Sequence stratigraphy mineralogy and paleogeography of Triassic marginal marine and continental deposits of the Wind River Basin west-central Wyoming

Andrew Olin Urie
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Sequence Stratigraphy, Mineralogy, and Paleoaeoaraphy of Triassic Marginal Marine and Continental Deposits of the Wind River Basin, West-Central Wyoming

By

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B.S., The University of Delaware, 2000

Presented in partial fulfillment of the requirements for the degree of Master of Science The University of Montana 2002

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5-22-02
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Abstract

Urie, Andrew O., M.S. Geology

SEQUENCE STRATIGRAPHY, MINERALOGY, AND PALEOGEOGRAPHY OF TRIASSIC MARGINAL MARINE AND CONTINENTAL DEPOSITS OF THE WIND RIVER BASIN, WEST-CENTRAL WYOMING.

Committee Chair: Marc S. Hendrix, Ph.D.

To investigate the record of Triassic sedimentation in west-central Wyoming, I studied the stratigraphy, sedimentology, and mineralogy of the Triassic strata of the Chugwater Group. These units appear to record two 2\(^{nd}\) order transgressive/regressive (T/R) sequences and a transition to wholly continental deposition following the Tr-3 unconformity.

The Red Peak formation records the first 2\(^{nd}\) order transgressive/regressive (T/R) sequence. Overprinted on this 2\(^{nd}\) order sequence are two 3\(^{rd}\) and 4\(^{th}\) order sequences. The 2\(^{nd}\) order sequence is bounded above by a correlative conformity, located at the top of the sandy facies, the point of maximum regression. The accommodation space of this first sequence was controlled by sea level as the fit with the Triassic sea level curve is nearly exact.

The second sequence, beginning with the Alcova limestone and reaching a maximum flooding surface at the top of algal lamination, is topped by the Tr-2 unconformity. The Middle Triassic Crow Mountain Formation maybe a third T/R sequence, bounded at the top by the Tr-3 unconformity and is possibly correlative with the Anisian T/R cycle from the Triassic sea level curve. This interpretation is tentative, as most middle Middle Triassic rocks are missing from the Western Interior. The third sequence likely represents the uplift of a new source, to the north and east, causing progradation of a shelf margin wedge. Mineralogic data indicating immaturity are consistent with this conclusion. Variations in regional thickness of these second and third sequences suggest that tectonics control the accommodation space.

Above the Tr-3 unconformity, sedimentation becomes wholly continental as an arc-continent collision collapsed the previous depositional basin. Upper Triassic rocks from the unnamed red bed unit form incised valley fill after the uplift event, while the latest Triassic Popo Agie formation contains fluvial-lacustrine deposits with volcanic sources originating from a new east-dipping subduction zone and associated volcanic arc.

Quantitative x-ray diffraction study provides not only a powerful device for analysis of provenance and paleoclimate, but will be an invaluable tool in sequence stratigraphy.
Acknowledgments

This thesis would not have been possible without the guidance and support of many individuals. First and foremost, I would like to thank my committee members. This project would never have been completed without the continued faith and unwavering support of Dr. Marc S. Hendrix, and Dr. Graham R. Thompson. The research and my potential for a Master's degree almost foundered five months later after a non-productive summer in the field. Fortunately, I received the inspiration and suggestion from Gray to investigate the detailed mineralogy of the Chugwater. I further benefited from a brief but extremely valuable field experience with Marc in Wyoming.

I would also like to thank Dr. Jim Jacobs not only for his interest in the project, but also for his assistance in editing this manuscript. My thanks also goes to Doug McCarty and ChevronTexaco who allowed me to use their revolutionary QXRD technique. Doug’s talents, expertise and patience during the learning process are gifts I will always be thankful for. My hope is that Doug will reap rewards that extend beyond the scope of this research.

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# Table of Contents

**ABSTRACT** ..........................................................................................................................................ii

**ACKNOWLEDGMENTS** .....................................................................................................................iii

**TABLE OF CONTENTS** .....................................................................................................................v

**LIST OF FIGURES** .............................................................................................................................vi

**INTRODUCTION** ..................................................................................................................................1

  - **Stratigraphic Nomenclature of the Triassic Rocks of Central Wyoming** ..................................1
  - **Depositional History of the Chugwater Group** ..............................................................................2
  - **Remaining Problems** ......................................................................................................................3

**GEOLOGIC SETTING** .........................................................................................................................8

**METHODS OF STUDY** .....................................................................................................................10

  - **Field Investigations** ......................................................................................................................10
  - **Laboratory Analysis and Quantitative X-Ray Diffraction** ............................................................11

**RESULTS** ...........................................................................................................................................14

  - **Sedimentology & Stratigraphy** ....................................................................................................14
  - **Mineralogy** ....................................................................................................................................31

**DISCUSSION** .....................................................................................................................................37

  - **Interpretation of Depositional Environment** ..............................................................................37
  - **Sequence Stratigraphy** ................................................................................................................47
  - **Mineralogy and Provenance** .........................................................................................................52
  - **Paleogeography** ..........................................................................................................................56
  - **Paleoclimate** ..................................................................................................................................58

**CONCLUSIONS** ..................................................................................................................................61

**REFERENCES CITED** ......................................................................................................................65

**FIGURES** .....................................................................................................................................71-130

**APPENDIX 1** .................................................................................................................................. INCLUDED ON CD
List of Figures

FIGURE 1. REGIONAL PALEOGEOGRAPHIC MAP OF THE WESTERN INTERIOR DURING EARLY TRIASSIC TIME .......................................................... 72

FIGURE 2. STRATIGRAPHIC NOMENCLATURE USED IN THIS STUDY .......................................................... 73

FIGURE 3. GEOLOGIC MAP SHOWING WESTERN WYOMING AND THE FIELD STUDY AREA ........... 74

FIGURE 4. SCHEMATIC DIAGRAM OF A HYPOTHETICAL CONTINENTAL MARGIN SHOWING THE DEVELOPMENT OF AN EROSIve SEQUENCE BOUNDARY BETWEEN TWO MARINE SHALE LAYERS ........................................................................... 75

FIGURE 5. PHOTOGRAPH OF DEEP VALLEY FORMED BY UNRESISTANT DINWOODY FORMATION AND LOWEST CHUGWATER GROUP .......................................................... 76

FIGURE 6. PHOTOGRAPH OF RED BLUFF CANYON STUDY SECTION ................................................ 77

FIGURE 7. PHOTOGRAPH OF RED CANYON STUDY SECTION ........................................................ 77

FIGURE 8. PHOTOGRAPH OF DALLAS DOME STUDY SECTION ..................................................... 78

FIGURE 9. PHOTOGRAPH OF RED BUTTE STUDY SECTION ........................................................ 78

FIGURE 10. RED BUTTE STUDY SECTION STRATIGRAPHIC COLUMN ........................................... 79

FIGURE 11. PHOTOGRAPH OF RIPPLE CROSS LAMINATED SILTSTONE IN LOWER PLATY FACIES AT RED CANYON SECTION ............................................................. 80

FIGURE 12. PHOTOGRAPH OF PARALLEL LAMINATION IN LOWER PLATY FACIES AT RED CANYON SECTION ............................................................. 80

FIGURE 13. PHOTOGRAPH OF RIPPLE MARKS IN THE LOWER PLATY FACIES AT RED CANYON SECTION .......................................................... 81

FIGURE 14. TYPICAL EXPOSURE OF THE ALTERNATING FACIES IN THE STUDY AREA ........... 81

FIGURE 15. PHOTOGRAPH OF RIPPLE CROSS-LAMINATED SILTSTONE WITH BURROW FROM THE ALTERNATING FACIES AT RED CANYON ............................................................ 82

FIGURE 16. PHOTOGRAPH OF CLIMBING RIPPLE CROSS-LAMINATION IN THE ALTERNATING FACIES AT RED BUTTE .......................................................... 82

FIGURE 17. DISTRIBUTED STRATIFICATION OF PICARD (1978) .................................................. 83

FIGURE 18. PHOTOGRAPH OF TYPICAL COARSENING UPWARD CYCLE IN THE ALTERNATING FACIES AT RED BUTTE .......................................................... 84
FIGURE 19. PHOTOGRAPH OF THE SANDY FACIES OF THE RED PEAK FORMATION AT RED CANYON ............................................................... 84

FIGURE 20. PHOTOGRAPH OF THE ALCOVA LIMESTONE AT RED CANYON SECTION ........... 85

FIGURE 21. PHOTOGRAPH OF HIGHLY RIPPLED FABRIC IN THE BASAL SANDSTONE OF THE
CROW MOUNTAIN FORMATION .................................................................................................................. 85

FIGURE 22. PHOTOGRAPH OF THE UPPER SANDSTONE AND SILTSTONE UNIT AT RED BUTTE
SECTION .................................................................................................................................................... 86

FIGURE 23. PHOTOGRAPH OF THE BASAL BED OF THE LOWER CARBONATE UNIT AT RED
BUTTE ..................................................................................................................................................... 86

FIGURE 24. ANGULAR UNCONFORMITY OF HIGH AND PICARD (1965) ........................................ 87

FIGURE 25. DALLAS DOME STUDY SECTION STRATIGRAPHIC COLUMN .................................. 88

FIGURE 26. PHOTOGRAPH OF FINING UPWARD CYCLES IN THE UNNAMED REDBED UNIT AT
DALLAS DOME ................................................................................................................................... 89

FIGURE 27. PHOTOGRAPH OF PINCH AND SWELL BEDS IN THE UNNAMED REDBED UNIT AT
DALLAS DOME .................................................................................................................................. 89

FIGURE 28. PERPENDICULAR PHOTOGRAPH OF OUTCROP IN FIGURE 27 SHOWING A
CHANNELED APPEARANCE .................................................................................................................... 90

FIGURE 29. RED CANYON STUDY SECTION STRATIGRAPHIC COLUMN ................................... 91

FIGURE 30. PHOTOGRAPH OF COARSENING UPWARD CYCLE IN THE ALTERNATING FACIES AT
RED CANYON ...................................................................................................................................... 90

FIGURE 31. PHOTOGRAPH OF A CHANNEL IN THE ALTERNATING FACIES AT RED CANYON ... 92

FIGURE 32. PHOTOGRAPH OF SOFT SEDIMENT DEFORMATION IN THE ALTERNATING FACIES AT
RED CANYON ..................................................................................................................................... 92

FIGURE 33. FIELD STRATIGRAPHIC CONTEXT OF THE TR-3 UNCONFORMITY REVISIONS
SHOWN SCHEMATICALLY IN FIGURE 34 ............................................................................................... 93

FIGURE 34. NEW INTERPRETATION OF TR-3 UNCONFORMITY SEPARATING UPPER TRIASSIC
POPO AGIE FORMATION FROM JURASSIC NUGGET SANDSTONE .............................................................. 94

FIGURE 35. RED BLUFF CANYON STUDY SECTION STRATIGRAPHIC COLUMN ...................... 95

FIGURE 36. PHOTOGRAPHY OF CORRELATIVE EXPOSED SECTION ACROSS THE VALLEY FROM
RED BLUFF CANYON ............................................................................................................................. 96

FIGURE 37. X-RAY DIFFRACTION PATTERN FOR SAMPLE RB-01 ............................................ 97
FIGURE 63. A CARTOON OF THE INFERED DEPOSITIONAL ENVIRONMENT DURING POPO AGIE TIME

FIGURE 64. COMPARISON OF THE RED BUTTE STUDY SECTION WITH THE SEA LEVEL CURVE OF HAQ ET AL. (1988)

FIGURE 65. STABILITY RELATIONS OF SOME PHASES IN THE SYSTEM Na2O - Al2O3 - SiO2 - H2O AT 25 DEGREES C AND 1 ATMOSPHERE

FIGURE 66. SCHEMATIC RECONSTRUCTION OF PANGEA SHOWING THE APPROXIMATE TRIASSIC LOCATION OF THE UNITED STATES

FIGURE 67. GENERAL TECTONIC SETTING OF THE EARLY TRIASSIC WESTERN INTERIOR

FIGURE 68. PALEOGEOGRAPHY OF THE WESTERN INTERIOR DURING THE ALCOVA (LATE SPATHIAN) TRANSgression

FIGURE 69. LATE TRIASSIC PALEOGEOGRAPHY AND BASINS OF THE WESTERN INTERIOR

FIGURE 70. LOCATIONS OF LATE TRIASSIC ROCKS CONTAINING LARGE PORTIONS OF ALTERED VOLCANIC ASH
Introduction

The Chugwater Group is a deposit of Triassic age in Wyoming and Southwestern Montana. The Triassic system is defined as sequence of redbeds (Chugwater Group), limestones, and mudstones (Thaynes and Dinwoody Formations) that thicken from nearly zero feet in far western Kansas and South Dakota and far eastern Colorado to between four and five thousand feet in the Utah-Idaho trough (Figure 1) (Lawton, 1994; Peterson, 1994). These facies (and formations) change over short distances, both laterally and vertically, and the changes occur primarily by intertonguing of, gradation between, and erosion and redeposition of lithic units (Picard, 1978). Such abrupt and ubiquitous variations have lead to longstanding puzzles in both stratigraphy (for which a general solution has been found) and paleoenvironmental analysis. The remainder of this document will deal with these two enigmas.

