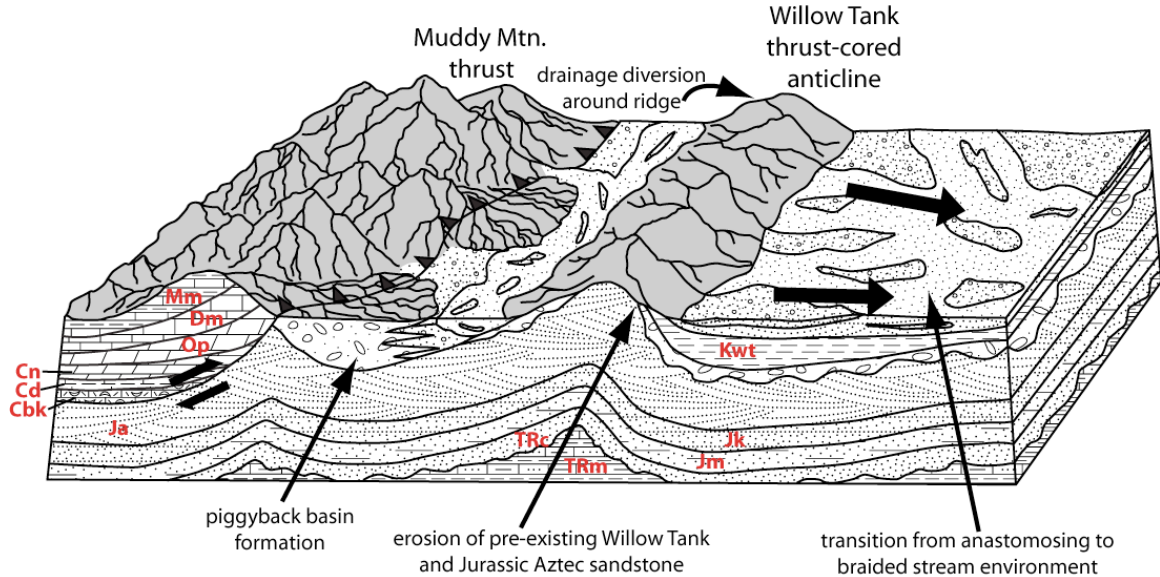


Figure 5.2: Block diagram showing Upper Willow Tank deposition, during growth of the frontal Willow Tank blind thrust-cored anticline. The mud-dominated sequence (anastomosing fluvial system) was overwhelmed with an influx of quartz sand from erosion of the Jurassic Aztec sandstone from the growing fold. Movement on the Muddy Mountain thrust has ceased by this time, and it is being passively uplifted on the hanging wall of the Willow Tank thrust. Stratigraphic abbreviations are listed in Fig. 5.1. Diagram is not drawn to scale.

White Member, Baseline Formation

Studies of the White Member show evidence of deposition contemporaneous with movement on the anticline (Fig. 4.19; Aschoff & Schmitt, 2008). The presence of growth strata and abundance of well-rounded, well-sorted quartz-rich sand throughout this member points toward continued growth and erosion of the Jurassic Aztec sandstone on the frontal fold (Fig. 5.3).

Sedimentological analyses indicate deposition in debris-flow and sheetflood-dominated alluvial fan and braided stream depositional environments (Slaughenhoop & Schmitt, 2000; Schmitt & Aschoff, 2003). Significant relief and

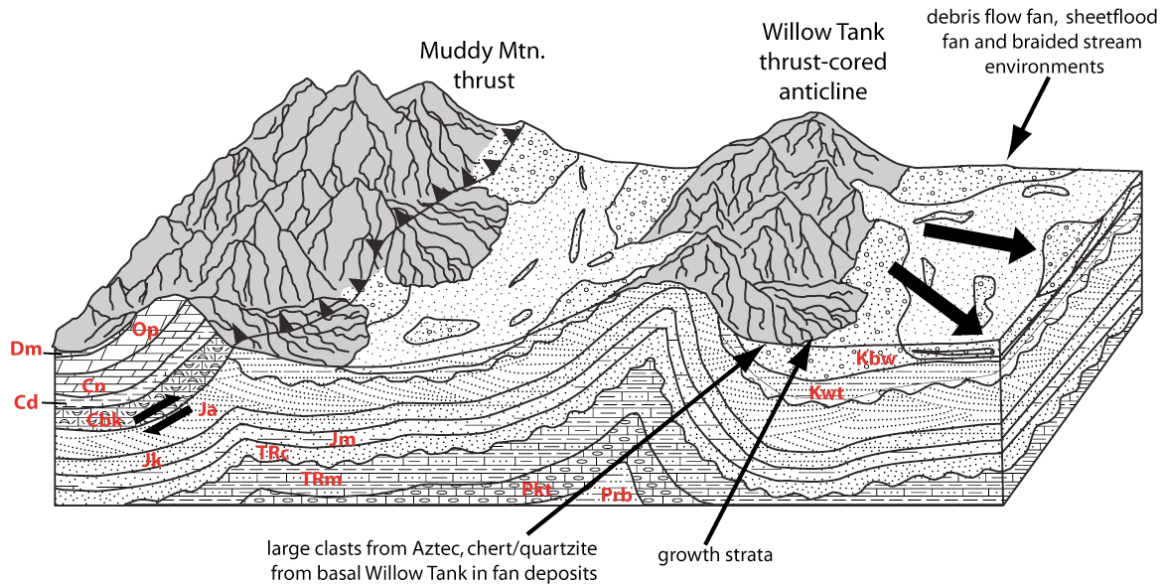


Figure 5.3: Block diagram showing White Member deposition, during further eastward propagation of the frontal Willow Tank blind thrust-cored anticline. The presence of growth strata, and lithofacies analyses and clast composition point toward deposition coeval with deformation. Stratigraphic abbreviations are listed in Fig. 5.1. Diagram is not drawn to scale.

proximal, localized deposition is interpreted due to the presence of growth strata and large Aztec clasts and quartzite/chert pebbles from recycled basal Willow Tank in poorly sorted and organized debris-flow conglomerates (Figs. 4.17 & 4.19; Aschoff & Schmitt, 2008). Fossils and K-Ar ages of 95.8 ± 3.5 m.y. and 96.9 ± 3.6 m.y. on volcanoclastic units indicate a Cenomanian age for this member (Hewett, 1936; Carpenter & Carpenter, 1987).

Red Member, Baseline Formation

Lower Red Member

The lower Red Member is characterized by an abundance of debris flow-fan conglomerates that exhibit a spectacular unroofing sequence (Fig. 4.35).

Siliciclastic clasts of Jurassic Aztec, Kayenta, Moenave, and Triassic Chinle

Formation at the base of section give way to an influx of Paleozoic carbonates moving upsection, documented by CC 7, approx. 228 meters from the base (Figs. 4.36 & 4.37). The strata indicate continued unroofing, erosion and deposition proximal to the frontal anticline (Figs. 4.42, 4.43 & 5.4). Further evidence of a western, proximal source is documented by eastward paleoflow in this study (Fig. 4.39).

Exactly when movement on the frontal anticline terminated is ambiguous during this time. A single K-Ar age date of 93.1 ± 3.4 m.y. indicates a Cenomanian age (Carpenter & Carpenter, 1987). If movement has ceased by this time, then thrusting is bracketed between 95.8 ± 3.5 and 93.1 ± 3.4 m.y. (Carpenter & Carpenter, 1987).

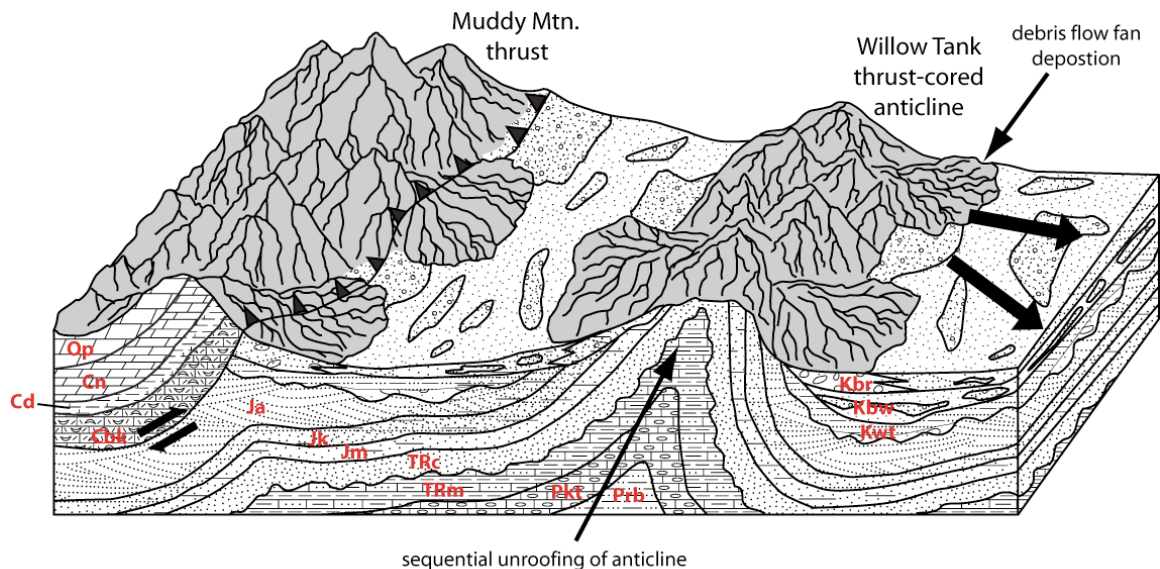


Figure 5.4: Block diagram showing initial Red Member deposition. The sequential erosion of strata in the hanging wall of the Willow Tank thrust is shown by clast counts in debris flow alluvial fan conglomerates. The abundance, large clast size and poor organization of these units suggests high relief and proximal deposition. Stratigraphic abbreviations are listed in Fig. 5.1.

