1999

Sedimentology taphonomy and alluvial sequence stratigraphy of the Lower Two Medicine Formation (Campanian) near Choteau Montana

Eric M. Roberts
The University of Montana

Sedimentology, Taphonomy, and Alluvial Sequence Stratigraphy of the Lower Two Medicine Formation (Campanian) near Choteau, Montana

By

Eric M. Roberts

B.A. Geology and Environmental Studies, Cornell College, 1996

Presented in partial fulfillment of the requirements

For the degree of

Master of Science

The University of Montana

1999

Approved by:

Chairperson

Dean, Graduate School

12-17-99

Date

Roberts, Eric M., M.S., December 1999 Geology

Sedimentology, Taphonomy, and Alluvial Sequence Stratigraphy of the Lower Two Medicine Formation (Campanian) near Choteau, Montana

Director: Marc Hendrix

A detailed sedimentologic, taphonomic, and nonmarine sequence stratigraphic analysis was performed on the lower Two Medicine Formation (Campanian) near Choteau, Montana. $^{40}Ar/^{39}Ar$ age dates on bentonites from within the field area permit correlation with the type area of the Two Medicine Formation (near Cutbank, MT) and correlative marine units in the Western Interior Basin. Alluvial architectural analysis reveals a distinctive change in channel/floodplain ratio, channel geometry, and fluvial style mid-way through the section. This change occurs at a position in the section which is chronostratigraphically correlative with the position of the regionally extensive ~80 Ma sequence boundary that crops out in marine deposits throughout the Western Interior Basin. These changes are consistent with current nonmarine sequence stratigraphic models for third-order sea level change, and likely reflect the alluvial response to the transition from the Telegraph Creek-Eagle Regression (R7) to the Claggett Transgression (T8) in the Western Interior Seaway.

The taphonomic analysis of a newly discovered petrified forest in the field area permits new constraints on the pre-thrusting position of the Boulder batholith and Elkhorn Mountain Volcanics. The petrified forest consists of more than 200 charcoalified sub-aligned trees completely encased within an ash flow/surge tuff, dated at 80.002+/- 0.114 Ma ($^{40}Ar/^{39}Ar$ on plagioclase), and immediately overlying bentonite. The tuff and bentonite are interpreted to record a single catastrophic volcanic event that blew down and entombed the forest. The mean azimuth, which is interpreted as the paleocurrent direction for the ash flow/surge, is 047^0.

Based upon age, mineralogy, paleocurrent direction, and the absence of other penecontemporaneous volcanic centers, the Late Cretaceous Elkhorn Mountain Volcanics are interpreted as the most likely source for the tuff and bentonite that encases the trees. The mean azimuth of tree trunks is consistent with palinspastic restorations of the northern Rocky Mountain fold-thrust belt that place the Elkhorn Mountain Volcanics and their plutonic equivalent, the Boulder batholith, ~65-110 km northwest of their present position during Campanian time. This restored position is ~150-200 km from the petrified forest, making the ash flow/surge one of the farthest-traveled flows/surges ever described with enough power to topple mature trees.

ACKNOWLEDGEMENTS

I would like to express my deep appreciation to my advisor, Professor Marc Hendrix, for his support and encouragement. Thank you for your guidance and patience. I would also like to thank Dr. Ray Rogers for his role in helping me to design this thesis and for the continuous help during the course of this project. I also thank my committee members, Professor Don Winston and Professor Andrew Ware, and the rest of the Geology Department faculty at the University of Montana.

I thank my brother Scott for his invaluable help in the field and for making sure that I never suffered from a "Vitamin R" deficiency during the field season. I also thank The Old Trail Museum in Choteau, MT and Dr. David Varricchio for land access and other support in the field. I thank Jason Hinkle, the Camp Makela crew, and Chuck Miller for their assistance. This project was partially supported by a grant awarded to Dr. Marc Hendrix from the Petroleum Research Fund.

Thanks to all of my fellow graduate students, without whom I would have graduated on time. I especially blame Tip Meckel and Dave Goodwin, but I'm not forgetting about my fellow SLACKERS (esp. Mike, Jeannie, Sue) and my archenemies, the SWINGERS (Matt, Brian, Warren, Josh?, et al.). Thanks to all the others whom I failed to mention.

I also thank all my climbing partners, namely Ben Osburne, for their role in keeping me in Missoula longer than I should have been. And to Dana Hagers, whose support and love saw me through this project. Finally, I'd like to thank my parents and family for their unending support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: Variable Response to Third-Order Sea Level Change in Nonmarine Strata: Sedimentology of the Lower Two Medicine Formation, Upper Cretaceous, Montana

INTRODUCTION

Over the last 20 years the application of sequence stratigraphic concepts has provided a powerful new means of describing and predicting the geometry of sedimentary strata. Until recently, this tool has been applied exclusively to the marine realm (Vail et al., 1977). As resolution and understanding of sequence stratigraphy has improved, various workers have attempted to apply these principles and approaches to alluvial strata. Recent models and studies (Posamentier et al., 1988; Posamentier and Vail, 1988; Shanley and McCabe, 1991 and 1994; Schumm, 1993; Wescott, 1993; Wright and Marriott, 1993; Gibling and Bird, 1994; VanWagoner, 1995; Rogers, 1998) have shown that sequence stratigraphy may be equally useful in alluvial strata.

Non-marine sequence stratigraphic analysis is used to correlate primarily terrestrial rocks with their correlative marine counterparts through conceptual models linking base level change, accommodation space, sediment supply, fluvial architecture, and various other factors. Empirical sequence stratigraphic studies suggest that depositional facies occur in predictable patterns within a depositional framework (Posamentier and Vail, 1988; Shanley and McCabe, 1991; Wright and Marriott, 1993; Van Wagoner, 1995). Stratigraphic studies are commonly aimed at dividing alluvial strata into a sequence stratigraphic framework by identifying sequence-bounding unconformities and vertical changes in alluvial architecture (Shanely and McCabe, 1989, 1991, and 1993; VanWagoner et al., 1990; Gibling and Bird, 1994; and Rogers, 1998). Models have been developed from these stratigraphic studies, which suggest that during a third-order base level fall and subsequent rise, alluvial architecture should change in a predictable fashion in response to changing rates of generation of accommodation (Posamentier and Vail, 1988; Wright and Marriott, 1993). Interestingly, various models appear to be contrasting in nature. Wright and Marriott (1993) predicted that during a highstand phase, there should be an increase in channel deposits, due to the slowdown in the generation of accommodation. In addition they predicted a high channel to floodplain ratio for highstand situations and development of mature paleosols which may be poorly preserved due to erosion caused by channel migration across the floodplain. Conversely, during a transgressive phase, accommodation space is made available and the potential for floodplain storage of sediment increases, resulting in poorly developed soils, isolated channel deposits, and an overall decrease in the channel/floodplain ratio. In contrast to Wright and Marriott's (1993) model is a model developed by Posamentier and Vail (1988) and studies by Shanely and McCabe (1991) based on Upper Cretaceous rocks in the Kaiparowits Plateau of Utah. These workers suggested that isolated channel deposits and greater preservation of fines should occur during the highstand systems tract, while amalgamated channel deposits should dominate the transgressive systems tract.

The differences between these models and case examples attest to the need for additional empirical studies of this nature. Alluvial systems also respond to numerous other factors, including tectonics, climate, and slope, making it difficult to fully assess the degree to which base level change is responsible for architectural changes (Schumm, 1993; Miall, 1986). Another important factor that must be considered is lateral variation in response to base level change, which is likely to occur within the same basin or even in the same river system (Wright and Marriott, 1993; Shanely and McCabe, 1991).

TWO MEDICINE FORMATION

The Two Medicine Formation in northwestern Montana is appropriate for this kind of study because it is well studied, has excellent chronostratigraphic control, and was deposited in the Western Interior Foreland Basin, where multiple sea level cycles influenced sedimentation. The Two Medicine is a relatively thick (600 m), laterally continuous formation that extends from the Canadian border south to the town of Wolf Creek, Montana (Figure 1). The formation is part of the extensive Montana Group of Elderidge (1889) and correlates with the Eagle, Claggett, Judith River, and Bearpaw Formations in central Montana (Figures 2). The Two Medicine Formation overlies the regressive beach sandstones of the Virgelle Formation and, is in turn, overlain by the transgressive Horsethief Sandstone and/or Bearpaw shale (Lorenz, 1981). Based upon excellent ammonite zonation and radioisotopic dating of bentonites in correlative marine units (Gill et al., 1972; Gill and Cobban, 1973; and Obradovich, 1993), and on radioisotopic dating of bentonite from within the Two Medicine (Goodwin and Deino, 1989; Rogers et al., 1993), the age of the formation is well constrained and spans the Campanian Stage. It was deposited in a foredeep setting within the synevolving Western Interior foreland basin (Lorenz, 1981). Siliciclastic detritus of the Two Medicine Formation was derived from sedimentary rocks in the actively evolving thrust belt to the west and from the contemporaneous Elkhorn Mountains and possibly the Adel Mountains volcanic piles to the south and west (Figure 1).

The Two Medicine represents the proximal alluvial facies of two eastward-thinning clastic tongues deposited during two third-order regressive-transgressive cycles (R7-T8 and R8-T9 of Kauffman, 1977) in the Western Interior Seaway (Lorenz, 1981 and Rogers, 1994 and 1998)(Figure 3). The strata of the lower Two Medicine was deposited during the Telegraph Creek-Eagle regression (R7) and the Claggett transgression (T8) in the Western Interior Seaway. An 80 Ma sequence boundary delineating R7 from T8 is widely recognized throughout the Western Interior Seaway and is identified by a distinctive series of ash beds, collectively called the Ardmore bentonite, which have been dated at ~ 80 Ma (Gill and Cobban, 1973; Obradovich, 1993). Strata of the upper Two Medicine was deposited during the Claggett regression (R8) and the subsequent Bearpaw transgression (T9).

Rogers (1994 and 1998) performed a detailed stratigraphic study on the alluvial responses to both third-order sea level cycles (R7-T8 and R8-T9) in the type area of the Two Medicine Formation, near Cut Bank, Montana. In the lower part of the formation he documented an erosional discontinuity interpreted to reflect a relative drop in sea level at ~80 Ma, overlain by transgressive systems tract shoreface deposits. He interpreted this erosional discontinuity as the terrestrial expression of the ~80 Ma sequence boundary. Furthermore, he documented a change in alluvial architecture, interpreted to reflect a sedimentary response associated with turn-around from R7 to T8 in the Western Interior Seaway.

PURPOSE OF STUDY

In the study presented here, a nonmarine sequence analysis similar to that of Rogers (1998) was performed in the lower Two Medicine Formation, near Choteau, Montana (Figure 1). In order to determine whether or not the Claggett (R7-T8) sea level cycle produced any effect on alluvial stratigraphy in the Choteau area, I measured multiple sections at the sub-meter scale. Based upon a series of $^{40}Ar/^{39}Ar$ age dates on bentonites from both the Type area and the Choteau area (Rogers et al., 1993), strata between the two localities can be correlated with relative precision. A disconformity (80 Ma sequence boundary) recording the transition from R7-T8 does not exist in the Choteau area, as it does in the type area. However, the relative position of the sequence boundary can be inferred with excellent precision in the Choteau area by dated ash beds and a distinctive lithic-crystal tuff bed. Rogers et al. (1993) dated the lithic-crystal tuff and an immediately overlying bentonite horizon to 80.002 +/- 0.114 and 79.771 +/- 0.096 Ma (Ar^{40}/Ar^{39} on plagioclase) respectively. These age dates are correlative with the 80 Ma sequence boundary, providing an indirect link to the transition from R7 to T8 in the Choteau section. The Two Medicine section is hence divided into two alluvial packages corresponding to deposits above and below the sequence boundary.

The purpose of this thesis, once good chronostratigraphic control was established in the lower Two Medicine, was three-fold. The primary objective was to test whether or not sea level change, associated with the transition from R7 to T8, had any effect on alluvial stratigraphy in the Choteau area. Second, to compare the results of this study with two current and sharply contrasting non-marine sequence stratigraphic models. And finally, to compare the lateral variations in alluvial response to the R7-T8 sea level cycle, which are recorded between the Type (Rogers, 1998) and the Choteau areas (this study) of the Two Medicine Formation.

STRATIGRAPHY AND SEDIMENTOLOGY

This study focuses on exposures of Two Medicine strata ~10-15 km south of Choteau, MT along Highway 89 (Figures 4 and 5). Seven relatively undeformed sections in the 7-Mile Hill, Old Trail, and Robinson areas (all within 5 km of each other) were measured using a Jacob staff and Brunton compass and described at sub-meter scale (Figures 5 and 6-12). The individual sections vary from 30-140 meters in length and cover overlapping intervals of the stratigraphic column. Individual sections are correlated on the ~80 Ma lithic-crystal tuff horizon (Figure 13 and 14), which crops out throughout the field area and 15 km to the southwest along the Sun River.

Lithofacies

The facies of the lower Two Medicine Formation were classified using the schemes of Miall (1978) and Eberth and Miall (1991), with some minor additions (Table 1). Massive and laminated siltstone and claystone (Fl) are common in many environments and are typically bentonitic and locally contain invertebrate and vertebrate fossils, petrified wood, leaf and pinecone impressions, and trace fossils. At least 13 pure bentonite (Fb) horizons crop-out in the field area, each containing fresh biotite and plagioclase crystals and several containing charcoalified wood. Paleosols are uncommon, but are locally found within the R7 alluvial package. Sandstone units commonly display trough crossbedding (St), which falls into either small (Stii) or large (Sti) scale sets. The mean paleocurrent direction measured on troughs of crossbeds for all sandstones in the study area is 97.6^0

(n=194)(Figure 15), suggesting transverse river systems flowing eastward out of the syn-evolving foreland fold and thrust belt. Ripple cross-lamination (Sr) and planar bedding (Sp) are also fairly common. Diagenetic carbonate nodules (Ld) are quite common throughout the field area and invariably crop-out along lithologic boundaries in flat lying clusters.

Miall (1996) used the term architectural elements to define individual "component(s) of a depositional system equivalent in size to, or smaller than a channel fill, and larger than an individual facies unit, characterized by a distinctive facies assemblage, internal geometry, external form, and (in some instances) vertical profile". Following the classification systems established by Eberth and Miall (1991) and Miall (1996), with minor modifications, the Two Medicine Formation has been subdivided into 4 different architectural elements (Table 2): (1) major sandstone sheets; (2) major sandstone ribbons; (3) minor sandstone sheets and lenses; and (4) floodplain fines. Ribbon sandstones are distinguished from sheet sandstones using the criterion established by Friend et al. (1979) and Friend (1983), whereby sheets exhibit width/thickness ratios greater than 15 and ribbons have width/thickness ratios less than 15.

Major sandstone sheets

This element is characterized by high width/thickness ratios, generally exceeding tens of meters in length by .5-5 meters in thickness. Major sandstone sheets are usually arranged in stacks as multiple amalgamated storeys or as individual sheets interbedded with thin floodplain fines (Figure 16). Grain size is commonly fine to medium sand, with poorly developed upward-fining sequences locally present near the tops of beds. Trough cross stratification (Sti and Stii) is most common (Figure 17), with lithofacies Gm, Sr, Se, Sp, and Sh also common. Lag deposits (Gm) are typically found near the bases of individual sheets and are almost exclusively composed of intraformational mudstone clasts, fresh water mollusc shells (*Unio sp., Physa sp., Viviparus sp., and Lioplacodes sp.)*, petrified wood, and dinosaur bone fragments (Figure 19). Ripple cross lamination (Sr) is found near the tops of individual storeys and sheets and probably indicates waning flow conditions (Figure 18). Paleocurrent measurements on troughs of cross beds indicate unimodal eastward flow directions, with a mean azimuth of 98° (n=136)(Figure 15).

Interpretation of major sandstone sheets

These sandstones are interpreted as either broad, shallow, low-sinuosity, fluvial channel deposits or as unconfined sheet flow deposits. They are frequently characterized by basal mudstone rip-up lag deposits, internal scour surfaces, and planar stratification with parting lineations, all suggestive of at least partial deposition under ephemeral flow conditions (Picard and High, 1973; and Eberth and Miall, 1991).

Major sandstone ribbons

Ribbon sandstones typically display width/thickness ratios less than 15, being thicker and more laterally confined than sheet sandstones (Figure 20). They are commonly poorly indurated and hard to trace laterally, making lithofacies identifications difficult. They are mostly isolated from each other and encased within thick sequences of floodplain fines. There is no evidence for lateral accretion surfaces. The sandstone is generally composed of fine-medium grained sand, dominated by trough cross stratification (Sti and Stii), with local planar cross bedding (Sp), erosional scours (Se), and intraclast lag deposits (Gm). Local shell concentrations (*Unio sp., Physa sp., Viviparus sp., and Lioplacodes sp.*), petrified wood, and dinosaur bones are common. Paleocurrent measurements on trough crossbeds indicate unimodal eastward flow directions (mean= 97^0, n=58) (Figure 15).