Stratigraphic Nomenclature of Triassic Rocks of Central Wyoming

The Chugwater Formation was originally defined by Darton (1904) and included all of the redbeds between the Tensleep (Pennsylvanian) and Sundance (Jurassic) Formations in eastern Wyoming. Darton (1906) recognized that the basal Chugwater differed significantly from the main body of redbeds and defined the Embar formation to include most of the limestone, siltstone and mudstone between the redbeds and the Tensleep. Today this package is know as the Phosphoria (Permian) and Dinwoody (Lowest Triassic) Formations and Embar is
no longer accepted (Thomas, 1934). After Love (1939) separated the Chugwater into four members, Branson and Branson (1941) raised the Chugwater to group status, with the following formations recognized; Dinwoody, Red Peak, Alcova Dolomite, Crow Mountain, Popo Agie, Wyopo, and Gypsum Springs. In a plethora of publications, Picard and his co-workers and others (i.e. High and Picard, 1967; Picard and High, 1968; Picard, 1978; Cavaroc and Flores, 1991) developed the stratigraphic framework that is used in this study (Figure 2).

Depositional History of the Chugwater Group

Lower Triassic rocks represent the last widespread episode of marine deposition in the Cordilleran miogeocline, a depositional pattern inherited from the late Paleozoic (Carr and Paul, 1983). The westward thickening prism of the Triassic system represents a gradational transition from the stable craton in the east to the subsiding Cordilleran trough in the west, which was bounded on the west by the Sonoman orogenic belt (Irmen and Vendra, 2000). Maximum stratigraphic thickness developed in the Cordilleran miogeocline, which is now in central Utah and eastern Idaho (Figure 1).

Black shales and deep-water carbonate facies of the Thaynes Formation in eastern Idaho and western Wyoming grade eastward into shallow water carbonates and, eventually, into the dominantly siliciclastic sediments (Carr and Paull, 1983) of this study. Chugwater Group components were generally deposited in shallow marine, marginal marine, and continental environments (Picard, 1978). The fine-grained, red sediments of the Red Peak, Crow
Mountain, and Popo Agie Formations in west-central Wyoming were deposited on a stable, gently westward-dipping, nearly featureless plain with one brief interruption of restricted, brackish, marine carbonate sedimentation (Alcova Limestone) (Cavaroc and Flores, 1991; Johnson, 1993).

Remaining Problems

While outside the scope of this study, several interesting questions regarding stratigraphic relations of the central Wyoming shelf sequence (Red Peak and Crow Mountain Formations) to the miogeoclinal sequence (Thaynes and Woodside Formations) in western Wyoming and eastern Idaho (McKee et al., 1959) are worthy of future study. Correlations are particularly difficult because the Red Peak is unfossiliferous and the transition zone between the locations is structurally complex (Picard, Aadland, and High, 1969).

Problems also remain with the interpretation of strata in the Triassic Chugwater group, and these are the objectives of this study. In general, and specifically in the Chugwater group, the depositional processes of vast, featureless plains are not well understood. Several factors contribute to this lack of understanding: the nearly complete absence of fossils, the extremely lateral persistence of beds, and the uniform grain size of these sediments. Additionally, the units of the Triassic Chugwater Group of central Wyoming do not match any described marine or non-marine environments, either ancient or modern.

The first objective of this study is to test the validity of high-resolution sequence stratigraphic analysis (outcrop scale) using the “natural laboratory” provided by the Triassic strata in west-central Wyoming exposed along the
eastern flank of the Wind River Range (Figure 3). Two approaches in characterizing the sequence stratigraphic architecture of the Triassic Formations were used: 1) detailed section measurements and 2) quantitative mineral analysis. The hope was that mineralogic variations can be used to help identify the otherwise poorly displayed sequence boundaries present in shale-on-shale contacts that are common on continental shelf deposystems (Figure 4). The Chugwater group, which consists of siliciclastic red-beds and minor carbonates deposited in continental, marginal marine, and shallow shelf environments (Picard, 1978), provides a unique opportunity to test the high-resolution applications of sequence stratigraphy—the hypothesis that fluctuations in sea level govern the architecture of coastal plain, marginal marine, and marine deposits.

The concept behind sequence stratigraphy is that sedimentary strata are deposited in genetically related packages, called “sequences,” that are separated by unconformities or their correlative conformities. The architecture of these sequences and sequence boundaries is controlled mainly by the position of sea level, but may also be controlled significantly by changes in the relative rates of subsidence and sedimentation, as well as tectonics (Pitman 1978; Hubbard et al., 1985). Vail et al. (1977) summarized work carried out through the 1960’s and 1970’s by his co-workers and himself at the Exxon Production Research Corporation, and described the basic methods used in sequence stratigraphy. In the late 80’s and early 90’s, many sequence stratigraphy publications appeared, some of which apply the tools and techniques without questioning their validity,
while others are strongly critical of the method (Miall, 1991; Galloway, 1989; Schlager, 1992; Cloetingh, 1988; and Kooi and Cloetingh, 1991).

While seismic-scale sequence stratigraphy is at this point generally accepted, it has only a relatively coarse resolution of tens to hundreds of meters. The most recent developments in sequence stratigraphic analysis have been in the area of high-resolution subseismic-scale sequence stratigraphy, which includes integrating analyses of outcrops, well-logs, and cores (Van Wagoner et al., 1990). However, the validity of high-resolution sequence stratigraphic analysis has not been universally accepted (e.g., Miall, 1991; Galloway, 1989; Kooi and Cloetingh, 1991), and additional tests of the methods are warranted. In particular, the applications of high-resolution sequence stratigraphy to mixed carbonate-siliciclastic systems are not well understood. The lithology, stratigraphy, and areal distribution of the Triassic Formations in the study area are ideal for testing the sequence stratigraphic analysis because: 1) independent Triassic sea-level curves have been published and 2) Triassic stratigraphic units were deposited on a continental margin and contain a variety of lithofacies that should yield abundant paleoenvironmental information (Picard 1978). High and Picard (1969), Picard (1966; 1978), Tohill and Picard (1966), and Irmen and Vondra (2000) discussed the nearby petrology and depositional environments in detail and interpreted the Chugwater group as representing a stable, very gently westward dipping, nearly featureless plain with marine, marginal marine, and continental settings.
Sequence stratigraphic analysis will also form the basis of the second objective of this thesis: a revised interpretation of the depositional history of the Chugwater group. This depositional systems analysis will then be used to update the paleogeography and climactic regime of the Triassic with special emphasis on identifying pulses of uplift, erosion, and deposition caused by the suturing of the western Sonoman orogenic belt and possible sources of volcano-genetic sediments in the late Triassic Popo Agie Formation (Dubiel, 1994; Lawton, 1994).

The final objective of this research is the application of a tool new to sedimentary geologists and stratigraphers, quantitative mineral analysis by X-ray diffraction (QXRD). Developed in 2001 for ChevronTexaco (Srodon et al., 2001), QXRD provides a quick and extremely precise method, with errors of less than 2% by weight per mineral, to analyze the bulk mineralogy of rocks. This technique has broad applications to sedimentology, stratigraphy, provenance analysis, and mineralogy. The Chugwater Group is an ideal setting for this analysis for several reasons. First, the lateral persistence and homogeneity of beds in the Chugwater allow for testing of the precision of the analysis and the development of techniques in mineralogical correlation. Second, the fine-grained nature of the rocks in the study area make them difficult to characterize in terms of classic sequence stratigraphy. With the lack of a source area to shed coarse material typical of bounding surfaces recognized in sequence stratigraphy (e.g. transgressive lags, strata eroded and lithologies from below redeposited higher in section), and coarse resolution (> 20 meters) vertical mineral homogeneity
(within 5% by weight) throughout the section, sequence and parasequence boundaries can be easily missed with field study. QXRD can detect minute mineralogical variations of 2 wt. %, per mineral and trace minerals (abundances of less than 1 wt %), which are otherwise missed by hand-sample and outcrop studies, that can be created by subaerial weathering at disconformities. Finally, Picard (1978) refers to a source area change at the base of the Crow Mountain formation recognized by changes in mineralogy. This situation provides a good opportunity to test QXRD as a tool in stratigraphic analysis.
Geologic Setting

The Triassic Chugwater Group outcrops in the study area as one nearly continuous band along the northeast flank of the Wind River Range. The Lowest Triassic Dinwoody Formation underlies the Chugwater Formations. The Dinwoody Formation unconformably overlies the Permian Phosphoria Formation (Love, 1957) (Tr-0 of Pipiringos and O'Sullivan, 1991), which is one of the more resistant Phanerozoic units, and forms a shallow dipslope on the Permian units. The contact between the Dinwoody Formation and Chugwater Group is gradational and is placed variously by different authors (Picard, 1966; Kummel, 1954; Heim, 1962). In the study area, the uppermost Dinwoody Formation and lowest Chugwater Group weather recessively into a deep valley, which is often irrigated and farmed by local ranchers and grazed by their herds (Figure 5).

The four study sections start from the southeast at the Red Bluff Canyon (Figure 6) section and run to the northwest through the Red Canyon (Figure 7) section, the Dallas Dome Section (Figure 8) and, finally, the Red Butte section (Figure 9). From south to north, the study area is approximately thirty miles in length and five miles in width. The outcrops are part of the northeast dipslope and slightly more easterly anticlinal structures (Dallas Dome, Hudson Dome) of the Wind River uplift and run nearly continuously along the entire northeastern slope of the mountain range.

This study area is of particular importance because it has not been investigated in detail and because of its position between well-studied sections to
the west and northwest (Picard, 1964, 1965, 1966, 1967; Tohill and Picard, 1966; and High and Picard 1965, 1967), and northeast (Cavaroc and Flores, 1990; and Johnson, 1993). These zones are well-documented as being tidal flat, marine beach, and dune deposits to the northeast and shallow marine and continental deposits to the west and northwest. Therefore, the location of this study in the non-marine to marine transition region is of particular importance—locally, regionally, and globally. This transitional nature is also an ideal location from which to study sequence stratigraphy because changes in sea level should have the most profound effect on sedimentary deposits in the region where the sea comes in contact with the land surface.
Methods of Study

Field Investigation

Reconnaissance work began in late June and early July of 2001 when more than twelve possible sections were scouted from just south of the Wind River Indian Reservation, six miles north of Lander, Wyoming on Highway 287 to twenty-four miles south of Lander, off Highway 287. Sections were compared and chosen based on ease of access to the section, permission from ranch owners, degree of exposure, and completeness of section. Four sections were chosen from north to south, they are: 1) Red Butte, located just west of Lander, off Baldwin Creek Road; 2) Dallas Dome, located southeast of Lander, off Highway 287; 3) Red Canyon, located ten miles southeast of Lander, off of Highway 28 and Red Canyon Road; and 4) Red Bluff Canyon, located twenty-four miles southeast of Lander, off Highway 287 and Twin Creek Road.

Field investigations began in Late July of 2001. Sections were measured first at Red Canyon, followed by Red Butte, Dallas Dome, and Red Bluff Canyon. At each exposed locality, sections were measured using a tape and Brunton compass. The sections were described at a sub-meter scale resolution, and units were described at each significant vertical lithology change. Special attention was paid to bedding styles, bedforms, and contacts between units to identify sequences and sequence boundaries using methods described by Van Wagoner et al. (1990). Samples were originally taken at random from distinct units at intervals ranging from one to sixty meters. After the decision was made
to perform quantitative x-ray diffraction, sampling procedures became more rigid and regular in interval. Sample resolution was increased to a maximum of 10 meter intervals between samples at Red Canyon, Dallas Dome, and Red Butte (Red Bluff Canyon was unavailable as the author had “worn out his welcome” at Red Bluff Canyon Ranch).

**Laboratory Analysis and Quantitative X-Ray Diffraction**

Laboratory analysis included minor petrographic and quantitative X-ray diffraction (QXRD) studies to characterize the petrology and mineral content of the samples. Petrographic analysis was minimal and designed largely to observe textures of various mineral phases and to view representative samples from the three formations present in the Chugwater Group.

QXRD was performed at ChevronTexaco’s Briarpark facility in Houston, Texas under the supervision of Douglas McCarty during January of 2002. A summary of the QXRD technique and procedures is presented below (Srodon, 2001).

**Sample Preparation and Loading.** Samples were first disaggregated using a large (4 inches in diameter) plunger and collar to crush the rocks. For the second phase of disaggregation, a steel mortar and pestle was used to grind the sample so it would pass through a <20 micron sieve. This sample was then weighed to 2.7000 grams, and .3000 (10 weight percent) grams of zinc oxide were added before grinding (to ensure homogenization) as a spike for quantitative analysis. This 3.000 gram sample was then wet ground with 4ml of hexane for five minutes in a McCrone Micronizing Mill to reduce the sample to
<20 um. Hexane reduces drying time by evaporating quickly, thus avoiding swelling of shales which could dissaggregate individual clay crystals. Samples were densely packed by vigorously tapping 2.5 cm diameter side-loaders, designed for use in a forty-position sample automatic sample changer to minimize preferred orientations of clays as described in Srodon et al. (2001).

**XRD Recording Conditions.** A Siemens D-5000 diffractometer was used for collecting XRD data. The diffractometer was equipped with a forty-position sample holder, theta-theta goniometer, and a Kevex Peltier cooled silicon solid-state detector. CuKα radiation was used at 40 kV with a 40 mA current. Counting times of 2 seconds per 0.01° 2θ was used for the majority of the scan with 5 seconds per 0.01° 2θ for the 59° to 64°2θ region for 060 clay mineral quantification. Goniometer settings were as follows: 2.0 mm divergence slit, 2.3° incident beams Soller slit, and a 0.6 mm receiving slit.