Upper Red Member

This sequence of the Red Member records the upsection transition from debris flow-dominated alluvial fan to braided stream deposition (Fig. 5.5). The intertonguing zone between these packages exhibits evidence of fluvial reworking in debris flow conglomerates and an anomalous influx of Jurassic Aztec sandstone clasts in conglomerates from 480 to 520 meters above the base (Fig. 4.32 & 4.38). This increase in Jurassic clasts does not conform to the unroofing sequence and is possibly a result of renewed exposure of the Aztec in

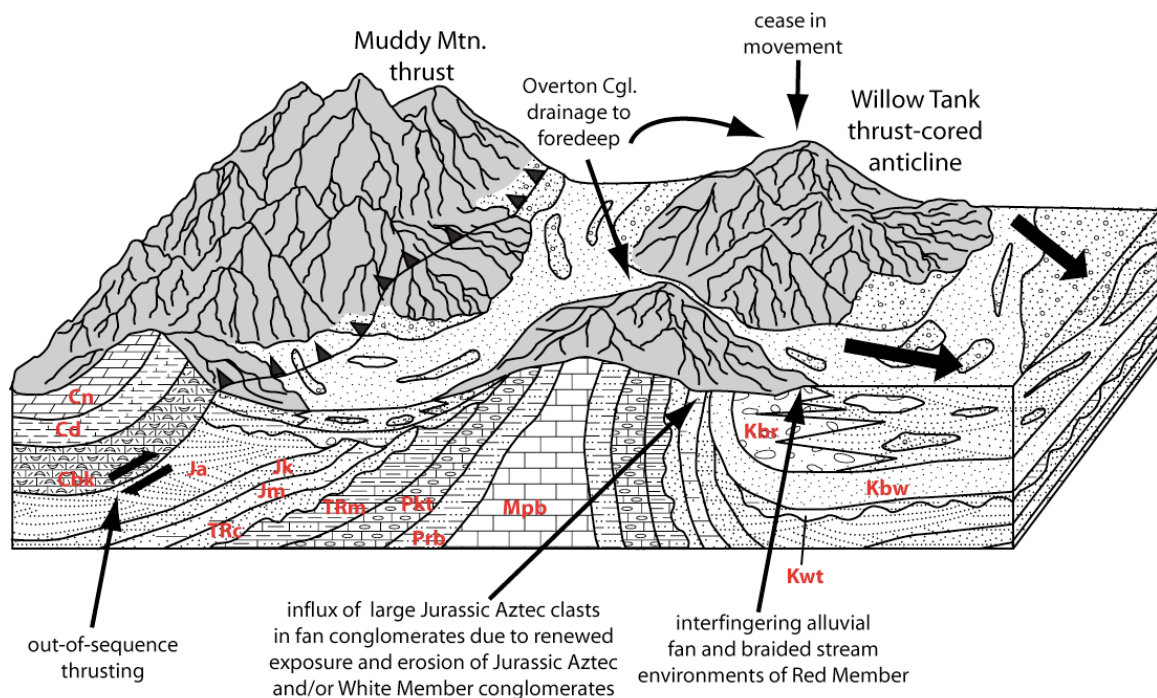


Figure 5.5: Block diagram showing Upper Red Member and Overton Conglomerate deposition. Propagation of the Willow Tank thrust has slowed or ceased and Muddy Mountain thrusting has ensued, based on: 1) Overton conglomerate clast suite, 2) interfingering of these members, and 3) structural relations. Red Member stratigraphy exhibits a dramatic change from debris flow fan to braided stream deposition moving upsection. Stratigraphic abbreviations are listed in Fig. 5.1. Diagram is not drawn to scale.

the source area and/or recycling of the White Member debris flow conglomerates. Movement on the Willow Tank thrust is proposed to have slowed or ceased by this time due to the decreasing amount of debris-flow conglomerates.

An upward transition from fan to fluvial environments does not necessarily reflect variation in subsidence patterns, but more likely reflects changes in environments along the strike of the fold (Fig. 5.5). Conglomerate clast count data from both the interfingering zone and braided-stream environments exhibit no clasts older than the Pennsylvanian Bird Spring Limestone (Figs. 4.37 & 4.38), providing evidence of locally sourced drainage in both environments. This implies the existence of more than one drainage basin with consequent drainage (i.e. headward stream erosion into progressively older strata) along the strike of the Willow Tank anticline (Fig. 5.6; Oberlander, 1965; DeCelles, 1988). Recent studies have shown that the presence of a precipitation gradient influences the size and spacing of drainages on the leeward side of a mountain belt (Bonnet, 2009). This information, in association with clast count and paleoclimate data, show that it is entirely possible that the Upper Red Member was sourced from numerous, closely-spaced, small drainage outlets tapping equivalent source sections on the same structure (Fig. 5.6).

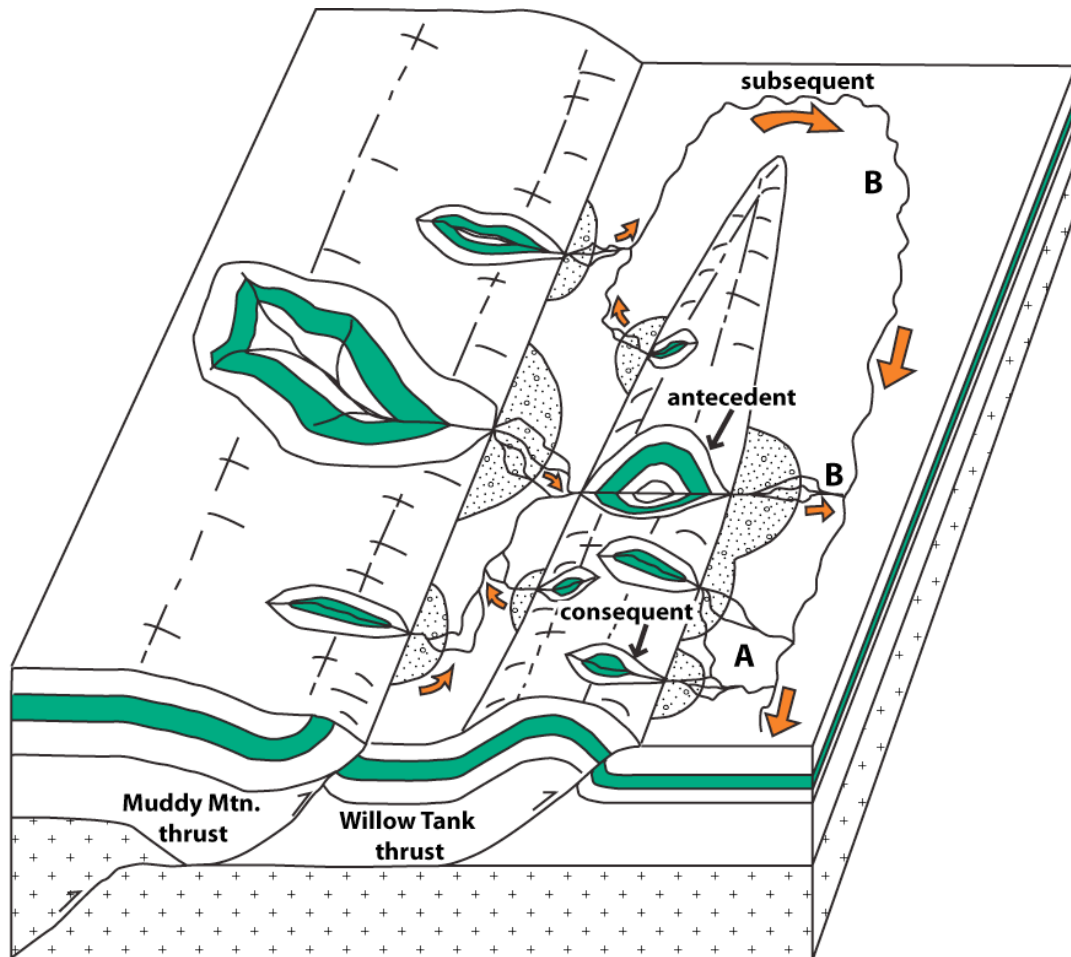


Figure 5.6: Diagram showing structural influences on provenance and sediment dispersal. Proposed sources and alluvial systems responsible for deposition of both the Red Member (A) and Overton Conglomerate Member (B) are outlined. A) The Red Member alluvial fan and fluvial deposits were the result of erosion and consequent drainage of the frontal Willow Tank anticline. Red Member strata contain no units older than Pennsylvanian, pointing to a Willow Tank hanging wall source. B) The Overton Conglomerate was sourced from the Muddy Mountain thrust and detritus was transported in a subsequent or antecedent fashion to the foredeep, where it intermingled with Red Member braided stream deposits (after Decelles, 1988).

Overton Conglomerate Member, Baseline Formation

Interfingering Overton/Red Member

The Overton Conglomerate Member interfingers with the principally fluvial Upper Red Member northeast of the field area (Fig. 2.3), but contains a much different conglomerate clast suite of dominantly carbonate and quartzite. These well-sorted, subrounded, granule- to pebble-sized framework clasts occur in graded to stratified conglomerates, which represent deposition in a gravel-dominated braided stream. The texture and lack of labile clasts are evidence of transport over a larger distance relative to deposits of the Red Member (Fig. 5.6). Furthermore, paleoflow data from the Overton Conglomerate and the equivalent Iron Springs Formation point toward a western source (Fillmore, 1991, 1993). Paleocurrent, compositional and textural data suggests that this unit is sourced from the Muddy Mountain thrust (Longwell, 1949; Bohannon, 1983b) and was transported eastward (Fillmore, 1993) in an antecedent (incised through the structure) or subsequent (around the structure) fashion to the foredeep (Fig. 5.6; Oberlander, 1965; DeCelles, 1988).

In contrast, fluvial strata of the Red Member are proposed to be sourced solely from drainage basins tapping the frontal anticline. The Muddy Mountain thrust has overridden both the Red and Overton Conglomerate Members (Longwell, 1949; Bohannon, 1983b). Additionally, both members onlap the trace of the Willow Tank thrust. If this is the case, this implies that movement on the

Muddy Mountain thrust postdates both Red Member alluvial fan deposition and Willow Tank thrust movement (post-93.1 $\pm$ 3.4 m.y.; Carpenter, 1989). Out-of-sequence propagation of the Muddy Mountain thrust is shown by both folded strata in the Willow Tank thrust hanging wall (Bohannon, 1983b) and large Paleozoic carbonate rocks (>100 m in size) from the overriding thrust sheet incorporated in the Overton Conglomerate (Longwell, 1949).

CONCLUSIONS

Provenance and sedimentological/stratigraphic examination of both the Cretaceous Willow Tank Formation and Red Member of the Baseline Formation, in association with previous studies, record the interaction between wedgetop depozone propagation and foredeep alluvial sedimentation in the southern Nevada portion of the Rocky Mountains. Basal conglomerates of the Willow Tank Formation represent initial foreland basin sedimentation from western faults of the thrust-belt interior. Ensuing eastward fault movement and foredeep subsidence due to tectonic loading caused a transition from gravelly braided fluvial to mud-dominated anastomosing fluvial deposition. The growth of a blind thrust-cored frontal anticline (Willow Tank thrust) disrupted previous foredeep alluvial deposystems by causing drainage diversion around the frontal fold and choking proximal environments with an influx of quartz sand from the unroofing and erosion of the Jurassic Aztec sandstone. Sandstone petrography and lithofacies analyses of the upper Willow Tank document these events, as well as the transition from an anastomosing to a sandy braided stream environment.

Proximal deposition to the frontal fold is recorded by debris flow-and sheetflood-dominated alluvial fan conglomerate deposits of the White Member. Episodic uplift on the frontal fold and is confirmed by the presence of syntectonic progressive unconformities near the surface manifestation of the Willow Tank thrust.

Sedimentary analyses of Red member strata indicate sedimentation occurred synthetically in contiguous, alluvial fan and braided stream depositional environments proximal to the frontal anticline. Evidence of interfingering depositional environments is shown by the: 1) replacement of poorly-sorted and organized coarse-grained conglomerates by well-sorted stratified to normally-graded conglomerates, 2) overall decrease in grain size and soft-sediment deformation, and 4) increase in both lateral bed continuity and bioturbated sandstones. A reverse depositional sequence contained in debris flow fan conglomerates confirms the sequential unroofing of the Jurassic Aztec sandstone downward through the Pennsylvanian Bird Spring on the hanging wall of the Willow Tank thrust allochthon.