Interpretation of major sandstone ribbons

The major ribbon sandstone bodies are also interpreted as fluvial in origin and judging by their low width/thickness ratios (<15), their lack of lateral accretion deposits, and their unimodal paleocurrent directions, they probably represent stable, low-sinuosity, fixed channel deposits. These characteristics are consistent with ribbon sand bodies described from other formations including the Cutler Formation of New Mexico (Eberth and Miall, 1991) and the St. Mary River Formation of Alberta (Nadon, 1994), both of which are interpreted as anastomosed fluvial deposits. It is possible that the ribbon sandstones in the study area may also represent anastomosed fluvial deposits.

Minor sandstone sheets and lenses

The minor sandstone sheets and lenses are generally between .2-1 meters thick and they extend laterally for tens of meters, with the sheets (~25-100+ m) being more extensive than the lenses (~5-25 m). This element is composed of fine sand-silt sized particles and is frequently interbedded between thick (.5-15 m) packages of floodplain fines. The most common facies associations are Sh and Sr (Figure 21). Tops of many units are extensively bioturbated (Figure 22).

Interpretation of minor sandstone sheets and lenses

The minor sandstone sheets are interpreted as crevasse splays or sheet splays deposited during periods of overbank flooding or sheet flooding (Miall, 1996). The minor sandstone lenses likely represent either crevasse channel deposits or small fluvial channels. The abundance of crevasse splays and potentially crevasse channels throughout the formation suggests that seasonal flooding was common and sedimentation rates were relatively high in the Two Medicine Formation at that time.

Floodplain fines

This element is predominantly composed of thick packages of massive mudstone lithofacies (Fl) (up to 10-15 m thick), interbedded with thin, wispy sand and silt horizons (.1-1m thick). The mudstone is commonly bentonitic and/or sandy, drab green colored, and blocky. Thin coal seams (C) (.05-.3m thick), invertebrate shells, and dinosaur bones occur locally. As many as 13 pure bentonite horizons (B)(.4-2 m thick) were identified within the floodplain fines (Figure 23). Siltstone beds (fl) commonly preserve invertebrate shell concentrations and leaf impressions. Uncommon, but well developed paleosols are found in the study area, composed of red color banding, mottling, and slickensides in mudstone (Figure 24), and root traces, rare ferruginous nodules, and yellow-orange mottles within sandstone.

Interpretation of floodplain fines

This element represents deposition of fine-grained sediment in floodplain environments (Lorenz, 1981). These are likely suspension deposits produced when overbank flooding caused temporary inundation of the floodplain. The massive bedding of the mudstone suggests intense bioturbation. The paleosols are most likely spodosols, because of their red color banding and lack of caliche (Mack et al., 1993).

CORRELATION OF THE LOWER TWO MEDICINE FORMATION WITH THE R7-T8 SEA LEVEL CYCLE

Fluvial processes on a broad, low relief alluvial plain deposited the lower Two Medicine Formation in the study area during the R7-T8 sea level cycle. Chronostratigraphic correlation with transgressive-regressive events in the seaway and with strata in the type area of the Two Medicine formation permit assessment of the alluvial response to base level change in the study area. The Choteau section can be subdivided into regressive and transgressive alluvial facies below and above the distinctive lithic-crystal tuff dated at ~80 Ma. The lithic-crystal tuff is correlative with the Ardmore bentonite (~80 Ma sequence boundary), which delineates R7 from T8 in the Western Interior Seaway. Thus, strata below the inferred position of the sequence boundary correlate with the R7 regressive phase of the Claggett sea and deposition during the highstand systems tract, a period of slow relative sea level rise, stillstand, and slow relative sea level fall. Conversely, strata above the sequence boundary correlate with the T8 transgressive phase of the Claggett sea and deposition during the transgressive systems tract, a period of relative sea level rise.

COMPARISON OF STRATA BELOW AND ABOVE THE INFERRED POSITION OF THE ~80 MA SEQUENCE BOUNDARY

After measuring and drafting sections of the lower Two Medicine Formation in the study area, I was then able to compare strata from above and below the inferred position of the sequence boundary. Significant differences, including changes in the channel/floodplain ratio, distribution of architectural elements, and presence/absence of paleosols were identified above and below the inferred position of the sequence boundary.

Below the inferred position of the sequence boundary in R7, the section is marked by a channel/floodplain ratio of 1.33 and a preponderance of major sheet sandstones, which increase in both density and thickness upwards (Figures 6-13). The R7 portion of the section volumetrically contains lesser amounts of floodplain fines, fewer minor sandstone sheets and lenses, and fewer major sandstone ribbons than T8 (Figure 13). Paleosols are rare, but do exist below the inferred position of the sequence boundary (Figure 13).

Above the sequence boundary in T8, the channel/floodplain ratio decreases dramatically to .56 (Figure 13). The section displays a major increase in floodplain fines, as well as minor sandstone sheets and lenses and major sandstone ribbons (Figures 6-12). Also in T8, major sandstone sheets, which dominate R7, are rare, and major sandstone ribbons are more common, typically isolated and packaged between thick sequences of floodplain fines. Finally, there is no evidence for paleosol development in T8.

DISCUSSION

As discussed above, evidence from this study indicates that an abrupt change in fluvial style coincides with the turn-around from R7 to T8 within the Western Interior Seaway. No major unconformity or hiatus was identified within the study area, except for minor erosional scour at the base of some channel sandstones. In contrast, work by Rogers (1998) described an 80 Ma sequence bounding disconformity in the type area of the Two Medicine Formation near Cut Bank, establishing a record of the R7-T8 turn-around within the formation. Significant changes in alluvial architecture were noted in this study across the inferred position of the 80 Ma sequence boundary in the Choteau area. The ratio of channel/floodplain deposits shifts from 1.33 below the inferred position of the sequence boundary to .56 above it. R7 is dominated by sheet sandstones, which are interpreted to represent either broad, shallow, low-sinuosity channel deposits or unchannelized sheet-flood deposits. These sandstones are interbedded with floodplain fines, including rare, but moderately well developed paleosols. In contrast, floodplain fines, which show little evidence of paleosol development, and isolated major ribbon sandstones, interpreted as possibly anastomosing style rivers, dominate T8.

Architectural changes recorded above and below the 80 Ma sequence boundary in the study area may be interpreted to reflect an alluvial response to base level change. Alternatively, these architectural changes might reflect an alluvial response to regional or local tectonics, climate change, or a myriad of other intrinsic or extrinsic factors. This question is one of major importance and must be considered.

Tectonic vs. Eustatic Controls

The question of whether tectonic or eustatic controls influenced alluvial architectural changes in the study area must be addressed before placement of the section into a sequence stratigraphic framework can be attempted. Although numerous intrinsic and extrinsic factors effect alluvial systems, in this situation, the primary control on alluvial stratigraphy was probably eustasy. The preponderance of evidence suggests that the changes in alluvial architecture in this study are correlative with a widespread (~80 Ma) sequence boundary, which affected stratigraphy throughout the Cretaceous Western Interior Seaway. Extensive subaeriel exposure and regional truncation has been attributed to this regional or potentially global fall in sea level at ~80 Ma (DeGraw, 1975; Shurr and Reiskind, 1984; Van Wagoner et al., 1990). This sequence boundary can be correlated throughout marine deposits of the Niobrara Formation and the Pierre Shale, as far away as North Dakota, South Dakota, and Nebraska. It is commonly characterized by tens of meters of erosional relief and in some cases north-south trending trellis drainage patterns (DeGraw, 1975; Shurr and Reiskind, 1984; and Weimer, 1988). This same unconformity was identified in the Powder River Basin of eastern Wyoming and described as a type 1 (80 Ma) sequence boundary by Van Wagoner et al. (1993). The sequence boundary is overlain in many parts of the basin by the extremely extensive Ardmore bentonite, a composite marker horizon composed of numerous individual bentonite beds, and well dated at ~80.54+/- 0.55 Ma (Obradovich, 1993). Evidence in support of an even more global sea level change at 80 Ma is supported by correlative unconformities in the Woodbury Formation of New Jersey (Olsson, 1991) and by an early Campanian regressive event documented in western Europe (Hancock, 1975) and Israel (Flexer et al., 1986).

Rogers (1998) described an extensive erosional disconformity embedded within fluvial sandstone sheets in the type area of the Two Medicine Formation near Cut Bank, Montana, which he interprets as the terrestrial expression of the ~80 Ma sequence boundary. Nearby ash horizons were dated and confirm the chronostratigraphic relationships (Rogers et al., 1993). This disconformity is in the same stratigraphic position where other workers have placed the transition from regressive to transgressive phases within the Two Medicine Formation (Stebinger, 1914; Cobban, 1955; Lorenz, 1981).

Sedimentologic data from the type area of the Two Medicine Formation indicates no evidence for tectonic rejuvenation of the Cordilleran fold-and-thrust belt such as a change in provenance or extraformational clasts (Rogers, 1998). Similarly, there is no evidence of extraformational clasts or provenance changes in this study of the Two Medicine Formation, near Choteau, Montana. Although the Rocky Mountain fold-thrust belt was active during this time, there is no direct evidence for major tectonic activity affecting the Two Medicine at 80 Ma. It should be emphasized that although ecstasy is most likely the driving force for the changes in alluvial architecture documented in this study, the potential role of climate, local tectonics, and other intrinsic and extrinsic factors are difficult to fully assess and should not be ignored.

Comparison with Sequence Stratigraphic Models

The changes in alluvial architecture described above provide an opportunity to compare an empirical stratigraphic study with recent models of alluvial sequence stratigraphy (Posmentier and Vail, 1988; Schumm, 1993; Wescott, 1993; Wright and Marriott, 1993; Zhang et al., 1997). The alluvial responses to base level documented here are most consistent with the model offered by Wright and Marriott (1993). They predict that during the highstand phase, when the rate of eustatic sea level rise decreases to zero, the generation of accommodation decreases, reducing storage space within the system and causing rivers to comb their floodplains and rework fines (= high channel/floodplain ratio). Although they suggest that meandering rivers would normally dominate in this phase, they also suggest that a braided pattern may be expected if gradient is high enough. Mature paleosols should also develop, although they may not be well preserved due to fluvial reworking. R7 in the study area corresponds to deposition during the highstand systems tract (Rogers, 1998). Strata of the R7 package is marked by high channel/floodplain ratio, stacked sheet sandstone bodies, and the development of paleosols, which are all consistent with Wright and Marriott's model for highstand phase.

In the model by Wright and Marriott (1993), the transgressive phase is identified by an increase in the generation of accommodation space, allowing floodplains to store sediment, and the alluvial stratigraphy to be dominated by isolated channels packaged between thick sequences of floodplain fines (= low channel/floodplain ratio). Again these predictions are in agreement with the alluvial record of the transgressive systems tract (T8) in the study area, which is dominated by floodplain fines, crevasse splays, and isolated fluvial channels. Paleosol development is minimal in strata of the T8 alluvial package in the study area, which is also consistent with the model. Zhang et al. (1997) predicts similar alluvial responses to occur during the transgressive phase, in particular the development of anastomosing fluvial systems and low channel/floodplain ratios.

Comparison of Lateral Differences in Alluvial Response to R7/T8 Across the Two Medicine Formation

Wright and Marriott (1993) questioned the extent to which base level / sea level affects different parts of a river system. This question also relates to what affect base level / sea level change has on different areas within the same depositional system. Shanely and McCabe (1991) provided evidence that alluvial response to base level change can vary laterally across a formation. This study also reveals differences in alluvial response to base level change within the Two Medicine Formation.

Rogers (1994 and 1998) described the alluvial responses to the R7/T8 sea level cycle in the type section of the Two Medicine formation near Cut Bank, Montana, 75 km north of the study area described in this chapter. In the type area of the Two Medicine Formation, an erosional disconformity marks the 80 Ma sequence boundary and deposits of marine and marginal marine facies crop-out above the sequence boundary in T8 strata. Neither an erosional sequence bounding disconformity, nor marine or marginal marine depositional strata were identified in the Choteau area. Lorenz (1982) suggested that the Sweetgrass Arch, a Paleozoic tectonic feature, might have produced enough of a topographic barrier during Late Cretaceous time to partially deflect the Claggett Transgression from reaching the Choteau area. Alternatively, differences in accommodation space, subsidence rates, sediment supply, or local tectonics between the two areas may have produced these differences. Rogers (1998) also noted an up section decrease in the sandstone-body thickness and channel/floodplain ratio beneath the 80 Ma sequence boundary. This contrasts with an upward increase in both density and thickness of major sheet sandstones beneath the sequence boundary in the Choteau area. He interpreted this trend in the type area to be a physiographic artifact related to shifting positions on the stream profile, caused by domination of early highstand by large distributary channels/river mouths. The lateral variation in alluvial response to the R7/T8 marine cycle documented between the type area and the Choteau area provides evidence of the complex relationship between sea level change and alluvial stratigraphy.

CONCLUSIONS

The lower Two Medicine Formation near Choteau, Montana is characterized by fluvial deposition across a broad, flat alluvial plain. A distinctive change in fluvial style and channel/floodplain ratio occurs in the section. The change is chronostratigraphically correlative with the transition from the R7 regressive phase to the T8 transgressive phase in the Western Interior Seaway and is interpreted to reflect the alluvial response to a third-order sea level cycle. This provides an opportunity to test recent models of alluvial sequence stratigraphy against empirical stratigraphic study presented in this chapter.

The R7 section of the Two Medicine Formation displays a high channel/floodplain ratio (1.33), paleosol development, and abundant stacked sheet sandstone bodies, probably representative of shallow, low-sinuosity, fluvial channels or unconfined sheet flows. These characteristics are consistent with the model presented by Wright and Marriott (1993) for alluvial response to base level change during a highstand phase. An abrupt shift in alluvial architecture occurs at the inferred stratigraphic position of the 80

Ma sequence boundary. The key elements characterizing the section above the sequence boundary include low channel/floodplain ratio (.56), poor paleosol development, and isolated (possibly anastomosing) ribbon sandstone channels packaged in thick deposits of floodplain fines. This part of the section (T8) is also consistent with predictions for alluvial architecture during the transgressive phase in Wright and Marriott's model (1993).

Alluvial response to base level changes occurred laterally within different areas of the Two Medicine Formation approximately 75 km apart. The Two Medicine Formation near Cut Bank contains an erosional disconformity, corresponding to the 80 Ma sequence boundary. The T8 section in the Cut Bank area contains a thin sequence of brackish and shallow marine facies. Neither the sequence boundary, nor a marine incursion in the T8 alluvial package is recorded in the Choteau area. However, alluvial architectural changes are similar between the two areas. The variations recorded between the two areas likely represent local differences in paleogeography, accommodation space, subsidence rates, sedimentation rates, and local tectonics. This study shows the potential for intra-basinal variation in alluvial response to base level change. It also provides further empirical evidence useful for refining models used to predict alluvial sequence stratigraphy.

TABLE 1

Lithofacies types in the Two Medicine Formation, based upon Miall (1996) and Eberth and Miall (1991).