**Preliminary XRD Analysis.** XRD scans were first analyzed qualitatively to identify all detectable mineral phases. EVA software provided with the Siemens diffractometer was used for this preliminary analysis as well as the author's own experience with X-ray diffraction analysis. All “unknown” peaks were satisfactorily assigned to a specific mineral phase before moving on to QXRD analysis.

**QXRD Analysis.** QXRD provides for a previously unachievable precision in mineral analysis. Errors are <2 wt. % per mineral, which compares favorably with all other quantitative analysis techniques. Analyses were performed using a proprietary software program called QUANTA that uses full pattern fitting of
reference mineral diffraction data via genetic programming as a way to measure integrated intensity of diagnostic hkl reflections (Srodon et al., 2001).

Data Presentation. The final results from QXRD analysis are plotted as % by weight of mineral versus stratigraphic position of samples. Grapher was used to plot the data with equal scales to aid in comparison between study sections. The Alcova limestone interval is marked as a rectangle on each graph to make correlation easier.
Results

Sedimentology & Stratigraphy

General

Located on the flank of the Wind River Range in west-central Wyoming, the Triassic Chugwater Group is composed mostly of siltstone and mudstone with lesser amounts of sandstone, limestone, and analcime-rich siltstones. Three formations (Figure 2) are present in the study area. From oldest to youngest they are the Red Peak Formation (Lower Triassic), the Crow Mountain Formation (Lower - Middle? Triassic), and the Popo Agie Formation (pronounced Po-po-sah) (Upper Triassic) (Picard, 1993). The text to follow will show that, based on lithology, the formations result from two, and perhaps three, transgressive/regressive (T/R) cycles and a final episode of entirely continental deposition. Superimposed on this cycle are three to four smaller T/R cycles with a period of pronounced continental deposition to close the Triassic. The Chugwater group conformably overlies the basinal facies of the Lowest Triassic Dinwoody formation, and is unconformably overlain, (J-0 of Pipiringos and O'Sullivan (1978) by the Jurassic aged Nugget Sandstone.

Four stratigraphic sections are described, starting with the thickest and most well-exposed section to the northwest. They are the Red Butte (RB) section, the Dallas Dome (DD) section, the Red Canyon (RC) section, and finally, the Red Bluff Canyon (RBC) section.
In the pages that follow, descriptions of stratigraphy will proceed up section from the Red Peak formation. Lithologic descriptions will be presented first and will refer to the stratigraphic columns presented as figures in the text. Interpretations of depositional environment will follow.

**Red Butte**

**Observations**

The Red Butte study section (Figures 9 and 10) is located slightly northwest of downtown Lander off Baldwin Creek Road (SEC 8, T.33N, R.100W). This location was chosen for study because of its excellent exposure, continuity of section (lack of covered intervals), and overall stratigraphic completeness (containing most members of all formations). Approximately 240 meters of section were measured with the top 35 meters assigned to the Nugget Sandstone. The section was bounded below by lack of exposure in a low valley, and above by the J-0 unconformity of Pipiringos and O'Sullivan (1978) separating the Popo Agie Formation from the Nugget Sandstone.

*Red Peak Formation – Lower platy facies.* Exposed at the base of the Red Butte sections is just over nine meters of the Lower Platy Facies of High and Picard (1967). Individual beds range from 2 mm up to 1.2 meters but average about 2 to 5 cm thick. Thinner beds show well developed ripple cross-lamination (Figure 11) and beds thicker than 10 cm commonly have parallel lamination (Figure 12). Common rock types are orange-red (o-r) to brick-red (b-r) siltstone that increases upward and o-r to b-r and white mudstone and claystone. Other
common sedimentary structures include linear asymmetric ripple marks (Figure 13), and wavy stratification. Picard (1967, 1978, and 1993) makes mention of rare to common mudcracks in the lower platy facies; no mudcracks were seen during the field investigations of the lower platy facies this study.

Red Peak Formation – Alternating facies. The alternating facies (High and Picard, 1967) is approximately 100 meters thick and represents half of the depositional history of the Chugwater exposed in the study area. The exposures of the alternating facies are excellent (Figure 14) and form the bluffs and ledges most travelers recall as red rocks in Wyoming. This facies is so named because of the rhythmic alternation of the fining upward sequences; 1) sharp based massive o-r siltstone in beds up to 5 meters thick that grade up rapidly into 2) recessively weathering poorly sorted o-r, b-r, white, and green very thin bedded platy, fissile to non-fissile silty mudstone/claystone usually no more than 1 meter thick.

Sedimentary structures vary throughout, with the platy units being generally horizontally bedded, with lesser cross-lamination, and wavy stratification. Bedding in massive units is typically destroyed by bioturbation (Figure 15). Toward the top of the alternating facies the massive units commonly show small-scale sets of tabular cross-lamination and climbing ripple cross-lamination (Figure 16). Picard (1978) suggested that in the massive units “...40 to 80 percent of the bedding apparently sublenticular lamination or disturbed stratification.” According to Van Straaten (1954a, 1954b), this bedding style forms on mud flats and on the floor and banks of tidal gullies and channels.
speculate that the dominant bedding style in the massive units is climbing ripple cross-lamination, and the disturbed stratifications and sublenticular lamination of Picard (1978) is a gradational phase between well-preserved, climbing ripple cross-laminations and complete bioturbation caused homogeneity of the unit. Figure 17 is a reproduction of Figure 14 from Picard (1978) and I have highlighted the remnants of climbing ripple cross-lamination slip faces after an intermediate to intense level of burrowing.

The final noteworthy feature of the alternating facies is the cyclic nature of deposition. There are two large-scale upward coarsening sequences present within the alternating facies (Figure 18). These sequences are from 30 meters up to 70 meters and contain within them seven to fourteen small-scale, upward fining sequences that are described above.

*The Red Peak Formation – Upper platy facies.* The upper platy facies (High and Picard, 1967) is a 5 to 6 meter unit located at the top of the alternating facies and below the sandy facies. It clearly resembles the lower platy facies and appears to be transitional with the top unit of the alternating facies. The sedimentary structures are reminiscent of the lower platy facies with the exception of more abundant parallel lamination in the upper platy facies.

*The Red Peak – Sandy facies.* This unit is assigned to the base of the Crow Mountain sandstone by High and Picard, 1967 and Picard, 1978 and the top of the Red Peak formation by Cavaroc and Flores, 1991; Johnson, 1993; Irmen, and Vondra, 2000, and this study. The sandy facies (Figure 19) at this location comprises 2.7 meters of variegated (red, white, yellow, and gray), calcareous,
fine- to medium-grained, medium-bedded (15-20 cm) to massive sandstone. Sedimentary structures are difficult to identify as the color mottling masks them. Relict structures appear to be disturbed lamination and small scale cross-lamination. Bioturbation is the only readily identifiable structure and has likely destroyed most bedding details.

The contact with the overlying Alcova is sharp and appears conformable; however, Picard (1967) suggested the contact was disconformable, while Hose (1955) and Johnson (1993) suggest that the contact is erosional and may be an angular unconformity. Cavaroc and Flores (1991) describe root casts and disturbed stratification as evidence for paleosol development on the top of the sandy facies about 120 miles northeast of the study area.

*The Crow Mountain Formation – Alcova limestone.* The Alcova limestone member (Figure 20) (High and Picard, 1967) is 1 meter of silty to sandy micrite and microsparite limestone with local dolomitization. The color varies from gray to pinkish, depending on hematite content (Picard, 1978). The detrital fraction increased upward to produce a limey sandstone toward the top. Bedding is generally millimeter-scale laminations. The bottom 30 cm has a wavy look that has been identified as stromatolites by many authors (Carini, 1964; Tohill and Picard, 1966; Picard, 1978). The top 70 cm is characterized by very small (1 to 2 cm wavelength and <1 cm amplitude) ripple marks and ripple cross-lamination. Stylolites are common throughout and are usually perpendicular to bedding and less than 2 mm in width.
Carini (1964) describes what little biota there is in the Alcova. An advanced
northosaur (a reptile/amphibian), *Corosaurus alcovensis* is known as well as
gastropods, pelecypods, and blue-green and green algae. Minor work has been
done on the stable isotopes from the Alcova (Cavaroc and Flores 1991).
Carbon-13 values of three samples are $-1.0133$ (the average); the oxygen-18
values are $-5.2203$, which suggest brackish water and according to Picard
(1993) values typical of chalcs. Finally Ca:Mg ratios are greater than 70 (Picard,
1993) indicating nonspecific marine conditions. The top of the Alcova is irregular
and shows decimeter to meter scale relief (Tohill and Picard 1966). Locally,
karsting is present on top as small depressions, which are less than 5 cm deep
and filled with sand from the overlying sandstone.

*The Crow Mountain Formation – Basal sandstone unit.* The basal sandstone
(High and Picard 1967) is approximately 6.5 meters thick of medium-grained
calcite cemented quartz sandstone. The lowest basal sandstone in the Powder
River Basin to the northeast has been shown to have a thin, carbonate, pebble
conglomerate layer derived from the underlying Alcova limestone (Irmen and
Vondra, 2000; Pipiringos and O'Sullivan, 1978). The bottom 5 meters is thin-
bedded to massive and commonly contains drab discolorations from secondary
leaching of iron oxide. Bedding ranges from thin ($<5$ cm) to medium ($>20$ cm),
and each bed has characteristic structures. Thin beds are commonly parallel
laminated while medium beds have ripple cross-lamination. Less common
structures include ripple marks and minor local claystone-pebble conglomerate.
The top 1.5 meters show a highly rippled fabric with beds over 1 cm having
parallel lamination (Figure 21). The unit it topped by a 5 cm sandstone bed that erosionally overlies the rippled unit with 4 to 7 cm of relief.

*The Crow Mountain Sandstone – Upper sandstone and siltstone unit.* The upper sandstone and siltstone unit (Figure 22) (High and Picard, 1967) is distinguished from the basal sandstone by the thickness of bedding; while the basal sandstone is medium to thick-bedded, the upper sandstone and siltstone is platy to thin-bedded. The upper sandstone and siltstone unit is slightly over 5 meters thick of interbedded fine-grained quartz sandstone and siltstone. Sandstone beds are weather-resistant while siltstone tends to form reentrants between sandstone beds. Sandstones show abundant asymmetric ripple marks and siltstones are indistinct. Claystone-pebble conglomerate is more common in the upper sandstone and siltstone unit as is claystone that was rare to absent in the basal sandstone unit. An unconformity separates the upper sandstone and siltstone unit from the overlying unnamed redbed unit. It has been identified as the Tr-3 of Pipiringos and O-Sullivan (1978).

*The unnamed redbed unit.* The unnamed redbed unit is 26 meters of interbedded, very fine-grained sandstone, siltstone and mudstone. The sandstone occurs only in the bottom 5 meters. Cross-stratification and asymmetric ripple marks are the dominant structure in the lowest unnamed redbed unit. The upper 20 meters of strata are dominantly flaggy siltstone with interbedded recessive mudstone and claystone. The siltstone units have sharp bases and are commonly thick-bedded to massive (>50 cm) and are highly trough cross-bedded with forests as thick as 20 cm. The units fine upward to
very fine silt that is ripple laminated and, finally, into bioturbated mudstones and claystones.

*The Popo Agie Formation – Lower carbonate unit.* The lower carbonate unit (High and Picard, 1965) is approximately 4 meters of interbedded limestone conglomerate and massive structureless mudstone. The basal bed is 1.1 meters of reddish-gray lime matrix-supported limestone conglomerate (Figure 23) in beds from 2 to 40 cm. Pebbles are both rounded and angular and range in size from less than 1 cm up to 7 cm long by 3 cm wide. Angular clasts show moderate imbrication. Upward in the carbonate unit, limestone conglomerate decreases in abundance, and mudstone increases, grading upward into the overlying purple unit.

*The Popo Agie Formation – Purple unit.* The purple unit (High and Picard, 1965) is a 20 meter interval of purple, massive, bioturbated clay and thin siltstone toward the top of the section. The purple unit commonly weathers to badlands and is a distinctive marker bed in the field. The beds at the top are approximately 3 meters of thick-bedded to massive and ripple cross-laminated siltstone. Thinner units show parallel laminations.

*The Popo Agie Formation – Ocher unit.* The contact between the purple and ocher units is difficult to place in the Red Butte section and is based largely on regional stratigraphic thickness given by High and Picard (1965). The ocher unit fines upward from interbedded, ripple cross-laminated, silty analcimolite (a rock type with more than 50% analcime) and mudstone in the bottom 8 meters to predominantly yellowish-brown smectitic mudstone in the remaining 12 meters.
The mudstone is poorly exposed in the Red Butte section and there are few if any identifiable sedimentary structures. The ocher unit does not weather to badlands and this provides a reasonably accurate criterion to distinguish the two units in the field.

**The Popo Agie Formation** – **Upper carbonate unit.** Figure 1 of High and Picard (1965) shows the proposed angular unconformity separating the Popo Agie formation from the Jurassic (?) Nugget sandstone (Figure 24). The figure shows that the upper carbonate unit is truncated just north of Crooked Creek, approximately 120 miles northwest of the Red Butte section of this study. Field studies however showed clear evidence of two thin carbonate conglomerates just below the white cliff formed by the Nugget Sandstone, and further sections will extend the position of the upper carbonate unit still further to the southeast. The upper carbonate unit is a greenish yellow friable carbonate microconglomerate. It is present as two thin tongues, both approximately 50 cm thick, at the top of the section separated by a 1 meter yellowish brown limey mudstone unit.