Upper Red and Overton Conglomerate Member geometric relationships and distinct conglomerate clast suites suggest intermingling of braided depositional systems that tapped separate source areas. These observations, in association with structural relationships, point toward a cease in movement on the frontal Willow Tank thrust and out-of-sequence propagation along the Muddy Mountain thrust.

REFERENCES CITED

- Allen, P.A., 1970b, Studies in fluvatile sedimentation: a comparison of fining-upward cyclothems, with special reference to coarse-member composition and interpretation: *Journal of Sedimentary Petrology*, v. 40, p. 298-323.
- Allen, P.A., 1997, *Earth Surface Processes*: Oxford, Blackwell Science, 404 p.
- Anderson, R.E., 1973, Large-magnitude late Tertiary strike-slip faulting north of Lake Mead, Nevada: U.S. Geological Survey Professional Paper 794, 18 p.
- Armstrong, R.L. 1968, Sevier Orogenic Belt in Nevada and Utah: *Geological Society of America Bulletin*, v. 79, p. 429– 458.
- Armstrong, F.C., and Oriel, S.S., 1965, Tectonic development of Idaho-Wyoming thrust belt: *American Association of Petroleum Geologists Bulletin*, v. 49, p. 1847-1866.
- Aschoff, J.L., and Schmitt, J.G., 2008, Distinguishing syntectonic unconformity types to enhance analysis of growth strata: An example from the Cretaceous, southeastern Nevada, U.S.A.: *Journal of Sedimentary Research*, v. 78, p. 608-623.
- Ash, S.R., and Read, C.B., 1976, North American species of *Tempskya* and their stratigraphic significance: United States Geological Survey Professional Paper 874, 11 p.
- Azevedo, P.A., 1993, Tectono-sedimentary evolution of a Late Cretaceous alluvial fan, Beaverhead Group, southwestern Montana: (unpublished) M.S. thesis: Montana State University, Bozeman, 137 p.
- Bagnold, R.A., 1954, Experiments on a gravity-free dispersion of solid spheres in a Newtonian fluid under shear: *Proceedings of the Royal Society of London*, v. 225, p. 49-63.
- Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: *Journal of the Hydraulics Division, American Society of Civil Engineers*, v. 90, p. 117-126.
- Blair, T.C., 2000, Sedimentology and progressive tectonic unconformities of the sheetflood-dominated Hell's Gate alluvial fan, Death Valley, California: *Sedimentary Geology*, v. 132, p. 233-262.

- Blair, T.C. and McPherson, J.G., 1994a, Alluvial fan processes and forms, *in* Abrahams, A.D., and Parsons, A.J., eds., *Geomorphology of desert environments*: London, Chapman & Hall, p. 354-402.
- Blair, T.C. and McPherson, J.G., 1994b, Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages: *Journal of Sedimentary Research*, v. A64, p. 450-489.
- Blakey, R., 2009, Regional Paleogeography and Stratigraphy, Sedimentology, Geologic History of Colorado Plateau: <http://www2.nau.edu/~rcb7/index.html>
- Blakey, R., and Ranney, W., 2008, *Ancient Landscapes of the Colorado Plateau: Grand Canyon, AZ*, Grand Canyon Association, 156 p.
- Bohannon, R.G., 1979, Strike-slip faults of the lake Mead Region of southern Nevada, *in*. Armentrout, J.M. et al, eds., *Cenozoic paleogeography of the western United States*: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 3, p. 129-139.
- , 1983b, Mesozoic and Cenozoic tectonic development of the Muddy, North Muddy, and northern Black Mountains, Clark County, Nevada: *Geological Society of America, Memoir 157*, p. 125-148.
- , 1992, Geologic map of the Weiser Ridge Quadrangle, Clark County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1714, 1:24,000.
- Bonde, J.W., 2008, Paleocology and taphonomy of the Willow Tank Formation (Albian), southern Nevada: (unpublished) M.S. thesis: Montana State University, Bozeman, 96 p.
- Bonnet, S., 2009, Shrinking and splitting of drainage basins in orogenic landscapes from the migration of the main drainage divide: *Nature Geoscience*, v. 2, p. 766-771.
- Boothroyd, J C; Ashley, G M, 1975, Processes, bar morphology, and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska: *Society of Economic Paleontologists and Mineralogists*, no.23, p. 193-222.

- Bull, W.B., 1972, Recognition of alluvial fan deposits in the stratigraphic record, *in* Rigby, J.K., and Hamblin, W.K., eds., Society of Economic Paleontologists and Mineralogists Special Publication 16, p. 68-83.
- Burchfiel, B.C., 1965, Structural geology of the Specter Range quadrangle, Nevada, and its regional significance: Geological Society of America Bulletin, v. 76, p. 175-192.
- Burchfiel, B.C., Fleck, R.J., Secor, D.T., Vincelette, R.R., and Davis, G.A., 1974, Geology of the Spring Mountains, Nevada: Geological Society of America Bulletin, v. 85, p. 1013-1022.
- Cant, D.J., and Walker, R.G., 1978, Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada: Sedimentology, v. 25, p. 625-648.
- Carpenter, D.G., 1989, Geology of the North Muddy Mountains Clark County, Nevada and regional structural synthesis: Fold-thrust and Basin-Range structure in southern Nevada, southwest Utah, and northwest Arizona: (unpublished) M.S. thesis: Oregon State University, Corvallis, 145 p.
- Carpenter, D.G., and Carpenter, J.A., 1987, New K-Ar ages from the Baseline Sandstone (Cenomanian), North Muddy Mountains, Clark County, Nevada: Isochron/West, v. 49, p. 3.
- Carr, M.D., 1980, Upper Jurassic to Lower Cretaceous (?) synorogenic sedimentary rocks in the southern Spring Mountains, Nevada: Geology, v. 8, p. 385-389.
- Colombo, F., 1994, Normal and reverse unroofing sequences in syntectonic conglomerates as evidence of progressive basinward deformation: Geology, v. 22, p. 235-238.
- Coogan, J.C., 1992b, Structural evolution of piggyback basins in the Wyoming-Idaho-Utah thrust belt, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 55-81.
- Costa, J.E., 1988, Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows, *in* Baker, V.R., Kochel, R.C., and Patton, P.C., eds., Flood geomorphology: New York, Wiley, p. 113-122.

- Currie, B.S., 2002, Structural configuration of the Early Cretaceous Cordilleran foreland-basin system and Sevier thrust belt, Utah and Colorado: *The Journal of Geology*, v. 110, p. 697-718.
- DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A.: *American Journal of Science*, v. 304, p. 105-168.
- DeCelles, P.G., 1988, Lithologic provenance modeling applied to the Late Cretaceous synorogenic Echo Canyon Conglomerate, Utah: A case of multiple source areas: *Geology*, v. 16, p. 1039-1043.
- DeCelles, P.G., and Burden, E.T., 1992, Non-marine sedimentation in the overfilled part of the Jurassic-Cretaceous Cordilleran foreland basin: Morrison and Cloverly Formations, central Wyoming, USA: *Basin Research*, v. 4, p. 291-314.
- DeCelles, P.G., and Cavazza, W., 1999, A comparison of fluvial megafans in the Cordilleran (Upper Cretaceous) and modern Himalayan foreland basin systems: *Geological Society of America Bulletin*, v. 111, p. 1315-1334.
- DeCelles, P.G., and Coogan, J.C. 2006, Regional structure and kinematic history of the Sevier fold-and-thrust belt, central Utah: *Geological Society of America Bulletin*, v. 118, p. 84-864.
- DeCelles, P.G., and Giles, K.A. 1996, Foreland basin systems: *Basin Research*, v. 8, p. 105-123.
- DeCelles, P.G., Gray, M.B., Ridgway, K.D., Cole, R.B., Srivastava, P., Pequera, N., and Pivnik, D.A., 1991, Kinematic history of a foreland uplift from Paleocene synorogenic conglomerate, Beartooth Range, Wyoming and Montana: *Geological Society of America Bulletin*, v. 103, p. 1458-1475.
- DeCelles, P.G., Pile, H.T., and Coogan, J.C., 1993, Kinematic history of the Meade thrust based on provenance of the Bechler conglomerate at Red Mountain, Idaho, Sevier thrust belt: *Tectonics*, v. 12, p. 1436-1450.
- DeCelles, P.G., Tolson, R.B., Graham, S.A., Smith, G.A., Ingersoll, R.V., White, J., Schmidt, C.J., Rice, R., Moxon, I., Lemke, L., Handschy, J.W., Follo, M.F., Edwards, D.P., Cavazza, W., Caldwell, M., and Bargar, E., 1987, Laramide thrust-generated alluvial fan sedimentation, Sphinx Conglomerate, southwestern Montana: *American Association of Petroleum Geologists Bulletin*, v. 71, p. 135-155.

- Dickinson, W. R., 1985, Interpreting provenance relations from detrital modes of sandstones, *in* Zuffa, G. G., ed., *Provenance of Arenites*: Dordrecht, Netherlands, D. Reidel, NATO Advanced Study Institute Series 148, p. 333–361.p. 49-70.
- , 2004, Evolution of the North American Cordillera: *Annual Review of Earth and Planetary Sciences*, v. 32, p. 13-45.
- Dickinson, W.R., Lawton, T.F., and Inman, K.F. 1986, Sandstone detrital modes, central Utah foreland region: Stratigraphic record of Cretaceous–Paleogene tectonic evolution: *Journal of Sedimentary Petrology*, v. 56, p. 276-293.
- Dougherty, S.L., 1997, Alluvial fan and fluvial interaction in a foreland basin wedge-top depozone: Upper Cretaceous Beaverhead Group, SW Montana: (unpublished) M.S. thesis: Montana State University, Bozeman, 111 p.
- Fillmore, R.P., 1991, Tectonic influence on sedimentation in the southern Sevier foreland, Iron Springs Formation (Upper Cretaceous), southwestern Utah: *Geological Society of America Special Paper* 260, p. 9-25.
- Fillmore, R.P., 1993, Late Cretaceous paleogeography of the southern Sevier foreland, southwest Utah, southern Nevada, and northwest Arizona *in* Dunn, G., and McDougall, K., eds., *Mesozoic Paleogeography of the Western United States-II*, Pacific Section SEPM, Book 71, p. 417-432.
- Fisher, R.V., 1971, Features of coarse-grained, high-concentration fluids and their deposits: *Journal of Sedimentary Petrology*: v. 41, p. 916-927.
- Fleck, R.J., 1970, Tectonic style, magnitude and age of deformation in the Sevier orogenic belt in southern Nevada and southeastern California: *Geological Society of America Bulletin*, v. 81, p. 1705-1720.
- Fleck, R.J., Mattinson, J. M., Busby, C. J., Carr, M. D., Davis, G. A., and Burchfiel, B. C., 1994, Isotopic complexities and the age of the Delfonte volcanic rocks, eastern Mescal Range, southeastern California: Stratigraphic and tectonic implications: *Geological Society of America Bulletin*, v. 106, p. 1242–1253.
- Folk, R. L., 1980, *Petrology of sedimentary rocks*: Austin, Texas, Hemphill Publishing, 182 p.

