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Precambrian-Cambrian Sedimentology, Stratigraphy, and Paleontology in the Great Basin (Western United States)

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# Precambrian-Cambrian Sedimentology, Stratigraphy, and Paleontology in the Great Basin (Western United States)

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

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by

Aaron Dale Sappenfield

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# DEDICATION

For my family.

# ABSTRACT OF THE DISSERTATION

## Precambrian-Cambrian Sedimentology, Stratigraphy, and Paleontology in the Great Basin (Western United States)

by

Aaron Dale Sappenfield

Doctor of Philosophy, Graduate Program in Geological Sciences
University of California, Riverside, December 2015
Dr. Mary L. Droser, Chairperson

Thick accumulations of Neoproterozoic and early Phanerozoic strata are distributed throughout much of the arid continental interior of western North America, providing an expansive and well-exposed archive of this important time in Earth's history. The information presented herein supplements evaluations regarding the utility and limitations of this archive by providing an integrated sedimentological, paleontological, and geochronological description for Precambrian-Cambrian strata exposed in the area and by reporting the discovery of new trace and body fossils housed there.

The first chapter of this dissertation describes the sedimentology and stratigraphy of Precambrian-Cambrian conglomeratic and sandstone-dominated units exposed in the central Great Basin. Seven localities distributed along a 600 km north-south transect are described using existing data supplemented by information compiled from more than 5 kilometers of newly measured stratigraphic section. These data collectively facilitate development of a unified framework regarding the nature and timing of deposition in the area while also providing a series of stratigraphic tie points applicable to both regional and global correlation schemes. The second chapter reports the discovery of *Zoophycos* burrows from early Cambrian sediments exposed in eastern California. The *Zoophycos* ichnogenus is a well-known and considerably-studied deposit feeding trace fossil that, like other deposit feeding burrows, had not previously been reported in pre-Ordovician strata, making these the oldest examples of this celebrated burrow. Most importantly, *Zoophycos* burrows reported herein provide the earliest definitive evidence of deposit feeding to date, pushing back the advent of this feeding strategy to near the Precambrian-Cambrian boundary. This dissertation's final chapter reports medusozoan macrofossils from the early Cambrian Zabriskie Quartzite as the earliest fossil evidence of cnidarian medusae and the oldest example of a metazoan mass stranding event currently on record. Given that these are fossils of nonmineralized forms, the Zabriskie fossils also advance reconstruction of the taphonomic dynamics responsible for the preservation of soft-bodied macrofauna in nearshore facies through the Precambrian-Cambrian transition. The features of this comparison imply that a preservational bias may have been introduced near the onset of the Phanerozoic, shifting the predominant environment for soft-bodied preservation in sandstone facies from subtidal environments to the supralittoral zone.

TABLE OF CONTENTS

**Additional Supporting Materials Available on ProQuest**

CHAPTER 2

**Additional Supporting Materials Available on ProQuest**

CHAPTER 3

# LIST OF FIGURES

## INTRODUCTION

Sweeping and rapid environmental and ecological changes occurred during the Precambrian-Cambrian transition that forever altered the Earth system. These changes include but are not limited to the advent of three-dimensional bioturbation (Seilacher and Pflϋger, 1994), an expanding terrestrial biosphere (Kennedy et al., 2005), substantial increases in atmospheric oxygen (Berner et al., 2007), and the appearance of macrofaunal biomineralization (Germs, 1972). These all resulted in substantial alteration of ocean chemistry (Canfield and Farquhar, 2009; Berner et al., 2007), substrate conditions (Seilacher and Pfluger, 2004), sedimentology (Bottjer et al., 2000), and ecological structuring (Droser and Li, 2001; Droser et al., 1988). Coinciding shifts in basic components of both the abiotic and biotic realms suggest that the Precambrian-Cambrian transition was a pivotal time in the development of the inextricable link between metazoans and the remainder of the Earth system.

Neoproterozoic to lower Paleozoic strata are well exposed in western North America, extending from mainland Mexico well into the Arctic Circle (Stewart, 1972; Figure 1). Investigations targeting these rocks have yielded a number of key insights regarding the historical implications of this archive and its context in the global framework. Specifically, strata exposed in the Great Basin have yielded fossils of Neoproterozoic organisms (Signor et al., 1987; Hagadorn and Waggoner, 2000), a diverse array of trace fossils (Alpert, 1977; Jensen et al., 1998), and geochemical data which have been used for global stratigraphic correlation (Corsetti and Kaufman, 1994;

Jensen and Grant, 1996; Corsetti et al., 2000). However, the mere presence of these elements is quickly overshadowed by their general paucity in the area. Other than the aforementioned reports of sporadic macrofossils and opportunities for geochemical analyses, much of the Precambrian-Cambrian succession exposed in the Great Basin is barren of either a paleobiological or geochemical signature and thus, much of this record has remained considerably underexplored. As a result, the conceptual framework developed for Precambrian-Cambrian strata exposed in the Great Basin is plagued by inconsistencies and unsupported hypotheses surrounding regional correlation schemes, paleoenvironmental reconstructions and, at a most basic level, the location of the Precambrian-Cambrian boundary (e.g. see discussion in Hagadorn et al., 2011). These issues have long-precluded the significance of this record from being fully realized. Resolution to these issues requires a far more detailed and comprehensive review of the stratigraphic record than has been previously performed. This dissertation thus outlines an integrated sedimentological, paleontological, and geochronological framework for terminal Neoproterozoic and early Cambrian strata exposed in the Great Basin and also demonstrates the potential utility of this record by reporting the discovery of new trace and body fossils that yield considerable insight regarding metazoan evolution during this important time in Earth's history.

The first chapter of this dissertation synthesizes sedimentologic, stratigraphic, paleontologic, and geochronologic information in an evaluation of putative terminal Neoproterozoic and Early Cambrian conglomeratic and sandstone-dominated successions exposed in the central Great Basin. The compilation of published materials and newly measured stratigraphic sections presented herein provides a new basis for describing the general stratigraphy in the area. A large-scale regional unconformity recognized at the base of the succession has previously led to the assumption that this surface represents the onset of the Sauk marine transgression (Evans et al., 2003). The unconformity at the base of the Sauk transgression, often referred to as the "Great Unconformity" in cratonal sections, represents a key stratigraphic marker for western North America and recently has been forwarded as having a causal relationship with the evolution of biomineralizing taxa (Peters and Gaines, 2011). While the referenced basal unconformity in the central Great Basin bears evidence of significant erosional downcutting, as may be expected for an event as substantial as the start of the Sauk transgression, the information compiled herein suggests that this contact is likely more closely linked to local tectonism rather than resulting from an increase in eustatic sea level. A discrete and persistent signal for sea level rise likely attributable to early stages of the Sauk transgression is marked by a shift in lithofacies concurrent with the earliest occurrence of abundant, Cambrian ichnofossils well above this basal unconformity. Incorporating age constraints obtained from interbedded volcanics below this contact (Crittenden and Wallace, 1973) suggests that deposition associated with the Sauk transgression began in earnest no more than 20 million years prior to the onset of the Phanerozoic. Further, numerical age constraints coupled with the appearance of Early Cambrian trace fossils in the upper portions of these units suggests that the Precambrian-Cambrian boundary may be located within the upper Sauk hiatus, resolving the approximate location of this important contact for much of the Great Basin. Taken together, these details provide a number of key stratigraphic tie points that are herein applied to propose a regional correlation scheme for Precambrian-Cambrian strata exposed in the western United States.

Chapter 2 of the dissertation reports the discovery of the trace fossil *Zoophycos* from Early Cambrian strata exposed in the western Great Basin.  Eight specimens were collected in the Lower Member Wood Canyon Formation in eastern California approximately 40 m above the Precambrian-Cambrian boundary, making them significantly older than other examples of this ichnogenus.   *Zoophycos*-group burrows are abundant elements of the trace fossil record and are well-known as representing the systematic processing of bulk sediment by deposit-feeding taxa (Seilacher, 1967, 2007). The discovery of these specimens thus not only expands the range of *Zoophycos* nearly to the base of the Cambrian but also reveals evidence of deposit feeding organisms prior to the appearance of the trilobites, considerably earlier than has been suggested for the advent of this feeding style.  Given the significance of increased bioturbation through the Precambrian-Cambrian transition, the discovery of *Zoophycos* burrows in strata deposited just above the boundary provides additional insight into the biologically-mitigated evolution of the substrate (Seilacher and Pflüeger, 1994).  Chapter 2 thus also includes discussion of the potential significance of the production of *Zoophycos* burrows in the context of sediment mixing during the Precambrian-Cambrian transition.

This dissertation's final chapter reports the discovery of discoidal macrofossils from the Early Cambrian Zabriskie Quartzite in eastern California.  These fossils are herein interpreted to represent the oldest fossil evidence of a medusozoan stranding event.  As the Zabriskie fossils preserve evidence of nonmineralized taxa, the significance of their discovery extends well beyond the potential phylogenetic heritage of these structures. Details preserved within and surrounding the Zabriskie fossils advance reconstructions of the environmental and taphonomic dynamics responsible for the preservation of soft-bodied macrofauna in sandstones through the Precambrian-Cambrian transition. The preservation of non-mineralized tissues in sandstones is largely an Ediacaran and Cambrian phenomenon, with representative fossil assemblages becoming both exceedingly rare and bearing entirely different taxonomic signatures nearly coincident with the Precambrian-Cambrian boundary, providing fodder for debates regarding whether this shift in the fossil record reflects a preservational bias or a real extinction of Ediacaran metazoans (e.g. Seilacher, 1984). Previously forwarded models for the preservation of stranded medusae (Schäfer, 1941; Hagadorn et al., 2002; Hagadorn and Belt, 2008; Tarhan, 2008) are thus considered and supplemented through consideration of the paleoenvironmental setting of the Early Cambrian shoreline. The ensuing comparison of the taphonomic requirements for the preservation of stranded Cambrian medusozoans to those required for the preservation of the Ediacara biota identifies key differences in the taphonomic history of this mode of preservation across the Precambrian-Cambrian boundary. The features of this comparison imply that the preferred environment for the preservation of non-mineralized macrofauna likely shifted near the onset of the Phanerozoic from subtidal facies to the supralittoral zone.

Collectively this dissertation demonstrates that performing a detailed and integrated review of previously underexplored elements of the Precambrian-Cambrian record has the ability to yield considerable insight regarding environmental and ecological evolution during this important time in Earth's history. This dissertation is thus intended to provide a foundation for continued and expanded research involving Precambrian-Cambrian strata exposed in the Great Basin while also instigating similar efforts among comparable units exposed worldwide.

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# CHAPTER 1

## Patterns in Precambrian-Cambrian sedimentation in the central Great Basin (western United States): sequence stratigraphic, geochronologic, and paleontologic constraints along the craton margin

## Abstract

Terminal Proterozoic to early Cambrian craton margin strata are exposed nearly continuously across the central Great Basin (western United States). Provinciality in mapping efforts and a deficiency of detailed sedimentologic and stratigraphic information built into a coherent synthesis has resulted in these units being long-overlooked for the insight they may provide into this critical time in Earth's history. Close inspection of the craton margin stratigraphic record reveals a varied sedimentologic framework, abundant trace fossils and widespread, interbedded igneous materials. Each of these features provides a unique opportunity to refine and further integrate models for the craton margin into regional and global frameworks for the Precambrian-Cambrian transition. Sedimentologic, paleontologic, geochronologic, and sequence stratigraphic data are thus here compiled to: 1) provide a description of the facies architecture of Precambrian-Cambrian units in the area, 2) outline a depositional and sequence stratigraphic model for these strata, 3) constrain the approximate location of the Precambrian-Cambrian boundary, 4) evaluate potential time transgression within this succession, and 5) consider this information in regional and global frameworks.

Seven localities distributed along a 600 km north-south transect are described using existing data supplemented by more than 5 kilometers of newly measured stratigraphic section. These materials provide the basis for developing a unified framework regarding the nature and timing of deposition along the craton margin. A large-scale regional unconformity characterized by an abrupt facies transition, large-scale erosional features, and up to 3000 meters of missing stratigraphic section is recognized at the contact between the Inkom and Mutual Formations (and equivalents) across the region. The severity of this unconformity has previously led to the assumption that this surface represents the onset of the Sauk marine transgressive sequence. However, local and regional facies relationships, geochronological data, and structural models suggest that the stratigraphic record of sea level increase is obscured by local tectonism during the terminal phases of rifting in western Laurentia. Shoreline regression solely attributable to an increase in eustatic sea level along the craton margin occurs at a less pronounced horizon hundreds of meters above the lower unconformity. This contact is marked by a shift from terrestrial to marine lithofacies concurrent with the earliest occurrence of abundant, Cambrian ichnofossils. Age constraints obtained from underlying interbedded basalt flows, in conjunction with this sequence stratigraphic framework, suggest that deposition associated with the Sauk marine transgression began in earnest no more than 20 million years prior to the onset of the Phanerozoic, providing a much needed temporal constraint for the onset of both passive margin sedimentation and sea level transgression. While a protracted eastward regression of the paleoshoreline can be inferred for the Sauk Megasequence, previous application of trilobite biostratigraphy to demonstrate time transgression in the unit is skewed by pronounced facies biases. Further, the distribution of sedimentary facies, trace fossils, and geochronological data suggests that the Precambrian-Cambrian boundary may be located within the upper Sauk hiatus, and thus, basal Phanerozoic strata may be missing in the central Great Basin. Collectively, these details provide a robust and far greater resolved regional correlation scheme that is applicable to much of the Neoproterozoic and early Cambrian stratigraphic record exposed in the western United States.

## Introduction

Coinciding shifts in both the abiotic and biotic realms suggest that the Precambrian-Cambrian transition was a pivotal time in the development of the link between metazoans and the remainder of the Earth system. Sediments deposited through this interval and the environmental signals they preserve are thus key resources in constraining the evolution of modern Earth system dynamics. While terminal Proterozoic and early Cambrian sedimentary successions are well-exposed globally, interpretations surrounding the Precambrian-Cambrian transition are largely informed by data collected within a small subset of the available stratigraphic record. The majority of this subset consists of localities containing exceptionally preserved fossils (“lagerstätten”) and/or unique opportunities for geochemical analyses. While concentrated efforts within these localities have yielded key insight into the dynamics of the Precambrian-Cambrian transition, their spatiotemporal isolation precludes an understanding of the timing, duration and geographic extent of potentially critical events. The disappearance of

Earth's first large and complex metazoans, the Ediacara biota, has long been thought to take place near the Precambrian-Cambrian boundary (Grotzinger et al., 1995), however, the precise timing of this event, its duration, and whether these fossils disappear due to changing taphonomic conditions or as a result of a real mass extinction event remain unknown and heavily debated (Seilacher, 1984; Grotzinger et al., 1995; Jensen et al., 1998). Further, the relationship between geochemical shifts and evolutionary progress at the onset of the Phanerozoic Eon (Canfield and Farquhar, 2009) is poorly constrained. The data required to foster additional understanding of these and other similarly complex issues is most readily garnered by incorporating sedimentary successions that have yet to be fully considered.

The central Great Basin (western United States) houses an extensive, well exposed and largely undescribed Neoproterozoic to Paleozoic sedimentary succession deposited along the margin of the Laurentian craton. Despite their extensive exposure, cosmopolitan distribution, and temporal significance, Precambrian-Cambrian craton margin units remain largely unincorporated into regional and global models describing the transition into the Phanerozoic. Much of this is an artifact of these units being dominated by coarse-grained, siliciclastic lithofacies which have generally been considered to house an inconspicuous record. Regional efforts have thus largely focused on other areas of the Great Basin where lithofacies are more variable and/or fossil evidence is more prevalent. However, detailed inspection of terminal Neoproterozoic and early Phanerozoic craton margin stratigraphy, coupled with recent technological advance, suggests that additional sedimentological, paleontological, and geochemical study yield data valuable to the further refinement of Precambrian-Cambrian Earth System dynamics.  Attempts to incorporate these strata into local and global frameworks for the Precambrian-Cambrian transition have long been encumbered by provinciality in mapping efforts (Figure 1.1) coupled with the lack of detailed stratigraphic profiles collected from individual exposures. This investigation resolves these discrepancies by generating a regionally and globally applicable framework describing the lithostratigraphy, biostratigraphy, facies architecture, and geochronology of terminal Proterozoic and early Phanerozoic craton margin siliciclastics.

## Background

The following sections provide a general overview of the geologic history, stratigraphic setting, and current status of investigations surrounding the Precambrian-Cambrian transition in the western United States. This background provides the basis for ensuing discussions targeting the Precambrian-Cambrian record in the central Great Basin.

### Regional Geology

The tectonic and depositional history of Precambrian-Cambrian bedrock exposed in western North America is generally described by three key events: 1) accretion of juvenile basement materials and subsequent igneous intrusion to form the core of Laurentia, 2) orogenic and rifting events associated with the formation and breakup of the supercontinent Rodinia, and finally 3) passive margin sedimentation lasting from the terminal Neoproterozoic through the early Paleozoic.

At least four Archaean cratons (Slave, Churchill, Superior and Wyoming) accreted during the Paleoproterozoic to form what would become the core of the Laurentian continent (Hoffman, 1997; Snoke, 2005). Orogenic activity associated with the formation of Laurentia began in northern portions of the continent with the Medicine Bow Orogeny (1.78-1.74 billion years ago (Ga)) (Chamberlain), continued in the southern portion of the continent during the Yavapai Orogeny (1.76-1.70 Ga) (Whitmeyer and Karlstrom, 2007) and terminated with the cessation of the relatively short-lived Mazatzal Orogeny (1.64-1.63 Ga) (Amato et al., 2008). The zone of deformation associated with these orogenic events spans at least 1200 km and is well exposed throughout much of the southwestern United States (Snoke, 2005). Supplementing the Laurentian landmass supplied by the accretion of Archean orogenic belts, tectonic and magmatic activity during the Mesoproterozoic resulted in the widespread placement of plutonic complexes over much of the southwestern interior of Laurentia (Snoke, 2005; Hoffman et al., 2007). The resulting intrusions are well represented by ~1.4-billion-year-old crystalline basement materials exposed from southern California to the northern Rocky Mountains (Snoke, 2005). Radiogenic versus stable strontium isotope values ($^{87}Sr/^{86}Sr$) measured in basement materials suggest that the western edge of the Laurentian craton is delineated by a north-south trending 0.706 $^{87}Sr/^{86}Sr$ isopleth (Kistler and Peterman, 1973).