Facies	Lithology	Sedimentary Structures	Interpretations
Gm	intraformational mudstone clasts	crude stratification; clast framework	Lag deposits
Se	v. coarse to pebbly Ss; rip-up clasts	crude stratification; scours up to .5 m deep	Erosional scours
Sh	fine-coarse ss.	parting lineation	Plane-bed flow
Sti	fine-coarse ss.	tcs > 50 cm	Lower flow regime, 3D-dunes
Stii	fine-coarse ss.	tcs < 50 cm	Lower flow regime, 3D-dunes
Sp	fine-coarse ss.	planer crossbed sets	Lower flow regime, 2D-dunes
Sr	v. fine-coarse ss.	ripple cross lamination Sets < 4 cm thick	Lower flow regime, ripples
Fl	siltstone-claystone	massive-laminated	Suspension deposits
Fb	bentonite	massive	Pyroclastic air fall or flow deposits
Ld	silty-sandy carbonate	nodular	Postdepositional diagenetic nodules
C	coal, carbonaceous mud	plant, mud films	Vegetated swamp Deposits

TABLE 2

Characteristics and interpretations of architectural elements from the Two Medicine Formation

Element	Distribution	Geometry	Lithology	Lithofacies	Interpretation
Major sandstone sheet (CHS)	abundant below inferred seq. bndry; rare above it	w/d > 15; < km wide; .5-5 m thick	fine-med. ss.; intraform. lags	Sti, Stii, Sh, Gm, Se, rare Sp	Braided fluvial channel
Major sandstone ribbons (CHR)	rare below seq. bndry; abundant above it	w/d < 15; < 25m wide; <10m thick	fine-med. ss.; intraform. lags	Sti, Stii, Sh Sk, Gm, Se, rare Sp	Anastomosed fluvial channel
Minor sandstone sheets and lenses (CS)	more abundant above than below seq. bndry	tabular; .2-1 m thick; laterally extensive	mostly fine ss.	Sh, Sti, Sr, Se	Crevasse splays and crevasse channels
Floodplain fines (FF)	more abundant above than below seq. bndry	< 15 m thick	mostly massive mudstone, with thin ss. and slt. interlaminations	Fl, Fb, C, Ld	Floodplain deposit and paleosol

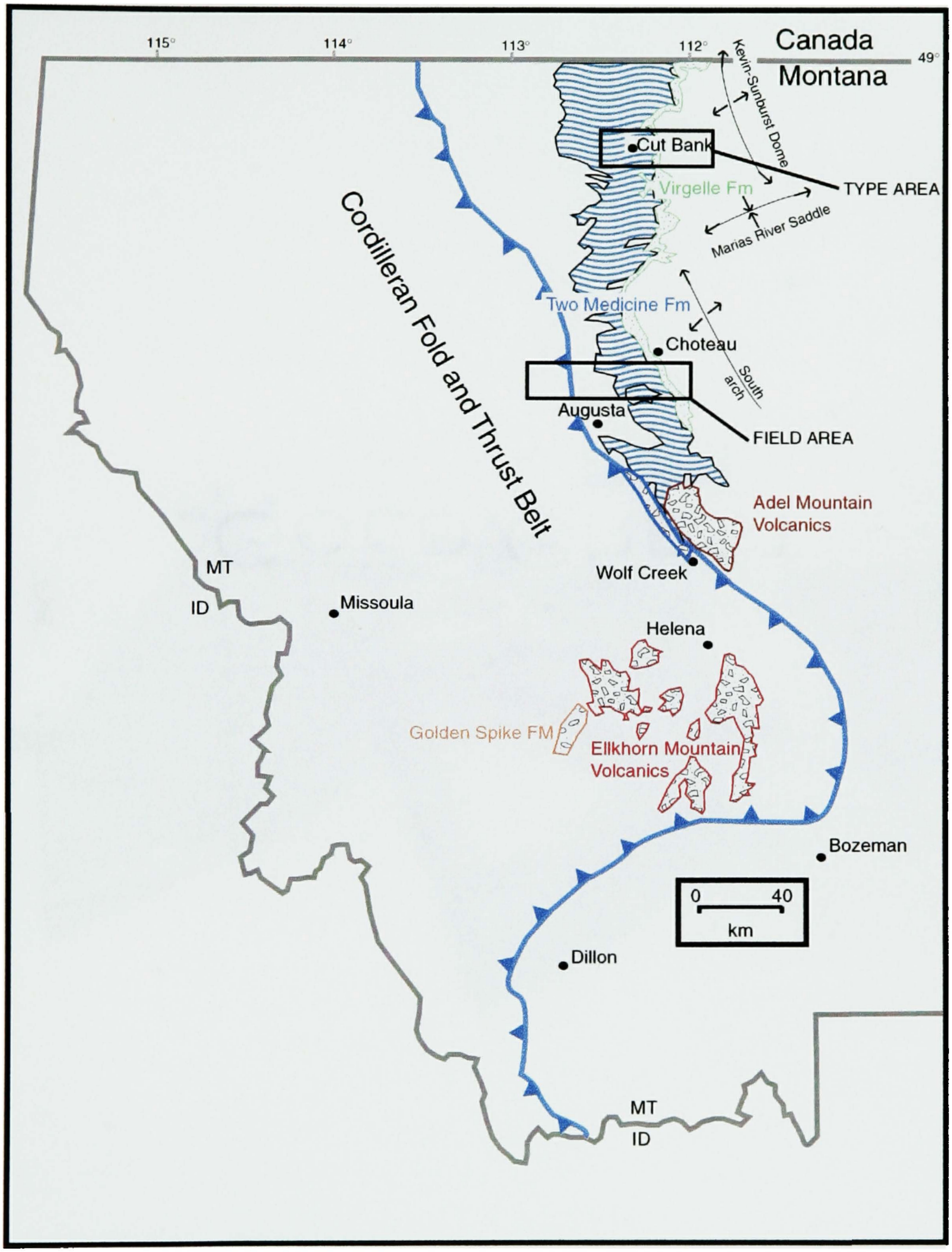

Figure 1.1. Regional tectonic map showing the study area and the type area in the Two Medicine Formation and related features in northwest Montana (modified from Rogers et al., 1993; and Lorenz and Gavin, 1984).

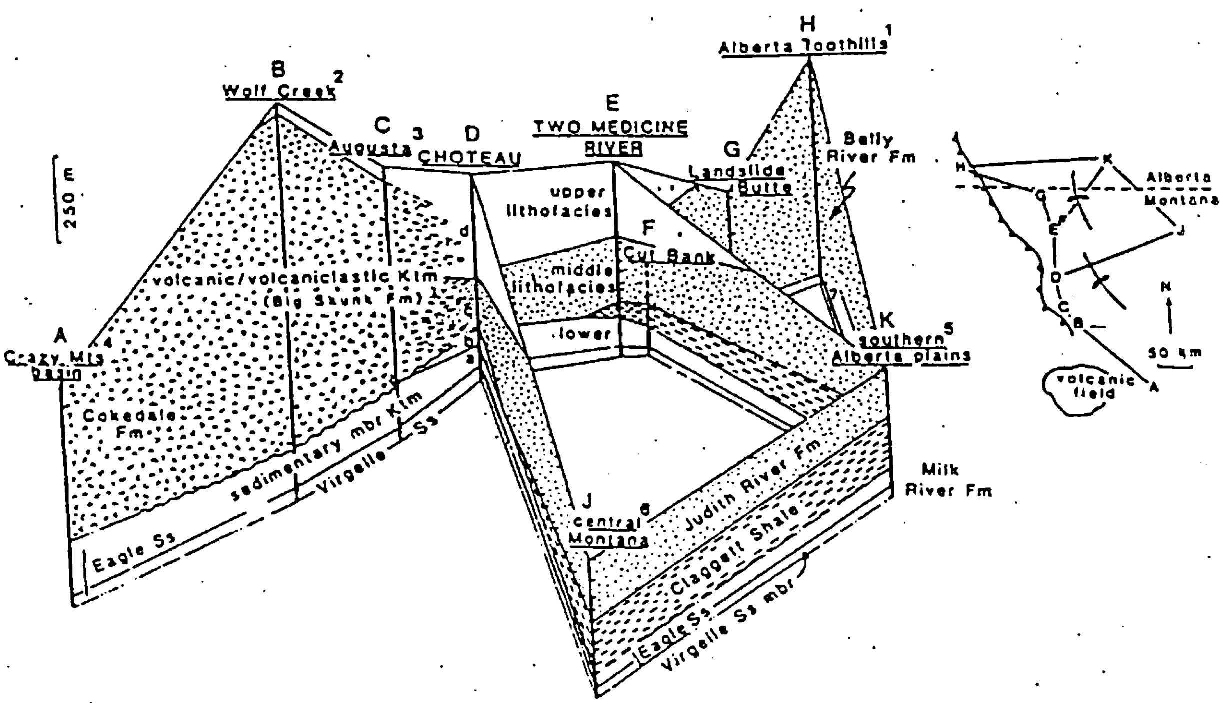

Figure 1.2. Fence diagram showing the stratigraphy of the lithofacies of the Two Medicine Formation and correlative formations. From Lorenz and Gavin (1984).

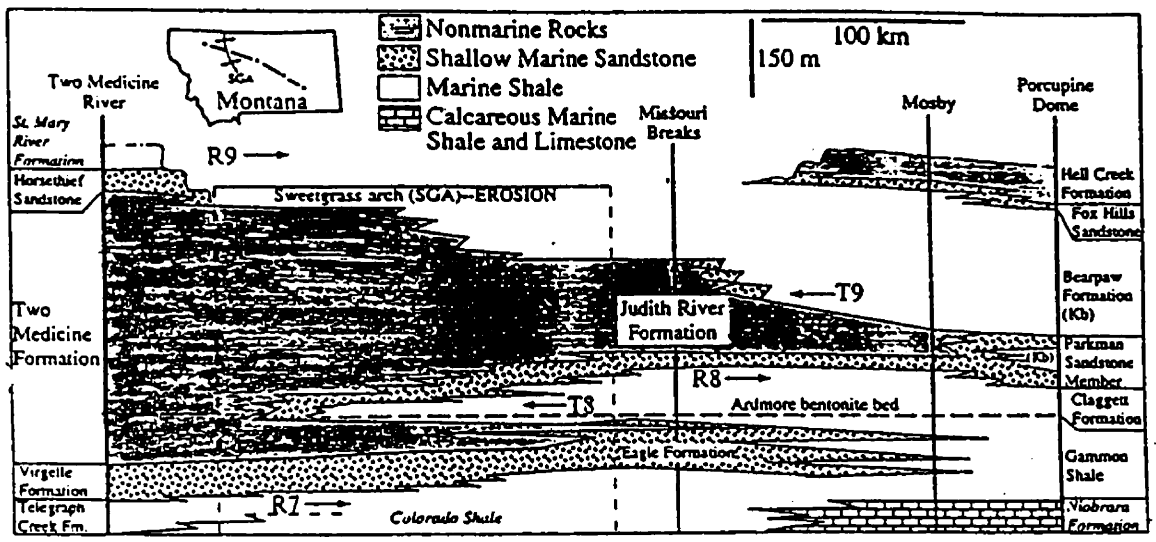

Figure 1.3. Schematic cross section of Montana Group, showing sea level cycles of Kauffman (1977). Italicized units are not included within the Montana Group. From Rogers (1998).

Figure 1.4. Typical badland style exposures of the lower Two Medicine Formation near Choteau, MT.

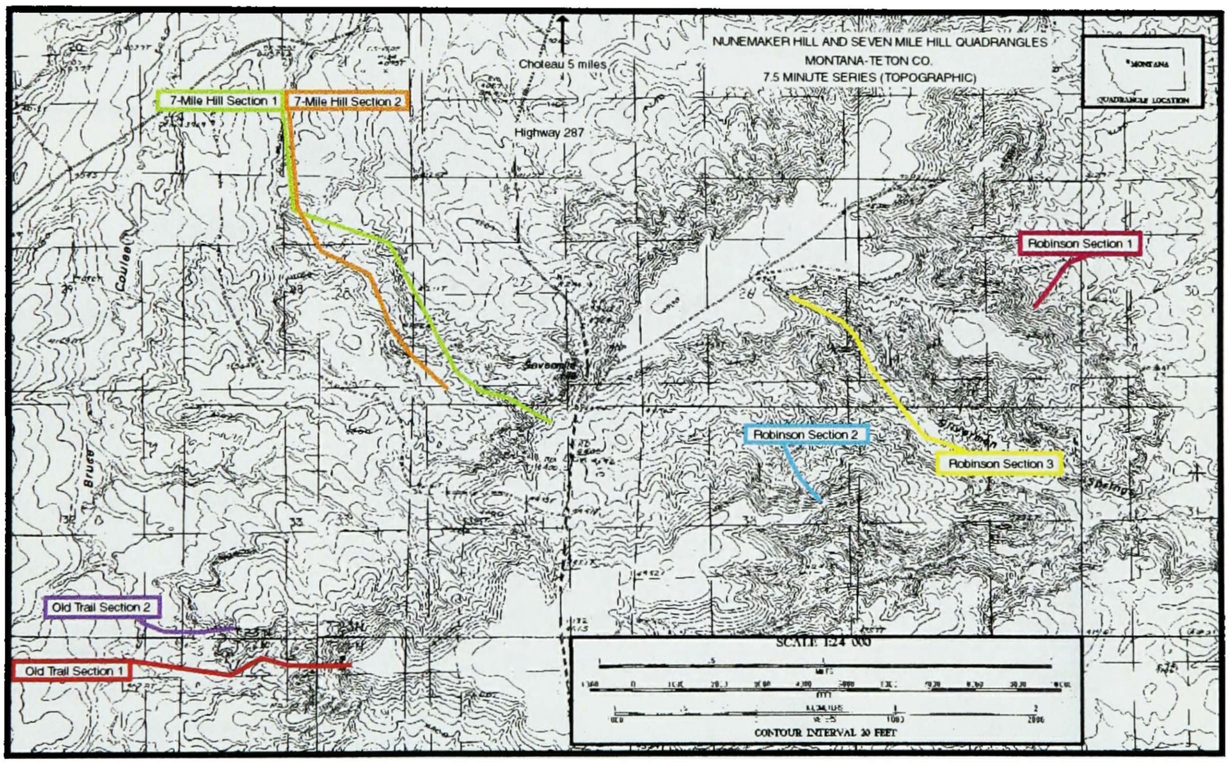

Figure 1.5. Topographic map of study area ~10 km south of Choteau, Montana, with the positions of individual sections marked by solid lines.

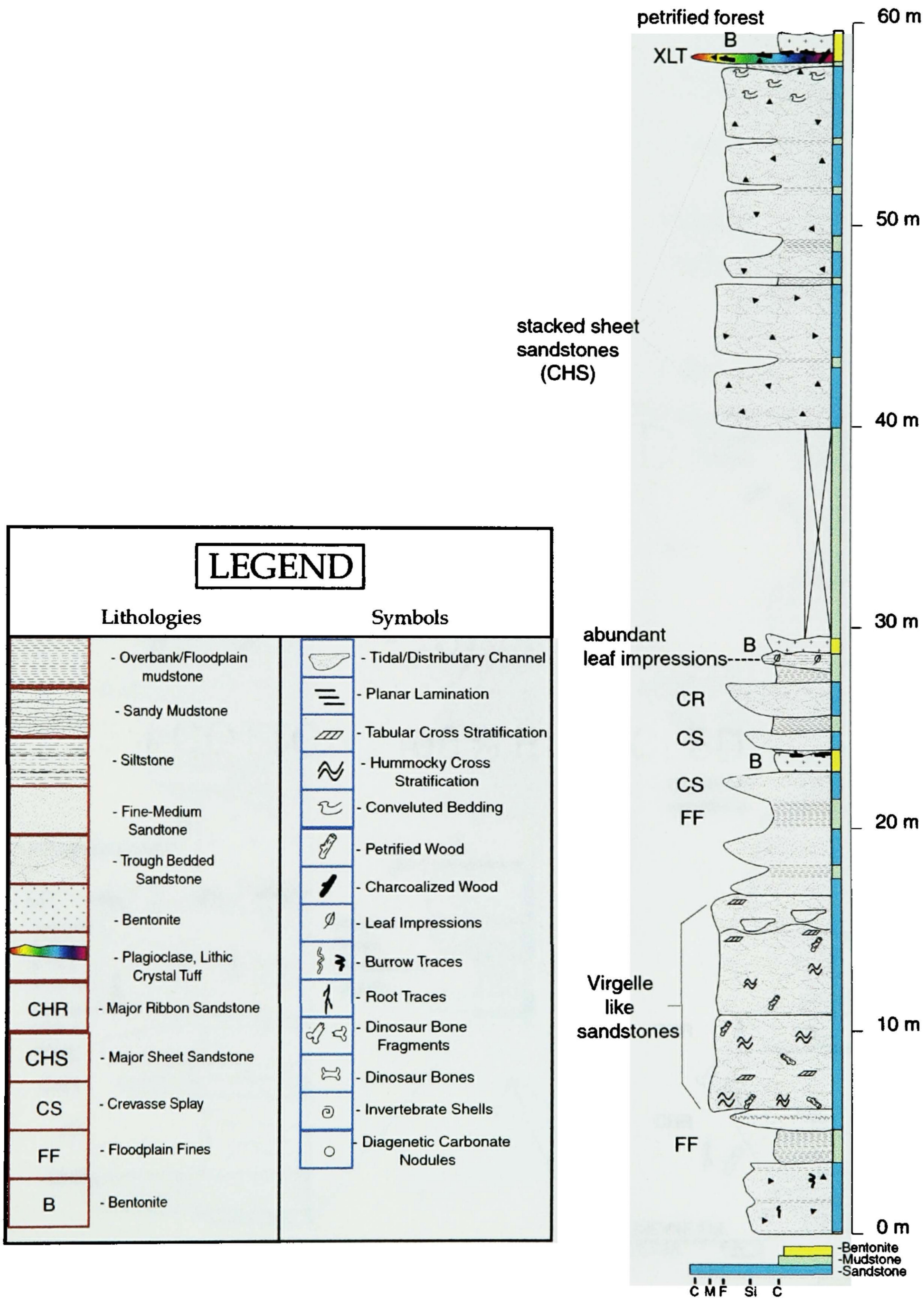

Figure 1.6. 7-Mile Hill Section 2. Legend covers all measured sections in this study.