- Gloppen, T.G., and Steel, R., 1981, The deposits, internal structure and geometry in six alluvial fan-fan delta bodies (Devonian, Norway)—a study in the significance of bedding sequence in conglomerates, *in* Ethridge, F., and Flores, R.M., eds., Recent and Ancient Nonmarine Depositional Environments: Models for Exploration: Society of Economic Paleontologists and Mineralogists, Special Publication 31, p. 46-69.
- Graham, S.A., Tolson, R.B., DeCelles, P.G., Ingersoll, R.V., Bargar, E., Caldwell, M., Cavazza, W., Edwards, D.P., Follo, M.F., Handschy, J.F., Lemke, L., Moxon, I., Rice, R., Smith, G.A., and White, J., 1986, Provenance modeling as a technique for analyzing source terrane evolution and controls on foreland sedimentation: Spec. Publs int. Ass. Sediment, v. 8, p. 425-436.
- Goldstrand, P.M. 1992, Evolution of late Cretaceous and early Tertiary basins of southwest Utah based on clastic petrology: Journal of Sedimentary Petrology, v. 62, p. 495– 50.
- , 1994, Tectonic development of Upper Cretaceous to Eocene strata of southwestern Utah: Geological Society of America Bulletin, v. 106, p. 145–154.
- Harms, J.C., and Fahnestock, R.K., 1965, Stratification, bedforms, and flow phenomena (with an example from the Rio Grande): Society of Economic Paleontologists and Mineralogists Special Publication 12, p. 84-115.
- Harms, J.C., Southard, J.B., Spearing, D.R., Walker, R.G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: Society of Economic Paleontologists and Mineralogists Short Course 2.
- Harms, J.C., Southard, J.B., and Walker, R.G., 1982, Structure and sequences in clastic rocks: Society of Economic Paleontologists and Mineralogists Short Course 9, 249 p.
- Hewett, D.F., 1931, Geology and ore deposits of the Goodsprings quadrangle, Nevada: U.S. Geological Survey Professional Paper 162.
- Hein, F.J., and Walker, R.G., 1977, Bar evolution and development of stratification in the gravelly, braided Kicking Horse River, British Columbia: Canadian Journal of Earth Science, v. 14, p. 562-570.

- Heller, P.L., Angevine, C.L., Winslow, N.S., and Paola, C. 1988, Two-phase stratigraphic model of foreland basin sequences: *Geology*, v. 16, p. 501–504.
- Heller, P.L., and Paola, C., 1989, The paradox of Lower Cretaceous gravels and the initiation of thrusting in the Sevier orogenic belt, United States Western Interior: *Geological Society of America Bulletin*, v. 101 p. 864-875.
- Hooke, R.L., 1967, Processes on arid-region alluvial fans: *The Journal of Geology*, v. 75, p. 438-460.
- Horton, B.K., and DeCelles, P.G., 2001, Modern and ancient fluvial megafans in the foreland basin system of the central Andes, southern Bolivia: implications for drainage network evolution in fold-thrust belts: *Basin Research*, v. 13, p. 43-63.
- Horton, B.K., Constenius, K.N., DeCelles, P.G., 2004: Tectonic control on coarse-grained foreland-basin sequences: An example from the Cordilleran foreland basin, Utah: *Geology*, v. 32, p. 637-640.
- Howard, J.L., 1993, The statistics of counting clasts in rudites: a review, with examples from the upper Palaeogene of southern California, U.S.A.: *Sedimentology*, v. 40, p. 157-174.
- Ingersoll, R.V., Bullard, T.F., Ford, R.L., Grimm, J.P., Pickle, J.D., and Sares, S.W., 1984, The effect of grain size on detrital modes: A test of the Gazzi-Dickinson point-counting method: *Journal of Sedimentary Petrology*, v. 54, p. 103-116.
- Ingersoll, R.V., Cavazza, W., Graham, S.A., and Indiana University Graduate Field Seminar Participants, 1987, Provenance of impure calcilithites in the Laramide foreland of southwestern Montana: *Journal of Sedimentary Petrology*, v. 57, p. 995-1003.
- Jackson, R.G., 1976, Depositional model of point bars in the Lower Wabash River: *Journal of Sedimentary Petrology*, v. 46, p. 579-594.
- Jordan, T. E., 1981, Thrust loads and foreland basin evolution, Cretaceous, western United States: *American Association of Petroleum Geologists Bulletin*, v. 65, p. 2506 –2520.
- Kirschbaum, M.A., and McCabe, P.J., 2006, Controls on the accumulation of coal and on the development of anastomosed fluvial systems in the Cretaceous

Dakota Formation of southern Utah: *Sedimentology*, v. 39, p. 581-598.

Lageson, D.R., and Schmitt, J.G., 1994, The Sevier orogenic belt of the western United States: recent advances in understanding its structural and sedimentological framework, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., eds., *Mesozoic Systems of the Rocky Mountain Region, U.S.A.*: Denver, Colorado, Rocky Mountain SEPM, p. 27-64.

Lawton, T.F., 1986, Compositional trends within a clastic wedge adjacent to a fold-thrust belt: Indianola Group, central Utah, U.S.A., *in* Allen, P. A., and Homewood, P., editors, *Foreland Basins: International Association of Sedimentologists Special Publication 8*, p. 411– 423.

———, 1994, Tectonic setting of Mesozoic sedimentary basins, Rocky Mountain region, United States, *in* Caputo, M. V., Peterson, J. A., and Franczyk, K. J., editors, *Mesozoic systems of the Rocky Mountain region, USA*: Denver, Colorado, Rocky Mountain Section SEPM, p. 1–26.

Lawton, T.F., Boyer, S.E., and Schmitt, J.G. 1994, Influence of inherited taper on structural variability and conglomerate distribution, Cordilleran fold and thrust belt, western United States: *Geology*, v. 22, p. 339– 342.

Lawton, T.F., and Trexler, J.H. Jr., 1991, Piggyback basin in the Sevier orogenic belt, Utah: Implications for development of the thrust wedge: *Geology*, v. 19, p. 827-830.

Longwell, C.R., 1949, Structure of the northern Muddy Mountains area, Nevada: *Geological Society of America Bulletin*, v. 60, p. 923-968.

———, 1960, Possible explanation of diverse structural patterns in southern Nevada: *American Journal of Science*, v. 258-A, p. 192-203.

Lowe, D.R., 1982, Sediment gravity flows: II Depositional models with special reference to the deposits of high-density turbidity currents: *Journal of Sedimentary Research*, v. 52, p. 279-297.

Makaske, B., 2001, Anastomosing rivers: a review of their classification, origin and sedimentary products: *Earth-Science Reviews*, v. 53, p. 149-196.

Miall, A.D., 1977, A review of braided-river depositional environments: *Earth Science Reviews*, v. 22, p. 261-308.

- , 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. 596-604.
- Miall, A.D., 1996, *The Geology of Fluvial Deposits*: Berlin, Springer-Verlag, 582 p.
- Middleton, G.V., 1965, Primary sedimentary structures and their hydrodynamic interpretation: Society of Economic Paleontologists and Mineralogists Special Publication 12, 265 p.
- Nadon, G.C., 1994, The genesis and recognition of anastomosed fluvial deposits; data from the St. Mary River Formation, southwestern Alberta, Canada: *Journal of Sedimentary Research*, v. 64, p. 451-463.
- Nemec, W., and Steel, R.J., 1984, Alluvial and coastal conglomerates: their significant feature and some comments on gravelly mass-flow deposits, *in* Koster, E.H., and Steel, R.J., eds., *Sedimentology of Gravels and Conglomerates*: Canadian Society of Petroleum Geologists, Memoir 10, p. 1-32.
- Oberlander, T., 1965, *The Zagros streams*: Syracuse Geographical Series, No. 1, 168 p.
- Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, Geological Society of America, *Reviews in Engineering Geology*, v. 7, p. 1-12.
- Pivnik, D.A., Thrust-generated fan-delta deposition: Little Muddy Creek Conglomerate, SW Wyoming: *Journal of Sedimentary Petrology*, v. 60, p. 489-503.
- Reese, J.A., 1989, Initial Deposition in the Sevier Foreland Basin of Southern Nevada: Conglomerates of the Cretaceous Willow Tank Formation, Clark County, Nevada: (unpublished) M.S. thesis: University of Nevada, Las Vegas, 145 p.
- Retallack, G.J., 1988, Field recognition of paleosols, *in* Reinhardt, J., and Sigleo, W.R., eds., *Paleosols and Weathering Through Geologic Time: Principles and Applications*: Geological Society of America Special Paper 216, p. 1-20.

- Rust, B.R., 1972, Pebble orientation in fluvial sediments: *Journal of Sedimentary Petrology*, v. 42, p. 384-388.
- , 1978, Depositional models for braided alluvium, *in* Miall, A.D., ed., *Fluvial sedimentology: Canadian Society of Petroleum Geologists Memoir* 5: p. 605-625.
- Schmitt, J.G., 1992, Long-term sustained delivery of gravel from interior of fold-thrust orogen to foreland basin: Upper Cretaceous-Paleocene conglomerates in NW Wyoming and SW Montana: *Society of Economic Paleontologists and Mineralogists Theme Meeting on Mesozoic of the Western Interior*, Ft. Collins, Colorado, p. 60.
- Schmitt, J.G., and Aschoff, J.L., 2003, Synorogenic sedimentation along the Cordilleran thrust belt front, southern Nevada: alluvial systems, sediment dispersal, and growth stratal development: *Geological Society of America Annual Meeting Abstracts with Programs*, v. 35, p. 642.
- Schmitt, J.G., and Aschoff, J.L., 2005, Distinguishing alluvial fan and fluvial system interactions at foreland basin margins: Criteria and significance: *Geological Society of America Annual Meeting Abstracts with Programs*, v. 37, p. 482.
- Schmitt, J.G., Jones, D.A., and Goldstrand, P.M., 1991, Braided stream deposition and provenance of the Upper Cretaceous-Paleocene (?) Canaan Peak Formation, Sevier Foreland Basin, southwestern Utah, *in* Nations, J.D., and Eaton, J.G., eds., *Stratigraphy, depositional environments, and sedimentary tectonics of the western margin, Cretaceous Western Interior Seaway: Geological Society of America Special Paper* 260, p. 27-45.
- Schmitt, J.G. and Kohout, J.B., 1986, Early Cretaceous sedimentary evolution of the Sevier Foreland Basin, Muddy and North Muddy Mountains, Nevada: *Geological Society of America Annual Meeting Abstracts with Programs*, v. 18, p. 181.
- Schmitt, J.G., and Steidtmann, J.R., 1990, Interior-ramp supported uplifts: Implications for sediment provenance in foreland basins: *Geological Society of America Bulletin*, v. 102, p. 494-501.
- Schumm, S.A., and Lichty, R.W., 1963, Channel widening and floodplain construction along the Cimarron River in southwestern Kansas: *United States Geological Survey Professional Paper* 352, p. 71-88.