The lateral accretion of juvenile bedrock and subsequent intrusion of igneous materials in Laurentia during the Paleoproterozoic and Mesoproterozoic is thought to have been at least partially associated with the formation and eventual breakup of the supercontinent Columbia (commonly also referred to as “Nuna” (Hoffman, 1997)) (Rogers and Santosh, 2002; Zhao et al., 2002). Amalgamation of Columbia is considered to have officially commenced with the assembly of Laurentia and Baltica by approximately 1.88 Ga, as evidenced by a series of 1.93-1.88 Ga orogenic belts in both Baltica and Laurentia (Pesonen et al., 2012). Paleomagnetic data suggest that the formation of Columbia continued until 1.53 Ga with the accretion of Amazonia along the southern margin of Baltica (Johansson, 2009; Pesonen et al., 2012). The eventual breakup of Columbia took place over several rifting episodes beginning at approximately 1.25 Ga with the separation of Baltica from the southern margin of Laurentia, lasting until approximately 1.10 Ga with the onset of formation of the supercontinent Rodinia (Pesonen et al., 2012).

The formation of Rodinia commenced with the Grenville Orogeny approximately 1.1-0.9 Ga. Breakup of Rodinia likely began at approximately 750 million years ago (Ma) with the separation of Laurentia from what would become Gondwanaland (Prave, 1999). The detachment of Laurentia likely took place over two separate and distinguishable episodes of rifting, separated by 100 million years or more (Prave 1999; Yonkee et al., 2014). Initial stages of rifting were most pronounced along northern portions of the western Laurentian margin in the area of what is now the Canadian Rockies. This initial phase of rifting eventually lead to the deposition of the Windermere

Supergroup and the formation of additional isolated basins in areas to the south (Prave, 1999; Snoke, 2005). A second stage of rifting (~540-600 Ma) continued along southern portions of the craton margin, progressing through what is now the southern and eastern perimeter of the Great Basin (Stewart, 1972; Prave, 1999; Fedo and Cooper, 2001; Yonkee et al., 2014). Resulting from these two rift events was the establishment of a well-developed passive margin along the entire western margin of Laurentia that would persist until the Late Devonian with the onset of the Antler Orogeny.

Cooling of juvenile crust following rifting of Rodinia and establishment of the passive margin during the Neoproterozoic and early Paleozoic resulted in protracted tectonic subsidence hinged along much of the craton margin of Laurentia. This activity resulted in the formation of a large basin, commonly referred to as the Cordilleran Miogeocline, extending from what is now northern Mexico into southern Canada (Figure 1.2) (Stewart, 1972; Stewart and Poole, 1974; Fedo and Cooper, 2001). Detrital zircon data suggests that sediments arriving at the Cordilleran Miogeocline were variably sourced by uplifted areas now east of the craton margin (Yonkee et al., 2014).

The Cordilleran Miogeocline is separated from partially correlative, thin cratonal deposits to the east by a feature commonly referred to as the “Wasatch Line” (Stokes, 1976) (Figure 1.2). The Wasatch Line is the hinging point for the depositional framework for western North American Precambrian-Cambrian sedimentation. This fundamental boundary represents the eastern terminus for Neoproterozoic sedimentary deposits and syndepositional faulting associated with the initial breakup of Rodinia and also defines the western limit of Paleozoic cratonal sedimentary sequences.

## Global Stratigraphic Framework

The stratigraphic record in the Great Basin reflects both local tectonism as well as the significant and relatively rapid evolution of the Earth system through the Precambrian-Cambrian transition. Development of the regional stratigraphic framework has largely resulted from investigations targeting the identification of key, global events occurring at this time. In general order from oldest to youngest, these events include: 1) the Sauk marine transgression, 2) the appearance of metazoan macrofossils, 3) trace fossil diversification 4) the Precambrian-Cambrian boundary, and 5) the appearance of trilobites. The identification and regional correlation of these events has refined both local and global models regarding this important time in Earth's history. Their expression in the Great Basin stratigraphic record is thus described herein as the foundation for expanding this framework to include Precambrian-Cambrian units deposited along the craton margin.

### ***Sequence Stratigraphy and the Sauk Marine Transgression***

Sequence stratigraphy groups strata into unconformity-bound packages, or depositional sequences, which can be correlated at a variety of scales. Rather than grouping strata based on their lithostratigraphy alone, sequence stratigraphy recognizes regional sedimentological trends and relates those features to changes in either eustatic sea level, sediment supply or basin morphology. The unconformities that bound depositional sequences are identified as sequence boundaries, which have varying levels of severity dependent on the duration and magnitude of changes in base level producing the erosional surfaces. While sequence boundaries are diachronous and in the absence of geochronologic and/or biostratigraphic controls cannot be used for precise age evaluation, sequence stratigraphic techniques have been employed as a useful tool in regional correlation of Precambrian-Cambrian sedimentary successions worldwide (Sloss 1963; Vail et al., 1977; Christie-Blick et al., 1990; Prave, 1999).

Depositional sequences are commonly classified using a hierarchical ranking system reflecting the time over which they were deposited (Vail et al., 1991). First-order sequence tracts, or “Megasequences” are of the longest duration and hence, most widely exposed depositional sequences. Megasequences generally span more than 50 million years and are housed by sequence boundaries generally recognized as ubiquitous erosional surfaces with significant evidence of prolonged subaerial exposure at the continental or global scale. Megasequences are composed of second-order sequence tracts, or “Supersequences”, which may last approximately 3-50 million years. Given the shorter duration of these events, Supersequence boundaries are variably expressed as local erosional surfaces and/or biostratigraphic discontinuities (Palmer, 1981). Third-order sequences tracts, or simply “Sequences”, are the fundamental building blocks of sequence stratigraphy. In general, Sequences may span timescales on the order of 1-3 million years and are composed of four distinct systems tracts: 1) a lowstand systems tract represented by basinward facies progradation, 2) a transgressive systems tract represented by facies onlap onto the platform or craton, 3) a highstand systems tract characterized by a basal, condensed section along a maximum flooding surface and overlying facies progradation, and 4) a falling stage systems tract represented by facies offlap and an overlying unconformity (or sequence boundary).

As first recognized by Sloss (1963), the Sauk Megasequence is the first of at least 6 first-order Phanerozoic sequence tracts in North America, reflecting a rise in eustatic sea level which lasted from the Neoproterozoic (?) to the Lower Ordovician (Sloss, 1963). The Sauk Megasequence is responsible for the sequence of quartzite, shale, and carbonate that generally characterizes terminal Neoproterozoic and basal Paleozoic sedimentary successions in the Great Basin. Palmer (1981) subdivided the Sauk Megasequence into three supersequences (Sauk I, Sauk II, and Sauk III) based on hiatuses evidenced by faunal discontinuities. As each successive superequence represents additional shoreline advance, exposure availability for each supersequence grows progressively with time. Supersequence boundaries first recognized by Palmer (1981) have since been supported by additional proxies including coastal onlap curves, conodont biostratigraphy, and geochemical shifts (Saltzman et al., 1998; Saltzman et al., 2000; Saltzman et al., 2004; Cowan et al., 2005; Haq and Schutter, 2008; Gill et al., 2011; Derby et al. 2012; Taylor et al., 2012; Dahl et al., 2014).

The base of the Sauk Megasequence is most famously recognized in the Grand Canyon at the interface between the Tapeats Sandstone and underlying Precambrian basement, a contact commonly referred to as the “Great Unconformity” (Sloss, 1963). This unconformity is well-pronounced among cratonal sections exposed throughout the eastern Great Basin. As is common in basinal sections, the base of the Sauk Megasequence is more subdued in Miogeoclinal successions and thus, identification of this unconformity in the western Great Basin has relied on detailed geologic mapping and cataloguing of Neoproterozoic sedimentary strata. The base of the Sauk Megasequence has not previously been formally identified along the craton margin but has been hypothesized as being located at the base of thick orthoquartzite units (e.g. Prospect Mountain Quartzite) that span the region (Link et al., 1987).

Cratonal and miogeoclinal sections provide few age constraints regarding the onset of the Sauk transgression, however, the presence of the Great Unconformity directly below Cambrian sandstones provides an upper age limit (Tucker, 1986; Fedo and Cooper, 2001). The Sauk lasted until the Middle Ordovician (~472ma) (Taylor et al., 2012), terminating with a hiatus spanning much of the Laurentian Whiterockian Series prior to the start of the Tippecanoe transgression (Sloss, 1963).

### *Metazoan macrofossils*

Fossils of the Ediacara biota are the oldest directly observable evidence of large and complex metazoan ecosystems on this planet and are key to constraining the nature of early animal, ecological, and environmental evolution. The spatiotemporal isolation of the localities from which the majority of these fossils have been described precludes the ability to rule out strong facies biases in the nature of the Precambrian fossil record

(Grazhdankin, 2004). Increasing the resolving power of the fossil record requires a far greater sample size than what is currently recorded.

Terminal Neoproterozoic macrofossils of the Ediacara biota are well documented in the Great Basin (Signor et al., 1983; Signor et al., 1987; Hagadorn and Waggoner, 2000; Hagadorn et al., 2000; Christie-Blick et al., 1988). This is also one of the few places where these fossils have been recovered in *both* Ediacaran and Cambrian rocks (Hagadorn et al., 2000).

### ***Trace Fossil Diversification***

Trace fossils provide vital data for evaluating the early evolution of bilaterians while also yielding critical biostratigraphic constraints (Crimes, 1992). As trace fossils are products of interactions between mobile organisms and the substrate, they provide key information regarding both paleobiological and environmental factors. Trace fossils have been shown to be sensitive proxies for behavioral diversification (Crimes, 1992, Sappenfield et al., 2012), fluctuating bottom water oxygen levels (Gaines et al. 2005; Garson et al. 2012), changes in substrate conditions (Droser et al. 2002; Tarhan et al., 2011), and mass extinction events (Pruss and Bottjer, 2004).

The likelihood of shallow and delicate trace fossils being preserved during the late Neoproterozoic and early Paleozoic was exceptionally high due to bioturbation being restricted to the shallowest portions of the substrate (Droser et al., 2002). Thus, trace fossils are the most diverse and abundant macroscopic components of the fossil record through the transition into the Phanerozoic Eon and have been reported from Precambrian-Cambrian successions worldwide (Crimes, 1992).

The increase in trace fossil diversity and complexity across the Precambrian-Cambrian boundary provides the basis for a globally recognized ichnostratigraphic framework (Crimes, 1992). Globally recognizable “ichnozones”, based on the first occurrences of index trace fossils, provide the primary means for biostratigraphic subdivision for strata that predate the appearance of trilobites (Crimes, 1992).

### ***The Precambrian-Cambrian Boundary***

The *Treptichnus pedum* ichnozone defines the base of the Cambrian at the GSSP in Newfoundland (Knoll et al., 2004). *T. pedum* is a distinct trace fossil that can be easily recognized in both bedding plane and cross sectional views. *T. pedum* is restricted to fine-grained facies, making definitive placement of the Precambrian-Cambrian boundary contingent on the availability of fine sediments. In the absence of *T. pedum*, identification of the Precambrian-Cambrian boundary relies on geochemical analyses of igneous materials for radiometric ages and/or carbonate materials for analyses of stable isotopes. A negative stable carbon isotope shift coincident with the Precambrian-Cambrian boundary is documented globally (Magaritz et al., 1986; Narbonne, 1994; Shen and Schidlowski, 2000), potentially including in the Great Basin (Corsetti and Kaufman, 1994; Jensen and Grant, 1996; Corsetti et al., 2000). Observations of this shift in conjunction with paleomagnetic (Kirschvink, 1978), sedimentological, and stratigraphic information provide additional proxies for identification of the Precambrian-Cambrian boundary in the region.

### ***Appearance of trilobites***

Trilobites first appear in the fossil record in Cambrian (Series 2, ca. 521 Ma) strata and subsequently become an increasingly refined resource for biostratigraphic correlation through time. Due to the endemic nature of individual Cambrian trilobite genera, separate trilobite biozonation schemes have been coordinated for various regions (see Peng et al., 2009). In North America, earliest Cambrian (i.e. Montezuman, Dyeran, and Delamaran) trilobite biozones include the *Fallotaspis*, *Nevadella, Olenellus*, *Plagiura-Poliella*, *Albertella*, and *Glossopleura* trilobite zones (Palmer, 1981). Unanimously, one of these zones directly overlies Precambrian-Cambrian boundary containing units in the Great Basin.

## Regional Stratigraphy

The lithostratigraphic and sedimentologic frameworks assembled for Neoproterozoic to earliest Cambrian strata in portions of the Great Basin (e.g. Hague, 1883; Misch and Hazzard, 1962; Hintze, 1962; Crittenden et al., 1971; Diehl, 1979; Fedo and Cooper, 1990) provide the basis for general stratigraphy, description of paleoenvironmental conditions, sequence stratigraphic context, insight into anactualistic depositional processes at this time, and constraints on the influence of post-burial processes. Neoproterozoic-Paleozoic sections in the Sonora, Mojave, Death Valley, White-Inyo, southeastern Idaho, and Grand Canyon regions have received the majority of the focus in the western United States, revealing a well exposed record of Neoproterozoic glaciomarine sediments (Crittenden et al. 1983; Prave 1999), Ediacaran fossils (Signor et al., 1987; Hagadorn and Waggoner, 2000; Hagadorn et al., 2000; Sour-Tovar et al., 2007), and a detailed record of the paleotectonic history in Laurentia (Stewart, 1970; Stewart and Poole, 1984; Fedo and Cooper, 2001).

The temporal framework for much of the Neoproterozoic-Cambrian succession in the Great Basin is loosely constrained as a result of the paucity of directly datable materials. In the absence of numerical age data, lower and upper boundaries on age are typically assigned to Neoproterozoic strata based on the recognition of correlatable events with well-defined ages. These include the Sturtian (≈760-700ma, Brasier et al., 2000), Marinoan (≈635ma, Hoffman et al., 2004) and Gaskiers (≈580ma, Bowring et al., 2003) glaciations, the Shuram (≈580-550ma, Fike et al., 2006) and Precambrian-Cambrian carbon isotope anomalies (Tucker, 1986), and paleomagnetic data (Kirschvink et al., 2005; Schmidt and Williams, 2010). Due to post-burial overprinting (Levy and Christie-Blick, 1989; Knauth and Kennedy, 2009; Prave, 1999; Mrofka, 2010; Verdel et al., 2011), the Great Basin preserves an inconspicuous record of these events.

Consequently, Ediacaran units in the Great Basin are conservatively assigned an age that generally encompasses the entire Neoproterozoic (Grotzinger et al., 1995). This places great emphasis on utilizing directly datable materials when they are available to refine the age and nature of time transgression for Neoproterozoic successions.

A lower geochronologic age for the majority of the Cordilleran sedimentary record comes from igneous intrusions dated at approximately 1.1 Ma in the Crystal Springs Formation in Death Valley (Heaman and Grotzinger, 1992; Dehler et al., 2010). Detrital zircon studies have attempted to refine this date, however, young (i.e. <700 ma) zircon grains are notoriously rare in the area (Gehrels et al., 2011). In the absence of stratigraphic correlation of the Crystal Springs Formation outside of the Death Valley region, this is a tentative lower age constraint and a more appropriate lower bracket may be the age of Precambrian basement in immediate contact with the overlying sedimentary succession (on average ≈1.2-1.5ga, [Damon and Giletti, 1961]), or numerical dates obtained from other localized datable materials including ash horizons, basalt flows and detrital zircons (e.g. Verdel, 2009; Dehler et al., 2010; Verdel et al., 2011).

The Ediacaran to Cambrian stratigraphic record in the western United States can be deconstructed into three general regions: 1) Miogeoclinal sections in the Death Valley and White-Inyo Mountain regions, 2) cratonal sections east of the Wasatch Line, and 3) craton margin sections immediately west of the Wasatch Line (Figures 2 and 3). Each of these regions can be distinguished by their general facies composition, which varies predominately as a result of their relative distances from the paleoshoreline.

### ***Miogeocline***

Miogeoclinal sediments include a westward thickening, 4000 km long wedge of Precambrian to Paleozoic strata exposed throughout the western Cordillera (Stewart and Poole, 1974; Fedo and Cooper, 2001; Stewart, 1970, 1972). More than 9 km of mixed siliciclastic and carbonate sediment accumulated in distal (i.e. western) portions of the miogeocline as a result of protracted subsidence hinged along the Wasatch Line (Stewart, 1972; Stewart and Poole, 1974; Fedo and Cooper, 2001). Cordilleran Miogeocline deposits can be differentiated into southern sections, consisting largely of siliciclastic sediment, and northern sections, containing a considerably larger volume of carbonate.

#### *Southern Cordilleran Miogeocline*

Southern Cordilleran Miogeocline units are extensively exposed in southern California and western Nevada, most prominently within and surrounding Death Valley National Park. In order of youngest to oldest, southern miogeoclinal lithostratigraphic units include the Johnnie Formation, Stirling Quartzite, Wood Canyon Formation (Precambrian-Cambrian boundary containing unit), Zabriskie Quartzite, and Carrara Shale. Extensive field efforts in these strata have identified numerous fossils of Neoproterozoic and Paleozoic organisms (Hagadorn and Waggoner, 2000), an abundant trace fossil record (Alpert, 1977; Jensen et al., 1998; Kennedy and Droser, 2011; Sappenfield et al. 2012), the Precambrian-Cambrian boundary (Horodyski et al., 1994), and key insights into the regional tectonics and paleogeographic setting for Laurentia through this temporal interval (Stewart, 1970).  Southern Miogeocline sediments notable preserve body and trace fossils of both Ediacaran and Cambrian forms and exceptionally, the Death Valley region is one of the few areas where elements of the Ediacara biota have been reported from Paleozoic strata (Hagadorn et al., 2000).  The trace fossil assemblage housed in the area has similarly proven to be a valuable resource in evaluating metazoan evolution through the Precambrian-Cambrian transition.  A single *Zoophycos* burrow reported from the Lower Member of the Wood Canyon Formation in close stratigraphic proximity to the Precambrian-Cambrian boundary is interpreted to represent the earliest direct evidence of deposit feeding (Sappenfield et al., 2012).   *Arenicolites* burrows in the Middle Member of the Wood Canyon Formation are interpreted to represent the earliest direct evidence of animal inhabitation of freshwater, terrestrial environments (Kennedy and Droser, 2011).