**Dallas Dome**

**Observations**

The Dallas Dome section (Figures 8 and 25) is located southeast of Lander, off Highway 287 (Sec. 13, T.32N, R.99W). This section was chosen because, while less of the Red Peak formation is exposed (approximately 100 meters), it has good exposure of the Crow Mountain sandstone and upper Popo Agie Formation. The section is exposed on the northeast wall of the northwest-to-
southeast oriented Dallas Dome anticline. It begins at the base of exposed rock above the small alluvial fan and ends at the regional angular unconformity with the Nugget Sandstone. A small, easily recognizable normal fault parallels the section and measurement was kept to one side of this fault to prevent duplication or deletion of section.

*Red Peak Formation – Alternating facies.* The 34 meters of alternating facies (High and Picard, 1967) exposed at Dallas dome is correlative with the highest of the upward coarsening sequences discussed above in the Red Butte section. Seven smaller upward fining packages are present, with the thicker siltstone beds showing few sedimentary structures. Those visible include minor ripple cross-lamination in both siltstone and thinner mudstone units, increasing toward the top of the facies.

*Red Peak Formation – Upper platy facies.* At the Dallas Dome section, the upper platy facies (High and Picard, 1967) grades out of the Alternating facies and is just over 6 meters thick, approximately half a meter thicker than at the Red Butte locale. The common structures are ripple cross-lamination, and parallel lamination with the former dominant in the coarser siltstone beds and parallel lamination ubiquitous in the mudstone beds. The contact with the overlying sandy facies where exposed is sharp and conformable.

*Red Peak Formation – Sandy facies.* The sandy facies, like that at the Red Butte section, is 2.7 meters of variegated fine- to medium-grained calcareous sandstone. Ripple cross-lamination appears more abundant at this location, but
the sub-parallel color banding makes identification of sedimentary structures tentative at best.

*Crow Mountain Formation – Alcova limestone.* The Alcova limestone (High and Picard, 1967) thickens from the Red Butte section to 1.5 meters at Dallas Dome. The bottom 50 cm displays wavy algal laminations similar to those previously described. The upper 1 meter shows ripples and is significantly sandier and grades on limey sandstone. Overall, the Alcova is remarkably similar to the same unit at Red Butte, and shows variation only in its thickness.

*Crow Mountain Formation – Basal sandstone unit.* 8 meters of medium to thick-bedded ripple cross-laminated sandstone make-up the basal sandstone unit (High and Picard, 1967). Ripple cross-lamination is abundant with some parallel lamination. The unit shows more pronounced drab discoloration, with discrete units thicker than 1 meter.

*Crow Mountain Formation – Upper sandstone and siltstone unit.* The contact between the basal sandstone and upper sandstone and siltstone at Dallas Dome is at the first persistent mudstone above the basal sandstone. Here, the upper sandstone and siltstone unit (High and Picard, 1967) is 3.5 meters in thickness and poorly displayed. The bottom is 1.6 meters of covered o-r, b-r, and green shale and mudstone. A 2 meter mudstone slope below a persistent siltstone bed tops this covered interval. Significantly thinner than the same unit at Red Butte, the Tr-3 (Pipiringos and O'Sullivan, 1978) unconformity has removed significantly more sediment in this location.
The unnamed redbed unit, and lower carbonate and purple unit of the Popo Agie Formation (Jelm?). 25.2 meters of undifferentiated siltstone and mudstone make up the unnamed redbed unit and lower half of the Popo Agie Formation at Dallas Dome (High and Picard, 1965, 1967). The lower carbonate unit is missing or poorly exposed, making it difficult to separate the basal Popo Agie from the underlying unnamed redbed unit. However, the interval begins with 5 meters of interbedded siltstone and mudstone in units from 1 to 2 meters thick. Ripple cross-lamination is common to abundant in the siltstone units and mudstone beds are very thin bedded.

Nine meters consisting of > 80% rippled o-r to b-r and white siltstone and interbedded b-r mudstone continue to the base of the next outcrop. Siltstone units are 5 to 80 cm thick and fine upward into very thin mudstone beds (Figure 26). Variably bedded mudstone and siltstone 3.8 meters thick overlie the unit below. The bottom 3 meters is mostly covered with a small mudstone outcrop below the 80 cm resistant siltstone. The siltstone shows an interesting pinch and swell type of bedding which has various interpretations (Figure 27). Beds swell to a maximum of 30 cm and pinch to < 2 cm. While two possibilities exist, a large-scale cross-bedding shown in an exposure perpendicular to bedding (Figure 28) supports a channeled interpretation. The next ~5 meters is more mudstone and minor siltstone in regular beds less than 20 cm thick. These become flaggy and poorly exposed in the top 3.6 meters. The unit ends with 2 meters of massive red and white, poorly bedded, highly weathered siltstone or mudstone.
The Popo Agie Formation – Ocher unit and Upper Carbonate Unit (Jelm?). The 10.5 meter interval of the ocher and upper carbonate units (High and Picard, 1965) consists at its base of 4 meters covered interval with grayish, b-r siltstone and mudstone float and one thin outcrop of o-r calcareous siltstone. Above this is 6.5 meters of mixed covered and exposed material. Well-exposed units are predominantly white and yellowish-brown mudstone, with lesser red and purple siltstone beds. In an interval approximately 300 meters to the southeast along strike is a better-exposed section. The mudstone is yellow brown and brown with little or no bedding visible. The section ends with two thin, approximately .5 meter thick, outcrops of greenish yellow-brown well-rounded, poorly cemented carbonate microconglomerate. The unit is identical to the upper carbonate unit described at the Red Butte section.

Figure 24 shows the angular unconformity of High and Picard (1965) separating the Popo Agie from the overlying Nugget Sandstone. As mentioned previously, the Dallas Dome study area shows the upper carbonate unit once again. This discovery pulls the erosional truncation of the upper carbonate unit beyond the Dallas Dome study section, extending it more than 130 miles further to the southeast than High and Picard (1965) discussed, and this is not the end of the revision to the proposed angular unconformity.
Red Canyon

Observations

The Red Canyon section (Figures 7 and 29) is located 13 miles southeast of Lander, off Highway 28 and Red Canyon Road (Sec. 35, T.31N, R.99W). Red Canyon is a nationally famous observation point at the southernmost extension of the Wind River Range. The exposure of the alternating facies of the Red Peak through lower carbonate unit of the Popo Agie (High and Picard, 1967) is excellent. The section is 150 meters thick and exposed along strike with the Red Butte section. The interval begins at the base of exposed rock above Red Canyon Road in the Crimson Meadow and ends at the covered valley between the upper carbonate unit and the cliff formed by the Nugget Sandstone.

The Red Peak Formation – Alternating Facies. Exposed at Red Canyon are the two (Figure 30) major upward coarsening sequences described above for the Red Butte section. The interval differs from the Red Butte section in two ways: first, the total thickness is slightly thinner totaling 87 meters; and second, the coarser siltstone units are generally thinner and more numerous, while the mudstones are thicker towards the top, and less well-developed at the bottom. The structures displayed are generally the same, except for the presence of rare small channels less than 2 meters in width with approximately 20 cm of scouring (Figure 31), and soft sediment deformation in the lower beds (Figure 32).

Red Peak Formation – Upper platy facies. The upper platy facies (High and Picard, 1967) is 8 meters of mostly covered flaggy mudstone and siltstone in
beds up to 30 cm. Plain parallel bedding is the dominant structure with subordinate ripple cross-lamination.

*Red Peak Formation – Sandy Facies.* The sandy facies is 1.8 meters thick and grades out of the upper platy facies from red calcareous sandstone to red, white, and yellow calcareous sandstone 96 cm up from the base of the interval. Again, structures are difficult to recognize due to color modeling, as was the case in each of the other two sections.

*Crow Mountain Formation – Alcova Limestone.* The Alcova at Red Canyon continues the thickening trend developed between Red Butte and Dallas Dome, resulting in a thickness of 1.8 meters with the bottom 20 cm containing the algal lamination and the upper portion displaying ripple cross-lamination.

*Crow Mountain Sandstone – Basal Sandstone.* The basal sandstone (High and Picard, 1967) is 9 meters thick and continues the thickening observed between Red Butte and Dallas Dome. Cross-bedding and ripples dominate the interval, and it becomes flaggy and less resistant toward the top.

*Crow Mountain Formation – Sandstone and Siltstone Unit.* Again, this transition is difficult to pick and is chosen as the first large siltstone unit above the Alcova limestone. Here, the unit is 5 meters thick and is topped by the Tr-3 unconformity of Pipiringos and O’Sullivan (1978).

*The Unnamed Redbed Unit.* 34 meters of mostly covered, interbedded siltstone and mudstone characterize the unnamed redbed unit at Red Canyon. The section is poorly exposed with only one, 2 meter bed of plain parallel bedded
siltstone well-exposed. Otherwise, sedimentary structures are inconspicuous and impossible to identify.

*The Popo Agie Formation – Lower Carbonate Unit.* A thin <1m carbonate microconglomerate is exposed before the long dipslope interval below the cliff-forming Nugget Sandstone. This bed is interpreted to be the basal bed of the Popo Agie formation and forms the last piece of evidence used to revamp the angular unconformity proposed by High and Picard (1966). This interpretation is shown on detailed stratigraphic columns in Figure 33 to illustrate the unconformity as accurately as possible, while Figure 34 is schematic and modified from High and Picard (Figure 24) and is a new interpretation of the angular unconformity considered to mark the Triassic/Jurassic boundary.

**Red Bluff Canyon**

*Observations*

The Red Bluff Canyon (Figures 6 and 35) study section was chosen primarily for its location to the extreme southeast of the study area. The section is located 24 miles southeast of Lander, off Highway 287/789 and Twin Creek Road. The section has good exposure of the upper alternating facies and upper platy facies, as well as an interesting sequence of strata above the Alcova limestone and below the Nugget Sandstone. The section starts on Red Bluff Canyon Ranch Road across from a fenced-in hay stall at the lowest outcrop.

*Red Peak Formation – Alternating Facies.* The alternating facies (High and Picard, 1967) exposed in this section continues the trends described above. 57
meters of interbedded platy mudstone and ripple cross-laminated siltstone are exposed and described. Mudstone beds are thicker and more abundant while siltstones thin further and become yet more numerous than those at Red Canyon. One full coarsening upward sequence is exposed at this section while the upper 2/3 of a second sequence is present at the very bottom of the bluff.

*Red Peak Formation – Upper platy facies.* 11.7 meters of interbedded mudstone (70%) and ripple cross-laminated siltstone are present in the Red Bluff Canyon section. This interval is 3.5 meters thicker than the same unit exposed to the northwest at Red Canyon a trend that is common throughout the Red Bluff Canyon section.

*Red Peak Formation – Sandy facies.* The sandy facies is 2.7 meters of variegated fine- to medium-grained sandstone. As is typical with this unit bedding styles are frustratingly difficult to determine. Relict disturbed bedding appears to be common, and ripple cross-lamination cannot be ruled out.

*Crow Mountain Formation – Alcova limestone.* The Alcova limestone reaches a maximum thickness of 4.3 meters in the Red Bluff study section. The additional thickness is accommodated in the upper rippled section as the basal algal section remains between .3 and .5 meters.

*Crow Mountain Formation – Basal sandstone unit.* The basal sandstone unit (High and Picard, 1967) maintains nearly constant thickness throughout the study area, and Red Bluff Canyon is no exception. The unit here is exposed as a shallow slope 9 meters in thickness with sandy detritus. Thin exposed units show minor ripple cross-lamination and massive bedding.
Crow Mountain Formation — Upper sandstone and siltstone unit. 1.8 meters of interbedded b-r to purple mudstone and o-r siltstone characterize the interval at this location. The Tr-3 unconformity is inferred in this location by the conspicuous variation in thickness (approximately 3 meters difference) between this section and Red Canyon 18 miles away.

Above the Tr-3 Unconformity (Jelm and Popo Agie?). At Red Bluff Canyon there is a 16 meter interval of exposed rock and 24 additional meters of covered interval. It consists of interbedded siltstone, very fine-grained sandstone, mudstone, and micrite limestone. The assemblage of rocks bears similarity to the Jelm as described by Picard (1978) and Figure 36 (the exposed section across the valley) is quite similar in appearance to the Jelm present at Red Mountain. Figure 36 also shows what appear to be beds of Popo Agie above the resistant sandstone (?). Future study could elucidate this relationship more clearly and place the unknown beds below the white cliff of Nugget Sandstone into their stratigraphic context.

Mineralogy

General

The mineralogy of samples was analyzed using the technique of Quantitative X-Ray Diffraction (QXRD) developed by Srodon et al. (2001). The X-ray diffraction data are presented in two ways. First, the *.raw files are included on compact disc for analysis by others in the future. The CD also displays the X-ray diffraction patterns analyzed by the EVA software provided with the Siemens D-
5000 diffractometer. Where chlorite has been identified on the diffraction patterns, mixed layer illite/smectite is probably the more dominant phase, with occasional chlorite (I was unable to access the software used to analyze these patterns. Therefore this change could not be included in the final draft of the figures). Several of the x-ray scans are included as figures in the text depicting the mineralogy of representative samples from each of the facies (Figures 37-42, 45-50, 53-57). Also on the CD is the % by weight mineral results from QXRD analysis presented as spreadsheets. Lastly, results are plotted as % by weight mineral versus stratigraphic position (Figures 43, 44, 51, 52, 58, and 59).