- Shapiro, R.S., Fricke, H.C., Fox, K., 2009, Dinosaur-bearing oncoids from ephemeral lakes of the Lower Cretaceous Cedar Mountain Formation, Utah: *Palaaios*, v. 24, p. 51-58.
- Shultz, A.W., 1984, Subaerial debris-flow deposition in the Upper Paleozoic Cutler Formation, western Colorado: *Journal of Sedimentary Petrology*, v. 54, p. 759-772.
- Slaugenhooop, G.L., and Schmitt, J.G., 2000, Sandy alluvial fan and fluvial systems of the Upper Cretaceous Baseline Formation (White Member), southern Nevada: Geological Society of America Annual Meeting Abstracts with Programs, v. 32, p. 38-39.
- Smith, D.G., 1983, Anastomosed fluvial deposits: modern examples from western Canada, *in* Collinson, J.D., and Lewin, J., eds., *Modern and Ancient Fluvial Systems*, International Association of Sedimentologists Special Publication 6, p. 83-91.
- , 1986, Anastomosing river deposits, sedimentation rates and basin subsidence, Magdalena River, northwestern Colombia, South America: *Sedimentary Geology*, v. 46, p. 177-196.
- Smith, E.I., 1981, Contemporaneous volcanism, strike-slip faulting and exotic block emplacement in the River Mountains, Clark County, southern Nevada: Geological Society of America Abstracts with Programs, v. 13, p. 107.
- Smith, N.D., and Smith, D.G., 1984, William River: An outstanding example of channel widening and braiding caused by bed-load addition: *Geology*, v. 12, p. 78-82.
- Sohn, Y.K., Rhee, C.W., and Kim, B.C., 1999, Debris flow and hyperconcentrated flood-flow deposits in an alluvial fan, northwestern part of the Cretaceous Yongdong Basin, Central Korea: *Journal of Geology*, v. 107, p. 111-132.
- Steidtmann, J.R., and Schmitt, J.G., 1988, Provenance and dispersal of tectogenic sediments in thin-skinned, thrust terranes, *in* Kleinspehn, K., and Paola, C., eds., *New Perspectives in Basin Analysis*: New York, Springer-Verlag, p. 353-366.

- Todd, S.P., 1989, Stream-driven, high density gravelly traction carpets: possible deposits in the Trabeg Conglomerate Formation, SW Ireland and some theoretical considerations of their origin: *Sedimentology*, v. 36, p. 513-530.
- Troyer, R., Barth, A.P., Wooden, J.L., and Jacobson, C., 2006, Provenance and timing of Sevier Foreland Basin sediments in the Valley of Fire, southern Nevada, from U-Pb geochronology: *Geological Society of America Annual Meeting Abstracts with Programs*, v. 38(7), p. 369.
- Tucker, M.E., 2003, *Sedimentary Rocks in the Field*: England, John Wiley & Sons, 234 p.
- Walker, R.G., and Cant, D.J., 1979, Facies models 3. Sandy fluvial systems, *in* Walker, R.G., ed., *Facies Models*: Geological Association of Canada, p. 23-31.
- Walker, J. D., Burchfiel, B. C., and Davis, G. A., 1995, New age controls on initiation and timing of foreland belt thrusting in the Clark Mountains, southern California: *Geological Society of America Bulletin*, v. 107, p. 742–750.
- Wernicke, B., Spencer, J.E., Burchfiel, B.C., and Guth, P.L., 1982, Magnitude of crustal extension in the southern Great Basin: *Geology*, v. 10, p. 499-502.
- Wiltschko, D.V., and Dorr, J.A., Jr., 1983, Timing of deformation in Overthrust Belt and foreland of Idaho, Wyoming and Utah. *American Association of Petroleum Geologists Bulletin*, v. 67, p. 1304-1322.
- Yingling, V.L., and Heller, P.L., 1992, Timing and record of foreland sedimentation during the initiation of the Sevier orogenic belt in central Utah: *Basin Research*, v. 4, p. 279-290.
- Zaleha, M.J., 2006, Sevier orogenesis and nonmarine basin filling: Implications of new stratigraphic correlations of Lower Cretaceous strata throughout Wyoming, USA: *Geological Society of America Bulletin*, 118. 886-896.

APPENDIX A:

LITHOFACIES DATA,
MEASURED SECTION LOCATIONS

Table A.1: Summary of Willow Tank and Red Member lithofacies. Lithofacies codes similar to Miall (1978) and interpretations from Middleton (1965) and Lowe (1982).

Facies

Code	Description	Interpretation
Gcu	clast-supported, massive ungraded, granule to boulder conglomerate	deposition by clay-poor, noncohesive debris flows
Gcn	clast-supported, normally graded, granule to boulder conglomerate	fluid turbulence and differential grain settling in noncohesive debris flows
Gci	clast-supported, inversely graded, granule to boulder conglomerate	buoyant forces and dispersive pressure in noncohesive debris flows
Gmu	matrix-supported, massive ungraded granule to pebble conglomerate	clast-poor debris flow with high matrix strength
Gh	clast-supported, horizontally stratified, granule to pebble conglomerate	transport & deposition in shallow, high velocity flows
Gt	clast-supported, trough cross-stratified, granule to pebble conglomerate	deposition by migrating 3D large ripples and/or dunes
Gl	clast-supported, low-angle stratified, granule to pebble conglomerate	deposition in scours or bedforms with low-angle stratification
Sm	very fine to medium, poorly- to well-sorted massive ungraded sandstone	result of rapid deposition, liquefaction, or bioturbation
Sn	very fine to medium, moderately- to well-sorted normally-graded sandstone	deposition under decelerating flow conditions
Si	very fine to medium, moderately- to well-sorted inversely-graded sandstone	dispersive pressure and/or kinetic sieving during sediment transport
Sw	very fine to medium, moderately- to well-sorted wavy-laminated sandstone	result of fluctuating hydraulic conditions
Sh	very fine to medium, moderately- to well-sorted horizontally stratified sandstone	deposition of plane bed phase in upper flow regime
Sl	very fine to medium, moderately- to well-sorted low-angle stratified sandstone	deposition by plane beds in scours or bedforms with low-angle stratification
St	very fine to medium, moderately- to well-sorted trough cross-stratified sandstone	deposition by migrating 3D large ripples and/or dunes
Sp	very fine to medium, poorly- to well-sorted planar tabular cross-stratified sandstone	migration of large scale 2D ripples or dunes in lower flow regime
Sr	very fine to fine, well-sorted ripple cross-laminated sandstone	migration of unidirectional ripples under lower flow regime
Sg	massive, medium to coarse, granular sandstone	result of rapid deposition, liquefaction or bioturbation
Spb	massive, medium to coarse, pebbly sandstone	deposition by noncohesive debris flows or hyperconcentrated flows
Sd	very fine to medium, soft-sediment deformed sandstone with convolute lamination/bedding and dewatering structures common	plastic deformation of partially liquified sediment after deposition by tectonism and/or loading
Sb	very fine to medium, bioturbated sandstone, root traces, burrows and mottling common, rare wood fragments	original structure destroyed due to biogenic processes
Spbl	medium to coarse, moderately- to well-sorted, low-angle stratified pebbly sandstone	deposition by plane beds in scours or low-relief bedforms
Spbt	medium to coarse, moderately- to well-sorted, trough cross-stratified pebbly sandstone	deposition by migrating 3D large ripples and/or dunes
Spbh	medium to coarse, moderately- to well-sorted horizontally stratified pebbly sandstone	deposition of plane bed phase in upper flow regime
Sgh	medium to coarse, moderately- to well-sorted horizontally stratified granular sandstone	deposition of plane bed phase in upper flow regime
Sgl	medium to coarse, moderately- to well-sorted low-angle stratified granular sandstone	deposition by plane beds in scours or low-relief bedforms
Fh	stratified siltstone or mudstone	deposition by suspension settling of fines in decelerating
Fm	massive ungraded siltstone or mudstone	result of rapid deposition, liquefaction, or bioturbation

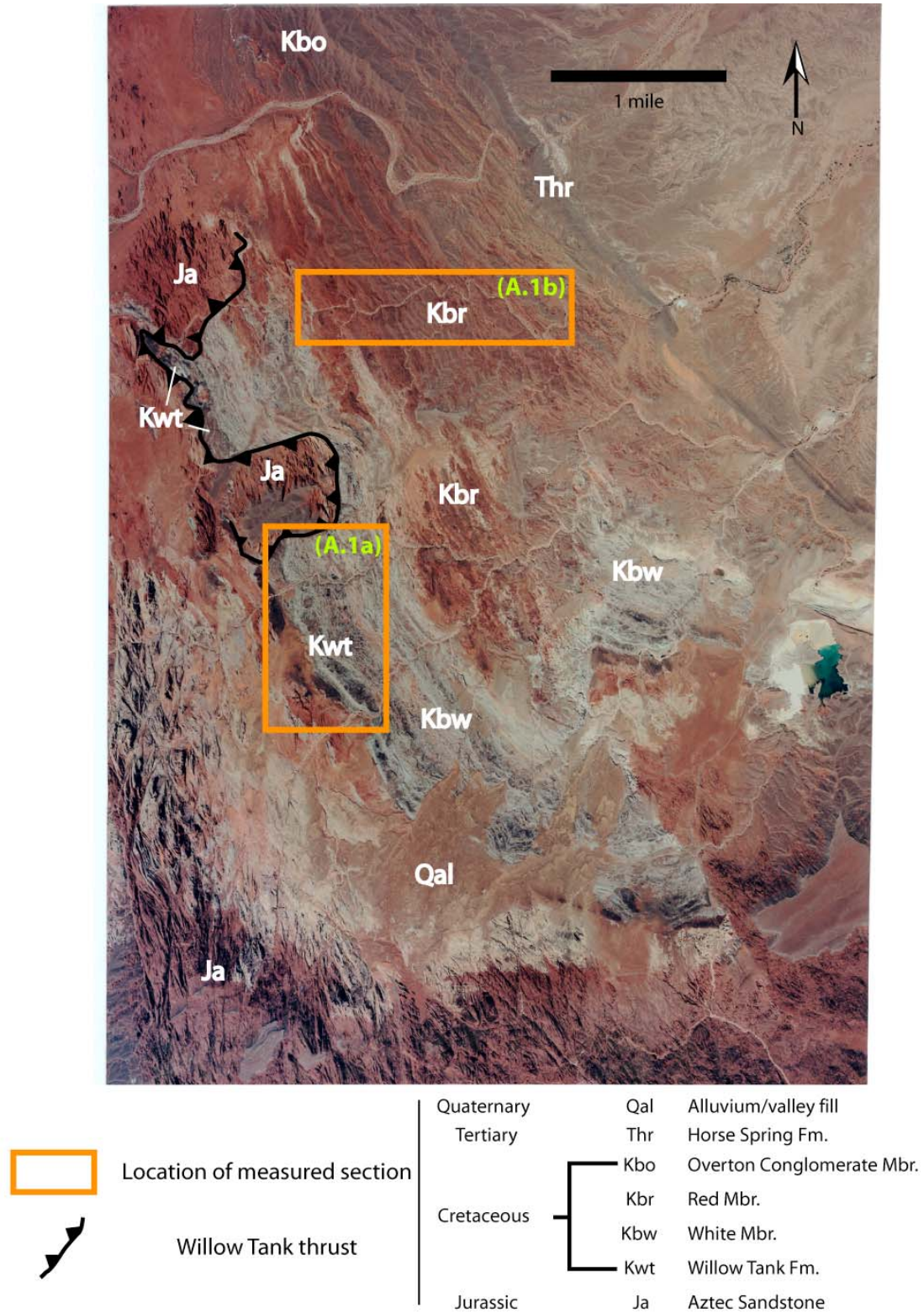
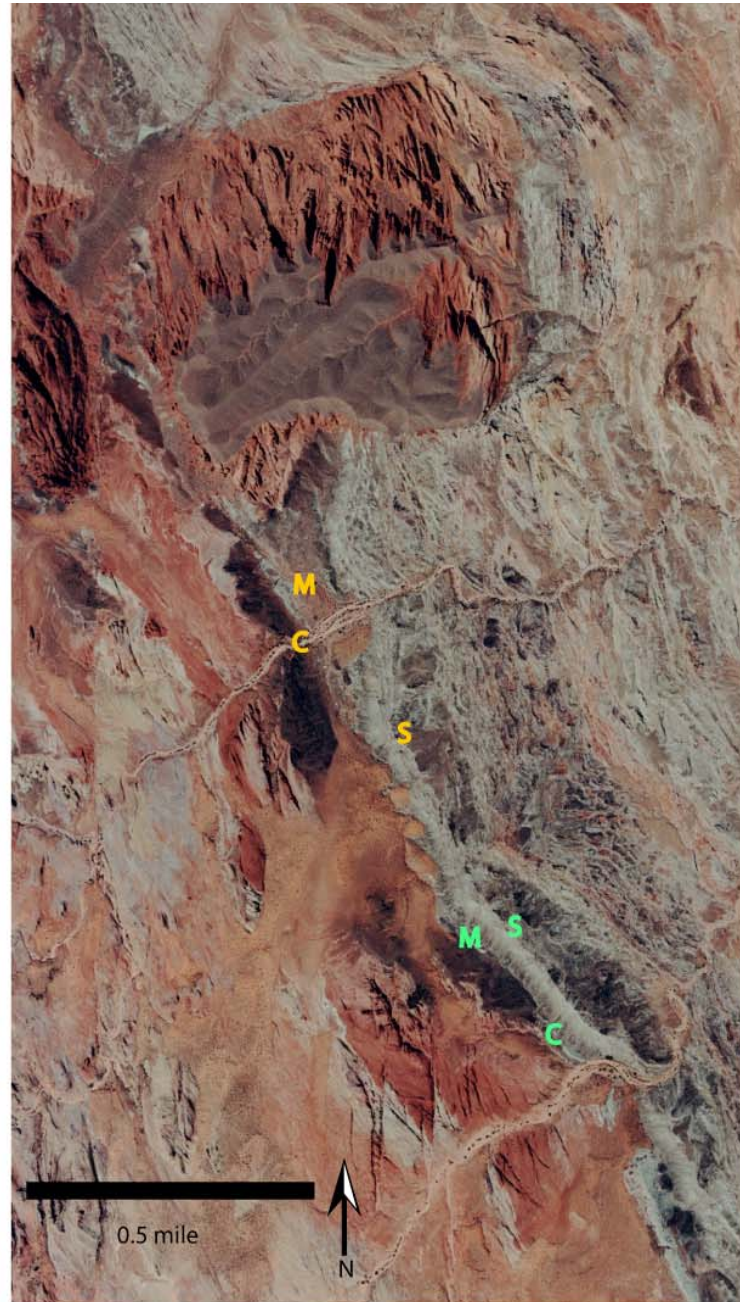