The Johnnie Formation is widely exposed in the southern Cordilleran Miogeocline and consists of approximately 200-1500 m of siliciclastic and carbonate strata (Stewart, 1970).  These materials are interpreted to have been deposited in a shallow marine environment marking the initial stages of deposition of materials solely derived from the Laurentian craton in the western Laurentian rift (Summa, 1993; Schoenborn, 2010).  The top of the Johnnie Formation is marked by a distinct unconformity containing evidence of several tens of meters of erosional relief (Levy and Christie-Blick 1989).

The Johnnie Formation is unconformably overlain by the Stirling Quartzite. The Stirling Quartzite is 100-700 m thick and has been divide into Lower, Middle, and Upper Members reflecting the three distinct sedimentary successions present within the unit (Fedo and Cooper, 2001; Schoenborn, 2010). The Lower and Upper Members are primarily composed of conglomerate and sandstone, reflecting deposition in a fluvial setting. The Middle Member consists of finer-grained detritus currently interpreted to have been deposited in an intertidal setting (Crangle and Fedo 1999). The Stirling Quartzite lies in conformable contact with the overlying Wood Canyon Formation (Christie-Blick et al., 1989)

The Lower Member of the Wood Canyon Formation predominantly consists of maroon siltstones and shales interbedded with dolomitic units. Less frequent sandstone beds are present throughout the Lower Member. The Precambrian-Cambrian boundary is placed in the upper portion of the Lower Member based on the earliest occurrence of *Treptichnus pedum* (Horodyski 1994 ). Geochemical profiles generated from the dolomitic ledges suggest a possible negative shift in stable carbon isotopes coincident with the current placement of the boundary, consistent with observations made in other boundary containing units (Corsetti et al., 2000).

In distal exposures of the Lower Member of the Wood Canyon Formation, 3 carbonate intervals, each ~5 meters thick, crop out as prominent ledges in otherwise gently-sloping topography. These carbonate units thin and become less frequent in eastern exposures of the Wood Canyon Formation (Fedo and Cooper, 2001) suggesting that either these materials were eroded during a sea level lowstand or that they are laterally discontinuous. Until recently, the eastward removal of successive carbonate units during a sea level lowstand was the preferred interpretation for the reduction and eventual absence of these units to the east (Fedo and Cooper, 2001). This combined with the pronounced unconformity between the Lower and Middle Members of the Wood Canyon Formation in some locations led to this contact being identified as the distal expression of the onset of the Sauk Megasequence (Fedo and Cooper, 2001). However, detailed field mapping and geochemical data suggest that carbonate units are likely to be laterally discontinuous and in some areas, the contact between the Lower and Middle Members of the Wood Canyon Formation may be conformable (Hogan et al., 2011). This suggests that significant downcutting into the Lower Member of the Wood Canyon Formation that would be expected to occur at the base of the Sauk Megasequence, likely is not present (Hogan et al., 2011). Rather, the onset of the Sauk Megasequence in the Death Valley region has been suggested to be recorded at the contact between the Neoproterozoic Johnnie Formation and the overlying Stirling Quartzite, where a considerable and laterally persistent erosional surface and coinciding large shift in facies is present (Hogan et al., 2011). This hypothesis is explored in greater detail later herein.

The contact between the Lower Member of the Wood Canyon Formation and the overlying Middle Member fluvial conglomerates is sharp and erosive. The Middle Member includes two discrete lithofacies assemblages separated along a sharp contact (Diehl, 1979): 1) a lower conglomeratic interval, and 2) an upper interbedded sandstone and shale interval. The upper sandstone and shale lithofacies assemblage grades conformably into the overlying Upper Member, which is lithologically comparable to strata of the Lower Member (Diehl, 1979). Ollenelid trilobites are present in the Upper Member indicating that these strata are at least Cambrian Series 2 (~521 ma) in age.

The Upper Member of the Wood Canyon Formation is overlain by relatively coarse sandstones of the Zabriskie Quartzite. The Zabriskie Quartzite is a ledge-forming unit characterized by prolific *Skolithos* piperock. Body fossils recently discovered in the Zabriskie Quartzite are the first to be reported from the unit and may represent the earliest fossil evidence of a medusozoan mass stranding event (Sappenfield et al., in prep). Detailed facies evaluation in the Zabriskie Quartzite by Prave (1992) suggests that the Zabriskie quartzite consists of two distinct sequence tracts separated by a regional unconformity. The lower sequence consists of prograding marine and terrestrial facies deposited during a sea level lowstand (i.e. a "lowstand systems tract") (Prave, 1992). This is capped by a transgressive lag and overlying transgressive systems tract initially marked by coastally deposited sediments eventually grading into green shales, interbedded sand beds and trilobite hash horizons of the upper Zabriskie Quartzite and overlying Carrara Shale (Prave, 1992). The unconformity separating these systems tract is regionally persistent, having been mapped in exposures spanning much of southeastern California and western Nevada.

### *Northern Cordilleran Miogeocline*

Northern Cordilleran Miogeocline sections are exposed in the western Great Basin within and surrounding the White-Inyo Mountains. Precambrian-Cambrian lithostratigraphic units in the area include the Wyman Formation, Reed Dolomite, and Deep Spring Formation. Deposition of this succession encompassed a variety of depositional environments from subtidal, storm-influenced siliciclastic facies to shallow carbonate shoals and tidal flats. The diversity of facies available in this area provides a variety of proxies for stratigraphic correlation hence, a robust stratigraphic framework has been established for the area which includes descriptions of the paleontological (Nelson, 1976; Mount et al., 1983; Signor and Mount, 1986; Grant, 1990), geochemical (Corsetti and Kaufman, 1994; Corsetti et al., 2000), and paleomagnetic (Kirschvink, 1978) records.

Two regional disconformities are currently recognized in the White-Inyo Mountains based on geochemical profiles generated through the Precambrian-Cambrian succession (Fritz, 1972; Corsetti et al., 2000). The lower hiatus separates the Wyman Formation from the overlying Reed Dolomite (Fritz, 1972; Corsetti et al., 2000). The younger hiatus occurs contact between the Deep Spring Formation and the overlying Campito Formation (Fritz, 1972). A third hiatus has been hypothesized at the contact between the Lower and Middle Members of the Deep Spring Formation (Corsetti et al., 2000), however, facies biases in the preservation of trace fossils and the geochemical signal have resulted in this interpretation being questioned (Jensen and Grant, 1996). In the absence of distinguishing features and/or robust age dates for the Sauk marine transgression, it has remained unclear as to which, if either, of these hiatuses represents the base of the Sauk Megasequence (Corsetti et al., 2000).

Trace and body fossils are preserved in both Precambrian and Cambrian strata in the White-Inyo Mountains. The Precambrian-Cambrian boundary is tentatively placed in shales of the Lower Member of the Deep Spring Formation based on the lowest occurrence of Lower Cambrian ichnofabrics coupled with a negative carbon isotope shift coincident with this stratigraphic location (Alpert, 1977; Corsetti and Kaufman, 1994; Corsetti et al., 2000). As documented globally, trace fossils increase in their diversity and abundance in Phanerozoic strata of the northern Miogeocline (Droser et al., 2002). *Treptichnus pedum*, *Cruziana* and *Diplichnites* have each been reported from the Upper Member of the Deep Spring Formation <100m above the Precambrian-Cambrian boundary (Corsetti and Hagadorn, 2000). An assortment of Precambrian biomineralized genera including *Cloudina, Nevadatubulus*, *Coleoloides*, and *Sinotubilites* have been reported from carbonate units of the Reed Dolomite in the eastern portion of the White-Inyo Mountain region (Signor and Mount, 1986). These fossils are commonly referred to as the "Small Shelly Fauna" which are characteristic elements of terminal Proterozoic and pretrilobitic Cambrian units containing an appreciable volume of carbonate (McMenamin,1996).

### *Craton*

Quartzite units of variable thickness dominate Precambrian-Cambrian successions adjacent to the Wasatch Line, forming the initial deposits of what is commonly referred to as the Paleozoic "inner detrital belt" (Palmer, 1981). These materials predominantly consist of coarse siliciclastic sediment of variable textural and mineralogical maturity, generally thought to have been transported onto the shelf by eolian input and mixed tidal- and storm-influenced shelf currents (Lindsey and Gaylord, 1992; Dott, 2003). The broad deposition of laterally contiguous sand bodies at the onset of the Phanerozoic is a global phenomenon that has been attributed to anomalously high levels of weathering and deposition resulting from both local tectonics and anactualistic environmental conditions present at the time (Dott, 2003). These conditions include a near-absence of terrestrial vegetation, limited bioturbation, elevated atmospheric concentrations of carbon dioxide and methane and increased tectonism associated with the breakup of the supercontinent Rodinia (Sloss, 1963; Dott, 2003; Hagadorn et al., 2011). In the absence of extensive terrestrial vegetation, sand-rich coastal systems and alluvial plains are thought have been far more widespread than is observed today (Lindsey and Gaylord, 1992; Dott, 2003). Long-term subsidence associated with crustal cooling was likely to have been the primary factor in determining the eventual thickness of these units (Simpson and Eriksson, 1989, 1990; Fedo and Cooper, 2001).

Immediately east of the Wasatch Line, cratonic sections consisting of thin (<100 meters thick), Cambrian sandstones of the inner detrital belt including the Tapeats Sandstone, Ignacio Quartzite, Tintic Quartzite and Ladore Sandstone rest directly atop Precambrian basement along the Great Unconformity (Figures 1, 2, and 3). These units generally vary from 30-100m in thickness and are conformably overlain by fine-grained units of the Pioche Shale or Bright Angel Shale. Overlying shales are trilobite-bearing indicating a Series 2 Cambrian age for these strata. This succession is interpreted to have been deposited during the Sauk II Supersequence when significant flooding of the cratonic interior is thought to have occurred (Palmer, 1981).

Abundant trace fossils (primarily *Arenicolites* and *Skolithos*) present immediately above the Great Unconformity observed in some cratonal sections have led to the general assignment of an early Cambrian age for these strata (Middleton, 2003). However, trace fossils do not occur immediately above the Great Unconformity in all sections and thus, it has been hypothesized that some basal cratonal sandstones may be at least have been partially deposited during the Neoproterozoic (Hagadorn et al., 2011).

Comparison of the first appearance datum (FAD) for Olenellid trilobites collected in transitional portions of the Tapeats sandstone in eastern portions of the Grand Canyon (McKee and Resser, 1945; Foster, 2011) and in the overlying Bright Angel Shale in western portions of the Grand Canyon (Schenk and Wheeler, 1942) was initially used in support of the hypothesis that basal cratonal sections are time transgressive to the east (McKee, 1945; Hagadorn et al., 2011). However, facies biases and the varying quality of exposure within these areas precludes this conclusion and rather, yields a less resolved statement that the upper portions of basal cratonal units were deposited during the Paleozoic, prior to Series 2 of the Cambrian Period (Hagadorn et al., 2011).

### ***Craton Margin***

The Precambrian-Cambrian stratigraphic record thickens substantially immediately west of the Wasatch Line, in a transitional zone commonly referred to as the craton margin, (Figures 2 and 3). Craton margin sediments form a nearly 200 km wide swath of thick accumulations of shale, conglomerate, and sandstone capped by Cambrian shales and limestones. Palinspastic reconstruction of the effects of Mesozoic crustal shortening and Cenozoic extension suggests that the current width of this zone is as much as two-times its original width (Dickinson, 2013) (Figure 1.3). Several partially or wholly correlative Precambrian-Cambrian lithostratigraphic units are exposed in the region including the Prospect Mountain Quartzite, Geertsen Canyon Quartzite, Camelback Mountain Quartzite, Corkscrew Quartzite, Tintic Quartzite, Brigham Quartzite, Osgood Mountain Quartzite, Pioche Shale, Bright Angel Shale, and portions of the underlying Mutual and Inkom Formations (Crittenden et al., 1971; Figure 1.3). Much of the disparity in nomenclature has been attributed to the wide geographic extent of craton margin exposures rather than lithological dissimilarities among these units (Crittenden et al., 1971).

Mapping by Crittenden et al. (1971) recognized the lithologic similarities between the Precambrian-Cambrian successions in northern craton margin exposures (an observation identified as a "startling continuity of both individual rock units and of rock sequences…"), yet opted to apply multiple identifiers to units that were likely correlative to maintain a regionalized nomenclature. This technique has been widely applied as is highlighted by the varied usage of Camelback Mountain Quartzite, Geertsen Canyon Quartzite, Prospect Mountain Quartzite, and Tintic Quartzite to describe what are identified as lithologically comparable Precambrian-Cambrian craton margin sandstones exposed in southern Idaho, northern Utah, eastern Nevada, and central Utah, respectively (Crittenden et al., 1971).

Mafic volcanics are interbedded within Neoproterozoic sections spanning much of the central Great Basin (Figure 1.3). This is a unique condition as interbedded Ediacaran volcanics are exceedingly rare for the majority of the western United States. Radiometric age dates have been assessed for these materials in exposures in the central Wasatch Range (Crittenden and Wallace 1973; Verdel 2009). Analysis of a dislocated basanite clast underlying the main flow provide an $^{40}Ar/^{39}Ar$ hornblende total gas age of 580 ±16 million years (ma) ($2\sigma$) (Crittenden and Wallace, 1973). Most recent evaluations of materials collected from the flow itself provide a 206Pb/238U age of 609±25ma ($2\sigma$) (Verdel, 2009).

Unconformities of varying scale are pervasive along the craton margin. At least two separate regional unconformities have been previously mapped in Precambrian-Cambrian craton margin strata. The lower of these unconformities separates Neoproterozoic marine facies from overlying terrestrial conglomerates and is readily identifiable at the majority of outcrops. The upper unconformity juxtaposes the same terrestrial conglomerates with overlying nearshore sandstones. This upper unconformity is less pronounced and is absent from several localities in the southern and central Great Basin (Crittenden et al., 1971; Christie-Blick and Levy, 1989; Link et al., 1987).

Despite the varied nomenclature and reduced dataset available for craton margin units, several generalizations are commonly applied regarding their age and paleontological signature. Most commonly, the Precambrian-Cambrian boundary is arbitrarily assigned to the base of thick orthoquartzites directly underlying Cambrian shales (Hintze, 1993), despite the universal absence of trace fossils in lower portions of the succession.  While trace fossils have been catalogued from upper portions of these units, the absence of detailed stratigraphic columns to accompany these data precludes description of their facies relationships and identification of their earliest occurrence. Further, an eastward time-transgressive element has been applied to the succession with little consideration for potential facies biases coincident with the contact with overlying Cambrian shales or limestones (Hagadorn et al., 2011).  The prior absence of these data has posed a fundamental data gap precluding evaluation of relative age and regional correlation of key stratigraphic markers within this succession.

## Problem Development

The established global and regional stratigraphic frameworks provide the primary means of regional correlation in the western United States, however, given the variability in the quality and/or quantity of data available in the area, the application of the global framework is inconsistent.  This is most evident in areas of the central Great Basin dominated by thick accumulations of seemingly innocuous siliciclastics which have previously received minimal consideration.  However, the age and geographic position of these units highlight their potential significance as an independent source of data and also as a keystone for stratigraphic correlation of key events between cratonal and distal stratigraphic sections in the western United States.

At the core of issues faced in refining craton margin stratigraphy in the regional and global frameworks is a deficiency of highly resolved stratigraphic and sedimentological data obtained from separate exposures throughout the region. Very few complete sections and/or detailed sedimentological descriptions have been compiled through the thickest exposures of these units. As a result, a sedimentological framework bearing sufficient resolution to provide additional points for regional correlation has previously been lacking. Additionally, the provinciality of mapping efforts coupled with the wide geographic area over which Precambrian-Cambrian sandstones are exposed in western North America has resulted in disparate nomenclature and definitions for what are likely temporally and lithologically equivalent units. The variety of terminology and boundary definitions complicates correlation of these strata over the length of their exposure. Deciphering these inconsistencies is the first step towards developing a robust and unified framework for these units, as is required for their incorporation into the well-established framework for the western United States. Doing so would further constrain the timing and geographic extent of key events while also transcribing these data over a far greater area than is currently available.

The current loosely bracketed age for Precambrian-Cambrian stratigraphy in the Great Basin greatly lessens its utility. Further refinement of temporal trends in these units is critical to recognizing and correlating key events in this record. The recently obtained radiometric age date from the Volcanic Member of the Browns Hole Formation in northern Utah (Crittenden et al., 1971; Verdel, 2009) suggests that comparable volcanic debris in other nearby localities may provide the necessary geochronologic constraint to accomplish this goal. Regional correlation of numerical ages from volcanic flows exposed within the craton margin succession provides a potentially key resource for units exposed throughout the Great Basin.

## Analytical Methods and Localities

The methods described herein were developed in pursuit of a lithostratigraphic, temporal, and biostratigraphic framework for Precambrian-Cambrian craton margin units. A primary goal of this research was thus to synthesize the current Ediacaran-Cambrian dataset and supplement those materials with stratigraphically-referenced data collected from previously uncatalogued sections spanning the central Great Basin. Here outlined are the tools utilized and localities visited during this study in pursuit of this goal.

Complete stratigraphic profiles incorporating new and available sedimentologic, paleontologic, and geochronologic data were generated for seven separate craton margin exposures in the central Great Basin. From north to south, these localities include: 1) Portneuf and Bannock Ranges (Pocatello, Idaho), 2) Bear River Range (Logan, Utah), 3) Sheeprock Mountains (Tooele County, Utah), 4) Central Wasatch Range (Huntsville, Utah), 5) Snake Range (Great Basin National Park, eastern Nevada), 6) Cricket Mountains (Utah), and 7) Wah Wah Mountains (Pine Valley, Utah) (Figures 2 and 3). These localities define a broad transect through Precambrian-Cambrian successions in the central Great Basin. Within this network, four previously undescribed stratigraphic sections were logged at the meter or finer scale through units previously noted as potentially housing or resting atop the Precambrian-Cambrian boundary. Graphic and written descriptions of rock type, bedding geometry, and fossil content were incorporated into the greater than 5km of stratigraphic section collected from these exposures (see supplementary materials available on ProQuest).