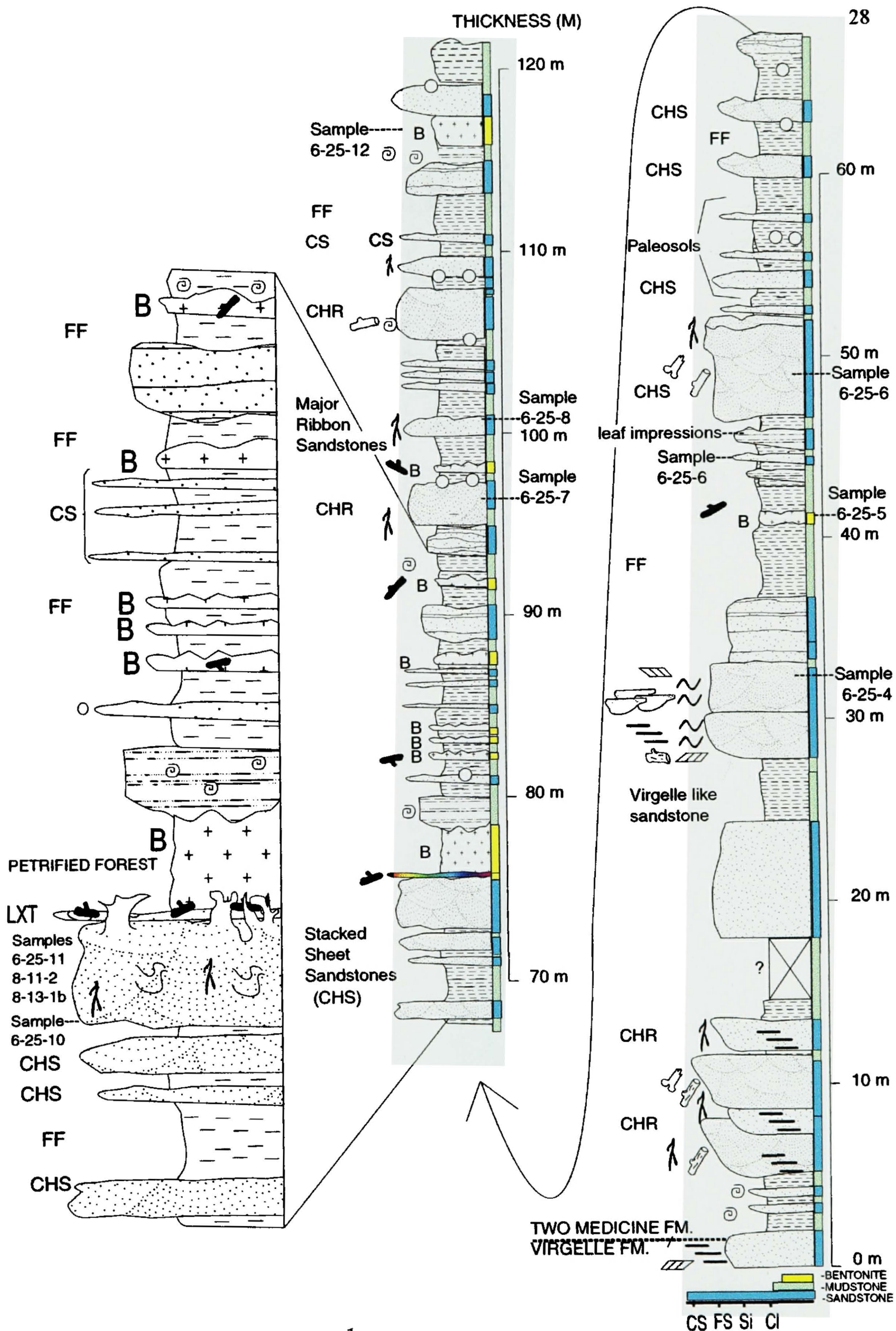

Figure 1.7. 7-Mile Hill Section [1].

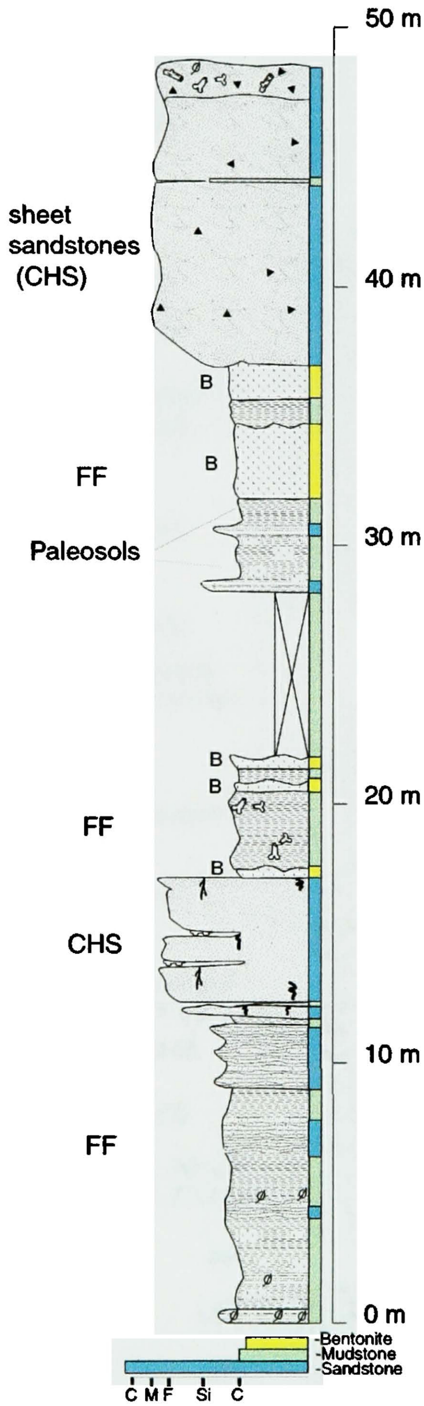

Figure 1.8. Robinson Section 1.

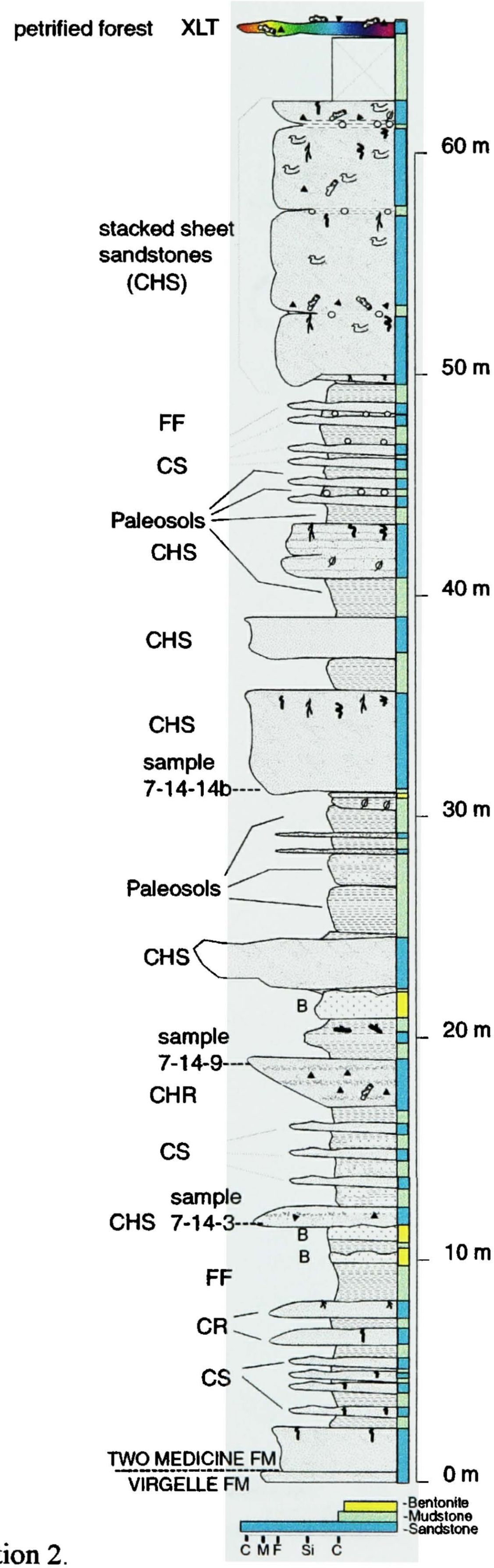

Figure 1.9. Robinson Section 2.

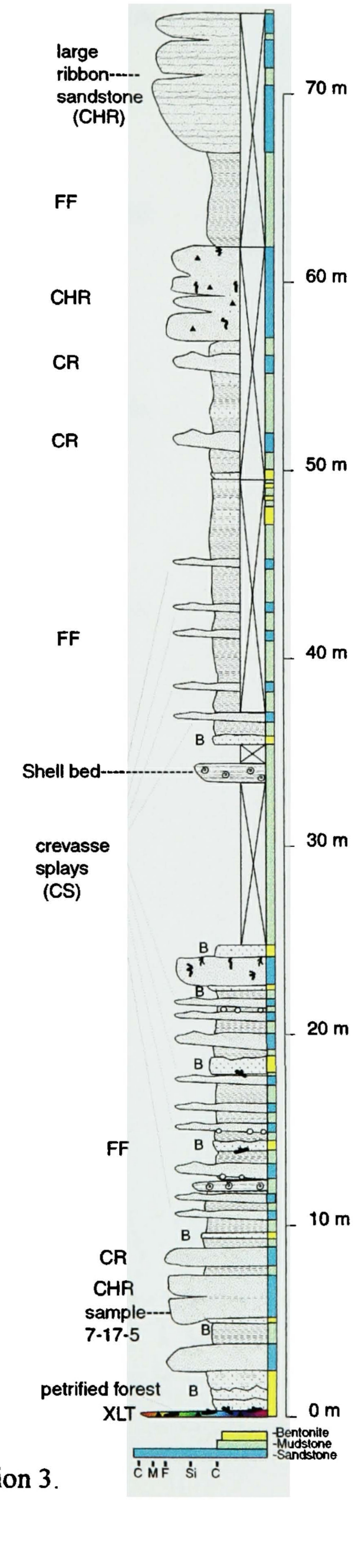

Figure 1.10. Robinson Section 3.

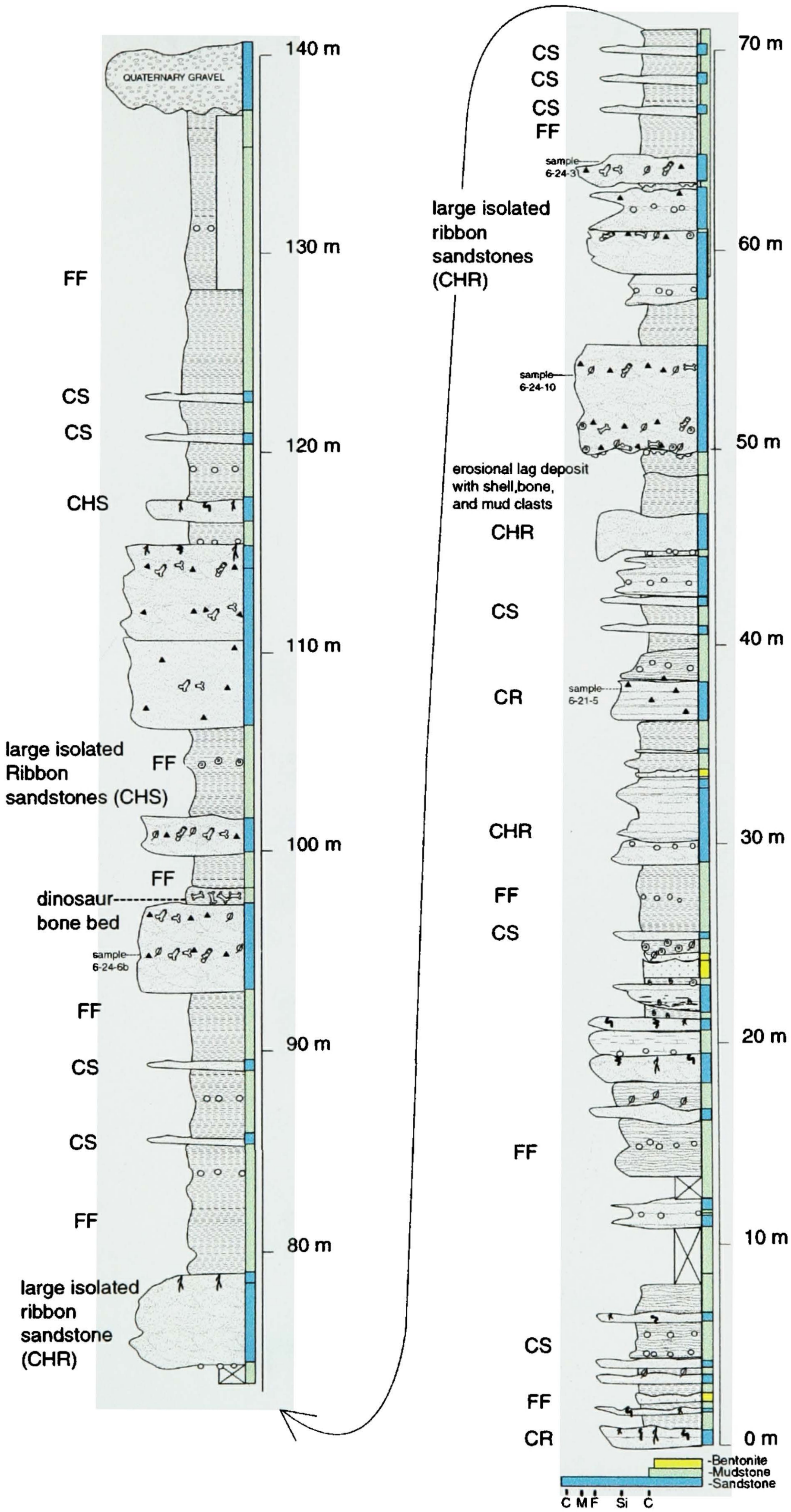

Figure 1.11. Old Trail Section 1.

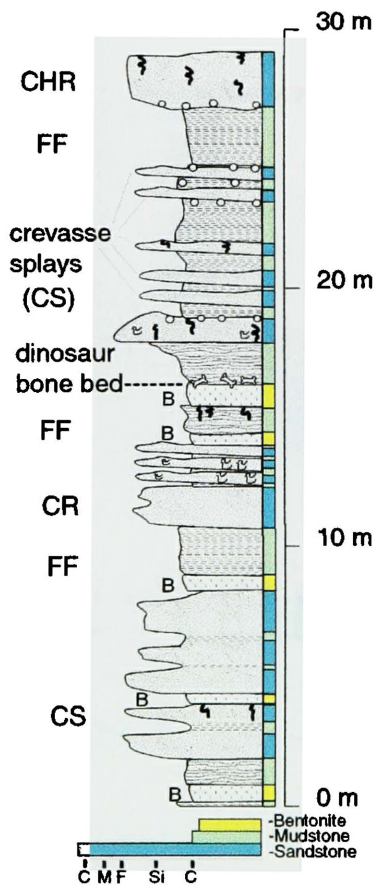

Figure 1.12. Old Trail Section 2.