Figure A.1: Study area aerial photo showing locations of Willow Tank (A.1a) and Red Member (A.1b) measured sections.



 Section 1	C basal conglomerate
 Section 2	M middle mud-dominated succession
	S upper sand-dominated succession

Figure A.1a: Aerial photo of Tearfault Mesa and locations of Willow Tank Formation measured sections. Composite sections were measured because of lateral discontinuity, largely due to faulting and local poor exposure.

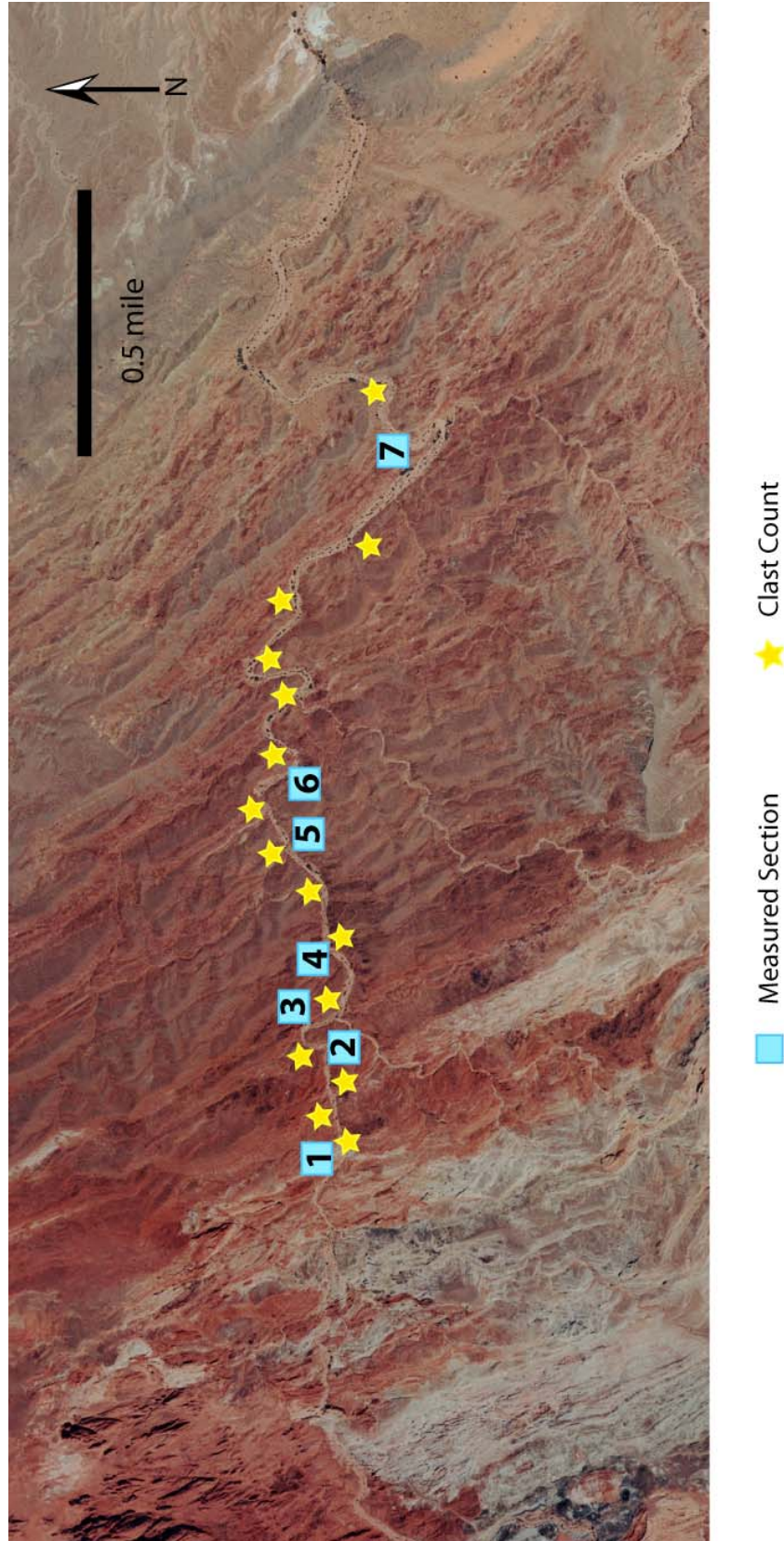


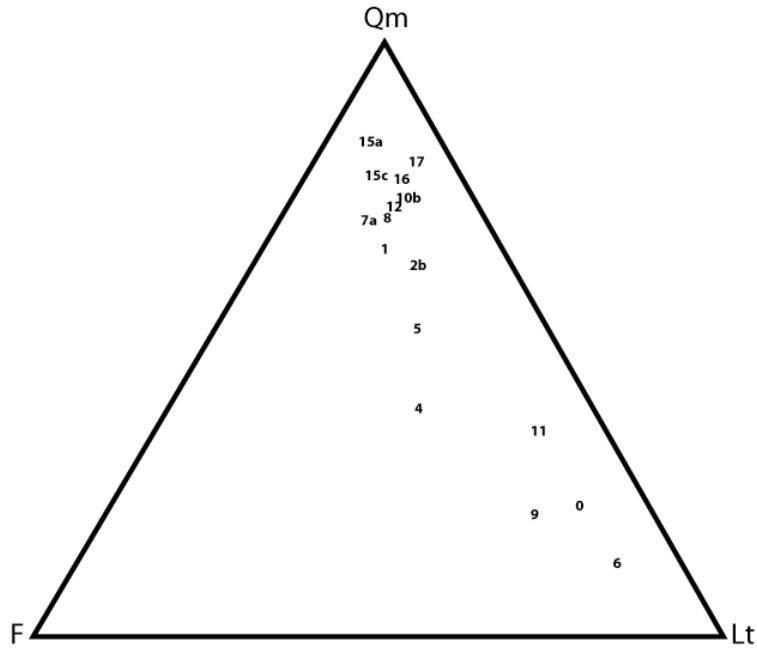
Figure A.1b: Aerial photo of Magnesianite Wash. The Red Member of the Baseline Formation was measured continuously from #1 to #7 along this wash. Stars denote conglomerate clast count locations.

APPENDIX B:

POINT AND CLAST COUNT RAW DATA,
SOURCE LITHOLOGY DESCRIPTIONS

Table B.1.: Willow Tank Formation sandstone point count data.