Data was compiled for localities described herein beginning below the base of the formation bearing the lowest stratigraphic occurrence of Cambrian ichnofabrics to the local FAD for trilobite-bearing strata. Trace fossil diversity, presence/absence data, and size were incorporated into the sections at the resolution feasible. Ichnofabric indices (Droser and Bottjer, 1986) were used to semiquantitatively describe intensity of bioturbation in each section. Previously published sedimentologic, paleontologic, geochronologic, and sequence stratigraphic data were incorporated into the stratigraphic columns to the extent and resolution feasible. Facies descriptions provided herein are founded on field observations and petrographic analyses of systematically collected and stratigraphically referenced materials.

Organic material was not observed in craton margin units visited during this investigation and thus, evaluation of the biological component of these strata relies solely on data obtained from sedimentary structures produced by the activities of bilaterians or the direct preservation of the bodies of macroorganisms. This is typical to Ediacaran-Cambrian successions worldwide as the overwhelming majority of fossils are confined to siliciclastic units with little or no organic detritus (Narbonne, 2005). Trace fossils were hence catalogued as to their ichnotaxonomy and first occurrence data.

Bulk samples of volcanic material were collected from exposures in northern and southern Utah. Petrographic analyses of collected samples were compared to previously collected materials in the region (i.e. Crittenden et al., 1971; Harper and Link, 1986; Verdel, 2009). Fusing of the petrologic, stratigraphic, and previously collected X-Ray Fluorescence (XRF) data compiled for craton margin volcanics provides the basis for description and regional correlation of these materials.

## Localities

The following sections provide a general overview of the localities utilized herein. This summary includes descriptions of the general geography, nature, and quality of exposure, local geologic setting, and associated key references for each area.

### ***1) Portneuf and Bannock Ranges (Pocatello, Idaho)***

The Portneuf and Bannock Ranges are located in southeastern Idaho, approximately 100 km north of the Utah border. Precambrian-Cambrian strata are well exposed in the area and have been mapped in detail by multiple parties (Trimble, 1965; Condie, 1969; Crittenden et al., 1971; Rodgers et al., 1999; Rodgers et al., 2006). Uplifted strata in the area are heavily folded and faulted as a result of Cenozoic compression and subsequent Basin and Range extension. Uplift of both ranges is accommodated along several north-south oriented normal faults along the western rangefronts and in the interior of the ranges.

### *2) Bear River Range (Logan, Utah)*

The Bear River Range houses several well-exposed sections of Precambrian-Cambrian strata. The Bear River Range straddles the Utah – Idaho border and separates Cache Valley from the Bear Lake and Bear River Grabens along the eastern portion of the range.

Precambrian-Cambrian strata crop out in the western interior of the Bear River Range along the western limb of the Logan Peak Syncline. Uplift in the Bear River range results from a complex interplay of normal faulting along the East Cache Fault (and associated splays) and thrust faulting along the Paris Thrust (Crook et al., 1985). An unnamed splay of the East Cache Fault truncates the base of the Precambrian-Cambrian stratigraphic section in the investigation area, juxtaposing Precambrian conglomerates against Tertiary Salt Lake Formation diamictites (Dover, 1995). Canyons carved by ephemeral creeks and sparse vegetation on the adjacent hillsides yield exposures of the Precambrian-Cambrian stratigraphy that can be easily accessed and mapped.

### *3) Sheeprock Mountains (Tooele County, Utah)*

The Sheeprock Mountains are located in central Utah along the western perimeter of Rush Valley. North-dipping, terminal Proterozoic and Paleozoic strata are exposed in the northern portion of the Sheeprock Mountain, west of the city of Vernon. Uplift via east-west trending thrust faults in the Sheeprock Mountains has produced a well-exposed Proterozoic to Cambrian succession in the northern and eastern portions of the range (Crittenden et al., 1971; Christie-Blick, 1982 ; Mukul and Mitra, 1998).

### *4) Central Wasatch Range (Huntsville, Utah)*

Precambrian-Cambrian strata are well-exposed in canyons eroded by the Middle and South Forks of the Ogden River north and east of Huntsville, Utah, respectively. Crittenden et al. (Crittenden et al., 1971) suggested that due to the prominence of these exposures, their completeness, and minimal disruption by faults, this area should be considered a standard for Precambrian-Cambrian stratigraphy in northwestern Utah. Neoproterozoic and early Cambrian craton margin strata in the hills east of Huntsville area are contained in the hanging wall above the Willard Thrust (Blackwelder, 1910; Crittenden et al., 1971; Sorensen and Crittenden, 1979; Crittenden et al., 1983). These strata are folded into a northeast-plunging anticline with its axis roughly aligned with the Middle Fork of the Ogden River. Strata exposed along both the north and south limb are well-exposed and readily accessible. It should be noted that the majority of exposures along the south limb are on private property and thus, in the absence of permission, investigations are limited to the roadside and creek bed.

### *5) Snake Range (eastern Nevada)*

The Snake Range is located in White Pine County in eastern Nevada, adjacent to the western border of Utah. Northern and southern portions of the Snake Range are separated by the Snake Range decollement, an east-west trending, Miocene detachment fault with an apparent domal shape resulting from reverse drag above a deeper and younger detachment fault (Bartley and Wernicke, 1984). Rocks exposed in the core of the northern Snake Range above the Snake Range decollement are similarly folded resulting in a broad exposure of Precambrian-Cambrian strata spanning much of the range, including Wheeler Peak. Ancillary faulting has disrupted much of the sedimentary sequence in the area; however, isolated continuous sections have been mapped in northern portions of the range near Interstate Highway 6 (Whitebread, 1969; Van Vickers, 2002).

### *6) Cricket Mountains (Milford, Utah)*

The Cricket Mountains are located in western Utah, approximately 40 km north of the city of Milford (Beaver County). The range is approximately 50 km in length and is predominately composed of an east-dipping succession of Proterozoic and Paleozoic sedimentary strata. Terminal Neoproterozoic and Cambrian strata are well exposed in southern portions of the range near the Cricket Mountains Off-Highway Vehicle Recreation Area. Access to the interior of the mountain range is facilitated by maintained dirt and gravel-paved roads which provide a thoroughfare for recreational and commercial travel across the floor of ephemeral Sevier Lake.

The Cricket Mountains are uplifted via a series of west-dipping normal faults along the western rangefront, typical of Basin and Range tectonism. Stratigraphic information available for the Precambrian-Cambrian succession in the Cricket Mountains is restricted to formational assignment based on a gross evaluation of facies. Geologic mapping by Hintze and Davis (2003) and Lemmon and Morris (1984) provide the most detailed, albeit still very general, review of the Proterozoic and early Paleozoic stratigraphy exposed in the area to date.

### ***7) Wah Wah Mountains (Pine Valley, Utah)***

The Wah Wah Mountains are a north-south trending mountain range in western Utah bearing east-dipping exposures characteristic of the Great Basin. The range separates Pine Valley on the west side of the Wah Wah Mountains from Wah Wah Valley to the east. Neoproterozoic and Paleozoic sedimentary strata are the primary rocks exposed in the Wah Wah Mountains. Complete and continuous sections of Precambrian-Cambrian strata are well exposed in the southern portion of the range.

Uplift of the Wah Wah Mountains is facilitated primarily by north-south trending normal faults, typical of Basin and Range horst and graben tectonism. In the investigation area, several east-west trending thrust faults cut into and juxtapose Neoproterozoic and early Cambrian strata with younger Paleozoic units.

Mapping by Steven et al. (1990) provides a general overview of the stratigraphy and outcrop pattern for the Neoproterozoic-Cambrian succession in the Wah Wah Mountains. Detailed cataloguing of trace fossils present in upper portions of the unit was included in an unpublished PhD thesis by Magwood (1996).

## Materials

The following sections summarize the observations and materials compiled during this investigation. This includes descriptions of the facies availability, paleontological records, geochronological data, and stratigraphic context for Precambrian-Cambrian units deposited along the craton margin.

### Sedimentology

While predominately composed of coarse siliciclastic detritus, Precambrian-Cambrian strata deposited along the craton margin house a variety of facies likely representing both marine and terrestrial deposition. Eight distinct lithofacies are described herein from localities in the central Great Basin. These are described as follows, in order of their general occurrence in the measured sections: A) conglomerate,

B) medium- to thick-bedded, medium to coarse sandstone, C) thin-bedded, fine to medium sandstone with Silt, D) laminated, fine to medium sandstone, E) fine to medium sandstone with silt and clay rip-up clasts, F) Interbedded sandstone and shale, G) siltstone/shale, and H) basalt. Each of these and associated sedimentary structures are described below as the basis for ensuing paleoenvironmental interpretation.

### *Conglomerate (Facies A) – Figure 1.4*

The conglomerate facies crops out as distinctive, Very Dusky Red (5R 3/4) to Grayish Red (10R 4/2) ledge-forming outcrops consisting of matrix supported pebble to cobble conglomerate present as isolated beds and amalgamated channel fills from 0.5m to a few meters thick. Poor- to moderately-sorted clasts are predominately composed of varying quantities of subrounded chert, jasper, quartz, and lithic fragments housed in a groundmass of medium to coarse feldspathic sand. Conglomeratic intervals commonly grade into gritty sandstones containing isolated pebble- and cobble-sized clasts comparable to those housed in the underlying conglomerate. Weathering of these materials occasionally results in removal of gravel and larger-sized clasts producing a distinctive "plucked" bedding-plane surface. Trough and planar laminations are abundant in intervening sandstone intervals. These features and their three-dimensional relationships suggest deposition in an active fluvial braid plain, consistent with previous interpretations for units in which this is the dominant lithofacies (Link et al., 1987).

### *Medium- to Thick-bedded Medium to Coarse Sandstone (Facies B) – Figure 1.5*

Medium to coarse orthoquartzite crops out as ledge-forming, Moderate Reddish Orange (10R 6/6) beds approximately 15-30cm thick. Sediment grains are subrounded and predominately composed of potassium feldspar and quartz. Large-scale planar and lenticular cross beds are common within beds in excess of 50cm thick. Bed contacts are typically sharp and in some instances, erosive.

### *Thin-bedded Fine to Coarse Sandstone with Silt (Facies C) – Figure 1.6*

Fine- to medium-grained sandstone beds are abundant in craton margin strata. Typically beds are 5-15cm thick and bear a distinctive Moderate Reddish Orange (10R 6/6) hue. Sediments grains are subrounded and predominately composed of quartz, feldspar and less common lithic fragments. Planar, trough and lenticular crossbeds are commonly associated with this lithofacies. Oscillation ripples, and desiccation cracks are also present in some exposures. These features are indicative of deposition in a shallow, nearshore marine setting experiencing periods of subaerial exposure.

### *Laminated Fine to Medium Sandstone (Facies D) – Figure 1.7*

The laminated fine to medium sandstone facies is most distinct in its Light Grey (N7) and Grayish Orange Pink (10R 8/2) color and banded weathering pattern. Sediments are predominately subrounded to rounded and consist almost exclusively of quartz. Planar laminations and small-scale crossbeds are abundant within this facies. These sediments are interpreted to have been transported by wave activity in a nearshore marine environment above fairweather wave base.

### *Medium to Coarse Sandstone with Abundant Siltstone Rip-up Clasts (Facies E) – Figure 1.8*

Facies E includes Moderate Reddish Orange (10R 6/6) medium to coarse sandstones containing abundant Dark Reddish Brown (10R 3/4) micaceous siltstone rip-up clasts. Rip-up clasts are variably well preserved with taphonomic end members represented as either *in situ* siltstone fragments or weathered cavities surrounded by a heavily oxidized hue. Sandstone beds housing these rip-up clasts are commonly gritty and may also contain gravel to pebble sized fragments of subangular to subrounded quartz and chert.

### *Interbedded Sandstone and Shale (Facies F) – Figure 1.9*

Fine sandstone and intervening shale beds typically form bedsets <1m thick. Sandstones contain abundant planar and low-angle crossbeds with less frequent hummocky cross stratification. Sandstones range in color from Light Gray (N7) to Moderate Reddish Orange (10R 6/6). Sandstone beds are lenticular and laterally discontinuous over the course of a few centimeters to tens of meters. Shales are laminated to thinly bedded and are generally either Greenish Grey (5G 6/1) or Pale

Brown (5YR 5/2). Facies F is interpreted to represent marine deposition below fairweather wave base with intermittent flux of coarser sediments during storm events.

### ***Siltstone/Shale (Facies G) – Figure 1.9***

Laminated to thinly bedded micaceous siltstone and less frequent shale are generally Greenish Grey (5G 6/1) or Pale Brown (5YR 5/2). Occasional discontinuous fine sandstone stringers are present within this facies. Positive relief pustules present within some siltstone/shale intervals have previously been interpreted to represent Microbially Induced Sedimentary Structures (MISS). Siltstones and shales are interpreted to have been deposited in a marine setting below storm wave base.

### ***Volcanics (Facies H) – Figure 1.10***

Craton margin volcanics range in color from Dusky Brown (5YR 2/2) to Pale Yellowish Brown (15R 6/2). Volcanics are generally phaneritic with less common vesicular and porphyritic materials present locally. In porphyritic samples, phenocrysts generally consist of light-colored plagioclase. Analysis of samples by X-ray fluorescence (XRF) by Verdel (2009) shows a low total alkali content versus silica ratio and a greater than 10 wt.% olivine component, indicative of a basanite classification (Le Maitre, 1984), though these materials are commonly referred to as basalt, as applied herein.

## Stratigraphy

Stratigraphic profiles compiled during this investigation are summarized below in the context of each individual locality. A brief overview of the local nomenclature is provided as the forward to each locality discussion. For ease of reference, these localities are discussed along a north to south transect, as they were introduced previously. Sedimentological and geochronological descriptions outlined above are incorporated into and stratigraphically referenced within these discussions.

### *1) Portneuf and Bannock Ranges (Pocatello, Idaho)*

Terminal Neoproterozoic and early Paleozoic strata exposed in the Portneuf and Bannock Ranges are assigned to the Brigham Group and include the Inkom Formation, Mutual Formation, Camelback Mountain Quartzite, and Gibson Jack Formation. These units were formerly assigned to the Brigham Formation (Anderson, 1928; Ludlum, 1942) prior to revisions by Crittenden et al. (1971) which lead to additional partitioning of the local nomenclature. Following revisions by Crittenden et al. (1971), Link et al. (1985) and later Link et al. (1987) provided additional descriptions of lithofacies and depositional contacts based on logging of multiple sections in the area.

The Portneuf and Bannock Ranges bear type sections for several of the Neoproterozoic and Cambrian units including the Inkom Formation, Camelback Mountain Quartzite and Gibson Jack Formation (Crittenden et al., 1971). Stratigraphic profiles for the region have been compiled for separate sublocalities by Jansen, 1986 (North Bannock Range), Halimdihardja, 1987 (North Portneuf Range), Lindsey, 1982 (South Portneuf Range), Bright, 1960 (South Portneuf Range), and Link, 1982 (South Bannock Range).

In the Portneuf and Bannock Ranges, the Inkom Formation generally consists of a 250-300m thick, siltstone-dominated unit (Facies G) bearing minor sandstone (Facies C). At its type section north of city of Inkom in the Portneuf Range, lower portions of the Inkom Formation are primarily composed of siltstone metamorphosed to green-colored phyllite, grading into argillites, slate, and occasional very fine-grained quartzite in the upper ~50m of the section (Crittenden et al., 1971). The unit thins considerably in the southern portions of both ranges to ~25m thick. Link et al. (1987) hypothesized that this thinning could have been attributed to unmapped, bedding parallel faulting; however, evidence in support of this interpretation has not yet been recovered.

The contact between the Inkom Formation and the overlying Mutual Formation is sharp, erosive, and easily distinguished based on an abrupt shift in color and lithofacies from Moderate Olive Brown (5Y 4/4) siltstones and argillites to Grayish Red (5R 4/2) sandstones and conglomerates (Crittenden et al., 1971; Link et al., 1987). This contact was identified as a sequence boundary by Link et al. (1987) and is estimated to have removed as much as 3,000 m of stratigraphic section in some exposures (Crittenden et al., 1971). In the Pocatello area, the Mutual Formation is a nearly 1 km thick unit and primarily consists of ubiquitously cross-bedded pebble conglomerates (Facies A) with lesser quantities of gritty sandstone (Facies B). A single, ~50 m thick argillaceous unit

(Facies G) is present at the top of the Mutual Formation in southern portions of the Bannock and Portneuf Ranges (Lindsey, 1982; Link, 1982). At these localities, the contact with the overlying Camelback Mountain Quartzite is sharp and erosive. However, in northern portions of the both ranges where the upper portion of the Mutual Formation is considerably more coarse, this contact is conformable and gradational (Crittenden et al., 1971).

The Camelback Mountain Quartzite is approximately 400-1000m thick in the Pocatello area (Lindsey, 1982). Mapping of the Camelback Mountain Quartzite is complicated by severe faulting and poor exposure at its type section near Camelback Mountain. The Camelback Mountain Quartzite is predominately a thick-bedded, Very Pale Orange (10YR 8/2) to Grayish Orange (10YR 7/4), medium-grained orthoquartzite (Facies B). Beds are mostly massive with some localized lenticular crossbeds. Rose diagrams compiled by Link et al. (1987) suggest strong unidirectional currents directed to the present-day northwest in exposures of the Camelback Mountain Quartzite in both the Portneuf and Bannock Ranges. The Precambrian-Cambrian boundary has been informally placed in the Camelback Mountain Quartzite based on the unit’s stratigraphic proximity to trilobitic strata of the overlying Gibson Jack Formation. *Skolithos* and *Arenicolites* trace fossils present approximately 50 m below the top of the formation support at least a Lower Cambrian age for these strata.

The Gibson Jack Formation is approximately 300 m thick and primarily consists of Light Olive Brown (5Y 5/6) interbedded siltstone and sandstone (Facies F). The contact with the underlying Cambelback Mountain Quartzite is gradational and conformable. A report of a single specimen of the Middle Cambrian (Series 3) fossil *Narnia* was reported approximately 100m above the base of the Gibson Jack Formation (Crittenden et al., 1971). This age assessment is consistent with the current assignment of the overlying Langston Dolomite to the *Albertella* trilobite biozone. Reports of olenellid trilobites in strata potentially equivalent to the Gibson Jack Formation by Crittenden and Palmer (personal communication to Oriel and Armstrong (1971)) may indicate that these strata are Series 2 Cambrian in age, however, the precise stratigraphic placement of these fossils has not been reported. Thus, the more conservative evaluation of the Gibson Jack Formation being at least Series 3 Cambrian in age is applied herein.