Observations

Red Butte

Qualitative results. Figures 37, 38, 39, 40, 41, and 42 are representative samples from each of the following stratigraphic units. Figure 37 corresponds to sample RB-01 from the lower platy facies. Qualitative analysis shows that quartz, plagioclase, k-spar, illite, calcite, dolomite, and mixed layer illite/smectite dominate the mineral phases of the lower platy facies. Figures 38 and 39 are from the siltstone (RB-09) and mudstone (RB-11) of the alternating facies respectively. Figure 38, the siltstone, shows the same proportions as the lower platy facies, but with a decrease in calcite and an increase in dolomite. Figure 39 shows the same minerals, with clays becoming dominant. Illite, and chlorite are abundant with lesser quartz, k-spar, plag, calcite, and dolomite. Figure 40 is of sample RB-14 from the unnamed redbed unit. Quartz is common with calcite and lesser k-spar and plagioclase. Clay content is low with illite and minor
illite/smectite. Figure 41 is of sample RB#1 from the lower carbonate unit of the Popo Agie formation. Calcite is by far the most common mineral in this limestone with some quartz and illite, illite/smectite, and k-spar. Finally, figure 42 is of Sample RB-17 the upper carbonate unit of the Popo Agie. Calcite and quartz are high as expected in a carbonate microconglomerate. Dolomite, smectite, analcime, and illite complete the abundant mineral phases.

Quantitative results. The results from the QXRD are plotted in figures 43 and 44. Several trends are immediately apparent. First is the significant drop in plagioclase feldspar from an average of ~12% below the Alcova in the Red Peak formation to ~6% in the upper Crow Mountain, unnamed redbed unit, and the Popo Agie formations. The second trend is related to the analcime: when analcime is present, smectite and mixed layer illite/smectite are also quite common, and illite/mica diminishes (grouped in with 2:1 Al-clay). Low values of feldspar (plagioclase and k-spar) coincide with increased analcime content in associated with the microconglomerate bed. Third, an inverse relationship exists between calcite and dolomite. The final important observation is the excellent correlation between siltstone units and quartz, and mudstone/claystone units and clay in the well-sampled, alternating facies fining upward unit. With regards to the clays, kaolinite is surprisingly low (save one sample), considering the amount of feldspar and the weathering relationship that exists between them.
Dallas Dome

Qualitative results. Samples DD#1 (Figure 45), DD-06 (Figure 46), DD#2 (Figure 47), DD-07 (Figure 48), DD-09 (Figure 49), DD-11.5 (Figure 50) are representative units from the alternating facies (siltstone), sandy facies, top Alcova limestone, basal sandstone unit, purple unit, and upper carbonate unit respectively. The resistant bed of the alternating facies (Figure 45) at Dallas Dome is a suite of quartz, plagioclase, dolomite, illite, and k-spar. The sandy facies (Figure 46) is characterized by the same assemblage as the resistant siltstone, but k-spar is significantly more abundant as is dolomite. The pattern in Figure 47 is from the top of the Alcova “limestone” bed; the mineral assemblage consists of calcite cemented quartzose sandstone, it consists of mostly quartz, with calcite, plagioclase, illite and lesser k-spar. The first bed of Crow Mountain sandstone is from sample DD-07 (Figure 48). Quartz again dominates with k-spar showing a dramatic increase as plagioclase drops off quickly, calcite is now the dominant cement and dolomite is all but absent. The mineral content of the purple unit of the Popo Agie is displayed in DD-09 (Figure 49). This unit consist mostly of analcime and smectite with lesser quartz and dolomite. Feldspars are conspicuously absent. The final representative sample is from the upper Popo Agie carbonate unit (Sample DD-11.5, Figure 50). Quartz, analcime, calcite, and smectite are the most abundant with lesser dolomite and again feldspars are absent.

Quantitative Results. Figures 51 and 52 display the results of the QXRD for the Dallas Dome study section. The same trends mentioned at Red Butte
appear at Dallas Dome. Plagioclase abundance varies drastically above the Alcova “limestone.” When analcime increases, so does smectite and mixed layer illite/smectite, while feldspars and mixed layer illite/smectite decrease in abundance. The inverse relationship still exists between calcite and dolomite. Kaolinite abundance is low.

**Red Canyon**

**Qualitative results.** Figures 53 through 57 represent various facies from the Red Canyon section. Figure 53 is from sample RC#6 a mudstone/claystone from the lower alternating facies. It is characterized by quartz, calcite, plagioclase, and illite, with lesser dolomite and chlorite. RC#14 (Figure 54) is from the middle of the sandy facies. Quartz and dolomite are abundant in the siltstone with lesser plagioclase, illite, and mixed layer illite/smectite (based on the diffraction pattern). Sample RC#16 (Figure 55) comes from the base of the Alcova “limestone.” The rock is a dolomite with minor amounts of quartz, illite, and calcite. The basal sandstone (sample RC-01, Figure 56) is dominated by quartz with calcite cement. Plagioclase, k-spar, illite, and illite/smectite are accessory minerals in this sandstone bed. The lower carbonate unit (Figure 57, sample RC-05) outcrops at the top of the Red canyon section and is characterized by quartz and calcite with microcline and illite.

**Quantitative results.** The QXRD results for Red Canyon are shown in Figures 58 and 59. Plagioclase content decreases from 15% below the Alcova to 5% in the Crow Mountain, and unnamed redbed unit. No significant analcime beds
were detected; I infer that this is due to the lack of Popo Agie exposure at Red Canyon. Calcite and dolomite continue their inverse relationship and this relationship is best exposed in the Red Canyon section.
Discussion

Interpretation of Depositional Environment

Red Peak Formation

General. Several researchers have worked on the paleoenvironments of the Red Peak Formation, and almost all have proposed shallow marine environments. Branson (1915; 1927) suggested marine origins for all of the Chugwater, which then included the Phosphoria, Dinwoody, Chugwater, and Nugget Formations. Reedside (1929) agreed with Branson on a marine origin for the redbeds. Darton (1906) proposed a widespread saline lake for redbed accumulation.

Picard (1967, 1978, and 1993) conducted a number of detailed studies of stratigraphy, paleoenvironments, and paleocurrents of the Red Peak Formation, concluding. "I believe that large amounts of wind-blown silt may have fallen on the Wyoming shelf, beginning with Red Peak deposition. The last Dinwoody sea was retreating slowly and was very shallow or partly ponded when lowermost Red Peak grains began to accumulate. The Wyoming shelf then had..." a northwest southeast oriented coastline (Picard, 1968) and "...paleolatitude between 15 and 25 degrees N (Robinson, 1971; 1973). Silt rained down on the land adjoining the sea, on islands, and in the shallow sea from great dust storms carried by northeasterly trade winds. Winds and currents in the remnant sea sorted the grains and formed sedimentary structures and bedding" (Picard, 1993).

Lower platy facies. The lower platy facies includes rippled beds, ripple cross-lamination, parallel lamination, burrows, and claystone-pebble conglomerate in
close association. Bedding is fairly regular ranging from 2 mm to 1.5 meters and averaging 1.3 cm. Paleocurrents (Figure 60) are dominantly to the southwest and northeast with lesser amounts to the northwest (High and Picard, 1968). According to High and Picard (1968), these directions are the result of wave drift, rip and longshore currents along the northwest-southeast oriented shoreline. So little of this formation is exposed in the study area of this investigation that the interpretation of a tidal flat deposit from Picard (1967, 1978) is relied upon.

*Alternating facies.* The alternating facies makes up half of the Chugwater formation and, is fundamental to understanding the history of this unique sedimentary sequence. Two large scale coarsening upward sequences are visible. The lowest is approximately 30 meters thick, and the upper sequence is about 70 meters thick. Within the upper portions of the coarsening upward sequences a series of seven to fourteen fining upward sequences have been identified.

The sedimentary structures are described in detail on pages 17-16, 32, 27, and 29 so only a review is presented here. Platy mudstones are dominated by cross-lamination, ripple cross-lamination, straight-crested asymmetric ripple marks, and disturbed stratification. Coarser massive units commonly contain burrowing traces and show bioturbation. Visible structures include cross-lamination, disturbed stratification, climbing ripple cross-lamination, tabular cross-lamination, “sublenticular lamination”, and some channels. As discussed in the Red Butte section, I believe there is evidence for a progressive bioturbation from unburrowed climbing ripple cross-lamination through moderately burrowed
disturbed stratification and "sublenticular lamination", to highly burrowed massive units of siltstone. This clearly represents higher competency transport than that described in Picard's (1993) interpretation of silt raining down on a flat featureless plain being gently reworked by a very shallow or partly ponded sea. This interpretation of higher competency flow is also consistent with the channels that are present in the same units.

Picard (1967; 1978; 1993) proposed a marine shelf environment for the massive units and tidal flat deposits, similar to the lower platy facies, for the platy mudstone intervals. In contrast, I infer that the upward coarsening deposits represent two 4th order transgressive/regressive cycles. The bottom platy mudstone of the alternating facies grades upward from the lower platy facies and represents marine shelf deposits of the initial transgression to a maximum at the top of the siltstone free interval (Figure 10). The few small beds of siltstone that appear towards the top of the mudstone before the first fining upward cycle signal regression. Maximum regression is indicated by the presence of fining upward cycles (Figures 10, 25, 29, and 35). These cycles are the deposits of large sheet floods draining off a shallowly dipping, featureless coastal sabkha (Figure 61). When a runoff event begins, coarser sediment is carried as sheets across the flat plain towards the sea. Sediment is deposited, sometimes in shallow channels (less than 2 meters wide and 20 cm deep) (Figure 31) during high runoff in the upper part of the lower flow regime as sets of climbing ripples. As the flood event wanes, less energy is present for carrying sediment, and finer sediments are deposited until the sharp contact with coarser sediment indicates
the beginning of the next major flood event. The tops of the mudstone in the fining upward sequence rarely show mudcracks, which indicate subaerial exposure.

Paleocurrent data (Figure 60) from High and Picard (1968) are scattered but mostly consistent with this interpretation. Dominant transport directions are to the northeast and northwest, with fewer to the southeast. These data are mostly from the platy mudstone units and are interpreted to represent wave drift and longshore currents, with lesser wave rip. Another interpretation more fitting with the interpretation suggested in this study is consistent with the data of High and Picard (1986). Their interpretation does not adequately explain paleoflow directions to the southwest and west, which can easily be explained by the runoff associated with flood events.

*Upper platy facies.* The structures of the upper platy facies are almost identical to those of the lower platy facies, except for the increase in abundance of parallel lamination and claystone-pebble conglomerate. Siltstone units commonly show ripple cross-lamination while muddy intervals are commonly parallel laminated. Intraformational conglomerates like this commonly occur in many ways, possibilities include wind set-up and set-down, and scour related to inflow and outflow of large masses of water during tidal cycles. This sequence of interbedded deposits is consistent with the interpretation of Picard (1967 and 1968) of tidal flats as the conditions of the lower platy facies return to the area. Mudstone intervals probably represent the supratidal and upper intertidal zones with siltstone present in lower intertidal, and shallow subtidal zones.
Sandy facies. This is the first abundant occurrence of sand in the Chugwater succession. Small-scale cross-stratification and disturbed stratification appear to be the dominant structures in this unit, although definitive identification is difficult. Classically these tentative structures have yielded a tentative interpretation of nearshore marine sand. Regional variations in thickness (thickest at Dallas Dome and Red Bluff canyon. Irmen and Vondra (2000) show thickness of ~5 meters in the Powder River Basin to the northeast, compared to 2-3 meters in this study) suggest that this is a flood of sand from the east and northeast deposited in a nearshore marine and beach environment or sheet flood events. The coarse grain size and lack of thin muds when compared to the alternating facies suggest that these deposits are located closer to the source area.

Crow Mountain Formation

Alcova Limestone. The Alcova Limestone covers 80,000 km² is relatively thin (averaging 3 meters and rarely exceeding 5 meters. This geometry supports an interpretations of an extremely shallow, topographically featureless, slope to the Wyoming shelf. The base of the Alcova is sharp and begins with 30 to 50 cm of stromatolitic algal limestone. Above this algal zone is 70 cm to 4 meters of ripple cross-laminated limestone, dolomite, and calcareous siltstone with nearly 20% feldspar and 10% illite and mica.

Chemical analysis and stable isotopes are non-diagnostic. Cavaroc and Flores (1991) reported that the mildly negative oxygen-18 values and carbon-13 values suggest brackish water. Picard (1993) points out that these values are
also close to those of typical chalks. The values are compatible with a marine depositional environment, but indicate no further environmental interpretations.

The upward transition from limestone with algal mats to ripple cross-laminated siltstone or limestone indicates that water depths probably shallowed with time, and the top of the algal limestone probably represents the time of highest sea level in the late Early Triassic (dating is difficult, but conodonts identified by B.R. Wardlaw at the U.S.G.S. provide the most reliable dating and indicate a (late?) Early Triassic age (Johnson, 1993)). Thus I infer the Alcova Limestone to be the deposit of a brackish, marine carbonate showing a single transgressive/regressive sequence.