Table D.1. - whole-rock X-ray diffraction (salvage) Point count data.																																
Sample meters			Folk Classification										Section Willow Tank 1										Section Willow Tank 2									
			Mono-	Quartz	Poly-	%	K-spar	Feldspar	Plag.	%	Chert	Carbonate	Volcanics	%	Mud	%	Silt	%	Sand	%	Biomite	%	Micas	%	Muscovite	%	Isotropics	%	Altered	%	Total	#
			229	(62.91)	6	(1.65)	61	(16.76)	0	(0.00)	35	(9.62)	0	(0.00)	25	(6.87)	1	(0.27)	3	(0.82)	0	(0.00)	1	(0.27)	2	(0.55)	1	(0.27)	0	(0.00)	364	(100.00)
KM1	3.30	feldspathic litharenite	198	(59.94)	38	(10.16)	54	(14.44)	0	(0.00)	66	(22.63)	120	(31.58)	6	(1.60)	2	(0.53)	3	(0.80)	1	(0.27)	1	(0.27)	0	(0.00)	1	(0.27)	0	(0.00)	374	(100.00)
KM 2b	3.50	feldspathic litharenite	72	(18.95)	24	(6.32)	41	(10.79)	0	(0.00)	86	(22.63)	120	(31.58)	8	(2.11)	9	(2.37)	13	(3.42)	2	(0.53)	3	(0.79)	1	(0.26)	0	(0.00)	1	(0.26)	380	(100.00)
KM 4	45.00	feldspathic litharenite	138	(36.80)	2	(0.53)	93	(24.80)	0	(0.00)	6	(1.64)	82	(22.47)	4	(1.07)	5	(1.33)	22	(5.87)	3	(0.80)	12	(3.20)	1	(0.27)	0	(0.00)	3	(0.80)	375	(100.00)
KM 5	49.00	feldspathic litharenite	184	(50.41)	2	(0.53)	71	(19.45)	0	(0.00)	6	(1.64)	82	(22.47)	0	(0.00)	4	(1.10)	10	(2.74)	0	(0.00)	2	(0.55)	1	(0.27)	0	(0.00)	1	(0.27)	365	(100.00)
KM 7a	56.88	feldspathic litharenite	238	(66.11)	10	(2.78)	38	(10.56)	3	(0.83)	21	(5.83)	0	(0.00)	5	(1.39)	12	(3.33)	25	(6.94)	3	(0.83)	2	(0.56)	2	(0.56)	0	(0.00)	1	(0.28)	360	(100.00)
KM 8	58.33	lithic arkose	270	(70.13)	8	(2.08)	50	(12.99)	0	(0.00)	37	(9.61)	5	(1.30)	6	(1.56)	2	(0.52)	7	(1.82)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)	385	(100.00)
KM 10b	59.83	lithic arkose	249	(68.75)	10	(2.80)	61	(17.09)	3	(0.84)	18	(5.04)	0	(0.00)	4	(1.12)	1	(0.28)	11	(3.08)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)	357	(100.00)
KM 12	61.30	lithic arkose	251	(68.34)	12	(3.31)	52	(14.36)	2	(0.55)	27	(7.46)	0	(0.00)	4	(1.10)	0	(0.00)	8	(2.21)	1	(0.28)	1	(0.28)	4	(1.10)	0	(0.00)	0	(0.00)	362	(100.00)
KM 15a	62.83	subarkose	306	(80.10)	14	(3.66)	40	(10.47)	1	(0.26)	18	(4.71)	0	(0.00)	1	(0.26)	0	(0.00)	1	(0.26)	0	(0.00)	1	(0.26)	0	(0.00)	0	(0.00)	0	(0.00)	382	(100.00)
KM 15c	64.28	subarkose	285	(74.22)	11	(2.86)	47	(12.24)	1	(0.26)	23	(5.99)	1	(0.26)	4	(1.04)	1	(0.26)	3	(0.78)	0	(0.00)	6	(1.56)	1	(0.26)	1	(0.26)	0	(0.00)	384	(100.00)
KM 16	66.18	sublitharenite	278	(75.96)	5	(1.37)	32	(8.74)	0	(0.00)	36	(9.84)	3	(0.82)	4	(1.09)	3	(0.82)	3	(0.82)	0	(0.00)	1	(0.27)	0	(0.00)	0	(0.00)	1	(0.27)	386	(100.00)
KM 17	67.78	subarkose	272	(75.84)	16	(4.52)	53	(14.97)	0	(0.00)	12	(3.39)	0	(0.00)	1	(0.28)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)	354	(100.00)
Section Willow Tank 2																																
KM 6	29.20	litharenite	45	(11.84)	38	(10.00)	32	(8.42)	0	(0.00)	56	(14.74)	173	(45.53)	7	(1.84)	15	(3.95)	8	(2.11)	2	(0.53)	2	(0.53)	1	(0.26)	1	(0.26)	0	(0.00)	380	(100.00)
KM 9	39.00	litharenite	66	(18.23)	23	(6.35)	63	(17.40)	0	(0.00)	33	(9.12)	123	(33.98)	7	(1.93)	25	(6.91)	15	(4.14)	5	(1.38)	0	(0.00)	0	(0.00)	0	(0.00)	2	(0.55)	382	(100.00)
KM11	50.60	litharenite	126	(33.42)	18	(4.77)	36	(9.55)	0	(0.00)	55	(14.59)	120	(31.83)	3	(0.80)	4	(1.06)	14	(3.71)	0	(0.00)	1	(0.27)	0	(0.00)	0	(0.00)	0	(0.00)	377	(100.00)



Willow Tank QmFLt Plot Raw Data

Section Willow Tank 1

<u>Sample</u>	<u>meters</u>	<u>Folk Classification</u>
KM1	3.30	feldspathic litharenite
KM 2b	3.90	feldspathic litharenite
KM 0	10.64	litharenite
KM 4	45.00	feldspathic litharenite
KM 5	49.00	feldspathic litharenite
KM 7a	56.88	feldspathic litharenite
KM 8	58.33	lithic arkose
KM 10b	59.83	lithic arkose
KM 12	61.30	lithic arkose
KM 15a	62.83	subarkose
KM 15c	64.28	subarkose
KM 16	66.18	sublitharenite
KM 17	67.78	subarkose

Section Willow Tank 2

KM 6	29.20	litharenite
KM 9	39.00	litharenite
KM11	50.60	litharenite

Figure B.1: QmFLt diagram showing stratigraphic location and classification of Willow Tank sandstone samples (classification follows Folk, 1980).

Table B.2: Red Member conglomerate framework clast descriptions and proposed source units.

Clast Population	Clast Type #	Description	Most Likely Source Unit
A	31	bone fragment	Cretaceous Baseline-Red Mbr
	34	white to light-gray fL, moderately well-sorted sandstone, friable, mottled	
	35	intraformational wood fragments	
	29	fU, well-sorted massive sandstone, red with white spots, mottled	Cretaceous Baseline-White Mbr
	10	white quartzite	Cretaceous Willow Tank Fm.
	12	black chert	
	13	salt & pepper, mL, moderately well-sorted massive sandstone	
	19	white silicified claystone, probably altered ash	
	21	off-white to light-gray fine-grained quartzite	
	22	light-red to mauve fine-grained quartzite, rare laminae	
	1	fU-mU, very well-sorted, laminated, commonly fractured orange to white sandstone	Jurassic Aztec Sandstone
	3	fU-mL, well-sorted, massive orange to white sandstone	
B	5	siltstone to fine sandstone, brick red to maroon, massive to laminated, rare wave ripple laminae	Jurassic Kayenta & Moenave Fm.
C	2	fU-cL, moderately well-sorted, laminated orange to white sandstone	Triassic Chinle Fm.
	4	fU-mU, moderately- to moderately-well sorted massive orange to white sandstone	
	6	light gray, fU, moderately well-sorted, crudely stratified to massive sandstone	
	7	light gray to white, mU to vCL, poor to moderately-sorted quartz-rich massive sandstone, sometimes with small chert pebbles	
	9	gray to yellow petrified wood	
	15	mustard yellow chert	
	18	red chert	
	20	chert pebble conglomerate composed of dominantly red and yellow chert	
	33	black fU-mL poorly-sorted sandstone, subangular fragments and micas, friable	
D	23	thinly-laminated light to dark gray micritic limestone, rare wavy lamination and sparse fossil fragments	Triassic Moenkopi Fm., Virgin Limestone
E	24	granule- to small pebble-carbonate chert conglomerate/breccia, subangular to subrounded framework with minimal matrix	Triassic Moenkopi Fm. Timpowep Mbr
F	25	medium-gray wackestone to packstone, common etched surfaces and light brown chert nodules	Permian Kaibab & Toroweap Fm.
	26	fossiliferous packstone with abundant shell fragments and carbonate rip-ups, commonly chert-rich and	
G	11	mustard yellow siltstone	Permian Red Beds
	16	yellow mudstone, crumbly	
	27	brick red carbonate-cemented siltstone to fine-grained massive sandstone, parallel and wave ripple laminae common	
	28	light yellow to gray carbonate-cemented massive siltstone, rare plumose fracture patterns	
H	8	medium-gray fossiliferous chert, rare horn corals, dull weathered surface	Pennsylvanian Bird Spring Fm.
	17	gray chert	
	30	massive wackestone with byzoan and sponge fossil fragments	
	32	silicified crinoid-rich wackestone to packstone	

Table B.3: Clast counts, stratigraphic position and populations. Letters A - H correspond to source units, listed in Table B.2.
Clast Count Raw Data

Clast Count	Strat. Position (m)	Clast Populations								Total Clast
		A	B	C	D	E	F	G	H	
CC-1	7.07									
# clasts		232	50	195	0	0	0	0	0	477
% clasts		48.6%	10.5%	40.9%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
CC-2	25.65									
# clasts		212	75	171	0	0	0	2	1	461
% clasts		46.0%	16.3%	37.1%	0.0%	0.0%	0.0%	0.4%	0.2%	100.0%
CC-3	64.63									
# clasts		252	28	174	0	0	0	1	10	465
% clasts		54.2%	6.0%	37.4%	0.0%	0.0%	0.0%	0.2%	2.2%	100.0%
CC-4	100.36									
# clasts		216	65	154	0	0	0	17	19	471
% clasts		45.9%	13.8%	32.7%	0.0%	0.0%	0.0%	3.6%	4.0%	100.0%
CC-5	124.4									
# clasts		212	13	229	0	0	0	23	13	490
% clasts		43.3%	2.7%	46.7%	0.0%	0.0%	0.0%	4.7%	2.7%	100.0%
CC-6	181.72									
# clasts		115	150	88	19	26	8	33	18	457
% clasts		25.2%	32.8%	19.3%	4.2%	5.7%	1.8%	7.2%	3.9%	100.0%
CC-7	228.08									
# clasts		159	11	99	54	33	78	72	16	522
% clasts		30.5%	2.1%	19.0%	10.3%	6.3%	14.9%	13.8%	3.1%	100.0%
CC-8	302.84									
# clasts		58	40	66	46	30	142	70	10	462
% clasts		12.6%	8.7%	14.3%	10.0%	6.5%	30.7%	15.2%	2.2%	100.0%
CC-9	355.55									
# clasts		77	84	71	53	15	108	53	37	498
% clasts		15.5%	16.9%	14.3%	10.6%	3.0%	21.7%	10.6%	7.4%	100.0%
CC-10	401.26									
# clasts		120	105	75	40	8	92	37	35	512
% clasts		23.4%	20.5%	14.6%	7.8%	1.6%	18.0%	7.2%	6.8%	100.0%
CC-11	471.4									
# clasts		91	95	66	40	21	113	31	31	488
% clasts		18.6%	19.5%	13.5%	8.2%	4.3%	23.2%	6.4%	6.4%	100.0%
CC-12	480.63									
# clasts		161	72	97	27	6	85	41	40	529
% clasts		30.4%	13.6%	18.3%	5.1%	1.1%	16.1%	7.8%	7.6%	100.0%
CC-13	488.88									
# clasts		178	65	98	27	12	67	40	31	518
% clasts		34.4%	12.5%	18.9%	5.2%	2.3%	12.9%	7.7%	6.0%	100.0%
CC-14	518.57									
# clasts		160	103	58	16	2	51	28	28	446
% clasts		35.9%	23.1%	13.0%	3.6%	0.4%	11.4%	6.3%	6.3%	100.0%
CC-15	583.17									
# clasts		95	75	78	33	19	101	31	53	485
% clasts		19.6%	15.5%	16.1%	6.8%	3.9%	20.8%	6.4%	10.9%	100.0%

Table B.4: Paleoflow measurements from Red Member strata.