### *2) Bear River Range (Logan, Utah)*

The general lithostratigraphic nomenclature applied in the Bear River Range (Dover, 1995) was developed by Crittenden et al. (Crittenden et al., 1971) coincident with the aforementioned nomenclature developed for the Portneuf and Bannock Ranges. Thus, some overlap exists in the terminology applied both in the Bear River Range and southeastern Idaho. The Bear River Range succession includes the Mutual-Inkom Formation, Browns Hole Formation, Geertsen Canyon Quartzite, and Langston Dolomite. The Langston Dolomite caps Precambrian-Cambrian strata analyzed during this investigation as the first trilobite-bearing formation in the region.

In the Bear River Range, the Mutual Formation is estimated to be greater than 1.8 km thick and primarily consists of conglomeratic sandstone with abundant lenticular pebble and cobble horizons (Facies A). The unit crops out as a distinct Grayish Red Purple (5RP 4/2) unit along the eastern rangefront. The Mutual Formation is underlain by a regional unconformity separating the unit from the underlying Inkom Formation in the Bear River Range. The Inkom Formation (variably also identified as the Kelly Canyon Formation) predominately consists of dark-colored argillite and quartzite.

Disconformably overlying the Mutual Formation, the Browns Hole Formation forms a distinct Dusky Red (5R 3/4) marker unit which can be traced laterally over much of the Bear River Range. The Browns Hole Formation is approximately 80m thick and consists of two distinct lithofacies: 1) a lower, volcanic flow (Facies H) cropping out as a distinct, ledge-forming unit, and 2) an upper quartzite (Facies B; often referred to as the "Terra Cotta Quartzite" due to its distinctive clay-like color) approximately 20m thick. Frosted quartz grains have been reported from the Terra Cotta Quartzite (Crittenden et al., 1971). Volcanic materials are banded in some portions of the unit.

The Geertsen Canyon Quartzite conformably overlies the Browns Hole Formation in the Bear River Range. The Geertsen Canyon Quartzite predominately consists of medium to coarse sandstone beds approximately 5-25cm thick with infrequent lenticular and bedding-parallel conglomeratic horizons approximately 10-30cm thick (Facies A, B and C). Planar and trough crossbeds are abundant throughout the unit.

Interbedded fine to medium sandstone and micaceous siltstone (Facies F) become increasingly prevalent beginning at approximately 1.35km above the base of the Geertsen Canyon Quartztite. It is herein noted that the stratigraphic position and lithologic character of these materials is comparable to those materials included in the Gibson Jack

Formation in southeastern Idaho (Crittenden et al., 1971). This shift in facies directly coincides with the lowermost occurrence of typical early Cambrian ichnofabrics. Trace fossils observed in siltstones and shales during this investigation include *Cruziana, Rusophycos, Taphrehelminthopsis, Planolites, Teichichnus*, and *Helminthoidichnites* (Figure 1.11). Ichnofabric indices (ii) in both fine- and coarse-grained facies range from 3 to 5. Trace fossils were also observed among amalgamated sandstone channels beginning at approximately 1.5km above the base of the Geertzen Canyon Quartzite. These assemblages contained densely packed (ii5) *Arenicolites* and *Skolithos* burrows (Figures 1.12 and 1.13).

The Naomi Peak Member of the Langston Dolomite overlies the Geertsen Canyon Quartzite in the Bear River Range along a local disconformity. The contact between the two units is marked by the appearance of a Medium Light Gray (N6) ledge-forming, bioturbated (ii3) dolomite. *Albertella* trilobites have been retrieved from the Naomi Peak Member indicative of at least a lower Middle Cambrian (Series 3) age for these strata (Hintze, 2003).

### ***3) Sheeprock Mountains (Tooele County, Utah)***

The lithostratigraphic nomenclature applied in the Sheeprock Mountains has undergone multiple rounds of revision. This has varied most distinctly in identification of craton margin sandstone units as either Tintic Quartzite or Prospect Mountain Quartzite (Cohenour, 1959; Groff, 1959; Moore and Sorensen, 1979; Christie-Blick, 1982). Christie-Blick (1982) provides the most highly resolved of these efforts and assigns much of the succession to the Brigham Group, as is applied herein. Proterozoic-Cambrian strata in the Sheeprock Mountains thus include the Mutual Formation, Prospect Mountain Quartzite, and the Pioche Shale (Moore and Sorensen, 1979). Structural complexity, exposure quality, and ease of access have resulted in a considerable focus seeking resolution to the general stratigraphy exposed in the Sheeprock Mountains (Christie-Blick, 1982).

In the Sheeprock Mountains, the Mutual Formation consists of Grayish Red (10R 4/2) conglomeratic sandstone (Facies A). The gravel component of these strata is commonly channelized and generally consists of quartz (~85%), chert (~10%) and lithic fragments (~5%). Beds range from 10cm-40cm thick and are erosive at their base. Total thickness of the Mutual Formation in the Sheeprock Mountains is approximately 500m. The base of the Mutual Formation is in sharp contact with the underlying Inkom Formation. The Mutual Formation grades into the overlying Tintic Quartzite over 65m of stratigraphic section in the exposures measured during this investigation and by as much as 100m in other portions of the Sheeprock Mountains (Christie-Blick, 1982).

The Prospect Mountain Quartzite is approximately 760m thick in the Sheeprock Mountains. Lower portions of the unit generally consist of fine to medium sandstone with infrequent lenticular gravels (Facies A and C). Three conglomeratic intervals were mapped spanning approximately 0-65m, 247-339m, and 413-434m above the base of the Prospect Mountain Quartzite. Conglomerates within these zones were comparable to those observed in the underlying Mutual Formation. Upper portions of the Prospect

Mountain Quartzite include appreciable siltstone beginning at approximately 613m above the base of the unit.

*Arenicolites* trace fossils were observed at approximately 628m above the base of the Prospect Mountain Quartzite, just below the first occurrence of significant and laterally continuous siltstone beds. Burrows were densely packed (ii5) and 1-5cm deep in cross section. Beds housing these trace fossils were 5-10cm thick. Overlying *Arenicolites*-bearing beds, a thicker, ledge-forming sandstone unit contains abundant *Skolithos* trace fossils (ii4-5). Bed thickness ranges from 5-10cm thick and cross beds are abundant. The uppermost, siltstone-bearing interval included in the Prospect Mountain Quartzite contains abundant Cambrian trace fossils including *Planolites, Helminthoidichnites*, and *Diplichnites*.

Light Olive Brown (5Y 5/6), argillaceous, cross-bedded quartzites are present as interbeds near the top of the Prospect Mountain Formation (Facies F). These olive-green quartzites are overlain by about 50 m of green to tan, fissile, highly micaceous shales (Facies G). Groff (1959) defined an undifferentiated limestone-and-shale sequence to include all the rocks overlying the Prospect Mountain and Pioche Formations.

The Prospect Mountain Quartzite is conformably and gradationally overlain by the Pioche Shale. The Pioche Shale is approximately 50-105m thick in the Sheeprock Mountains (Christie-Blick, 1982). Biostratigraphic constraints are provided by *Albertella* trilobites recovered from limestones in the overlying Tatow Formation, indicative of at least a Middle Cambrian (Series 3) age for these strata.

### *4) Central Wasatch Range (Huntsville, Utah)*

The lithostratigraphic nomenclature applied to Precambrian-Cambrian units exposed in the Central Wasatch Range near Huntsville, Utah was developed by Crittenden et al. (1971) coincident with the aforementioned nomenclature developed for southeastern Idaho and the Bear River Range. As observed among the Portneuf, Bannock, and Bear River Ranges, some overlap does exist in the terminology applied in the central Wasatch Range. However, as lower portions of the stratigraphy are not exposed in the Huntsville area and prevalent faulting obscures much of the section, Precambrian lithostratigraphic correlation becomes slightly more ambiguous. The Bear River Range succession thus includes strata mapped as undifferentiated Mutual-Inkom Formation below the Browns Hole Formation, Geertsen Canyon Quartzite, and Langston Dolomite.

Materials conditionally mapped as Inkom Formation include an approximately 100-150m section of thin-bedded, Light Olive Brown (5Y 5/6) and Grayish Red (10R 4/2) siltstones and shales (Facies G). These materials are unconformably overlain by conglomeratic materials (Facies A) assigned to the Mutual Formation. Estimates regarding the volume of material removed at this contact are unavailable.

The Mutual Formation is approximately 300m thick in the Huntsville area, considerably thinner than observed elsewhere. The unit is distinctly Pale Reddish Brown (10R 5/4) and is composed almost exclusively of coarse-grained, cross bedded sandstone (Facies B) with some local lenticular, discontinuous argillite interbeds (Facies G).

The Mutual Formaiton is disconformably overlain by approximately 60m of volcanics (Facies H) assigned to the Browns Hole Formation. Exposures of these volcanics northeast of Huntsville provide the aforementioned $^{40}$Ar/$^{39}$Ar hornblende age date of 580 ±16 million years (ma) (2σ) (Crittenden and Wallace, 1973; Christie-Blick et al., 1989) and recently revised 206Pb/238U apatite age of 609±25ma (2σ) (Verdel, 2009). As observed in the Bear River Range, Browns Hole Formation volcanics are disconformably overlain by quartzite bearing a distinctive reddish hue, often referred to as the Terra Cotta Quartzite.

The Browns Hole Formation grades conformably into the overlying Geertsen Canyon Quartzite. Here, the Geertsen Canyon Quartzite is approximately 1.3 km thick and consists primarily of Very Pale Orange (10YR 8/2) fine to coarse sandstone beds of variable thickness (Facies B and C) with lesser quantities of conglomerate (Facies A). The Geertsen Canyon Quartzite is divided into Lower and Upper Members near Huntsville based on the presence of a locally persistent zone of cobble conglomerate (Facies A) located approximately 400 m above the base of the Formation. The intervening conglomerate is approximately 30-65m thick and is composed of lenses 0.5-2m thick.

*Skolithos* and *Arenicolites* trace fossils are abundant in fine-medium grained sandstones (Facies C) approximately 100m below the Geertsen Canyon Quartzite-Langston Dolomite contact. Interbedded sandstones and shales (Facies F) approximately 30m below the same contact bear abundant early Cambrian trace fossils including

*Teichichnus*, *Cruziana*, and *Plagiogmus.* This succession is capped by the Langston dolomite which is considered to be Series 3 Cambrian in age.

### ***5) Snake Range (Great Basin National Park, eastern Nevada) – Central Craton Margin***

Precambrian-Cambrian lithostratigraphy applied in the Snake Range relies largely on type sections in eastern Nevada descibed by Hague (1883) and Misch and Hazzard (1962). Units mapped in the area include the Osceola Argillite, Prospect Mountain Quartzite, and Pioche Shale.

The Osceola Argillite is the uppermost Formation of the McCoy Creek Group in the Snake Range (Misch and Hazzard, 1962; Whitebread, 1969). Formerly, the lower portion of the Prospect Mountain Quartzite was included in the McCoy Creek Group as the Stella Lake Quartzite. Revision of this subdivision was suggested by Hose and Blake (1976). Remaining elements of the lithostratigraphic subdivision of the McCoy Creek Group still vary widely and thus, use of the moniker Osceola Argillite to describe the uppermost portion of the unit is largely restricted to this portion of eastern Nevada.

The Osceola Argillite consists of Medium Gray (N5) siltstone and shale (Facies G) commonly altered to phyllite. Interbedded sandstones (Facies F) are present sporadically in the unit. The contact with the overlying Prospect Mountain Quartzite is sharp and erosive, marked by an abrupt coarsening and color change to Light Gray (N7) to Pale Red Purple (5RP 6/2) conglomerate (Facies A) (Van Vickers, 2002).

The Prospect Mountain Quartzite is approximately 950 m thick in the Snake Range (Van Vickers, 2002). The basal 200 m of the Formation consists primary of pebble conglomerate (Facies A) interbedded with medium- to coarse-grained sandstone. Pale Yellowish Orange (10YR 8/6), fine to coarse sandstone (Facies B, C, and D) with infrequent conglomerate lenses (Facies A) occur from 200-650 m above the base of the Prospect Mountain Quartzite. Abundant (ii5) *Skolithos* and *Arenicolites* burrows are present in exposures of Facies C and Facies E approximately 350 m above the base of the unit.

A transition to interbedded sandstone and shale (Facies F) is marked by abundant Cambrian ichnofossils including *Teichichnus*, *Planolites*, and *Cruziana*. This transitional interval represents a transitional zone to the Pioche Formation. The Pioche Shale, as defined by its type section in eastern Nevada, caps the succession as the first trilobite-bearing formation (Ollenelus biozone).

### *6) Cricket Mountains (Black Rock Pass, Utah) – Southern Craton Margin*

Geologic mapping of Precambrian-Cambrian strata in the Cricket Mountains applies a hybrid of lithostratigraphic nomenclature developed for northern and western portions of the Great Basin (Hintze and Davis, 2003). The Inkom Formation and overlying Mutual Formation define the basal two units of the section, as defined by Crittenden et al. (1971) for southeastern Idaho and northern Utah. Overlying the Mutual

Formation, quartzitic strata are assigned to the Prospect Mountain Quartzite and Pioche Formation, as defined in eastern Nevada.

The Inkom Formation is not exposed in the Cricket Mountains so is described based on exposures in the San Francisco Mountains to the south. The unit consists of Dusky Yellow (5Y 6/4) and Moderate Brown (5YR 3/4) siltstones and shales (Facies G), commonly metamorphosed to phyllite and in some instances, slate. The unit is estimated to be approximately 150 m thick.

The Mutual Formation overlies the Inkom Formation along a sharp and erosive contact. The Mutual Formation is primarily composed of Grayish Brown (5YR 3/2) conglomerate (Facies A) with intervening thick-bedded sandstones (Facies B). Planar laminations and lenticular crossbeds are abundant in sandstone intervals. The contact with the overlying Prospect Mountain Quartzite is gradational and conformable.

The Prospect Mountain Quartzite exposed in the Cricket Mountains is approximately 1.6km thick and houses a variety of lithofacies. The lower 325 m of the unit consist of alternating conglomeratic (Facies A) and medium- to coarse-grained sandstone intervals (Facies B). A 12 m thick, Dusky Brown (5YR 2/2) to Very Dusky Red (10R 2/2) vesicular volcanic flow (Facies H) crops out approximately 300 m above the base of the formation. Facies B dominates the succession from approximately 325-804 m. Rip-up clasts (Facies E) become increasingly abundant upsection. Facies C and D become the predominant lithofacies from 804-1100 m above the base of the unit. Abundant *Arenicolites* and *Skolithos* trace fossils first appear (ii3-ii5) almost coincident with this shift in lithofacies. The succession is capped by alternating sandstone and siltstone beds (Facies F) containing abundant trace fossils including *Helminthoidichnites, Diplichnites*, and *Teichichnus.*

The contact between the Prospect Mountain Quartzite and Pioche Shale is gradational and conformable. *Bonnia-Olenellus* trilobites indicate a Series 2 Cambrian age for these strata.

### *7) Southern Wah Wah Mountains (Pine Valley, Utah) – Southern Craton Margin*

As in the Cricket Mountains, lithostratigraphic nomenclature in the Wah Wah Mountains applies a hybrid of terminology developed for other portions of the Great Basin. Here, the basal unit is identified as an undivided succession of the Mutual and Inkom Formations. Overlying these units in unconformable contact is the Prospect Mountain Quartzite. This is overlain by the Pioche Shale.

The Inkom and Mutual Formations are mapped as undifferentiated units in the Wah Wah Mountains (Steven et al., 1990). Materials presumably assignable to the Inkom Formation consist of Dusky Red (5R 3/4) siltstones and shales (Facies G) altered to phyllite. Conglomerates consistent with descriptions of the Mutual Formation overlie the Inkom Formation along a sharp and erosive contact. Mutual Formation sediments are primarily composed of Grayish Brown (5YR 3/2) conglomerate (Facies A) with intervening thick-bedded sandstones (Facies B). Planar laminations and lenticular crossbeds are abundant in sandstone intervals. Total thickness of the undifferentiated

Mutual and Inkom Formations is approximately 435m (Steven et al., 1990). The contact with the overlying Prospect Mountain Quartzite is gradational and conformable.

The Prospect Mountain Quartzite is approximately 1.1km thick in the Wah Wah Range. Alternating conglomeratic (Facies A) and medium- to coarse-grained sandstone intervals (Facies B) dominate the lower 200 m of the unit. A 50 m thick, Pale Yellowish Brown (15R 6/2) vesicular volcanic flow (Facies H) crops out approximately 220 m above the base of the formation. Facies B dominates the succession from approximately 200-600 m above the base of the Prospect Mountain Quartzite. Rip-up clasts (Facies E) are present throughout the formation but become most abundant near the top of the Facies B dominated interval. Facies C and D become the predominant lithofacies from 600-1000 m above the base of the unit and contain abundant *Arenicolites* and *Skolithos* trace fossils (ii3-ii5). The succession is capped by alternating sandstone and siltstone beds (Facies F) containing abundant trace fossils. An extensive cataloguing of trace fossils in the Wah Wah Range by Magwood (1996) recorded a diverse trace fossil assemblage including *Plagiogmus, Rusophycos, Cruziana, Taphrehelminthichnites, Diplocraterion,* and *Helminthoidichnites*.

The Prospect Mountain Quartzite and Pioche Shale are in gradational and conformable contact in the Wah Wah Range. *Bonnia-Olenellus* trilobites recovered from the Pioche Formation indicate a Series 2 Cambrian age for these strata.

## A Unified Framework

The data outlined above is here synthesized to generate a unified framework describing the facies architecture, sequence stratigraphic model, and age for craton margin stratigraphy (Figures 1.14 and 1.15).