Most researchers agree that a disconformity exists between the Alcova Limestone and the overlying Crow Mountain basal sandstone. Pipirigos and O’Sullivan (1978) have identified it as the Tr-2 unconformity and stated that it represents only a minor hiatus. There is much debate over whether or not significant erosion occurred at this time. Tohill and Picard (1966) reported about 30 cm of relief in west-central Wyoming. Pipiringos and O’Sullivan (1978) and Irmen and Vondra (2000) reported carbonate pebbles in the base of the overlying basal sandstone and karsting on top of the Alcova filled with sandstone; these are the most convincing evidence of erosion. However, Cavaroc and Flores (1991) show that algal head mounds on the top of the Alcova indicate no significant subaerial erosion. In the study area of this investigation I observed features in the uppermost Alcova that could be due to minor karsting but could
also be attributed to modern erosion as the top of the Alcova is often exposed to the elements.

**Basal Sandstone unit.** This unit contains the coarsest sandstone of the entire Triassic system in Wyoming and more carbonate cement than the lower facies. Paleocurrents of the entire Crow Mountain Formation studied by Tohill and Picard (1966) in northwestern Wyoming are strongly bimodal, indicating wave and tidal forces. Structures vary throughout, but are closely associated with bedding. Medium- to thick-beds commonly show small scale cross-stratification and a highly rippled, cross-laminated fabric with erosional contacts displaying 4 to 7 cm of relief (Figure 21). Thinner beds are commonly parallel-laminated, indicating a higher competency and deposition in the upper flow regime. Other minor structures include claystone-pebble conglomerate, ripples, and disturbed stratification.

These structures, higher sorting and coarser grain size, and higher proportion of carbonate cement indicate a marine shelf to nearshore marine environment of deposition with constant reworking (Figure 62). This interpretation is consistent with previously described sections to the east and northeast, or paleolandward. Tohill and Picard (1966) studied sections north-northeast of this study and suggested a more landward shallow nearshore marine depositional environment. Cavaroc and Flores (1991) and Johnson (1993) studied rocks at the western edge of the Powder River Basin and suggested a shoreface environment. Irmen and Vondra (2000) studied the same rocks as Tohill and Picard (1966), but, based on the presence of wind ripple, rainfall and grainflow strata, and lag
deposits, they, for the first time, recognized and emphasized, aeolian dune, wet interdune, and sabkha environments.

Upper sandstone and siltstone unit. Typical exposures of the upper sandstone and siltstone are shown in Figure 23. Resistant sandstone beds are often asymmetrically rippled with claystone-pebble conglomerate at their bases whereas interbedded siltstones are generally unstructured. Beds can rarely be correlated between localities, because facies changes are common. In addition, claystone appears in the upper sandstone and siltstone unit.

This sequence of structures developed in a low energy environment. The presence of parallel-laminated claystone indicates slack water, and the claystone-pebble conglomerates indicate occasional higher energy deposits. Pulses of fluvially dominated deposition are also present. The general picture is that of a tide-dominated estuary. During low tide, the majority of the sediment is exposed and dessicated. At this time, sediment is carried in suspension in small meandering channels and small-scale fining upward sequences from claystone pebble conglomerate in siltstone and sandstone to asymmetric ripples developed in siltstone. As the tide rises, siltstone and claystone are deposited in parallel laminated and massive units (resulting from reworking by burrowing).

The Crow Mountain Formation described by Tohill and Picard (1966) shows a pronounced thickening and coarsening to the north and east. These observations suggest two possible interpretations: either the environment of deposition persisted longer in that direction, or the source area was to the north and east. I prefer the latter, largely because the coarsening is very conspicuous.
in a sequence as fine-grained as the Chugwater Group and because of mineralogic data discussed later.

The top of the Crow Mountain Formation is topped by an unconformity of regional extent. This is the Tr-3 unconformity of Pipiringos and O'Sullivan (1978) who have said that it “is one of the most widespread, conspicuous, and widely recognized unconformities” in the Triassic and Jurassic in the Western Interior United States. The unconformity separates the Middle (?) Triassic Crow Mountain from the overlying Late Triassic unnamed red bed unit.

**Unnamed red bed unit (Jelm Formation)**

Trough and planar cross-stratification, asymmetric ripples, parallel lamination, and burrowing characterize the unnamed red bed unit. Sandstone is common in the basal 5 meters with siltstone and mudstone increasing towards the top. Well-developed channels (Figures 27 and 28) too are common in the unit. Micritic limestone is present in a few locations. Finer beds show ripple cross-lamination and abundant burrowing especially in the mudstone intervals. These associations are suggestive of a westward-extending, fluvial plain or incised valley. Thin carbonates, probably formed in lakes, scattered across the floodplain.

**The Popo Agie Formation**

*Lower Carbonate Unit.* The lower carbonate unit is a limestone conglomerate that shows pebble imbrication parallel to bedding. A fluvial environment is
interpreted, which transported and imbricated rounded and angular carbonate pebbles from associated local ponds and small lakes.

**Purple unit.** The purple unit is generally massive and highly bioturbated. Locally, beds of analcimolite are developed (Dallas Dome), and, towards the top, ripple cross-laminated siltstone appears. The unit represents a large floodplain deposited by low-gradient meandering streams (Figure 63). Local beds of analcimolite indicate the presence of isolated alkaline lakes. Volcanic ash, washed in by streams and carried to the basin by winds, settled on a vast alluvial plain and was altered to mostly smectite clay and analcimolite.

**Ocher unit.** Silty, analcimic, mudstone and analcimolite characterize the ocher unit. Keller (1952) noted that the ocher units are predominantly massive, and burrows are common. This is the deposit of a large alkaline lake. Ash from distant volcanoes carried by winds rained into the lake where it accumulated, and altered to smectite and analcime. Picard (1993) proposed that "Lake Popo Agie" covered an area greater than 70,000 mi² and suggested it was much larger during its maximum extent (removed by erosion during exposure that created the J-0 unconformity of Pipiringos and O'Sullivan (1978) in eastern Wyoming).

**Upper carbonate unit.** Carbonate microconglomerate of the upper carbonate unit closely resembles the deposits of the lower carbonate unit excepting the greater roundness of clasts present in upper unit. As such, a fluvial origin is proposed with pebbles derived from nearby lakes and ponds.
**Sequence Stratigraphy**

A stratigraphic sequence has been described as "a stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities" (Mitchum et al. 1977). After much confusion caused by the definition of an "unconformity," Van Wagoner et al. (1988) clarified, saying an unconformity is "a surface separating younger from older strata along which there is evidence of subaerial erosion and truncation and subaerial exposure and along which a significant hiatus is indicated." Using these definitions, I interpret two major 2nd order transgressive/regressive cycles in the Chugwater group with 4-5 smaller-scale T/R cycles, followed by a period of pronounced continental deposition (Figure 64).

Figure 64 compares the Red Butte section (the most complete section studied) with the Triassic Sea Level Curve (Haq et al., 1988), which was aligned using the best age constraint available. The interpretations below are not exclusive to Red Butte; the lateral persistence of beds in the study area makes this description general enough to describe all the sections, with few exceptions that will be noted in the text.

The first sequence is entirely contained within the various facies of the Red Peak Formation. The paralic nature of the silty claystone facies (not studied in this investigation) (Picard, 1978) begins the post-Griesbachian regression following the Dinwoody maximum flooding surface. The ripples, parallel lamination, and claystone-pebble conglomerate of the lower platy facies (first
exposed facies of this study) record deposition in a tidal flat, and the maximum regression and early transgression of Red Peak time. The first thick mudstone of the alternating facies records marine shelf deposition. This transgression continues to a maximum flooding surface, which is difficult to precisely place, but occurs near the base of the first small siltstone bed. These siltstones reflect the onset of regression, which continues until the top of the final upward fining sequence before the second large mudstone interval. Maximum regression is recorded by the thick siltstone fining upward sequences of the middle alternating facies. These fining upward cycles represent flood events on a flat featureless coastal sabkha. Occasional mudcracks at the top of the fining upward cycles indicate subaerial exposure.

Above these coarse siltstone fining upward sequences, a second large platy mudstone interval occurs. This represents the return to transgression, of the second 3rd or 4th order sequence, leading to a maximum flooding surface in the zone below the first thin resistant siltstone bed. These siltstones mark the return of regression leading to a maximum with the second occurrence of fining upward sequences.

The upper platy facies tidal flat deposits signals continued sea level regression. The close of the first 2nd order T/R cycles is marked by the forced regression caused by a progradational flood from the east of very fine sand in nearshore and beach environments or as a series of stacked sheet floods, the sandy facies. The top of the sandy facies is a sharp contact, and a correlative sequence boundary with the overlying Alcova Limestone.
Correlation of the Red Butte section (and others) with the Haq curve is remarkable (if alignment is correct) down to 3rd and 4th order cycles. This correlation suggests that sea level is the dominant factor controlling accommodation space during the early Triassic, at least until sandy facies deposition.

The second 2nd order T/R cycle is not so clearly defined as the first. Transgression across the flat featureless plain is very rapid, and variations in thickness of the Alcova limestone (from no deposition to 5 meters) suggest that eustasy was not the only factor (sedimentation rates were likely very important) controlling the late Early Triassic sequence. Alcova transgression continues to a maximum flooding surface marked by the contact between algal lamination, and ripple cross-laminated limestone and siltstone in the Alcova limestone. The Alcova sea regressed as quickly as it transgressed marked by the transition from ripple cross-laminated limestone and dolomite to ripple cross-laminated limy siltstone. The top of the Alcova limestone is a regional disconformity or unconformity, the Tr-2 of Pipiringos and O'Sullivan (1978). In the study area of this report, the surface is only a minor hiatus or correlative conformity. However, Cavaroc and Flores (1991) and Irmen and Vondra (2000) reported karsting and Alcova Limestone pebbles, on the Alcova, and in the base of the Crow Mountain Formation, respectively in northwestern Wyoming and the Powder River Basin.

Following the Alcova Limestone T/R cycle, sand, silt and mud, in that order of abundance, prograded from the north and east over the Tr-2 boundary. The basal sandstone unit records a period of marine shelf to nearshore marine
deposits. The upper sandstone and siltstone unit, which records tidally
dominated estuary deposition, tops these beds. This could be interpreted as a
single T/R cycle that could be consistent with the first fully Anisian T/R cycle of
the Haq curve (Figure 64). This is tentative at best, as most middle Middle
Triassic rocks are missing from the Western Interior United States and the
amount of sediment deposited seems too little to represent such a long period of
time. In addition, the nature of the thickening and coarsening to the north and
east of the basal sandstone suggest progradation and a possible shelf margin
wedge (SMW). There is no evidence for an incised valley to supply sediment for
this SMW however. The Jelm formation of southeastern Wyoming is a possible
candidate for the incised valley but the sources for the two rocks are significantly
different with the Jelm coming from the ancestral Rocky Mountains to the south
(Picard, 1978). A likely candidate would be to the northeast, but Jurassic erosion
has removed Late Triassic sediments in that direction. Future subsurface
investigations in the Bighorn and Powder River Basins could provide answers to
these questions.

It is my opinion, however, that this is a tectonically-controlled transition,
resulting from newly uplifted sources to the north and east shedding sediment to
the south and west.

Following Crow Mountain time, a regional unconformity separates the Crow
Mountain Formation and the Upper Triassic unnamed red bed unit, the Tr-3 of
Pipiringos and O’Sullivan (1978). Following this event of uplift and erosion,
marine sediments were never again deposited in the Wind River Basin during the
Triassic. Instead, a steady and large progression from incised valley fill in the unnamed redbed unit (if the basin, and therefore fluvial base level is shifted drastically to the east, as is indicated, then valley incision is required to maintain stream equilibrium), to fluvial deposits of the lower carbonate of the Popo Agie Formation, to a large floodplain deposited by low-gradient meandering streams and local lakes with minor volcanic sources of the purple unit, to wholly lacustrine deposits with major volcanism of “Lake Popo Agie (Picard 1993)” from the ocher unit, and finally a return to fluvial with associated lakes with minor volcanic events in the upper carbonate unit of the Popo Agie formation.

Correlation with the Haq curve is nonexistent (Figure 64). This is indicative of a major tectonic event in the Middle to Upper Triassic. A partly volcanic source for the Popo Agie Formation supports this hypothesis.

The Triassic ends with the J-0 unconformity of Pipiringos and O'Sullivan (1978). The unconformity is regionally angular and bevels the upper Popo Agie Formation in eastern Wyoming.
Mineralogy and Provenance

For the following discussion, refer to whole-rock mineralogy plots in Figures 43, 44, 51, 52, 58, and 59, for the Red Butte, Dallas Dome, and Red Canyons respectively.

Plagioclase Variations

QXRD analysis shows a major drop in plagioclase feldspar content from 12% to 15% in the Red Peak Formation to 5% to 7% in the overlying Crow Mountain Formation, unnamed red bed unit, and Popo Agie Formation that has several possible interpretations. The simplest explanation is that of a source area change. Three different types of source rocks have been proposed for the Chugwater Group. They are, sedimentary, acid plutonic, and gneiss-schist terranes (Picard, 1966; Tohill and Picard, 1966). The abundance of 2:1 aluminum clays, especially detrital mica (up to 8% according to Picard (1966)) suggests that sedimentary deposits are of little to moderate importance, as these clays minerals are unlikely to survive more than one cycle of erosion and deposition in the large quantities seen in the Chugwater Group. Acid plutonic rocks are of principal importance because they contain abundant k-feldspar and mica. Finally, gneiss-schist terranes are excellent sources of feldspars, especially plagioclase.

These mineralogical characteristics suggest that all three rock types could be the primary sources for the Red Peak Formation as it is high in k-spar, plagioclase, and detrital mica. The upper formations (unnamed redbed unit and
Popo Agie Formations) have significantly less plagioclase and coarse mica, which is compatible with the hypothesis that acid plutonic rocks are the primary source for the unnamed redbed unit and Popo Agie Formation, with significant additions from volcanic sources and sedimentary strata. Minor contributions from gneiss-schist terranes, and basic igneous sources cannot be ruled out.