Red Member Paleocurrent Data				
Sedimentary Structure:	Alluvial Fan		Braided Stream	
	Azimuth:		Azimuth:	
Trough cross-Stratification	135°		132°	148°
	124°		106°	053°
	070°		078°	045°
	078°		077°	094°
	043°		057°	073°
			051°	045°
			094°	110°
			112°	060°
			095°	120°
			125°	165°
Mean:	090°	(n=5)	092°	(n=19)
Ripple cross-Lamination	117°			
	117°	(n=1)		
Imbricated Clasts	122°	(n=5)	171.25°	(n=4)
	100°	(n=3)	161.55°	(n=11)
			106.2°	(n=6)
	111°		146°	
Ripple Marks	120°/300°		110°/290°	
	120° / 300°	(n=1)	110° / 290°	(n=1)
Scour Axes	140°/320°	025°/205°	015°/195°	160°/340°
	045°/225°	010°/190°	040°/220°	
	040°/220°		170°/350°	
	030°/210°		160°/340°	
	020°/200°		170°/350°	
	044° / 224°	(n=7)	119° / 299°	(n=6)
Trough Axes	115°/295°		015°/195°	
			030°/210°	
			110°/290°	
			030°/210°	
			100°/280°	
	115° / 295°	(n=1)	057° / 237°	(n=5)

APPENDIX C:

MEASURED SECTION LEGEND,
WILLOW TANK FORMATION AND RED MEMBER
MEASURED SECTIONS

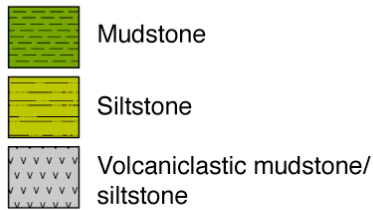
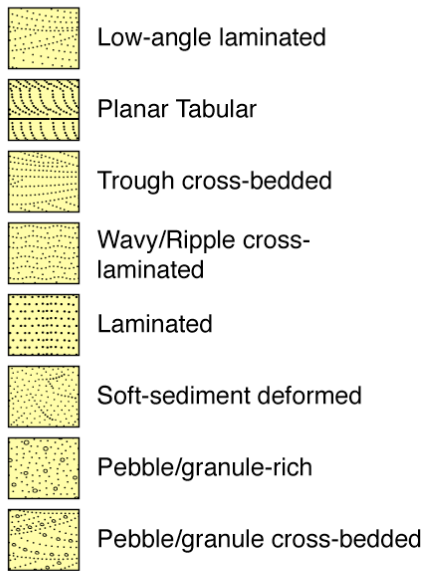
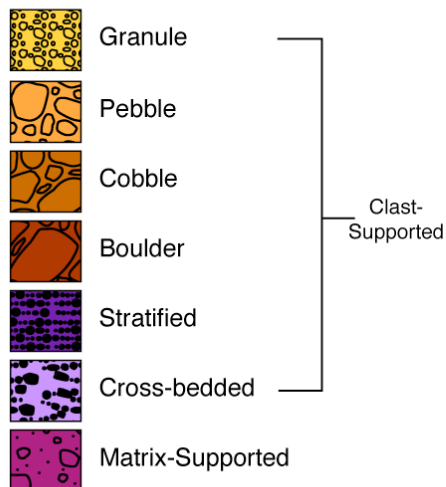
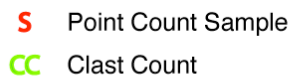
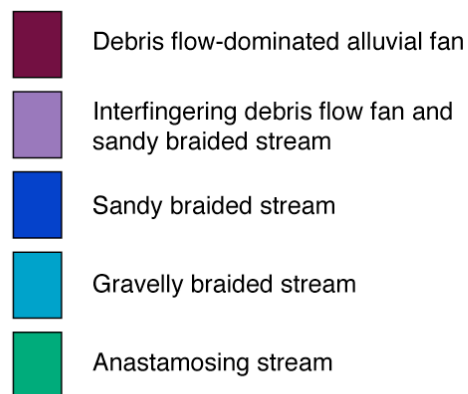
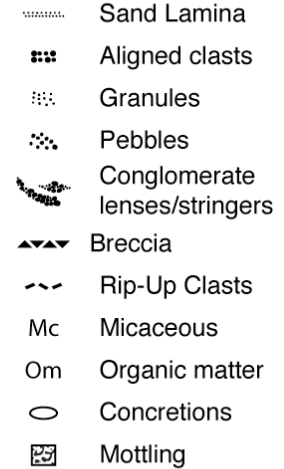
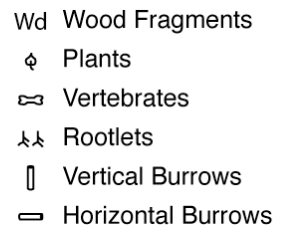
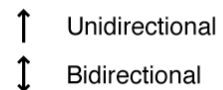
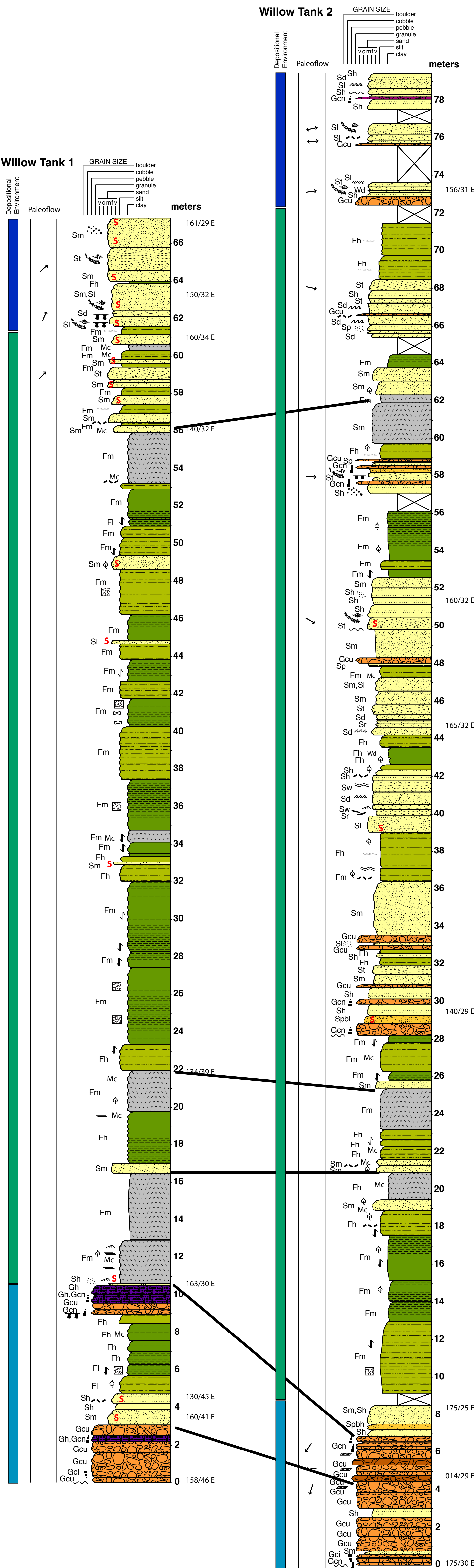
Fine-grained:**Sandstone:****Conglomerate:****Legend****Sedimentary Structures****Samples/Clast Counts****Depositional Environment****Lithologic Accessories****Fossils/Ichnofossils****Paleoflow**

Figure C.1: Legend for measured sections (Figs. C.2 - C.4).



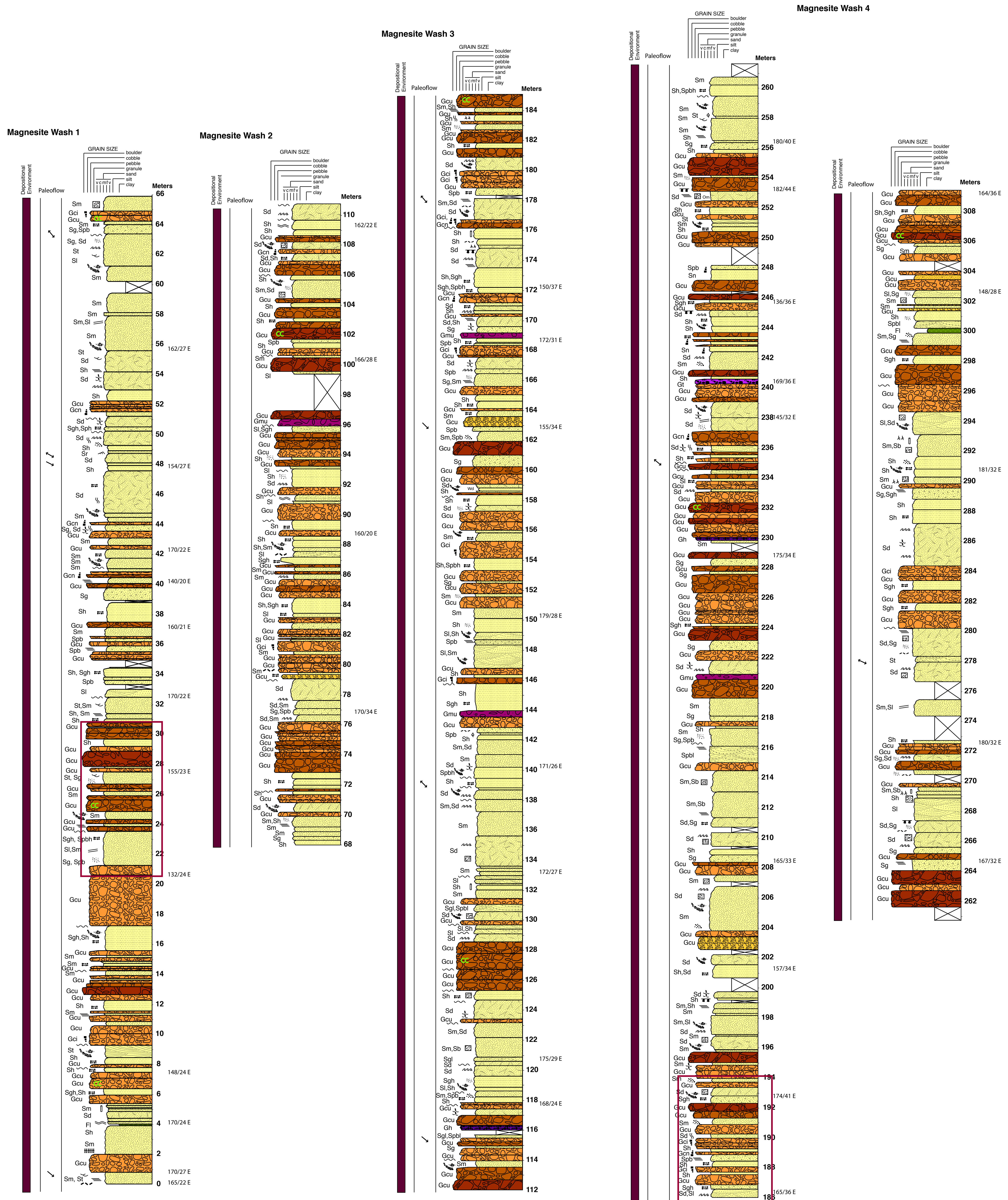


Figure C.3: Red Member Sections 1 through 4. Location of measured sections (Fig. A.1b) is included in Appendix A.