### Facies Architecture

The localities targeted during this investigation are distributed over much of the Great Basin; yet, these exposures yield a detailed facies architecture that is remarkably consistent normal to depositional strike. This is a unique and significant feature of the craton margin as no other portions of the Precambrian-Cambrian stratigraphic record in the western United States demonstrates this degree of lithostratigraphic invariability over this wide of a geographic area. The facies architecture described herein recognizes this consistency and uses primary sedimentological data to alleviate correlation biases that arise when considering locally developed lithostratigraphic nomenclature. The generalized stratigraphic column resulting from this exercise is thus well resolved and also widely applicable.

Precambrian-Cambrian strata deposited along the craton margin are categorized into one of four distinct facies associations: 1) a lower conglomeratic unit deposited atop a regional unconformity, 2) a lower sandstone unit characterized by thick beds and intermittent lenticular gravels, 3) an upper sandstone characterized by thinner beds, rip-up clasts and abundant trace fossils, and 4) a series of interbedded siltstones, shales and sandstones housing abundant Lower Cambrian ichnofossils capped by shale or limestone bearing Lower to Middle Cambrian trilobites. Each of these groups, the lithostratigraphic units to which they've been assigned, and the nature of their variability among the localities visited during this investigation is explored in greater detail below.

### ***Facies Association 1: Lower Conglomerate***

The basal portion of the succession is composed of conglomerate (Facies A) with lesser quantities of medium- to thick-bedded sandstone (Facies B) (Figure 1.14). These materials have been variably assigned to the Mutual Formation, Prospect Mountain Quartzite and upper McCoy Creek Group (Figure 1.15). The thickness of the basal conglomeratic interval ranges from approximately 200-1000 m, progressively thinning to the south. Interbedded rhyolitic tuffs are noted in exposures of Facies Association 1 in southeastern Idaho (Crittenden et al., 1971).

The base of the lower conglomeratic interval is characterized by a large-scale regional unconformity. Most commonly, Precambrian units underlying this unconformity consist of siltstones and shales assigned to either the Inkom Formation or the upper McCoy Creek Group. In southeast Idaho, this unconformity juxtaposes the Mineral Fork Tillite, a Precambrian diamictite of potential glacial origin (Crittenden et al., 1983; Christie-Blick et al., 1989), with overlying conglomeratic materials, indicating the absence of approximately 1 km of underlying section.

### *Facies Association 2: Lower Cross Bedded Sandstone*

An approximately 500-1500 m thick interval of light-colored, medium- to thick bedded sandstone (Facies B) overlies the basal conglomerate at each locality (Figure 1.14). Lesser quantities of conglomerate (Facies A), thin-bedded sandstone (Facies C), and rip-up clasts (Facies E) are also present. Rip-up clasts are most prevalent in southern exposures. Several localities also include an interbedded volcanic flow (Facies H), 10-50 m thick in the lower portion of this interval. Radiometric age dating of these materials indicates that these materials are Neoproterozoic in age (Crittenden and Wallace, 1983; Verdel 2008). Facies Association 2 is variably assigned to the Camelback Mountain Quartzite (southeastern Idaho), Geertsen Canyon Quartzite (northern Utah), Browns Hole Formation (northern Utah), Prospect Mountain Quartzite (western Utah and Nevada), Tintic Quartzite (central Utah), and Brigham Quartzite (central Utah) (Figure 15).

Though the contact with the underlying conglomeratic interval had previously been noted as a persistent regional unconformity (Sloss 1963), the lower cross bedded sandstone interval was observed to be in gradational and conformable contact at several localities. Gradational contacts span approximately 100-200 m of stratigraphic section.

### *Facies Association 3: Upper Sandstone*

The base of Facies Association 3 is marked by a sharp and abrupt fining and thinning of beds (Facies C) (Figure 1.14). This interval is absent in sections in northern

Utah and southeastern Idaho but thickens rapidly to the south where this interval ranges from 3 m thick in the Sheeprock Mountains to approximately 450 m thick in the Wah Wah Mountains. At these locations, Facies Association 3 is typically assigned to upper portions of either the Prospect Mountain Quartzite or Tintic Quartzite (Figure 15). Symmetrical ripples observed in this portion of the stratigraphy indicate oscillatory flow. Infrequent mudcracks provide evidence of limited subaerial exposure. At each location, the appearance of Facies Association 3 immediately coincides with the first occurrence of either *Skolithos* or *Arenicolites* trace fossils, suggesting that these strata are at least Lower Cambrian in age.

### *Facies Association 4: Interbedded sandstone/siltstone*

A slope break above exposures of the upper sandstone interval marks a gradational transition to a series of interbedded sandstone/siltstone beds (Facies F) (Figure 1.14). This interval ranges from 100-300 m in thickness, thinning considerably to the south. Facies Association 4 strata have been mapped as the Prospect Mountain Quartzite, Gibson Jack Formation, Pioche Formation, Geertsen Canyon Quartzite, and Tintic Quartzite (Figure 1.15). Body fossils have not been recovered from this interval, however, abundant Cambrian trace fossils including *Cruziana*, *Planolites*, and *Teichichnus* indicate that they are at least early Cambrian in age. These materials are variably overlain by shales assigned to the *Olenellus* trilobite biozone (Series 2 Cambrian) or limestones assigned to the *Albertella* or *Glossopleura* biozones. The correlation of these biozones with distinct lithofacies suggests a strong facies bias linked to the FAD of diagnostic trilobite fossils.

## Depositional and Sequence Stratigraphic Model

The depositional and sequence stratigraphic models developed based on the facies architecture described above suggests that the Precambrian-Cambrian record preserved along the craton margin records two distinct depositional episodes: 1) progradation of terrestrial facies forced by local tectonism, and 2) shoreline advance during the onset of the Sauk marine transgression. The sequence of sedimentary materials and geochronological data from *in situ* volcanics and detrital zircons are paired to generate a refined depositional model for the succession with robust age constraints for the timing of sea level advance.

Thick accumulations of Facies Associations 1 and 2 observed across the craton margin are diagnostic of fluvial and dune-field deposition, respectively. These facies associations are thus collectively interpreted as marking the advance of a prograding Neoproterozoic delta front and braidplain. Detrital zircon spectra compiled for these strata suggest that they were predominately sourced by materials eroding from the Wyoming and Yavapai Provinces, immediately northeast and east of the craton margin, respectively (Yonkee et al. 2014).

Facies Association 1 was deposited above a regional unconformity produced during a change in relative base level likely caused, at least in part, by regional tectonics. Rift-related tectonism during the deposition of these materials is strongly supported by the proliferation of interbedded, mafic volcanic flows in the central Great Basin (Crittenden et al., 1971; Stewart and Poole, 1974; this investigation) and the angular nature of this unconformity recorded in exposures in southeastern Idaho (Crittenden et al., 1971) and northern Utah (Christie-Blick et al., 1989). Further, radiometric age dates collected from interbedded volcanics directly overlap with previous estimates for the final stages of rifting in western Laurentia (Christie-Blick et al., 1989; Prave 1999; Yonkee et al. 2014). Collectively, Facies Associations 1 and 2 do not thin or thicken normal to depositional strike suggesting a fairly uniform sediment flux and subsidence pattern along the paleoshoreline. Evidence for continued tectonism was not observed above Facies Association 2.

Abundant marine ichnofossils coupled with abundant trough and lenticular cross bedded sandstones and interbedded shales and siltstones strongly suggest that Facies Associations 3 and 4 were deposited in a nearshore marine environment during the initial phases of a significant marine transgression. Detrital zircon spectra compiled for upper portions of the succession in northern Utah and southeast Idaho suggest similar sources as observed in lower portions of the Member (Yonkee et al. 2014). However, these younger materials also unanimously contain older spectra peaks indicating an increased flux of older detritus from the Wyoming Province (Yonkee et al. 2014), potentially as a result of unroofing of the igneous complex.

The interface between terrestrial (Facies Associations 2) and marine deposits (Facies Association 3 and 4) represents a fundamental shift from tectonically-mitigated deposition to passive margin sedimentation attributable to an increase in eustatic sea level. The regional persistence of this facies shift is thus indicative of a major marine transgression spanning the craton margin, herein interpreted to represent the onset of the Sauk Marine Transgression. The progressive northward thickening of Facies Associations 1 and 2 and thinning and eventual absence of Facies Association 3 in northern exposures is thus likely the result of non-uniform sediment reworking during this advance, as would be predicted for materials deposited along the craton margin as the paleoshoreline would have migrated towards the primary sediment sources to the north and east. While sediments assigned to Facies Association 3 and 4 may represent the earliest deposition of sediments exclusively attributable to retrogradation of the paleoshoreline, the absence of significant erosional features along the top of Facies Association B suggests that subaerial exposure of this surface may have been relatively short-lived. This is consistent with a model suggesting that the drivers for the eventual rise in eustatic sea level likely began prior to the establishment of the passive margin, yet sedimentological effects resulting from changes in eustatic sea level were initially outpaced by basin subsidence. Establishment of the passive margin quickly reversed this trend resulting in the transgressive sequence that characterizes much of the terminal Proterozoic and Lower Cambrian records in the western United States. Thermal subsidence models coupled with detrital zircon data suggest that the transition from rift-related deposition to passive margin sedimentation may have occurred approximately 540

Ma (Yonkee et al. 2014), consistent with this model and the geochronological framework established by radiometric ages collected from underlying volcanic flows.

Placement of the Precambrian-Cambrian boundary along the craton margin is complicated by the near-absence of fine-grained marine facies. This absence precludes the direct preservation of the boundary-defining ichnotaxon, *Treptichnus pedum*. As a matter of convenience, the boundary has commonly been placed at the base of Facies Association 1 or 2 (Stewart, 1970, 1972; Hintze, 1993) or somewhere within Facies Association 3 (Crittenden et al., 1971; Christie-Blick, 1982; Yonkee et al., 2014). However, radiometric age dates obtained from interbedded volcanic flows indicate that the base of the succession is Neoproterozoic in age. Abundant *Skolithos* and *Arenicolites* trace fossils observed in Facies Association 3 indicate that upper portions of the succession were deposited by at least the early Cambrian. Immediately overlying and in conformable contact with trace fossil-bearing material, trilobite body fossils similarly support a Lower-Middle Cambrian age for the top of this succession. Thus, while it can be reasonably inferred that the Precambrian-Cambrian boundary may be held in Facies Association 2, direct evidence in support of this hypothesis is currently lacking. Sedimentation rates cannot be utilized as a proxy for time as depositional rates were likely to have been highly variable, as evidenced by the hiatuses and diversity of facies housed within this succession. It is also possible that the onset of the Phanerozoic Eon began during a period of non-deposition along the craton margin and thus, the boundary may not be preserved, as is commonly observed in cratonal sections. This possibility is loosely supported by an estimated age of approximately 540 Ma for the interface between Facies Associations 2 and 3 (Yonkee et al., 2014).

Neoproterozoic and Lower Cambrian craton margin strata have long-been considered to be time transgressive as the conformable upper contact of Facies Association 4 with overlying shales and limestones coincides with either the *Bonnia-Ollenelus* or *Albertella* trilobite zones (Palmer, 1971; Figure 1.14). Because this contact spans two trilobite zones, it has considered diachronous with the youngest exposures occurring in northern Utah and southeast Idaho and the oldest exposures present in eastern Nevada. However, a regular pattern for time transgression is not apparent when considering that the appearance of trilobites coincides with marked shifts in depositional facies, specifically the transition from siliciclastic-dominated facies in the southwest to carbonate-dominated facies in the northeast. Preservational bias is thus highly likely and thus, time transgression is not biostratigraphically evidenced at the contact between Precambrian-Cambrian sandstones and overlying Cambrian units.

## Regional Correlation

A regional correlation scheme is developed by integrating the depositional, sequence stratigraphic, biostratigraphic, and geochronologic information outlined for the craton margin with comparable datasets collected from Cordilleran Miogeocline and Cratonal deposits to the west and east, respectively. This integration and the resulting depositional model are schematically represented in Figure 1.16.

The sequence stratigraphic model developed herein highlights two significant regional surfaces, and thus two principal datums, within the craton margin succession. The first of these occurs at the base of conglomerate-dominated intervals (Facies Association 1) and is interpreted herein to mark the seaward progression of a braidplain delta system during the final stages of rifting in western Laurentia (Figure 1.16C). The second and younger surface is highlighted by a sharp transition from terrestrial to nearshore marine facies interpreted to represent the onset of the Sauk marine transgression (Figure 1.16D) and thus, the definitive base of the Sauk Megasequence along the craton margin.

Exposure surfaces comparable to those observed along the craton margin have been noted in both cratonal and miogeoclinal sections. Lower Cambrian cratonal sedimentary successions lie atop the Great Unconformity, a pronounced Type 1 sequence boundary separating these materials from underlying and variably tilted Precambrian sedimentary and igneous units. Miogeoclinal sections are more heavily nuanced as several Type 1 and Type 2 sequence boundaries have been mapped throughout much of the succession. As basin effects may result in heightened deposition or erosion locally, the severity of these contacts (e.g. amount of downcutting, presence of erosional features, prominence of facies change, etc.) cannot be used as a metric to relate individual sedimentary sequences. Rather, application of multiple proxies, including regional mapping, is required to constrain these contacts in both space and time.

In general, cratonic sections bear a similar lithostratigraphic framework as observed along the craton margin, albeit, these materials are not directly analogous as they are severely compressed and also variable in their facies contribution. These differences are likely the result of three factors: 1) limited accomodation space in proximal settings, 2) multiple hiatuses during deposition of platformal sections along the Cambrian shoreline, and 3) local variation in the paleotopography which would have had a more pronounced impact on sedimentology and stratigraphic thickness along the platform. Detailed evaluation of facies assemblages (so-called "Facies Suites") within southern cratonal exposures by Hagadorn et al. (2011) (based on work initially performed by Hardy, 1986) listed three general stratigraphic packages that roughly parallel the Facies Associations observed within craton margin exposures: 1) Facies Suite A - a basal conglomeratic unit with minor quantities of sandstone and shale and devoid of trace fossils, likely deposited in a terrestrial environment, 2) Facies Suite B - a cross bedded sandstone bearing abundant *Skolithos* and *Arenicolites* trace fossils, interpreted to have been deposited in an intertidal to shallow subtidal setting, and 3) Facies Suite C – interbedded sandstone and siltstone bearing typical early Cambrian ichnofossils. Facies Suite A is only mapped in western cratonal exposures and thins substantially to the east. The lithological character, stratigraphic position, and absence of trace fossils suggest that this interval is correlative with Facies Association 1. This interpretation is also consistent with the eastward removal of this lithofacies from cratonal sections as these areas would have been exposed to additional erosion pending the Sauk Marine Transgression. Similarly, the facies, paleobiological record and stratigraphy expressed in Facies Suites B and C are analogous to those in Facies Associations 3 and 4for the craton margin, respectively, and thus are likely correlative (Figure 1.16A).

Direct correlation between nearshore and basinal sections is complicated by the comparably disparate facies assemblage exposed in the Cordilleran Miogeocline. Regional correlation from the platform to the Cordilleran Miogeocline thus relies heavily on stratigraphic constraints yielded by the depositional and sequence stratigraphic models, source correlation, and age evaluated in both basinal and craton margin sediments.

Based on the mineralogical and geochemical records, deposition in the Cordilleran Miogeocline exclusively sourced from the Laurentian craton is interpreted to have begun with deposition of the Neoproterozoic Johnnie Formation (Fedo and Cooper, 2001; Schoenborn, 2010; Schoenborn and Fedo 2011; Schoenborn et al., 2012). Stratigraphic relationships and lithologic similarities have led to the current interpretation that the Johnnie Formation is correlative with the Inkom Formation in Utah and the upper McCoy Creek Group in eastern Nevada (Stewart, 1970; Crittenden et al., 1971; Christie-Blick et al., 1989). This assignment is consistent with the pronounced unconformity separating the Johnnie Formation from the overlying Stirling Quartzite being correlative with the lower unconformity observed along the craton margin at the interface between the Inkom Formation (and equivalents) and Facies Association 1. Correlation of this datum at this stratigraphic position in the Cordilleran Miogeocline is also supported by the recent reevaluation of the base of the Sauk Megasequence as likely occurring at the Johnnie Formation-Stirling Quartzite interface (Hogan et al., 2011). This contact has previously been discussed as marking the transition from deposition in a rift-related basin to sedimentation along a passive margin (Fedo and Cooper, 2001; Schoenborn, 2010;

Schoenborn and Fedo, 2011; Schoenborn et al., 2012). This interpretation is complicated by evidence of tectonic activity in overlying portions of the stratigraphy (Diehl, 1979) coupled with the correlation, dating, and identification of this contact herein as a tectonic feature along the craton margin. Diehl (1979) noted a sharp transition in paleocurrent direction within the Middle Member of the Wood Canyon Formation and in conjunction with detailed facies evaluation, interpreted that fluvial detritus within the Middle Member was likely deposited in a rift-related basin. Facies comparable to those observed in the Middle Member are also common in the Lower and Upper Members of the underlying Stirling Quartzite (Stewart, 1970) and in lower portions of the overlying Zabriskie Quartzite (Prave, 1992), suggesting that pulsed-rifting may have occurred during deposition of significant portions of this succession. Thus, rift activity likely continued through much of the Precambrian-Cambrian succession in the Cordilleran Miogeocline, consistent with observations made herein along the craton margin.

Terrestrial deposits in the lower portion of the Zabriskie Quartzite are capped by a marine succession of alternating siltstone and sandstone in the upper portion of the formation (Prave, 1984, 1992). The interface between this transition zone and underlying conglomeratic facies has previously been identified as a regionally persistent transgressive surface (Prave, 1992). This contact marks the termination of fluvial input in early Cambrian strata deposited in the Cordilleran Miogeocline. This fundamental boundary is thus consistent with the facies shift and depositional history of the upper transgressive surface identified at the top of Facies Association 2 along the craton margin. This suggests that the base of the transgressive lag separating the lower and upper portions of the Zabriskie Quartzite incontrovertibly marks the termination of pulsed delivery of terrestrial detritus to the area and thus, the onset of passive margin sedimentation along the Cordilleran Miogeocline.

The presence of several hiatuses and persistent marine facies in northern miogeoclinal sections complicate direct correlations with exposures along the craton margin. Correlation between these areas is thus largely secondary to correlations between northern and southern miogeoclinal sections (Stewart and Poole, 1974; Farmer and Ball, 1997).