Another possible explanation for the variation in plagioclase is modification by climate. Feldspars, both potassium and plagioclase varieties, are not resistant to weathering and alter quickly to clays. The high feldspar content and nearly complete lack of kaolinite, except in the Popo Agie formations suggest that climate was semi-arid to arid (Barschadd, 1966). It also suggests that weathering in the source area was slow, and variations in plagioclase content are mostly controlled by source area change and not weathering.

**Analcime and Smectite**

The presence of analcime and smectite is interesting, but not new to the body of knowledge gathered from the Popo Agie Formation of the Chugwater Group (Keller, 1952; High and Picard, 1965). The occurrence of analcime and smectite has been interpreted to be the result of synsedi-mentary alteration of volcanic ash in sodic alkaline lakes (High and Picard, 1966). The antipathetic relationship between feldspars and analcime described in this study is new, however. In beds where analcime occurs in amounts as little as 15%, feldspars are nonexistent. This relationship is easily explained as the result of alteration of plagioclase and k-spar to form analcime. Petrographic analysis demonstrates
that this, however, is not the case. No evidence of reaction rims on feldspars turning to analcime has been seen in this or other studies and another interpretation must be sought.

Several processes are likely working in conjunction to cause these mineralogical variations in analcime and feldspars. First, is the climate of the Late Triassic during Popo Agie time. A periodically warm and humid climate would result in rapid weathering of feldspars into clay minerals, especially kaolinite. The conspicuous spike in kaolinite (25% by weight) in the upper carbonate unit of the Popo Agie Formation at Red Butte supports this hypothesis (Figure 44). A second possible process is related to the stability fields of analcime and plagioclase (Figure 65). This figure clearly illustrates that under chemical conditions of low dissolved silica analcime precipitation is stable and favored while plagioclase dissolves. Only under very specific conditions (the shared phase boundary of analcime and plagioclase) can analcime and plagioclase coexist. The final mechanism is the source area change described in the previous section.

A three-component system is proposed for the decrease in and eventual removal of feldspars. First, a source depleted in feldspars, especially plagioclase, decreased the initial concentration. Second, a possibly warm, humid climate altered feldspars to clay minerals during erosion and transport from the distant source area. The remaining feldspars (where associated with analcime) were unstable in silica deficient sodic alkaline lakes and dissolved.
**Calcite/Dolomite**

A strong inverse correlation exists between calcite and dolomite throughout the Chugwater, including the Alcova Limestone. This relationship is interpreted as resulting from dolomitization of carbonate muds and cements during diagenesis. The relationship is not as sharp in the Popo Agie formation as calcite increases in abundance. This is likely the result of a wetter climate and the decrease of dissolved magnesium in typical groundwater and formation water.

**Mineralogic Correlation and Sequence Stratigraphy**

One of the goals of this study was to assess the possibility of using mineralogy in correlation and sequence stratigraphy. Two intervals of higher sample resolution Figures 43 and 44, from 92 meters to 97 meters; and Figures 58 and 59, from 97 to 102 meters provide insight into the possibility of QXRD mineralogic correlation. At Red Butte, Figures 43 and 44, a fining upward sequence was sampled once every meter. The data suggest that correlations are possible, based on increases in % total clay indicating fine-grained muddy units, and high % quartz indicating coarser silty and sandy units. If sample resolution were condensed to 1 meter intervals, it is likely that detailed correlations could be completed between adjacent localities. The same is indicated at Red Canyon (Figures 58, 59) in a well-sampled region through the sandy facies and the Alcova Limestone.
I propose that one-meter resolution and the tracking of clays and trace elements—for instance, analcime, hornblende, and pyrite—along with general mineralogy would likely allow for a high resolution, time-based correlation in lacustrine and shallow to deep marine environments. For instance, at a set point in time, the detrital mineralogy of a place on Earth is theoretically constant. Therefore, horizons with equal mineralogy (within error) are potential high-resolution timelines that could be correlated across a consistent basin. Care must be taken however when distinct facies boundaries are crossed (marine beach to marine shelf) as mineralogy is capable of changing as sediment moves from a beach (coarse-grained and highly-sorted) to a basin (fine-grained and poorly-sorted). Inside of a major facies boundary, however, correlations are potentially timelines. Further testing is required to verify this hypothesis.

**Paleogeography**

Lowest Triassic rocks of the Dinwoody and Red Peak Formations inherited their depositional pattern from the late Paleozoic and possibly the late-Precambrian Carr and Paull (1983). The western margin of the Pangean supercontinent was at approximately the central part of present Nevada and at between 15° and 25° north of the paleoequator (Figure 66). There was a classic north-south trending miogeocline, but additionally a relatively deep basin centered in southeastern Idaho influenced depositional patterns throughout the Early Triassic (Lawton, 1994) (Figure 67). As discussed in the section on sequence stratigraphy, marine deposition continued into west-central Wyoming
until at least the end of the Spathian (Alcova Transgression) (Figure 68) and perhaps the early Anisian (Crow Mountain Formation). Carr and Paull (1983) provided a detailed history of Early Triassic paleogeography.

A major transition in depositional style occurred in the earliest Anisian (?), and marine sediments shifted to far northwestern Nevada (Dubiel, 1994) and were never afterwards deposited in the Western Interior in the Triassic, as recorded by the unnamed redbed unit (Jelm Formation) and the Popo Agie Formation. This major shift is marked by a major regional angular unconformity, the Tr-3 of Pipiringos and O Sullivan (1978). The unconformity separates Middle (?) Triassic Crow Mountain rocks from the Late Triassic unnamed redbed unit and Popo Agie Formation. Although the unconformity is outside of the initial age range of the effect of the Sonoma Orogeny (Silberling and Roberts, 1962), it has been attributed to uplift and erosion associated with the Sonoma orogeny (Speed, 1978). An alternative hypothesis is that Middle Triassic rocks were never deposited, and miogeoclinal sedimentation ceased as the basin closed with arc-continent collision at the western margin, and continued development of the volcanic arc.

Upper Triassic rocks of the Wind River Basin are wholly continental in origin and are complex associations of incised valley fill (Dubiel, 1991) with associated lakes (unnamed redbed unit, Jelm Formation), and fluvial-lacustrine sequences with volcanic sediments (Popo Agie Formation) (Figure 69).

Volcanism in the Late Triassic is well-established and marks the first appearance of abundant Mesozoic volcanic ash in the continental interior (Figure
The fluvial-lacustrine rocks of the Popo Agie contain the evidence of this volcanism in Wyoming. These ash beds are the result of a magmatic arc developed over newly developed east-dipping subduction zone. The most active part of the arc was in what is now the southwestern United States where plutons define a belt parallel to the continental margin (Christiansen et al., 1994). The large distances between arc and deposits of the Popo Agie Formation suggest that the ash came from large plinian eruptions of silicic magma associated with subaerial caldera formation (Christiansen et al., 1994).

**Paleoclimate**

*General.* The Triassic paleoclimate of the Western Interior has been quite well studied on the Colorado Plateau (Dubiel et al., 1991; Parrish, 1993). Only a brief review will follow with the purpose of including the Wyoming sequence in the picture. Parrish et al. (1983) described the climate of Pangea as monsoonal. As Pangea moved north prior to and during the Early Triassic, exposed land was distributed evenly across the equator (Parrish, 1985). Seasonality would have become stronger and the equatorial continental interior would have been arid.

*Early to earliest Middle Triassic.* Early Triassic to earliest Middle Triassic paleoclimates are recorded by the Lower Triassic Red Peak Formation and early Middle Triassic Crow Mountain Formation. Each has rare, thin beds of gypsum, which suggest warm-arid evaporative setting (Picard 1966; 1978; 1993). Picard (1965) presents convincing evidence that the red color of the Chugwater
formation was acquired post-depositionally, and this requires oxidizing conditions during deposition that were largely controlled by the dry climate (dry climate $\rightarrow$ low water table$\rightarrow$ preservation of ferric oxide)(McKee, 1974). Rare shrinkage cracks indicate at least temporary dry conditions existed during Red Peak time. Mineralogy also implies climactic conditions. First, dolomitization requires waters concentrated in magnesium, which dry climates are likely to produce. High feldspar content and lack of kaolinite also suggest that the climate was arid to semi-arid and slow to weather the sediment in transport during the Early and earliest Middle Triassic.

**Late Triassic.** The Late Triassic has been suggested as an unusually wet period in the Western Interior (Dubiel et al., 1991). Sediments of the Popo Agie Formation both support and refute this hypothesis. High and Picard (1965) discuss organic remains in the lowest Popo Agie Formation that indicate warm and moist conditions during deposition of the lower carbonate unit and much of the purple unit. Feldspars and kaolinite interpretations (as discussed in the Mineralogy and Provenance section) support this hypothesis of a humid warm and wet phase. Finally, the presence of numerous small lakes indicates a relatively wet period of time.

Conversely, the distribution of analcime and smectite in lacustrine facies of the middle and upper Popo Agie Formation (the purple unit and entire ocher unit) ("Lake Popo Agie") reflect deposition in a more arid setting (High and Picard, 1967) as a result of their position just north of the direct influence of monsoonal precipitation (Dubiel et al., 1991). Finally, the high kaolinite content and
fluvial/lacustrine nature of the rocks of the upper carbonate unit reflect a return to the warm and wet period common during the lower carbonate deposition.

The overall picture of the Late Triassic is a cyclic climate starting with a humid, warm, and wet phase during lower carbonate, and lowest purple unit deposition. The rocks of the upper purple unit, and ocher unit reflect a more arid setting as a result of the northward drift of Pangea away from the equator and outside of the direct influence of the monsoonal precipitation (Dubiel et al., 1991). The latest Triassic concludes with rocks of the upper carbonate unit which reflect a return to the warm humid wet conditions that prevailed during lower carbonate deposition.
Conclusions

This thesis presents a detailed stratigraphic, sedimentologic, and mineralogic study of the Triassic Chugwater Group within the west central Wind River Basin of Wyoming. One purpose of the study was to determine the depositional history of the exposed strata in terms of sequence stratigraphy, paleogeography, and paleoclimate. A secondary purpose was the application of a new tool to sedimentology, Quantitative x-ray diffraction (QXRD) developed by Srodon et al. (2001), and its uses in sequence stratigraphy and provenance analysis. The following conclusions can be drawn from this study.

1) Sedimentologic interpretations

   A. Red Peak Formation

      1. Lower platy facies: The lower platy facies represents deposits of a regressive tidal flat.

      2. Alternating facies: The alternating facies represents transgressive and highstand marine shelf deposits, and upward fining lowstand coastal sabkha sheet floods.

      3. Upper platy facies: Tidal flats, and a return to a system like the lower platy facies.

      4. Sandy facies: A progradational sandstone wedge representing nearshore marine and marine beach facies or sheet flood events.
B. Crow Mountain Formation

1. Alcova Limestone: The Alcova is a single transgressive/regressive cycle from algal mats to rippled carbonate and siltstone.

2. Basal sandstone unit: A package of marine shelf to nearshore marine sandstone.

3. Upper sandstone and siltstone unit: This unit records deposition in a tidally dominated estuary.

C. Unnamed redbed unit (Jelm)

1. A westward extending fluvial plane or incised valley fill with associated lakes.

D. Popo Agie Formation

1. Lower carbonate unit: Fluvial deposition of intraformational limestone conglomerate.

2. Purple unit: The unit represents a large floodplain deposited by low-gradient meandering streams. Local beds of analcimolite indicate the presence of isolated alkaline lakes with volcanic sources.

3. Ocher unit. This interval records deposition in a large alkaline lake with abundant volcanism.

4. Upper carbonate unit: Fluvial deposition of intraformational limestone microconglomerate.
2) Sequence Stratigraphy

1. The Chugwater group deposits show two 2\textsuperscript{nd} order stratigraphic sequences. The bottom sequence is topped by a correlative conformity and controlled by sea level. The second sequence is topped by the Tr-2 (Pipiringos and O'Sullivan, 1978) disconformity and is controlled by various factors (sedimentation rate, tectonics, eustasy).

3) Mineralogy and Provenance

1. QXRD reveals trends in mineralogy that are attributed to source area changes, weathering and climactic phenomena, and authigenic and diagenetic features.

4) Paleogeography

2. Lower and Middle (?) Triassic rocks record the continued miogeoclinal sedimentary pattern inherited from the late-Paleozoic.