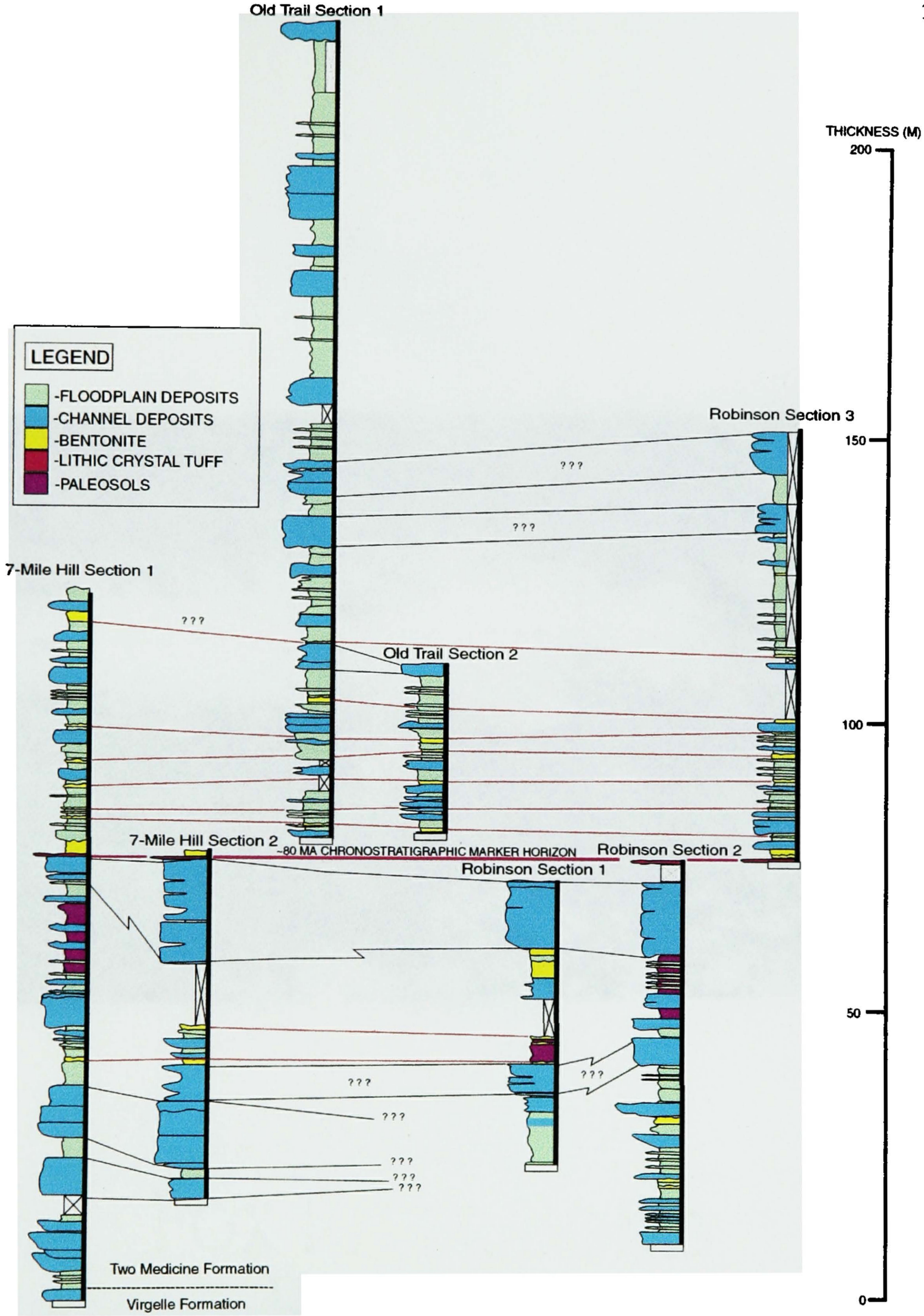

Figure 1.13. Stratigraphically correlated sections from the lower Two Medicine in the study area. The pink line correlates a regionally extensive ~ 80 Ma lithic crystal tuff bed that records the position of the turn-around from R7 to T8 within the section. Certain sandstones (black lines) and bentonites (red lines) have also been correlated.

Figure 1.14. Photograph of the regionally extensive plagioclase-lithic crystal tuff bed, which has been dated by Rogers et al. (1993) at ~80 Ma.

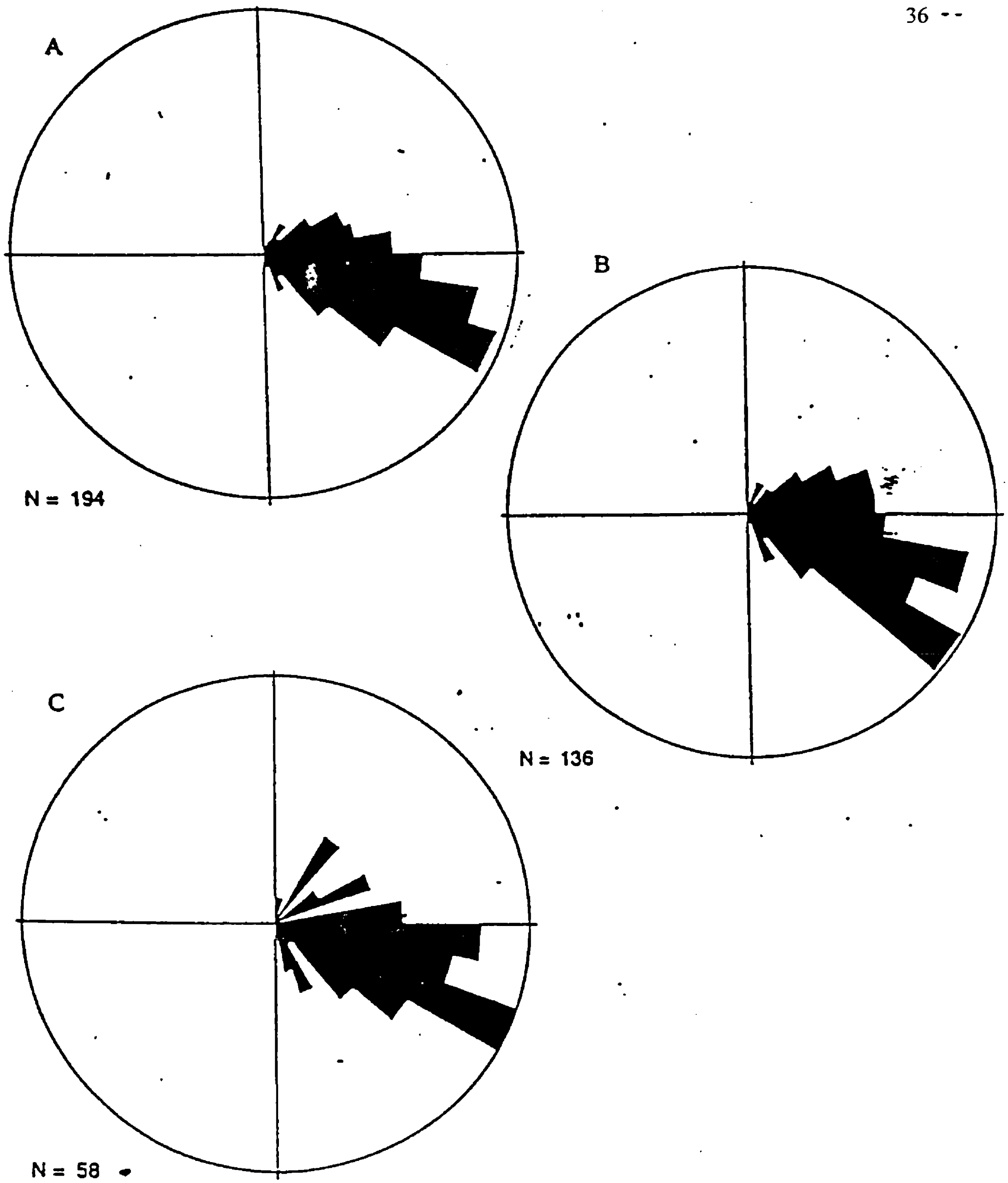

Figure 1.15. Rose diagrams showing paleocurrent orientations measured on troughs of cross beds from sandstone beds in the field area. A). Total paleocurrents measured in entire section (mean=98^0; n=194). B). Paleocurrents measured in the R7 alluvial package from major sheet sandstones (mean= 98^0; n=136). C.) Paleocurrents measured in the T8 alluvial package from major ribbon sandstones (mean=97^0;n=58).

Figure 1.16. Photograph of trough-cross bedded resistant sandstone sheets interbedded with recessive floodplain fines.

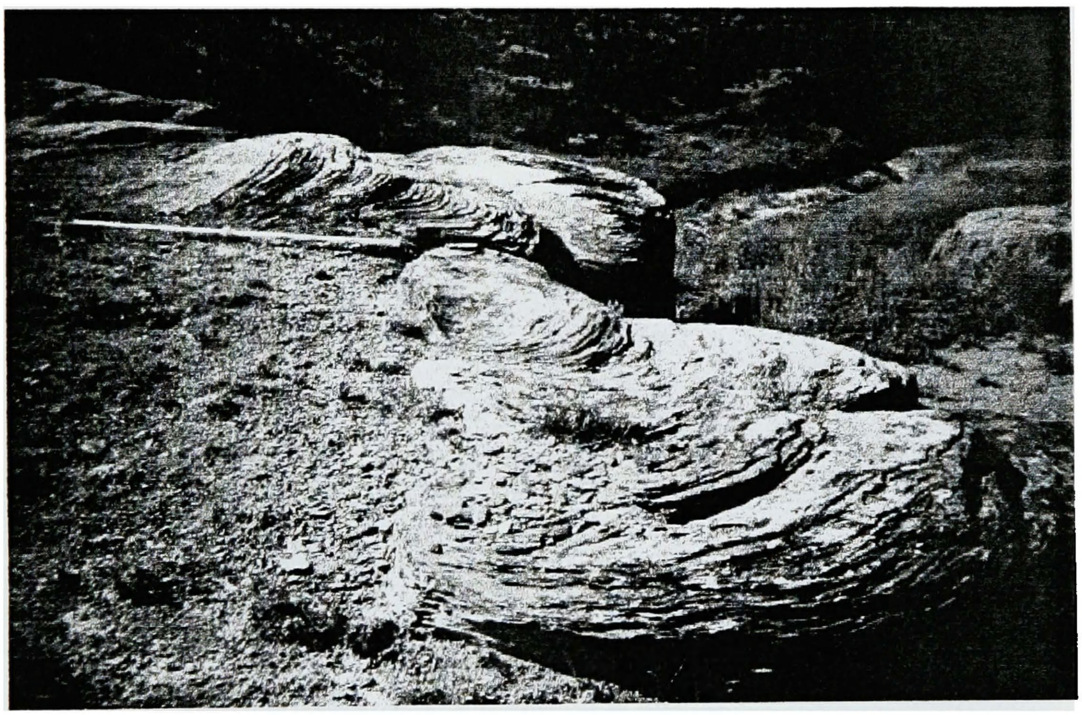

Figure 1.17. Photograph of trough crossbedding (Sti) common is major sheet sandstones.

Figure 1.18. Photograph showing a fresh water bivalve shell concentration (*Unio sp.*). This is one of several basal lags in the major sheet and ribbon sandstones.

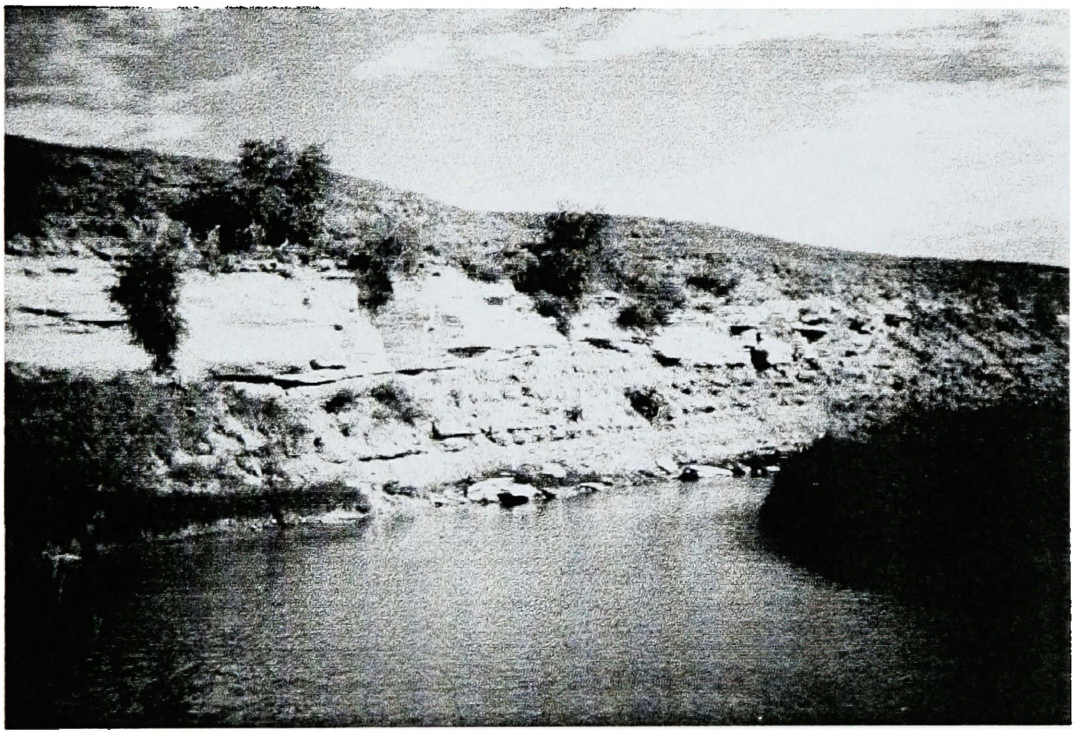

Figure 1.19. Photograph of major ribbon sandstone in study area.

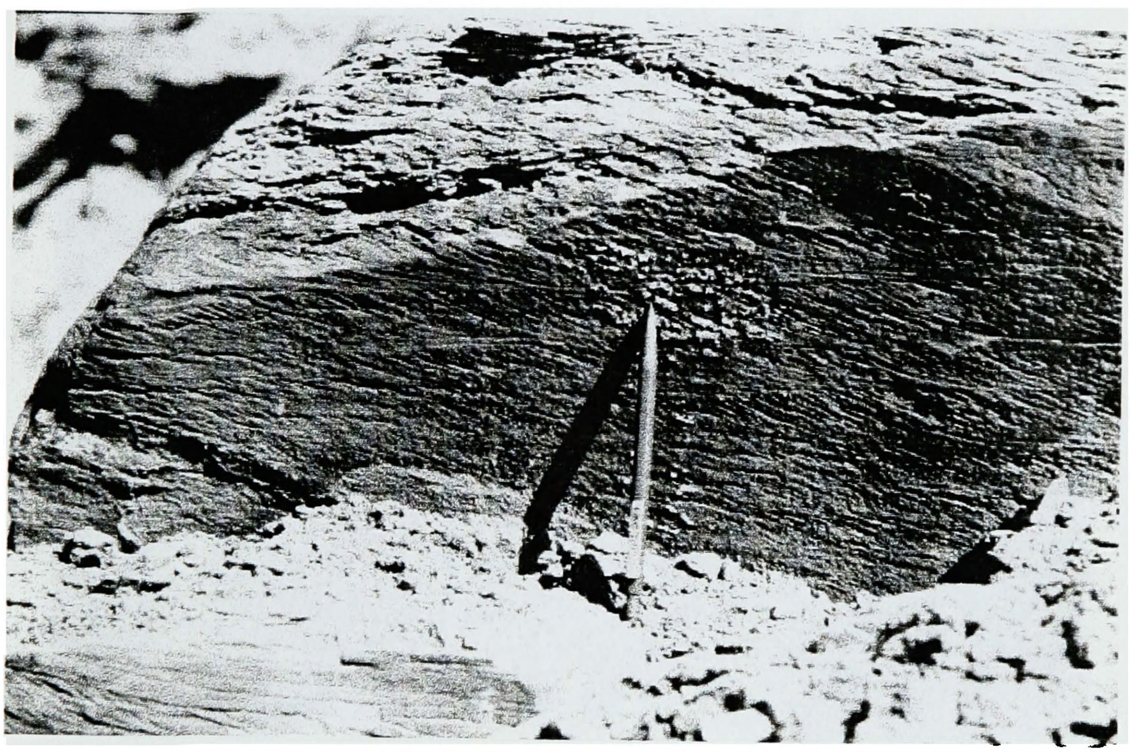

Figure 1.20. Photograph of a typical minor sheet sandstone displaying ripple cross lamination (Sr).

Figure 1.21. Photograph showing a bioturbated upper surface of a minor sheet sandstone.