The pattern of two prominent disconformable horizons is similarly preserved in northern Cordilleran Miogeocline Precambrian-Cambrian sections. The first of these occurs at the base of the Reed Dolomite, separating this unit from the underlying Wyman Formation (Stewart, 1970; Christie-Blick et al., 1989). The Wyman Formation has been wholly correlated with the Johnnie Formation based on sedimentology and stratigraphic position (Stewart, 1970). This suggests that the erosional contact separating the Johnnie Formation from the Stirling Quartzite is correlative with the Reed Dolomite – Wyman Formation contact. The second significant unconformity in the northern Cordilleran Miogeocline occurs at the contact between the Deep Spring Formation and the overlying Campito Formation. This contact has previously been correlated with the base of the Middle Member of the Wood Canyon Formation in the southern Cordilleran Miogeocline. However, identification of the basal Middle Member contact as conformable in some areas (Hogan et al., 2011) may preclude this broad of a regional correlation. As the base of the Campito Formation marks the onset of persistent marine transgression in the northern Cordilleran Miogeocline (i.e. the beginning of “Grand Cycle A” (Greene et al., 1987; Mount and Signor 1991)), it is more likely that this transgressive surface is correlative with the base of the transgressive sequence in the upper portion of the Zabriskie Quartzite.

## Regional Depositional Model

Regional correlation of cratonal, craton margin, and Cordilleran Miogeocline sequences yields a detailed depositional framework for Precambrian-Cambrian strata in the western United States (Figure 1.16). Based on age evaluations of the Johnnie Formation (Summa, 1993) and detrital zircon data (Schoenborn 2010; Schoenborn and Fedo 2011; Schoenborn et al., 2012), rifting of the Laurentian craton from the remainder of Rodinia was substantial enough such that Laurentian detritus was the soul flux of sediment to the newly formed basin during the Ediacaran Period. Pulsed rifting likely continued and migrated westward through deposition of the Stirling Quartzite and overlying Lower and Middle Members of the Wood Canyon Formation in the southern Cordilleran Miogeocline, the Wyman Formation, Reed Dolomite and Deep Spring Formation in the northern Cordilleran Miogeocline, Facies Associations 1 and 2 along the craton margin, and Facies Suite A along the craton. This tectonic activity resulted in multiple hiatuses among distal sections and the emplacement of fluvial materials throughout much of the Precambrian and early Cambrian successions. The subsequent establishment of passive margin sedimentation near the top of the Zabriskie Quartzite in the southern Cordilleran Miogeocline, the Deep Spring Formation in the northern

Cordilleran Miogeocline, Facies Association 2 along the Craton Margin, and Facies Suite A along the craton begins a long-lived interval of marine sedimentation, highlighted by the prolific quartzite-shale-carbonate pattern characteristic of Cambrian exposures in the western United States.

The relative completeness of sections exposed in the Cordilleran Miogeocline (i.e. the preservation of the Precambrian-Cambrian boundary) as compared to those exposed along the craton margin and craton suggests that the transition from rift-related deposition to passive margin sedimentation and eustatic sea level rise may have been more rapid in this area. This is consistent with what would have been a westward progradation of fluvial facies during basin subsidence followed by an eastward advance of the paleoshoreline during a rise in eustatic sea level. The model of an eastward regressing paleoshoreline also suggests that the transgressive surface highlighted herein is diachronous, becoming younger to the east. However, in the absence of robust and regional age constraints near these contacts, the significance of this diachroneity is currently unknown.

## Significance

Substantial portions of the Precambrian-Cambrian stratigraphic record remain underexplored, yet, increasingly, these strata are proving to be invaluable in developing a better understanding of Earth System evolution. In the absence of the detailed cataloguing required for the utility of terminal Neoproterozoic and Lower Cambrian strata exposed in the western United States to be fully explored, inadequately supported and/or conflicting interpretations regarding key features within this record have been common. The temporal significance of Precambrian-Cambrian strata requires that each exposure be adequately considered and described and subsequently placed into its appropriate spatiotemporal context. Doing so provides an opportunity to supplement the current dataset while testing the utility of units that have long-remained unincorporated in reconstructions of the Precambrian-Cambrian transition.

The synthesis of data outlined herein suggests that rift-related tectonism continued in western Laurentia well into the Cambrian Period, contrary to some interpretations that a passive margin was well-established in the area during the Neoproterozoic (Fedo and Cooper, 2001; Schoenborn, 2010; Schoenborn et al. 2012). This is strongly supported by sedimentologic, sequence stratigraphic, biostratigraphic, and geochronologic data in conjunction with structural models (Yonkee et al. 2014). While persistence of this rifting into the Phanerozoic is only evidenced in distal sections, this is likely a preservational bias related to erosion along the contact between terrestrial and marine facies in eastern exposures which may have removed much of the succession, including Precambrian-Cambrian boundary containing strata.

Ongoing tectonism through the Precambrian-Cambrian transition in western Laurentia complicates sequence stratigraphic models developed for the region as contacts resulting from regional tectonics versus those resulting from changes in eustatic sea level are commonly difficult to resolve. This difficulty is elevated in western Laurentia given the paucity of numerical age constraints paired with the commingling of both tectonic activity and forces that could account for considerable changes in eustatic sea level (i.e. deglaciation during the terminal Neoproterozoic). This highlights the importance of analyzing the stratigraphy at a high resolution to identify regionally persistent unconformities that are commonly quite subtle (Christie-Blick et al., 1988).

Regional correlations and stratigraphic descriptions presented herein for what has previously been identified as the base of the Sauk Megasequence along the craton margin and in the western portions of the Grand Canyon, suggests that at least a portion of what is commonly referred to as the "Great Unconformity" may be a feature more closely related to regional tectonics than to global sea level rise. This suggests that global correlation of this basal contact may be complicated as the sedimentologic record of the onset of the Sauk marine transgression in North America may be blurred by local, syndepositional tectonic activity in eastern exposures. The significance of temporally resolving tectonically-induced versus passive margin sedimentation is embodied by the recent hypothesis that the evolutionary advent of metazoan biomineralization may be directly related to the rise in eustatic sea level associated with the Sauk Megasequence (Peters and Gaines, 2012)

Though the depositional model presented herein predicts an eastward time transgressive element for sediments deposited during the Sauk marine transgression, direct evidence that could be used to evaluate diachroneity in this record has not yet been recovered. Pronounced facies biases associated with trilobite preservation precludes meaningful interpretation of those data. Further, while the erosional contact at the top of Facies Association 2 in the craton margin spans the Precambrian-Cambrian boundary, differential uplift related to rifting cannot currently be ruled out as the cause of this phenomenon.

## Conclusions

The availability, exposure quality, and continuity of terminal Proterozoic and Paleozoic strata in the western United States provides a key resource in evaluating evolving Earth system dynamics through this critical time in Earth's history. The efforts outlined herein provide a comprehensive account of the sedimentologic, biostratigraphic, and geochronologic datasets available within units deposited along the craton margin, an arena that has largely escaped detailed study. The following list provides a summary of the major conclusions of this investigation.

1) Deposition along the craton margin was laterally persistent parallel to depositional strike. Four major lithofacies groups, herein identified as Facies Associations 1 through 4, are exposed throughout the central Great Basin with minimal change in the general lithologic character and sequence in which these subunits occur. Recognition of this invariability and detailed logging of stratigraphic sections at key localities resolves overlap in the current lithostratigraphic nomenclature and also provides the primary basis for environmental interpretation through the succession.

2) Two regionally persistent disconformities are identified in the craton margin succession. The lower disconformity separates underlying marine successions from overlying fluvial deposits and is interpreted to represent deposition along a still-rifting western Laurentian margin. The upper surface occurs at a more discrete contact hundreds

of meters above and separates a prograding fluvial succession from an overlying transgressive marine sequence. The subsequent persistence of marine transgression above this contact is indicative of a steady and protracted rise in eustatic sea level, herein interpreted as the onset of the Sauk marine transgression.

3) The Precambrian-Cambrian boundary provides a vital stratigraphic tie point in the evaluation of strata deposited through this interval. The appearance of lower Cambrian ichnofabrics coincident with the facies transition overlying the upper transgressive surface identified herein in conjunction with radiometric age dates obtained from underlying units and structural models suggests that a substantial period of non-deposition may have occurred along this contact. This implies that the onset of the Phanerozoic may be marked by a hiatus along the craton margin. This is consistent with similar observations made within cratonal exposures to the east.

4) Evaluating the diachroneity of Neoproterozoic and Cambrian strata exposed in the western United States is precluded by pronounced facies biases surrounding the ichnologic and body fossil records. Evidence consistent with the regression of the paleoshoreline spanning several biozones is thus currently unavailable.

5) Regional correlation of the craton margin succession unifies depositional models presented for both the craton and the Cordilleran Miogeocline and in doing so, yields a revised and more highly refined correlation scheme for much of that record. Correlation of craton margin and cratonal sections suggests that the gross sequence of lithofacies observed along the craton margin are similarly expressed in cratonal exposures, with lower facies associations observed along the craton margin being

successively thinned and removed to the east.  Correlation between the craton margin and basinal sections in the southern and northern Cordilleran Miogeocline is heavily reliant on application of the two regional sequence boundaries identified along the craton margin as principal datums.  The resulting correlation scheme suggests that a substantial portion of Neoproterozoic and early Cambrian strata were deposited along a tectonically active margin.  This is in stark contrast to previous models which have hypothesized that passive margin sedimentation may have begun prior to the Ediacaran Period.

6) Exposures of the "Great Unconformity" in the Great Basin result from both tectonic and passive margin sedimentation.  In eastern exposures, this contact is unified into a single contact.  This contact bifurcates somewhere in the vicinity of the western Grand Canyon to reflect both tectonic and passive margin depositional processes.  These contacts further separate to the west.

7) The timing of rift cessation in the western United States is vital to global correlation of the Sauk Megasequence.  Though the "Great Unconformity" is commonly considered as the archetype for defining the base of a sedimentary sequence, the onset of eustatic sea level rise is obscured by local tectonics, potentially complicating direct temporal correlation of global sea level increase elsewhere.

These data and interpretations are presented as a foundational resource and thus, are intended to spawn continued efforts in this succession.  Several exposures of interbedded basalt flows, particularly in the southern central Great Basin, have yet to be dated directly.  Numerical age dates from these materials would provide additional insight as to the age of surrounding strata and timing the cessation of rifting in the area.

Additional attention should also be given to mapping the primary disconformities highlighted herein within transitional exposures between the craton margin and Cordilleran Miogeocline. This may yield additional refinement regarding the severity of erosion along this contact, and thus the amount of time missing from both craton margin and cratonal exposures. Paleomagnetic evidence stored in these strata may also prove to be a vital record in evaluating the completeness of exposures along the craton margin.

The variety of facies, fossil evidence, and the presence of directly datable materials provide the necessary evidence for incorporating the craton margin record into discussions of the transition into the Phanerozoic Eon at a variety of scales. Presentation of these data provides the basis for continued work in these strata while also highlighting a methodology for and illustrating the importance of expanding the current dataset to include other similarly underexplored, entirely siliciclastic units in reconstructions of the Precambrian-Cambrian transition. New evidence obtained in Precambrian-Cambrian craton margin units exposed in the central Great Basin will further constrain the nature of the Precambrian-Cambrian transition in western Laurentia. Building on this framework, regional correlation of craton margin units will allow that information to further contextualize neighboring stratigraphy and the record of the Precambrian-Cambrian transition as a whole.

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## Figures

Figure 1.1. Field locality map showing the provinciality of mapping efforts performed in the Great Basin. Stratigraphic and locality information from Hintze (1993), Crittenden et al. (1971), Christie-Blick et al. (1988), Verdel (2009), Whitebread (1969), Nelson (1959), Hyde and Huttrer (1970), and Kellogg (1963).

**Figure 1.1**

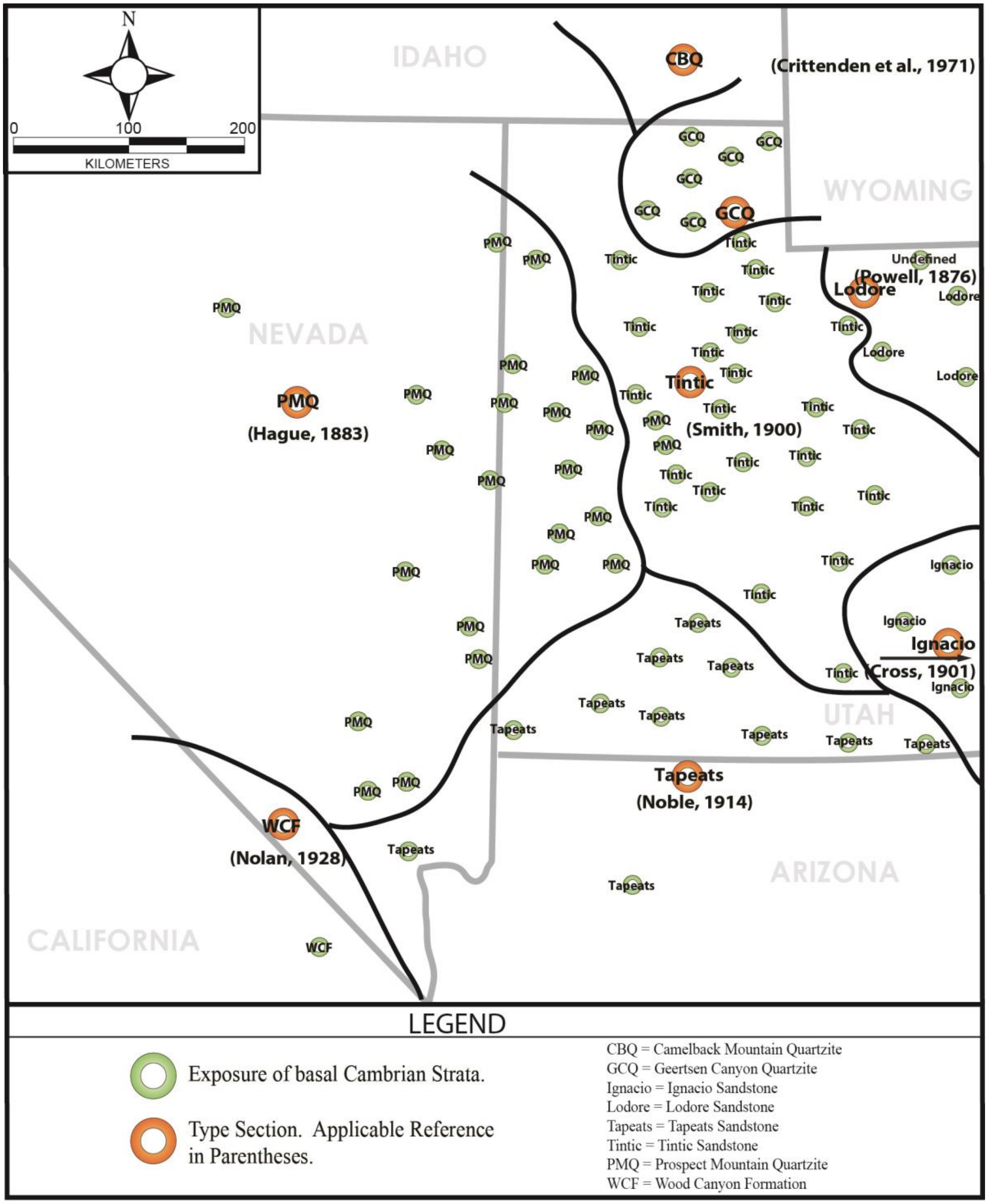
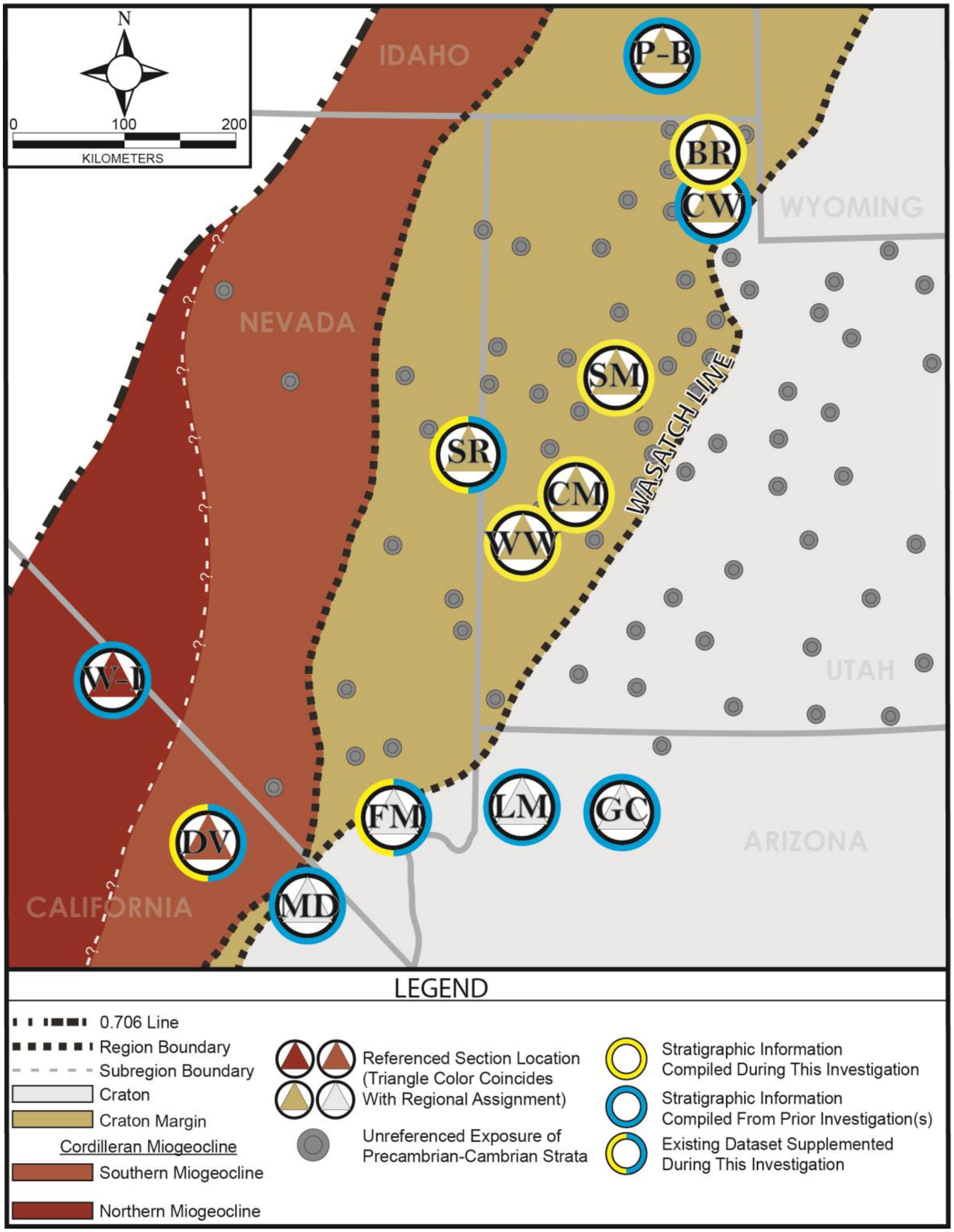