3. Upper Triassic rocks are deposited after the Tr-3 (Pipiringos and O'Sullivan, 1978) unconformity and record continental deposition with volcanic sources after the arc-continent collision of the Middle Triassic.
5) Paleoclimate

1. Lower Triassic climates in Wyoming are arid to semi-arid.

2. Upper Triassic rocks record an episodic climate with warm, humid, wet phases bracketing an arid to semi-arid phase during deposition of the upper purple unit and ocher unit.
References Cited


Figures
Figure 1. Regional paleogeographic map of the Western Interior during Triassic time (modified after McKee et al., 1999; Dubiel, 1994). Isopachs are thicknesses of Lower Triassic Strata (in feet); includes Dinwoody and Red Peak Formations. Contour interval is 500 to 1000 feet.
<table>
<thead>
<tr>
<th>Period</th>
<th>Formations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jurassic</td>
<td>Sundance Formation</td>
</tr>
<tr>
<td></td>
<td>Gypsum Spring Formation</td>
</tr>
<tr>
<td></td>
<td>Nugget Sandstone</td>
</tr>
<tr>
<td>Triassic</td>
<td>Popo Agie Formation</td>
</tr>
<tr>
<td></td>
<td>unnamed redbed unit (Jelm Formation)</td>
</tr>
<tr>
<td></td>
<td>Upper Sandstone and Siltstone</td>
</tr>
<tr>
<td></td>
<td>Basal Sandstone</td>
</tr>
<tr>
<td></td>
<td>Alcova Limestone</td>
</tr>
<tr>
<td></td>
<td>Sandy Facies</td>
</tr>
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<td></td>
<td>Upper Platy Facies</td>
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<td></td>
<td>Alternating Facies</td>
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<td></td>
<td>Lower Platy Facies</td>
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<tr>
<td></td>
<td>Silty Claystone Facies</td>
</tr>
<tr>
<td></td>
<td>Dinwoody Formation</td>
</tr>
<tr>
<td>Permian</td>
<td>Park City Formation</td>
</tr>
</tbody>
</table>

Figure 2. Stratigraphic nomenclature used in this study (modified after Irmen and Vondra, 2000).
Figure 3. Geologic map showing western Wyoming and the field study area (black box). The inset shows a close up of the four measured sections.
Figure 4. Schematic diagram of a hypothetical continental margin showing the development of an erosive sequence boundary between two marine shale layers. Time A shows sea level during a highstand with sand on the shelf, and shale on the slope and basin floor. Time B shows a sea level lowstand creating an unconformity. Time C shows the following sea level transgression, and the development of a shale on shale contact separated by a sequence boundary. The asterix denotes the area of interest, and the arrows indicate the sea level for each time line.
Figure 5. Photograph of the deep valley formed by the unresistant Dinwoody Formation and lowest Chugwater Group. The large dipslope to the left is held up by the Phosphoria Formation. The Alcova Limestone (white) is visible towards the right of the photograph.
Figure 6. Photograph of Red Bluff Canyon study section. Alcova Limestone for scale midway up photograph is 4.5 meters thick.

Figure 7. Photograph of Red Canyon study section. Top of Alcova Limestone is visible toward the left of the photograph.
Figure 8. Photograph of Dallas Dome study section.

Figure 9. Photograph of Red Butte study section.
Figure 10. Red Butte Study Section stratigraphic column. Abbreviations are as follows, MDST = mudstone, SLTST = siltstone, SS = sandstone, LSC = limestone conglomerate, LS = limestone, UPF = upper platy facies, SF = sandy facies, AL = Alcova Limestone, BS = basal sandstone, US = upper sandstone and siltstone, LC = lower carbonate, UC = upper carbonate.
Figure 11. Photograph of ripple cross-laminated siltstone in the lower platy facies at Red Canyon section. Pencil for scale.

Figure 12. Photograph of parallel lamination in the lower platy facies at Red Canyon section. Lens cap for scale.
Figure 13. Photograph of ripple marks in the lower platy facies at Red Canyon section. Lens cap for scale.

Figure 14. Typical exposure of the Alternating facies at Red Butte section.
Figure 15. Photograph of ripple cross-laminated siltstone with burrow (arrow) from the alternating facies at Red Canyon. Lens cap for scale.

Figure 16. Climbing ripple cross-lamination in the alternating facies at Red Butte. Rope in top right corner for scale.
Figure 18. Disturbed stratification of Picard (1978), sample shows the vestiges of climbing ripple cross-lamination after an intermediate level of burrowing. Stratigraphic up is toward the top of the photograph.
Figure 18. Photograph of a typical coarsening upward succession in the alternating facies at Red Butte. Four upward fining cycles are visible at the top of the photo. Second fining upward cycle is ~3 meters thick.

Figure 19. Photograph of the sandy facies in the Red Peak formation at Red Canyon. Rock hammer for scale.
Figure 20. Photograph of the Alcova Limestone at Red Canyon section. Sharp contact with the sandy facies is visible near the bottom of the photograph. Rock hammer for scale.

Figure 21. Photograph of highly rippled fabric in the basal sandstone of the Crow Mountain formation. Scoured contact is below the white sandstone at the top of the photograph. Lens cap for scale.
Figure 22. Photograph of the upper sandstone and siltstone unit at Red Butte section. Rock hammer for scale.

Figure 23. Photograph of the basal bed of the lower carbonate unit at Red Butte. Minor imbrication is present in angular clasts. Pencil for scale.
Figure 24. Angular unconformity of High and Picard (1965).
Figure 25. Dallas Dome study section stratigraphic column. Abbreviations are as follows, MDST = mudstone, SLTST = siltstone, SS = sandstone, LSC = limestone conglomerate, LS = limestone, UPF = upper platy facies, SF = sandy facies, AL = Alcova Limestone, BS = basal sandstone, US = upper sandstone and siltstone, LC = lower carbonate, UC = upper carbonate.
Figure 26. Photograph of fining upward cycles in unnamed redbed unit at Dallas Dome section. The two white beds near the top of the outcrop are approximately 1 meter thick combined. The fault discussed in the text is clearly visible in this photograph.

Figure 27. Photograph of pinch and swell beds in the unnamed redbed unit at Dallas Dome. Hammer, notebook and tape measure for scale.
Figure 28. Perpendicular photograph of outcrop in Figure 27 showing a "channeled appearance". Knife for scale.

Figure 30. Photograph of coarsening upward cycle in the alternating facies at Red Canyon. Juniper in middle of photograph is ~ 1.5 meters high.
Figure 29. Red Canyon study section stratigraphic column. Abbreviations are as follows. MDST = mudstone, SLTST = siltstone, SS = sandstone, LSC = limestone conglomerate, LS = limestone, UPF = upper platy facies, SF = sandy facies, AL = Alcova Limestone, BS = basal sandstone, US = upper sandstone and siltstone, PA = Popo Agie formation, LC = lower carbonate.
Figure 31. Photograph of a channel in the alternating facies at Red Canyon. Lens cap for scale.

Figure 32. Photograph of soft sediment deformation preserved in the alternating facies at Red Canyon. Pencil for scale.
Figure 33. Field stratigraphic context of the J-0 unconformity revision shown schematically in Figure 34. The figure clearly shows the erosional removal of the upper carbonate, ocher unit, and purple unit between the Red Butte section to the northwest to the Red Canyon section to the southeast. Abbreviations as follows: AL= Alcova Limestone, BS= basal sandstone, US= upper sandstone and siltstone, LC= lower carbonate, UC= upper carbonate.
Figure 34. New interpretation of J-O unconformity (Pipinosos and O'Sullivan, 1970) separating Upper Triassic Popo Agie formation from Jurassic Nugget sandstone. (modified after High and Picard, 1966)
Figure 35 Red Bluff Canyon study section stratigraphic column. Abbreviations are as follows, MDST = mudstone, SLTST = siltstone, SS = sandstone, LSC = limestone conglomerate, LS = limestone, UPF = upper platy facies, SF = sandy facies, AL = Alcova Limestone, BS = basal sandstone, US = upper sandstone and siltstone, LC = lower carbonate, UC = upper carbonate.
Figure 36. Photograph of correlative exposed section across a valley from the Red Bluff Canyon section. The unit above the Tr-3 appears similar to the Jelm of Picard (1978), and there are possible beds of the Popo Agie Formation above the Jelm (?). Alcova Limestone in the middle of the photograph is 4.5 meters thick.
Figure 37. X-ray diffraction pattern for sample RB-01. ZnO is a spike added for QXRD analysis.
Figure 38. X-ray diffraction pattern for sample RB-09. ZnO is a spike added for QXRD analysis.
Figure 39. X-ray diffraction pattern for sample RB-11. ZnO is a spike added for QXRD analysis.
Figure 40. X-ray diffraction pattern for sample RB-14. ZnO is a spike added for QXRD analysis.
Figure 41. X-ray diffraction pattern for sample RB#1. ZnO is a spike added for QXRD analysis.
Figure 42. X-ray diffraction pattern for sample RB-17. ZnO is a spike added for QXRD analysis.
Figure 43. QXRD results for the non-clay fraction at Red Butte. Red box indicates the position of the alcova limestone.

Abbreviations as follows: CM= Crow Mountain formation, CM'= Crow Mountain formation, 
uru= unnamed redbed unit, PA= Popo Agie Formation. Error bars are plus and minus 2% by weight for each sample.
Figure 44. QXRD results for clay fraction at Red Butte. Red box indicates the position of the Alcova Limestone.
Abbreviations as follows: CM= Crown Mountain formation, uru= unnamed redbed unit, PA= Popo Agie formation.
Error bars are plus and minus 2% by weight for each sample.
Figure 45. X-ray diffraction pattern for sample DD#1. ZnO is a spike added for QXRD analysis.
Figure 46. X-ray diffraction pattern for sample DD-06. ZnO is a spike added for QXRD analysis.
Figure 47. X-ray diffraction pattern for sample DD#2. ZnO is a spike added for QXRD analysis.
Figure 48. X-ray diffraction pattern for sample DD-07. ZnO is a spike added for QXRD analysis.
Figure 49. X-ray diffraction pattern for sample DD-09. ZnO is a spike added for QXRD analysis.
Figure 50. X-ray diffraction pattern for sample DD-11.5. ZnO is a spike added for QXRD analysis.
Figure 51. QXRD Results for the non clay fraction at Dallas Dome. Red box indicates the position of the Alcova Limestone. Abbreviations as follows: CM= Crow Mountain Formation, uru= unnamed redbed unit, PA= Popo Agie Formation. Error bars are plus and minus 2% by weight for each sample.
Figure 52. QXRD results for clay fraction for Dallas Dome. Red box indicates the position of the Alcova Limestone.
Abbreviations as follows: CM= Crow Mountain Formation, uru= unnamed redbed unit, PA= Popo Agie Formation.
Error bars are plus and minus 2% by weight for each sample.
Figure 53. X-ray diffraction pattern for sample RC#6. Zno is a spike added for QXRD analysis.
Figure 54. X-ray diffraction pattern for sample RC#14. ZnO is a spike added for QXRD analysis.
Figure 55. X-ray diffraction pattern for sample RC#16. ZnO is a spike added for QXRD analysis.
Figure 56. X-ray diffraction pattern for sample RC-01. ZnO is a spike added for QXRD analysis.
Figure 57. X-ray diffraction pattern for RC-05. ZnO is a spike added for later QXRD analysis.
Figure 58. QXRD results for non clay fraction at Red Canyon. Red box indicates the Position of the Alcova Limestone. Abbreviations as follows: Crow Mt. = Crow Mountain formation, unnamed rb. = unnamed redbed unit, PA = Popo Agie Formation. Error bars are plus and minus 2% by weight for each sample.
Figure 59. QXRD results of the clay fraction at Red Canyon. Red box indicates the position of the Alcova Limestone.
Abbreviations as follows: Crow Mt. = Crow Mountain formation, unnamed rb. = unnamed redbed unit, PA = Popo Agie Formation. Error bars are plus and minus 2% by weight for each sample.
Figure 60. Red Peak paleocurrents in west-central Wyoming (modified after High and Picard, 1966). Colors signify the percentage of indicators facing that direction, with black being the largest percent, followed by gray, and white indicates no flow indicated in that direction. Data are measured from ripple marks, and ripple cross-laminations.
Figure 61. A cartoon of the inferred depositional environment during Red Peak time. After a storm a flood of water rushes over a virtual flat shallowly dipping surface toward the sea. Thaynes and Woodside formations are correlative with Red Peak in western Wyoming.
Figure 62. A cartoon of the inferred depositional environment during latest Red Peak and earliest Crow Mountain time. Eolian, and wet interdune deposits to the northeast after Irmen and Vondra (2000). The environment for the Sandy Facies is nearly identical.
Figure 63. A cartoon of the inferred depositional environment during Popo Agie time. Black slashes indicate volcanic ash which is preserved and altered in lakes to analcimolite.
Figure 64. Comparison of Red Butte study section, with the sea level curve of Haq et al. (1988). Depositional environments are shown on the far left with formations. Abreviations are as follows: UPF= upper platy facies, SF= sandy facies, AL= Alcova Limestone, BS= basal sandstone, US= upper sandstone and siltstone, LC= lower carbonate, UC= upper carbonate, TF= tidal flat, NM= nearshore marine, BMS= brackish marine shelf, MS= marine shelf, E= estuary, Fw/V= fluvial with volcanic sources, Lw/V= lacustrine with volcanic sources.
Figure 65. Stability relations of some phases in the system Na₂O - Al₂O₃ - SiO₂ - H₂O at 25 degrees C and 1 atmosphere. Modified after Garrel and Christ (1972).
Figure 66. Schematic reconstruction of Pangea showing the approximate Triassic location of the United States (shaded). Inset: partial reconstruction of Pangea for the Late Triassic (modified after Dubiel, 1994).
Figure 67. General tectonic setting of the Early Triassic Western Interior (modified after Dubiel, 1994).
Figure 68. Paleogeography of the Western Interior during the Alcova (late Spathian) transgression (modified from Dubiel, 1994).
Figure 69. Late Triassic paleogeography and basins of the Western Interior. Incised valleys to the south are of the Chinle formation (modified after Lawton, 1994).
Figure 70. Locations of Late Triassic Rocks containing large portions of altered volcanic ash (filled circles). The locations of Late Triassic granitic plutons (open circles) show that a well-developed magmatic arc existed on the continental margin (modified after Christiansen et al., 1994).