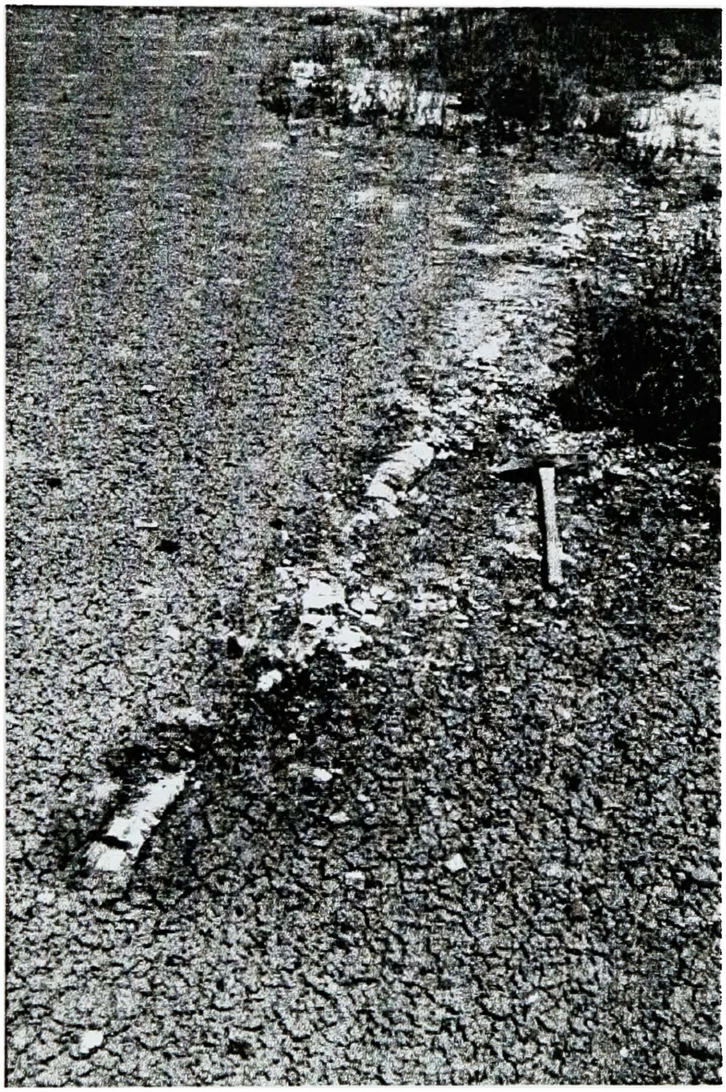

Figure 1.22. Photograph showing the typical outcrop expression of a bentonite. Notice the charcoalified wood and the diagnostic popcorn texture of the bentonite.

Figure 1.23. Photograph shows palesol development (~50-60 meter interval in 7-Mile Hill 1) in the R7 alluvial package. Width of field of view in foreground is approximately 15 m.

CHAPTER 2: Taphonomy of a Petrified Forest in the Two Medicine Formation (Campanian), Northwest Montana: Implications for Palinspastic Resoration of the Boulder Batholith and Elkhorn Mountain Volcanics

INTRODUCTION

The Late Cretaceous Boulder batholith in northwestern Montana covers an area greater than 6000 km^2 and intrudes its own cover, the Elkhorn Mountains Volcanics (Smedes, 1966; Klepper et al., 1971). Early studies of the batholith focused on whether it is a shallow (~5 km), composite sheet of granite (e.g. Hamilton and Myers, 1974), more consistent with an allochthonous origin, or a steeply dipping, 15-20 km thick batholith (e.g. Klepper et al., 1971, 1974), more consistent with an autochthonous origin. The age of the Boulder batholith (80-70 Ma; Tilling et al., 1968) overlaps the timing of active eastward thrusting in western Montana (84-60 Ma; Harlan et al., 1988; Hyndman et al., 1988), and a variety of workers have suggested that syn-intrusive, eastward movement of the batholith occurred along a basal decollement (Hyndman et al., 1975; Schmidt et al., 1990; Burton et al., 1993). Indeed, seismic-reflection profiling of the batholith (Vejmelek and Smithson, 1995) imaged a series of horizontal reflectors 12-18 km deep that were interpreted as a basal decollement. Although an allochthonous origin for the Boulder batholith and Elkhorn Mountains Volcanics is now generally accepted, uncertainty remains over the distance the batholith moved since its initial emplacement. In this paper, we use the taphonomy of a Campanian petrified forest that was blown down and entombed by a single eruption from the Elkhorn Mountains Volcanics to constrain the Campanian position of the Elkhorn Mountains Volcanics and, by extension, the Boulder batholith.

Located to the northeast of the Boulder batholith and Elkhorn Mountains Volcanics field in northwest Montana and southern Alberta is the Two Medicine Formation, a Campanian sequence of bentonitic mudstone and sandstone deposited on a broad alluvial plain facing the Cretaceous Interior Seaway (Lorenz, 1981; Rogers, 1994; Roberts, 1998). The Two Medicine Formation contains a robust flora (Crabtree, 1987) and has long been famous for its prolific dinosaur faunas (Horner and Makela, 1979; Horner, 1989). Approximately 10 km south of the town of Choteau, Montana, the Two Medicine Formation contains a petrified forest consisting of >200 aligned, horizontal, silicified trees entombed within a volcanic tuff and overlying bentonite. This site is located in an autochthonous portion of the Two Medicine Formation east of the leading foreland thrust within the Rocky Mountain disturbed belt (Fig. 1).

In this paper, we describe evidence that the tuff and bentonite together constitute a single, catastrophic eruption that originated in the Elkhorn Mountains Volcanics center and was powerful enough to knock down, partially burn, and bury this forest. Using the paleocurrent direction indicated by the azimuth of the downed trees, we discuss the implications of the forest for the palinspastically restored position of the Elkhorn Mountains Volcanics and Boulder batholith and the magnitude of the eruption that knocked down and buried the forest.

DESCRIPTION AND INTERPRETATION OF THE TWO MEDICINE PETRIFIED FOREST SITE

Sedimentology

The petrified forest occurs in the lower Two Medicine Formation, ~10 km south of Choteau, Montana (Figs. 1 and 2). There, the Two Medicine Formation consists primarily of mudstone, sandstone, and devitrified volcanic ash (bentonite) interpreted to represent fluvial/floodplain deposition in a coastal plain environment (Lorenz, 1981; Roberts, 1998). Paleocurrent measurements throughout the Two Medicine Formation indicate flow from west to east, transverse to the syn-evolving foreland fold-thrust belt (Roberts, 1998). A facies change, interpreted to reflect the alluvial response to the transition from the Telegraph Creek-Eagle regressive phase (R7) to the Claggett transgressive phase (T8) of the Cretaceous Interior Seaway (Roberts, 1998), occurs at the approximate stratigraphic level of the petrified forest (Fig. 2A). Strata below the petrified forest contain 1-5 m thick, laterally continuous and pervasively trough cross-stratified sandstone beds, packaged between thinner overbank mudstone. Roberts (1999) interpreted this sedimentary style to reflect domination of avulsion and channel migration processes due to slow rates of aggradation and little generation of accommodation space associated with the R7 regression. Strata above the petrified forest are dominated by thick overbank mudstone, isolated ribbon sandstone bodies, and thin, lenticular rippled sandstone interpreted as crevasse-splay deposits. Roberts (1999) interpreted this sedimentary style to reflect greater preservation of overbank fines due to higher rates of aggradation and generation of accommodation space associated with the T8 transgression.

Volcanic Rocks and Petrified Forest

Lorenz (1981) first noted the presence of a plagioclase crystal tuff and an overlying bentonite with scattered, carbonized plant remains in the Choteau area. The petrified forest itself is encased within a 1-15 cm thick lithic crystal tuff and immediately overlying 0.5-2 m thick bed of bentonite, both of which can be traced across the field area for at least 15 km. The crystal tuff is primarily composed of euhedral to subhedral crystals of plagioclase, biotite, sanidine and quartz (Rogers et al., 1993). Lithic siltstone clasts are common and pyroxene crystals are absent.

The tuff and bentonite overlie overbank mudstone and fluvial channel sandstone in different parts of the study area, as expected for a volcanic drape across a broad fluvial braidplain. Where the crystal tuff and bentonite overlie sandstone, syn-deformed sandstone dikes and bulbous protuberances of sandstone intrude both overlying volcanic layers. A glassy rind several mm thick and characterized by abundant slickensides commonly coats the outer surface of these sandstone protuberances. We interpret synsedimentary deformation in the sandstone to reflect loading by rapid deposition of the overlying tuff and bentonite, and we interpret the glassy rinds to reflect quenching of the basal tuff by the underlying liquified sandstone.

Preliminary analysis of the wood microstructure suggests that most trees belong to the genus cf. *Cupressinoxylon* (C. Miller, 1998, pers. comm.). Trees and wood fragments occur commonly within the crystal tuff and overlying bentonite for several square miles across the field area, suggesting that the region was heavily forested at the time of the eruption. Individual tree trunks range from 20 centimeters to more than 1 meter in diameter and up to 10 meters in length. Microscopic analysis suggests that all of the trees are charcoalified, and field observations show that many trees taper to the northeast. We identified three rooted, vertical stumps in the field area and interpret these to be *in situ*. The presence of these rooted stumps and the fact that all trees are entirely encased within the volcanic deposit suggests that few, if any, of the trees were transported to the site of deposition by alluvial processes. Locally, the bentonite also contains charred dinosaur bone, including unidentified hadrosaur and therapod fragments (Fig. 3).

Using a Nikon DTM "Top Gun" total station, we surveyed the positions of both exposed ends of each tree within the two densest clusters of trees in the forest, and we measured the trend of each tree independently with a Brunton compass. The mean azimuth (n=98) is 047° NE (2_=35°) (Fig. 3).

Based on the charcoalified nature of all trees in the forest and their sub-alignment within the encasing crystal tuff and bentonite (Fig. 3), we infer that the Two Medicine trees were knocked down by a powerful pyroclastic flow or surge, represented by the tuff, and were then quickly buried by the subsequent ash fall, represented by the overlying bentonite. We interpret the mean northeastern azimuthal component of the trees to be the direction of the volcanic blast. Similar subaligned trees encased within ash flow tuff deposits were documented from the May 18, 1980, eruption of Mount St. Helens (c.f.: Lipman and Mullineaux, 1981). Ancient analogous volcanic eruptions that blew down and entombed fossil forests have been documented in New Zealand (Froggatt et al., 1981), Indonesia (Taylor, 1958), and Mongolia (Keller and Hendrix, 1997).

SOURCE OF THE VOLCANICS

The nearest plausible source for the crystal tuff and bentonite encasing the Two Medicine petrified forest is the Adel Mountains Volcanics which lie ~50 Km south of the Two Medicine petrified forest (Fig 1). Gunderson and Sheriff (1991) reported whole rock K-Ar dates from within the Adel Mountains Volcanics of 71.2-81.1 Ma, permitting the possibility that the Two Medicine crystal tuff was at least contemporaneous with active volcanism in the Adel Mountains. However, a more recent series of $^{39}Ar/^{40}Ar$ dates from the Adel Mountains Volcanics (Harlan et al., 1991) constrains the maximum age of the entire volcanic pile to 76 Ma, too young to be the source of the crystal tuff and bentonite encasing the Two Medicine fossil forest. Along with this mismatch in ages, the mafic composition of the Adel Mountains Volcanics makes it unlikely that these rocks were associated with explosive eruptions, such as that which produced the plagioclase-biotite-sanidine-quartz crystal tuff at our field site. Although Schmidt (1978) reported a latite tuff in the Adel Mountains that does contain plagioclase and sanidine in its groundmass, most of the Adel Mountains Volcanics consist of shonkinite with abundant clinopyroxene (salite; Cunningham, 1999).

Haystack Butte, a small diorite plug south of Augusta, Montana (Fig. 1) is the closest volcanic source to the petrified forest. However, this feature is probably too small, its composition too mafic, and its Oligocene-Miocene age (Mudge, 1982) too young to have been the source of the Two Medicine crystal tuff and bentonite. Other small Tertiary and Cretaceous plugs and cones south and east of Augusta are also unlikely sources because they are too mafic, too young, or both.

Viele and Harris (1965), Lorenz (1981) and Rogers (1993) all postulated that the source for volcanic strata (principally bentonite) in the Two Medicine Formation was the Elkhorn Mountains Volcanics, presently located between Helena and Butte, Montana (Fig. 1). Consistent mineralogies and concordant ages between the Two Medicine crystal tuff at our field site and Elkhorn Mountains Volcanics strongly support this hypothesis. Smedes (1966) reported mostly rhyolitic, rhyodacitic, andesitic and basaltic pyroclastic and epiclastic volcanics from the Elkhorn Mountains Volcanics, including rhyolitic ash flows and welded tuffs. The silica content of the crystal tuff is 65.10% (unpublished XRF data, this study), consistent with a rhyolitic composition, and the plagioclase-quartz-sanidine-biotite mineralogy of the Two Medicine tuff is consistent with the report of abundant K-feldspar, quartz, and plagioclase with subordinate biotite from rhyolite ash flows within the Elkhorn Mountains Volcanics (Smedes, 1966). Rogers et al. (1993) dated plagioclase from the tuff at 80.002 +/- 0.114 Ma via $^{39}Ar/^{40}Ar$ on plagioclase, well within the range of 74-83 Ma obtained from the Elkhorns Mountains Volcanics (Tilling et al., 1968).

CAMPANIAN POSITION OF ELKHORN MOUNTAINS VOLCANICS

Although the composition of the crystal tuff and overlying bentonite suggest that both were derived from the Elkhorn Mountains Volcanics and the taphonomy of the trees indicates that they were blown down in a single catastrophic event, the present location of the Elkhorn Mountains Volcanics is inconsistent with the azimuth of the trees in the Two Medicine Formation. That is, the trees 'point' away from an Elkhorn Mountains Volcanics source that is well to the northwest of the present day position of the Elkhorn Mountains Volcanics field and associated Boulder Batholith (Fig. 4). This problem is resolved by restoration of the Elkhorn Mountains Volcanics and related Boulder batholith west to their syn-eruptive position.

Based upon the construction of a series of balanced cross-sections, Sterne (1996) concluded that the pre-thrust position of the Boulder batholith and Elkhorn Mountains Volcanics was 65-110 km west of their present position and that both underwent between 5-45° of clockwise rotation during thrusting. Using similar balanced cross-section techniques, Burton et al. (1993) estimated >80 km of eastward displacement on the Lombard thrust that contains both the Boulder Batholith and the Elkhorn Mountains Volcanics in its hanging wall (Fig. 1). The restored position of the Elkhorns Mountains Volcanics, based on these palinspastic reconstructions (Fig. 4), is in excellent alignment with the azimuth of trees in the petrified forest. The restored position of the Elkhorn Mountains Volcanics and Boulder Batholith is also consistent with the interpretation by Schmidt et al. (1990) that a large caldera complex was located at the northern end of the Elkhorn Mountains Volcanics field.

MAGNITUDE OF ERUPTION

The Elkhorn Mountains Volcanics cover more than 25,000 km^2, making them one of the largest ash flow tuff fields in the world (Smith, 1960; Smedes, 1966; Klepper et al., 1974). Eruptions in the Elkhorns are cited as the source for ash beds in southern Alberta (Thomas et al., 1990) and are interpreted to be the source for the extensive Ardmore bentonite succession, a 3 m thick series of bentonite beds that crop out as far away the Dakotas and Nebraska (Spivey, 1940; Gill and Cobban, 1973). The Ardmore bentonite succession is dated at ~79.5 Ma via K-Ar (no error reported; Gill and Cobban, 1973) permitting the interpretation that the crystal tuff and bentonite at our field site is the proximal, chronostratigraphic equivalent to a portion of the more distal Ardmore bentonite succession.

Our study strongly suggests that the Elkhorns Mountains Volcanics center was capable of producing eruptions of enormous proportions. The Two Medicine petrified forest is located between ~150 and 200 km from the restored, Campanian position of the Elkhorn Mountains Volcanics, making the pyroclastic flow/surge that entombed the trees one of the farthest-reaching such flows ever documented. By comparison, the smaller Taupo Volcanics in New Zealand toppled mature trees at least 70 km away from the source (Froggatt et al., 1981). Ancient analogous pyroclastic flows documented to have traveled similar distances include the Fish Canyon tuff (100 km) and Sapinero Tuff (110 km), both in the San Juan Mountains, and the Morrinsville ignimbrite (225 km) in New Zealand (Cas and Wright, 1987).

We infer that the low relief and the gently sloping nature of the Campanian coastal plain facilitated the long distance run-out of pyroclastic flows east of the Elkhorn Mountains, such as that documented in this paper. The paucity of synorogenic conglomerate, abundance of fine-grained sandstone, and ubiquity of extensive sheet sand and crevasse-splay deposits in the Two Medicine Formation all are consistent with the interpretation of a low relief topography during Campanian time (Lorenz, 1981; Rogers, 1994; Roberts, 1998).

CONCLUSIONS

Based on taphonomic and mineralogic evidence, the Elkhorn Mountains Volcanics likely were the source of a catastrophic volcanic eruption during Campanian time that knocked down, buried, and preserved a petrified forest in the Two Medicine Formation of northwestern Montana. The direction of alignment of trees in the fossil forest and palinspastic restorations of the foreland fold and thrust belt suggest that, during Campanian time, the Elkhorn Mountains Volcanics and Boulder batholith were located 65-110 km north-northwest of their present day position and ~150-200 km from the petrified forest. Other possible sources for the crystal tuff and bentonite that encase the Two Medicine petrified forest are either too mafic, contain inconsistent mineral assemblages, or are too young to have produced the volcanic strata. These results suggest that the eruption that destroyed the Two Medicine petrified forest was one of the largest and most powerful documented and that the far-traveled nature of this flow was likely facilitated by the gentle, east-sloping topography of the Campanian coastal plain on which the forest resided.

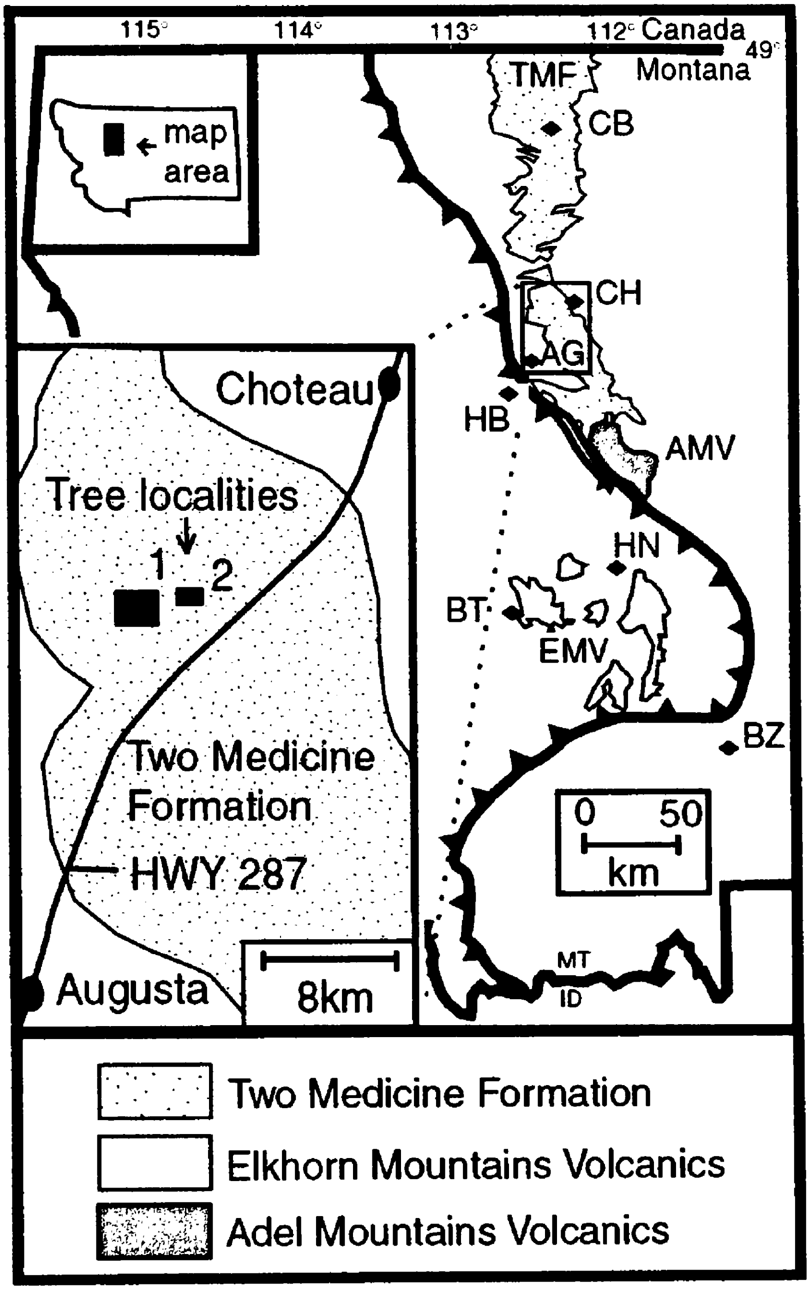

Figure 2.1. Regional tectonic map of western Montana showing field area and tree localities (modified from Rogers et al., 1993 and Lorenz and Gavin, 1984) AMV= Adel Mountain Volcanics, EMV= Elkhorn Mountain Volcanics, HB= Haystack Butte, TMF= Two Medicine Formation, AG= Augusta, BT= Butte, BZ= Bozeman, CB= Cut Bank, CH= Choteau, and HN= Helena.

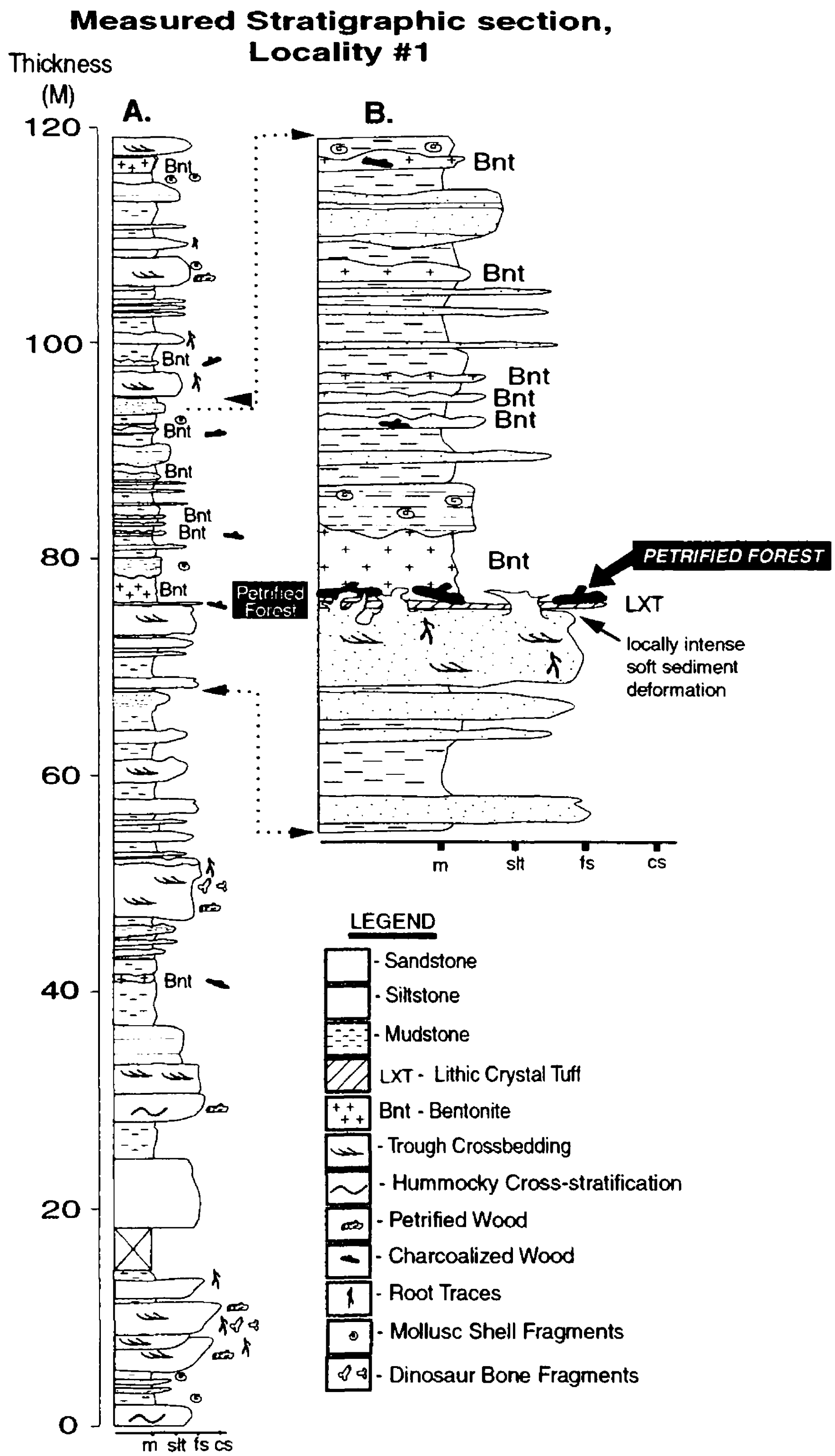

Figure 2.2. Measured stratigraphic section of Two Medicine Formation in the present study area, showing overall stratigraphic relations within the lower Two Medicine (A) and the detailed stratigraphic relations associated specifically with the lithic crystal tuff and overlying bentonite that encases the forest (B).

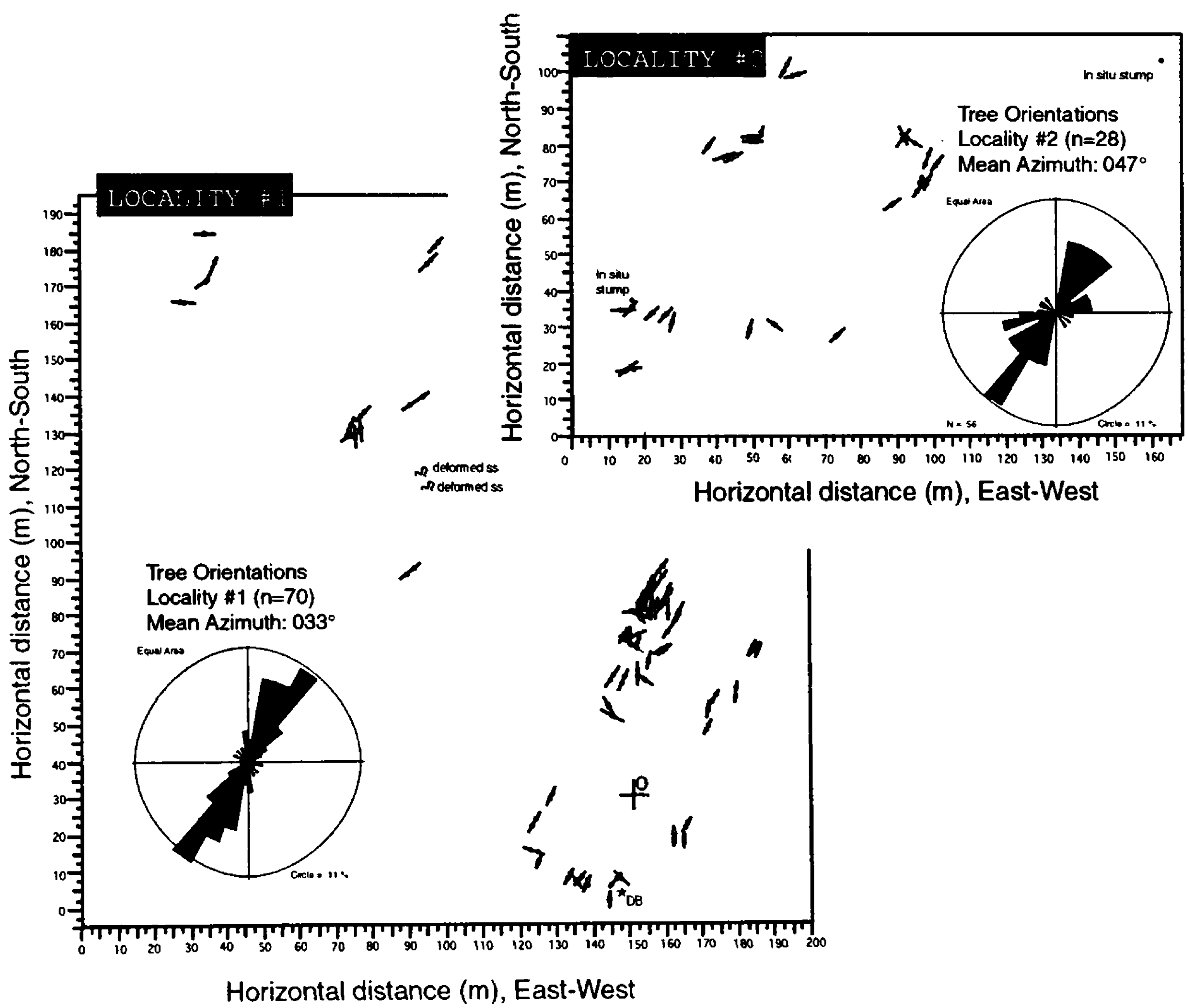

Figure 2.3. Maps of the two densest clusters of trees within the Two Medicine petrified forest. See Figure 2.1 for location of each mapped cluster. Each tree trunk azimuth is denoted by a single line. Trunk terminations, surveyed with a total station, are shown by the closed circles on each line. The surveying error is less than 1/10th the size of each closed circle. DB= location of dinosaur bones found encased in bentonite.

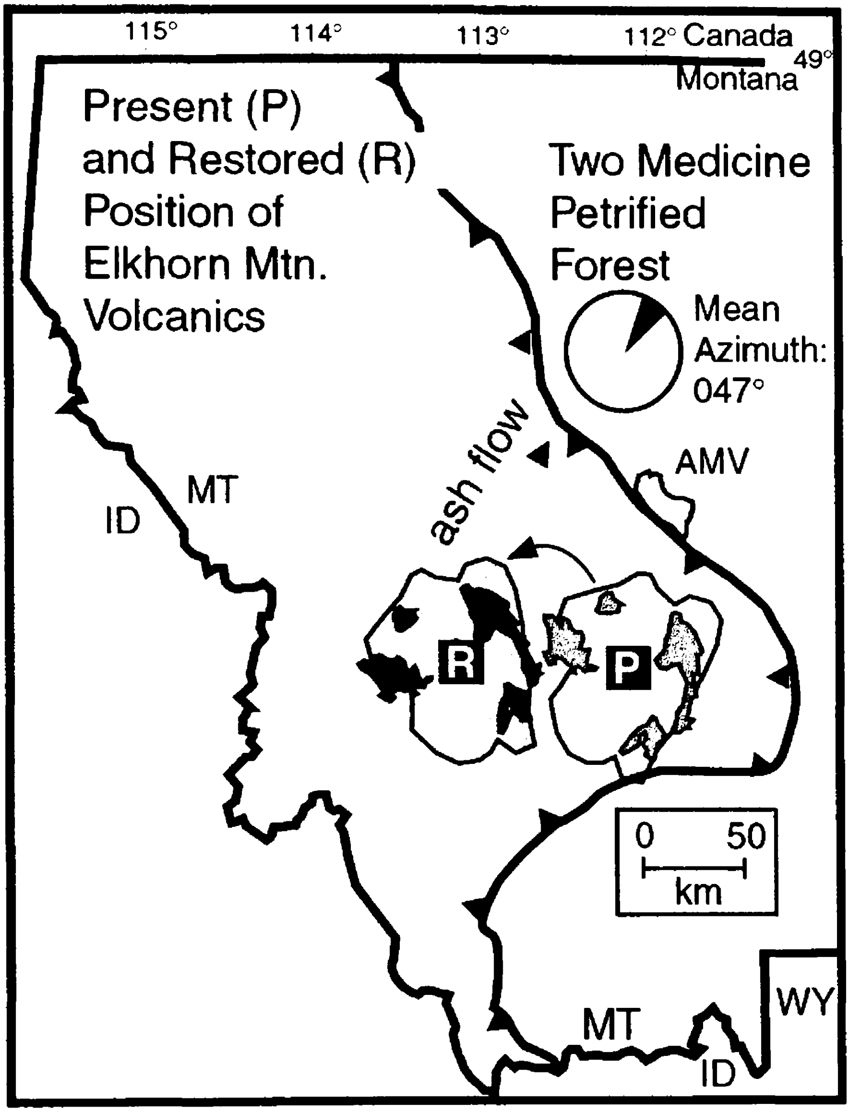

Figure 2.4. Simplified tectonic map of the Rocky Mountain Fold and Thrust Belt showing the present position (P) and the inferred restored position (R) of the Elkhorn Mountain Volcanics and the Boulder Batholith. The Two Medicine petrified forest is located at the origin of the rose diagram that shows the azimuth of trees within the fossil forest. The thrust fault represents the leading edge of the disturbed belt in western Montana, after Rogers, 1993 and Lorenz, 1981. AMV= Adel Mountain Volcanics.

REFERENCES

Burton, B.R., Lageson, D.R., Schmidt, C.J., Ballard, D.W., and Warne, J.R., 1996, Large magnitude shortening of the Lombard thrust system, Helena salient, Montana fold and thrust belt: Implications for reconstruction of the Belt basin, *in* Berg, R.B., Proceedings of Belt Symposium III: Helena, Montana Bureau of Mines and Geology Special Publication.

Cobban, W.A., 1955, Cretaceous rocks of northwestern Montana: Billings Geological Society, 6th annual field conference guidebook, p. 107-119.

Crabtree, D., 1987, The Ealry Campanian flora of the Two Medicine Formation, northcentral Montana[Ph.D. Dissertation]: The University of Montana, 357 p.

Cunnigham, B., 1999, Petrogenesis of the Adel Mountains Volcanic Field, central Montana [Masters Thesis]: The University of Montana, Missoula, MT, 82 p.

DeGraw, H.M., 1975, The Pierre-Niobrara unconformity in western Nebraska, *in* Caldwell, W.G.E., ed., The Cretaceous System in the Western Interior on North America: Geological Association of Canada, Special Paper 13, p. 589-606.

Eberth, D.A., and Miall, A.D., 1991, Stratigraphy, sedimentology, and evolution of a vertebrate-bearing, braided to anastomosed system, Cutler Formation (Permian-Pennsylvanian), north-central New Mexico: Sedimentary Geology, v. 72, 225-252.

Elderidge, G.H., 1889, Some suggestions upon the methods of grouping the formations of the middle Cretaceous and the employment of an additional term in its nomenclature: American Journal of Science, v. 146, p. 723-732.

Flexer, A. Rosenfeld, A., Lipson-Benitah, S., and Honigstein, A., 1986, Relative sea-level changes during the Cretaceous of Israel: American Association of Petroleum Geologists Bulletin, v. 70, p. 1685-1699.

Friend, P.F., 1983, Towards the field classification of alluvial architecture or sequence. In: Collinson, J.D., Lewin, J. (eds), Modern and ancient fluvial systems. International Association of Sedimentology Special Publication 6, p.345-354.

Friend, P.F., Slater, M.J., and Williams, R.C., 1979, Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain: Journal of the Geologic Society of London, v. 146, p.39-46.

Froggatt, P.C., Wilson, C.J.N., and Walker, G.P.L., 1981, Orientation of logs in the Taupo Ignimbrite as an indicator of flow direction and vent position: Geology, v .9, p. 109-111.

Gibling, M.R. and Bird, D.J., 1994, Late Carboniferous cyclothems and alluvial paleovalleys in the Sydney basin, Nova Scotia: Geological Society of America Bulletin, v. 106, p. 105-117.

Gill, J.R., Cobban, W.A., and Schultz, L.G., 1972, Correlation, ammonite zonation, and a reference section for the Montana Group, central Montana: Montana Geological Society 21st annual field conference guidebook, p. 91-97.

Gill, J.R., and Cobban, W.A., 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: United States Geologic Survey Professional Paper 776, 37 p.

Goodwin, M.B., and Deino, A.L., 1989, The first radiometric ages from the Judith River Formation (Upper Cretaceous), Hill County, Montana: Canadian Journal of Earth Sciences, v. 26, p. 1384-1391.

Gunderson, J.A., and Sheriff, S.D., 1991, A new Late Cretaceous paleomagnetic pole from the Adel Mountains, West Central Montana: Journal of Geophysical Research, v. 96, no. 131, p. 317-326.

Hamilton, W., and Myers, W.B., 1974, Nature of the Boulder batholith of Montana: Geologic Society of America Bulletin, v. 85, p. 365-378.

Hancock, J.M., 1975, The sequence of facies in the Upper Cretaceous of northern Europe compared with that in the Western Interior, *in* Caldwell, W.G.E., The Cretaceous System in the Western Interior on North America: Geological Association of Canada, Special Paper 13, p.83-118.

Harlan, S.S., Geissman, J.W., Lageson, D.R., and Snee, L.W., 1988, Paleomagnetic and isotopic dating of thrust-belt deformation along the eastern edge of the Helena salient, northern Crazy Mountains basin, Montana: Geological Society of America Bulletin, v. 100, p. 492-299.

Harlan, S.S., Mehnert, H.H., Snee, L.W., Sheriff, S., Schmidt, R.G., 1991, New 40Ar/39Ar isotopic dates from the Adel Mountains Volcanics: Implications for the relationship between deformation and magnetism in the Montana Disturbed Belt, western Montana: Geologic Society of America Abstracts with Programs, v. 23, n.5, p. A136.

Horner, J.R., 1989, The Mesozoic terrestrial ecosystem of Montana: 1989 Montana Geological Society, Montana Centennial Field Conference, p. 153-162.

Horner, J.R., and Makela, R., 1979, Nest of juveniles provides evidence of family structure among dinosaurs: Nature, v. 282, p. 296-298.

Hyndman, D.W., Talbot, J.L., and Chase, R.B., 1975, Boulder batholith: A result of emplacement of a block detached from the Idaho batholith infrastructure?: Geology, v. 3, p. 401-404.

Hyndman, D.W., Alt, D., and Sears, J.W., 1988, Post-Archean metamorphic and tectonic evolution of western Montana and northern Idaho. *In*: Ernst, W.G. (Ed.) Metamorphism and Crustal evolution of the Western United States. Prentice Hall, p. 333-361.

Kauffman, E.G., 1977, Geological and biological overview: Western Interior Cretaceous Basin: The Mountain Geologist, v. 14, p. 75-99.

Keller, A.M., and Hendrix, M.S., 1997, Paleoclimatologic analysis of a Late Jurassic petrified forest, southeatern Mongolia: Palaios, v. 12, p. 282-291.

Klepper, M.R., Robinson, G.D., and Smedes, H.W., 1971, On the nature of the Boulder batholith of Montana: Geol. Soc. America Bull., v. 82, p. 1563-1580.

Klepper, M.R., Robinson, G.D., and Smedes, H.W., 1974, Nature of the Boulder batholith of Montana: Discussion: Geol. Soc. America Bull., v. 85, p. 1953-1960.

Lipman, P.W., and Mullineaux, D.P., 1981, The 1980 eruption of Mount St. Helens, Washington: U.S. Geol. Survey Prof. Paper 1250, 844 p.

Lorenz, J.C., 1981, Sedimentary and tectonic history of the Two Medicine Formation, Late Cretaceous (Campanian), northwestern Montana: Unpublished PhD Dissertation, Princeton University, 215 p.

Lorenz, J.C., 1982, Lithospheric flexure and the history of the Sweetgrass arch, northwestern Montana: Denver, Colorado, Rocky Mountain Association of Geologists, p. 77-89.

Lorenz, J.C., and Gavin, W., 1984, Geology of the Two Medicine Formation and the sedimentology of a dinosaur nesting ground: Montana Geol. Soc. 1984 Field Conf. and Symposium Guidebook, p. 175-186.

Mack, G.H., James, W.C., and Monger, J.C., 1993, Classification of paleosols: Geologic Society of America Bulletin, v. 105, p. 129-136.

Miall, A.D., 1978, Lithofacies types and vertical profile models in braided river deposits: a summary. In: A.D. Miall (Ed), Fluvial Sedimentology. Can. Soc. Pet. Geol. Mem., 5, p. 597-604.

Miall, A.D., 1985, Architectural-element analysis; a new method of facies analysis applied to fluvial deposits. Earth Science Review, v. 22, p. 261-308.

Miall, A.D., 1986, Eustatic sea level changes interpreted from seismic stratigraphy: a critique of the methodology with particular refrence to the North Sea Jurassic record: A.A.P.G. Bulletin, v. 70, p.131-137.

Miall, A.D., 1991, Stratigraphic sequences and their chronostratigraphic correlations: Journal of Sedimentary Petrology, v. 61, p. 497-505.

Miall, A.D., 1996, The Geology of Fluvial Deposits: Springer-Verlag, New York, 582 p.

Mudge, 1982, A resume of the structural geology of the Northern Disturbed Belt, northwestern Montana, *in* Geologic Studies of the Cordilleran Thrust Belt, R.B. Powers (*ed.*): Rocky Mtn Assoc. of Geologists, Denver, Colorado, v.1, p. 91-122.

Nadon, G.C., 1994, The genesis and recognition of anastomosed fluvial deposits: data from the St. Mary River Formtion, southwestern Alberta, Canada: Journal of Sedimentary Research, v. B64, n. 4, p. 451-463.

Obradovich, J., 1993, A Cretaceous time scale, *in* Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin: Geological Associationn of Canada, Special Paper 39, p. 379-396.

Olsen, T., Steel, R.J., Hogseth, K., Skar, T., and Roe, S.L., 1995, Sequential architecture in a fluvial succession: sequence stratigraphy in the Upper Cretaceous Mesaverde Group, Price Canyon, Utah: Journal of Sedimentary Research, v. B65, p.265-280.

Olsson, R.K., 1991, Cretaceous to Eocene sea level fluctuations on the New Jersey margin: Sedimentary Geology, v. 70, p. 195-208.

Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988, Eustatic controls on clastic deposition, I. Conceptual framework. In: C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.G. Posamentier, C.A. Ross, and J.C. Van Wagoner (Editors), Sea-Level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral., Spec. Pub., 42, p.109-124.

Posamentier, H.W., and Vail, P.R., 1988, Eustatic controls on clastic deposition, II.- sequence and systems tracts models. In: C.K. Wilgus, B.S. Hastings, C.G.St.C.Kendall, H.G. Posamentier, C.A. Ross, and J.C. Van Wagoner (Editors), Sea level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral., Spec.Pub., 42, p.125-154.

Roberts, E.M., 1998, Variable Response to Third-Order Sea Level Change in Nonmarine Strata: Sedimentology of the Lower Two Medicine Formation, Upper Cretaceous, Montana: American Association of Petroleum Geologists Annual Convention, abstacts v. 7.

Roberts, E.M., and Hendrix, M.S., in Review, Taphonomy of a petrified forest in the TwoMedicine Formation (Campanian), northwest Montana: implications for palinspastic restoration of the Boulder Batholith and Elkhorn MountainsVolcanics: Palios, in review.

Robinson, G.D., Klepper, M.R., and Obradovich, J.D., 1968, Overlapping plutonism, volcanism, and tectonism in the Boulder Batholith region, western Montana: Geol. Soc. America Memoir 116, p. 557-576.

Rogers, R.R, 1998, Sequence analysis of the Upper Cretaceous Two Medicine and Judith River Formations, Montana: Nonmarine responses to the Claggett and Bearpaw marine cycles, Journal of Sedimentary Research, Vol. 68, No. 4, p. 615-631.

Rogers, R.R., 1994, Nature and origin of through-going discontinuities in the nonmarine foreland basin strata, Upper Cretaceous, Montana: Implications for sequence analysis: Geology, v. 22, p. 1119-1122.

Rogers, R.R., Swisher, C.C., and Horner, J.C., 1993, $^{40}Ar/^{39}Ar$ age correlation of the nonmarine Two Medicine Formation (Upper Cretaceous), northwestern Montana, U.S.A.: Can. J. Earth Sci., 30, p.1066-1075.

Schimdt, C.J., Smedes, H.W., and O'Neill, J.M., 1990, Syncompressional emplacement of the Boulder and Tobacco Root batholiths (Montana-USA) by pull-apart along old fault zones: Geological Journal, v. 25, p. 305-318.

Schmidt, R.G., 1978, Rocks and mineral resources of the Wolf Creek area, Lewis and Clark and Cascade Counties, Montana: U.S. Geol. Survey Bull. 1441, 91 p.

Schumm, S.A., 1993, River response to baselevel change: Implications for sequence stratigraphy: Journal of Geology, v. 101, p. 279-294.

Shanley, K.W., and McCabe, P.J., 1993, Alluvial architecture in a sequence stratigraphic framework: a case history from the Upper Cretaceous of southern Utah, U.S.A., *in* S. Flint and I. Bryant, eds., Quantitative modeling of clastic hydrocarbon resevoirs and outcrop analogues: International Association of Sedimentologists Special Publication 15, p. 21-55.

Shanley, K.W., and McCabe, P.J., 1991, Predicting facies architecture through sequence stratigraphy-an example from the Kaiparowits Plateau, Utah: Geology, v. 19, p. 742-745

Shanley, K.W., and McCabe, P.J., 1989, Sequence-stratigraphic relationships and facies architecture of Turonian-Campanian strata, Kaiparowits Plateau, south-central Utah: American Association of Petroleum Geologists of America Bulletin, v. 73, p. 410-411.

Shurr, G.W., and Reiskind, J., 1984, Stratigraphic framework of the Niobrara Formation(Upper Cretaceous) in North and South Dakota, in Stott, D.F., and Glass, D.J., eds.,The Mesozoic of Middle North America: Canadian Society of PetroleumGeologists, Memoir 9, p. 205-219.

Smedes, H.W., 1966, Geology and igneous petrology of the northern Elkhorn Mountains, Jefferson and Broadwater Counties, Montana: U.S. Geol. Survey Prof. Paper 510, 116 p.

Smith, R.L., 1960, Ash flows: Geological Society of America Bulletin, v.71, p. 795-841.

Spivey, R.C., 1940, Bentonite in southwestern South Dakota: South Dakota Geological Survey Report of Investigations 36, 56 p.

Stebinger, E., 1914, The Montana Group of northwestern Montana: U.S. Geological Survey Professional Paper 90-G, p. 60-68.

Stebinger, E., 1916, Geology and coal resources of northern Teton County, Montana: U.S. Geological Survey Bulletin 621-K, p. 117-156.

Stebinger, E., 1917, Stratigraphy of the Two Medicine Formation: U.S. Geological Survey Professional Paper 103, p. 1-3.

Sterne, E.J., 1996, Palinspastic map of thrust belt and foreland: Montana, Wyoming, and Idaho: *in* Thrust Systems of the Helena Salient Montana Thrust Belt: RMS Field Trip #4, A.A.P.G. Rocky Mountain Section Meeting, Billings, MT, 62 p.

Taylor, G.A., 1958, The 1951 eruption of Mount Lamington, Papua: Australia Bureau of Mineral Resources Bulletin 38, 117 p.

Thomas, R.G., Eberth, D.A., Deino, A.L., and Robinson, D., 1990, Composition, radioisotopic ages, and potential significance of an altered volcanic ash (bentonite) from the Upper Cretaceous Judith River Formation, Dinosaur Provincial Park, southern Alberta, Canada: Cretaceous Research, v. 11, p. 125 162.

Tilling, R.I., Klepper, M.R., and Obradovich, J.D., 1968, Potassium-argon ages and time of emplacement of the Boulder batholith, Montana: American J. of Science, v. 266, p. 671-689.

Tilling, R.I., 1974, Composition and time relations of plutonic and associated volcanic rocks, Boulder batholith region, Montana: Geol. Soc. Am. Bull, v. 85, p.1925-1930.

Vail, P.R., Mitchum, R.M., Jr., Todd, R.G., Widmier, J.M., Thompson, S. III, Songree, J.B., Bubb, J.N., and Hatelid, W.G., 1977, Seismic Stratigraphy – applications to hydrocarbon exploration: Am. Assoc. Pet. Geol. Mem. 26, p. 49-212.

Van Wagoner, J.C., 1995, Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A., *in* Van Wagoner, J.C. and Bertram, G.T., eds., Sequence Stratigraphy of Foreland Basin Deposits: American Association of Petroleum Geologists, Memoir 64, p. 137-223.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: Concepts for high resolution correlation of time and facies: American Association of Petroleum Geologists, Methods in Exploration Series, no. 7, 55 p.

Vejmelek, L., and Smithson, S.B., 1995, Seismic reflection profiling in the Boulder batholith, Montana: Geology, v. 23, no. 9; p. 811-814.

Viele, G.W., and Harris, F.G. II, 1965, Montana Group stratigraphy, Lewis and Clark County, Montana: American Association of Petroleum Geologists Bulletin., v. 49, p. 379-417.

Weimer, R.J., 1988, Record of relative sea level changes, Cretaceous of Western Interior, U.S.A., *in* Wilgus, C.K., Hastings, F.S., Posamentier, H.W., Van Wagoner, J., Ross, C.A., and Kendall, C.G.St.C., eds., Sea level Changes: An Integrated Approach: SEPM, Special Publications 42, p. 284-287.

Wescott, W.A., 1993, Geomorphic thresholds and complex responses of fluvial systems—Some implications for sequence stratigraphy: American Association of Petroleum Geologists Bulletin, v. 77, p. 1208-1218.

Wright, V.P., and Marriott, S.B., 1993, The sequence stratigraphy of fluvial depositional systems: The role of floodplain sediment storage: Sedimentary Geology, v. 86, p. 203-210.

Zhang, Z., Sun, K, and Yin, J., 1997, Sedimentology and sequence stratigraphy of the Shanxi Formation (Lower Permian) in the northwestern Ordos Basin, China: an alternative sequence model for fluvial strata: Sedimentary Geology, v. 112, p. 123-136.