N
0
100
200
KILOMETERS
IDAHO
WYOMING
NEVADA
UTAH
ARIZONA
CALIFORNIA
CBQ
(Crittenden et al., 1971)
GCQ
Tintic
(Smith, 1900)
Undefined
(Powell, 1876)
Lodore
PMQ
(Hague, 1883)
Ignacio
(Cross, 1901)
Tapeats
(Noble, 1914)
WCF
(Nolan, 1928)
LEGEND
Exposure of basal Cambrian Strata.
Type Section. Applicable Reference in Parentheses.
CBQ = Camelback Mountain Quartzite
GCQ = Geertsen Canyon Quartzite
Ignacio = Ignacio Sandstone
Lodore = Lodore Sandstone
Tapeats = Tapeats Sandstone
Tintic = Tintic Sandstone
PMQ = Prospect Mountain Quartzite
WCF = Wood Canyon Formation

Figure 1.2. Locality Map. W-I = White-Inyo Mountains, DV = Death Valley, MD = Mojave Desert, Frenchman Mountain, LM = Lake Mead, GC = Grand Canyon, WW = WahWah Mountains, SR = Snake Range, CM = Cricket Mountains, SM = Sheeprock Mountains, FM = CW = Central Wasatch Range, BR = Bear River Range, P-B = Portneuf and Bannock Ranges

**Figure 1.2**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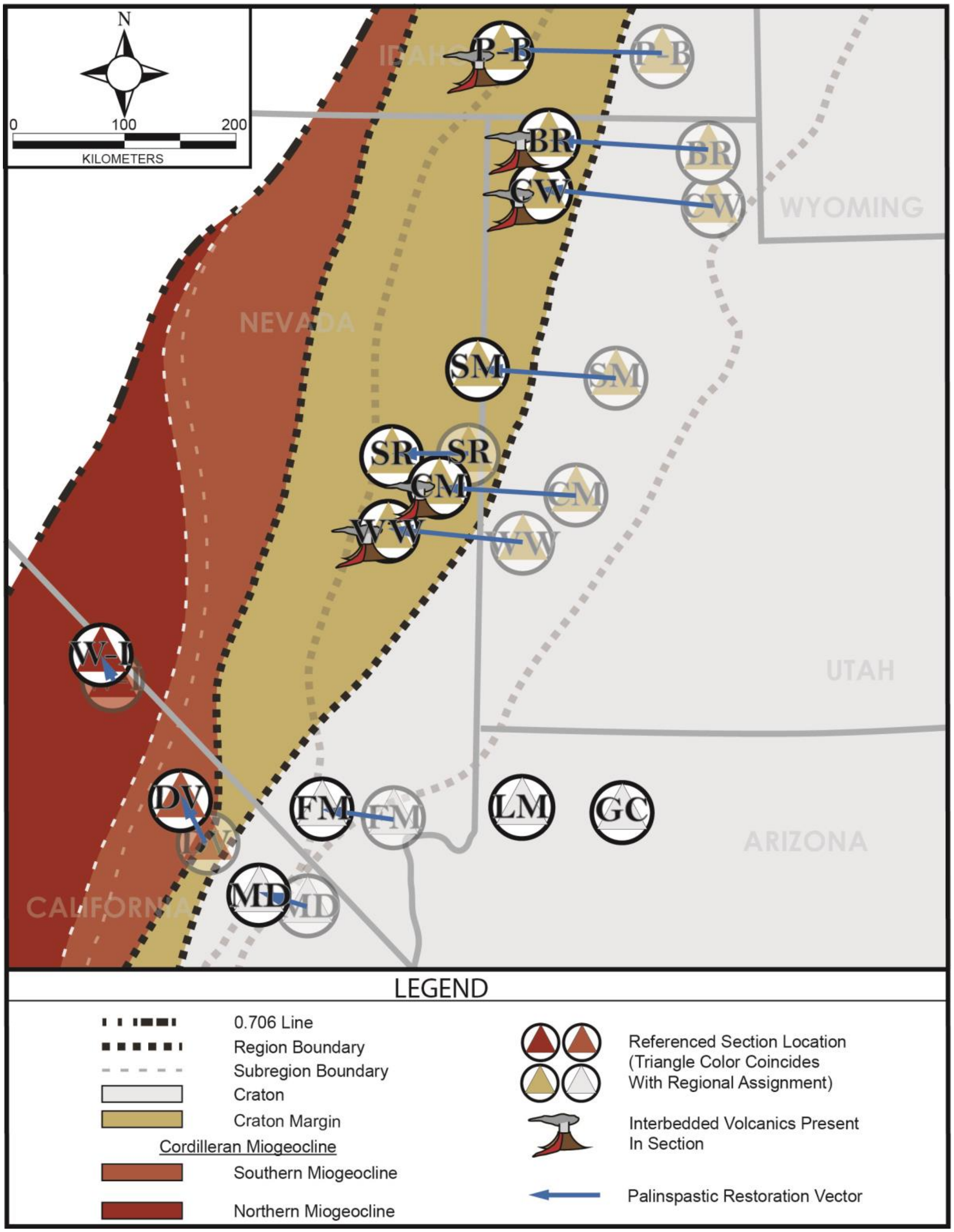
IDAHO
NEVADA
WYOMING
UTAH
ARIZONA
CALIFORNIA
WASATCH LINE
P-B
BR
CW
SM
SR
CM
WW
W-I
DV
FM
LM
GC
MD
LEGEND
0.706 Line
Region Boundary
Subregion Boundary
Craton
Craton Margin
Cordilleran Miogeocline
Southern Miogeocline
Northern Miogeocline
Referenced Section Location (Triangle Color Coincides With Regional Assignment)
Unreferenced Exposure of Precambrian-Cambrian Strata
Stratigraphic Information Compiled During This Investigation
Stratigraphic Information Compiled From Prior Investigation(s)
Existing Dataset Supplemented During This Investigation

Figure 1.3. Palinspastic reconstruction (adapted from Dickinson, 2003 and Yonkee et al., 2013) and locations of interbedded volcanics. Shaded lines show unrestored limits of regions identified herein. Note thinning of areal coverage of craton margin. Also note that additional interbedded volcanics not described in this investigation are mapped throughout central Utah. W-I = White-Inyo Mountains, DV = Death Valley, MD = Mojave Desert, FM = Frenchman Mountain, LM = Lake Mead, GC = Grand Canyon, WW = WahWah Mountains, SR = Snake Range, CM = Cricket Mountains, SM = Sheeprock Mountains, CW = Central Wasatch Range, BR = Bear River Range, P-B = Portneuf and Bannock Ranges.

**Figure 1.3**


N
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KILOMETERS
IDAHO
NEVADA
WYOMING
UTAH
ARIZONA
CALIFORNIA
P-B
BR
CW
SM
SR
CM
WW
W-I
DV
FM
LM
GC
MD
LEGEND
0.706 Line
Region Boundary
Subregion Boundary
Craton
Craton Margin
Cordilleran Miogeocline
Southern Miogeocline
Northern Miogeocline
Referenced Section Location (Triangle Color Coincides With Regional Assignment)
Interbedded Volcanics Present In Section
Palinspastic Restoration Vector

Figure 1.4. Facies A - A) Outcrop of conglomeratic facies in Huntsville, UT. Channels are highlighted by dashed black line. Scale bar is 1m. B) Inset of Figure 1A. Note that this gravel lens represents multiple depositional events, as evidenced by the reactivation surfaces highlighted here by dashed black lines. Scale bar is 25cm. C) Conglomeratic facies in the Sheeprock Mountains. Scale bar is 10cm. D) Conglomeratic facies exposed in the southern Wah Wah Range. Erosional base of overlying deposit highlighted by white dashed line. Planar top of underlying bed highlighted by dashed black line. Intervening sand is medium to coarse grained and contains abundant cross beds. Scale bar is 10 cm. E) Conglomeratic facies exposed in the Cricket Mountains . Scale bar is 10 cm.

**Figure 1.4**

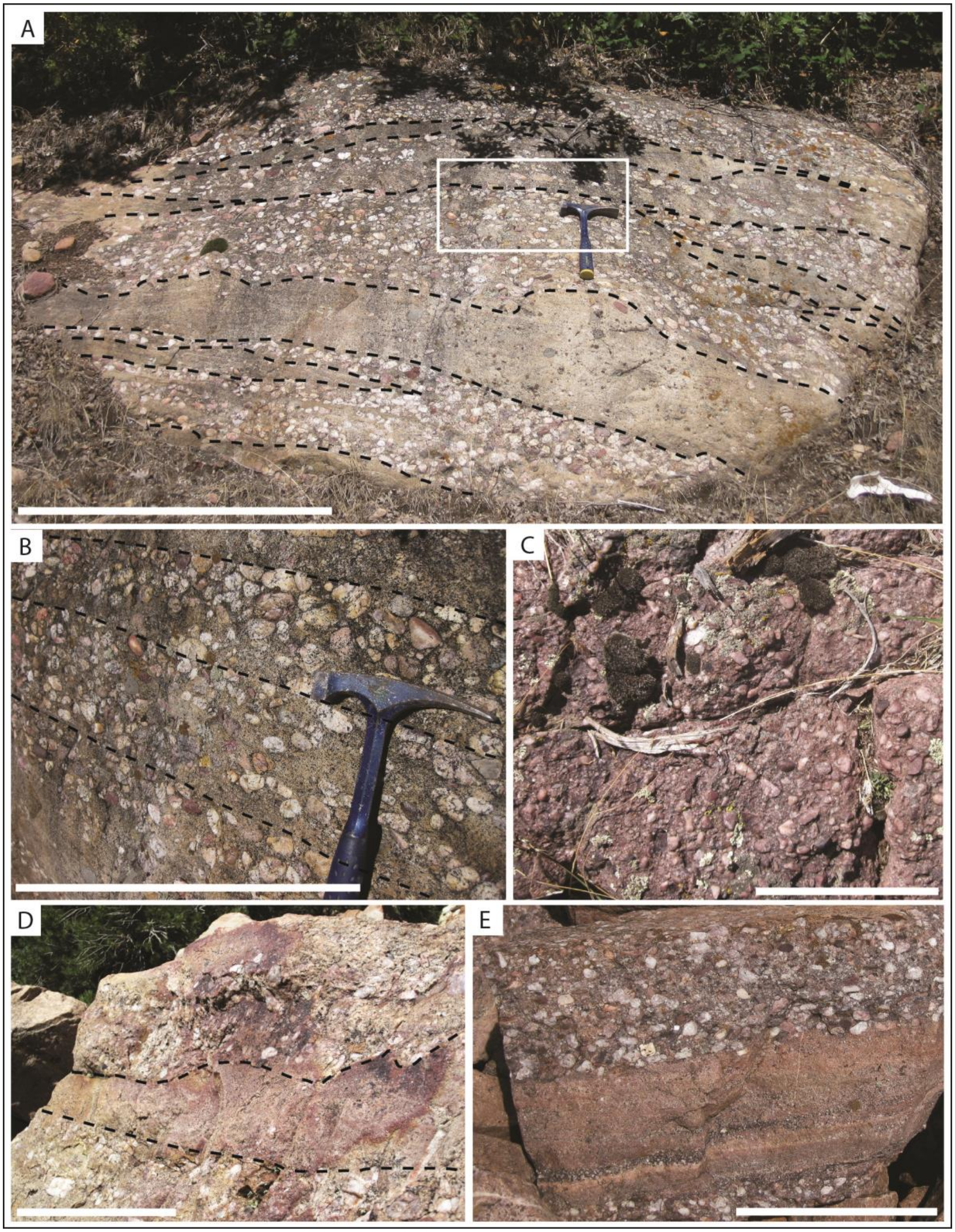


Figure 1.5. Facies B - A) Cross bedded interval (Cricket Mountains). Scale bar is 1 m. B) Amalgamated sand channels (Ogden, UT). Scale bar is 1 m. C) Amalgamated sand channels with occasional thin sandstone interbeds. Scale bar is 1 m. D) Amalgamated sandstone channels (southern Wah Wah Range). Scale bar is 10 cm. E) Massive sandstone bed (Logan, UT). Scale bar is 10 cm. E) Planar lamination (Frisco Mountains). Scale bar is 10 cm.

**Figure 1.5**

Figure 1.6. Facies C - A) Boulder in the southern Wah Wah Range with abundant tabular cross stratification. Reactivation surfaces highlighted by dashed white lines. Direction of sand migration indicated by white arrows. Scale bar is 10 cm. B) Outcrop of Facies C in the Sheeprock Mountains. Scale bar is 1 m. C) Oscillation ripples preserved along the top of a thin sandstone bed in the southern Cricket Mountains. Scale bar is 1 m. D) Mudcracks preserved along the top of a thin sandstone bed. Scale bar is 10 cm. F) Outcrop of Facies C in the southern Cricket Mountains. Scale bar is 1 m. F) Tabular cross beds in a thin sandstone bed cropping out in the northern Frisco Mountains. Scale bar is 10 cm.

**Figure 1.6**

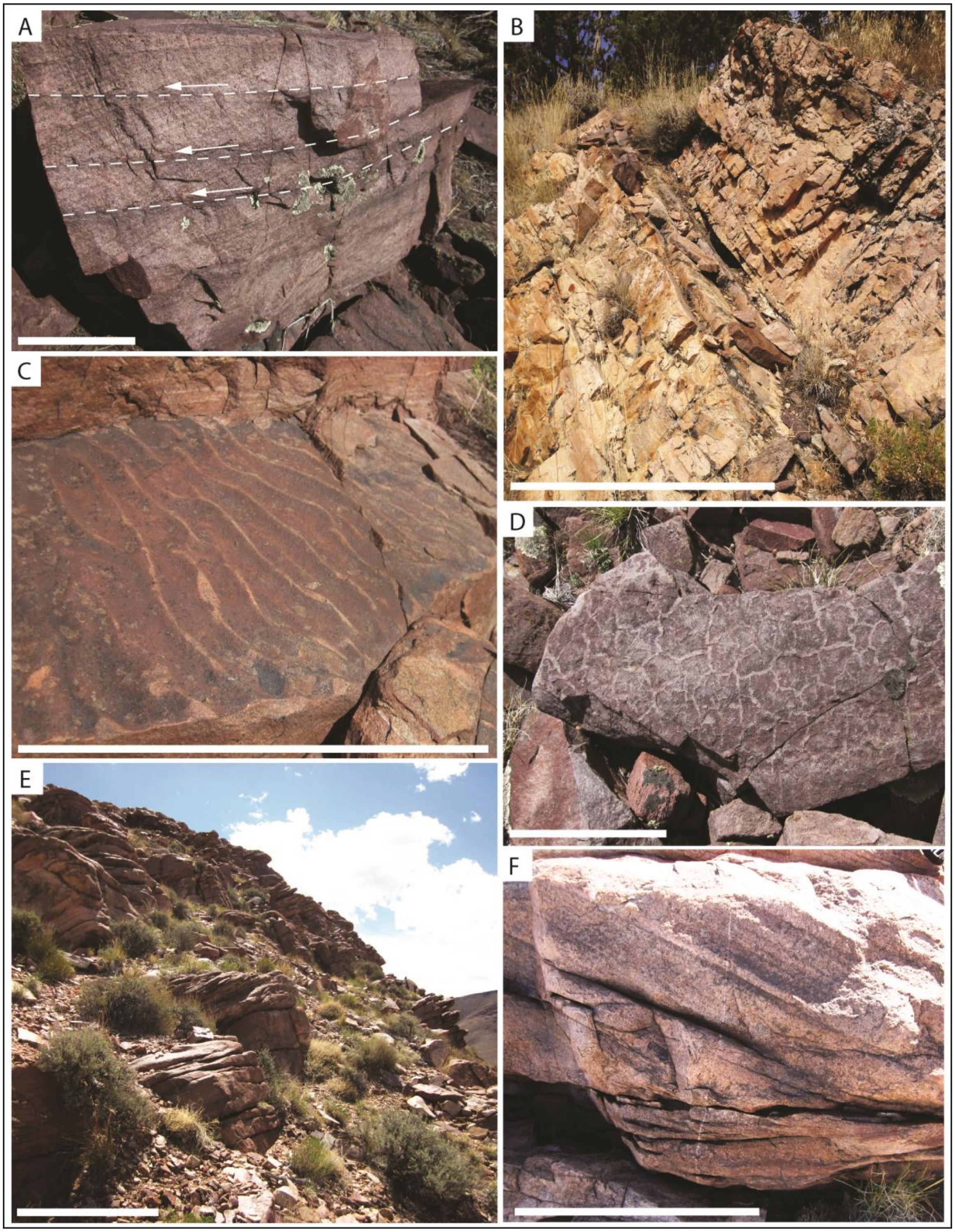


Figure 1.7. Facies D - A) Heterolithic bedding in the Sheeprock mountains with abundant tabular cross stratification. Reactivation surfaces composed of medium to coarse sand highlighted by dashed white lines. Scale bar is 10 cm. B) Outcrop of Facies E in the southern Cricket Mountains. Scale bar is 1 m. C) Whispy weathering pattern (highlighted by solid black line) common in Facies E (southern Wah Wah Range). Bedding planes within this outcrop indicated by dashed white lines. Scale bar is 10 cm. D) Whispy weathering pattern common in Facies E (Logan, UT). Scale bar is 10 cm. F) Typical weathering pattern of heterolithic bedding of Facies E (southern Cricket Mountains). Scale bar is 10 cm.

**Figure 1.7**

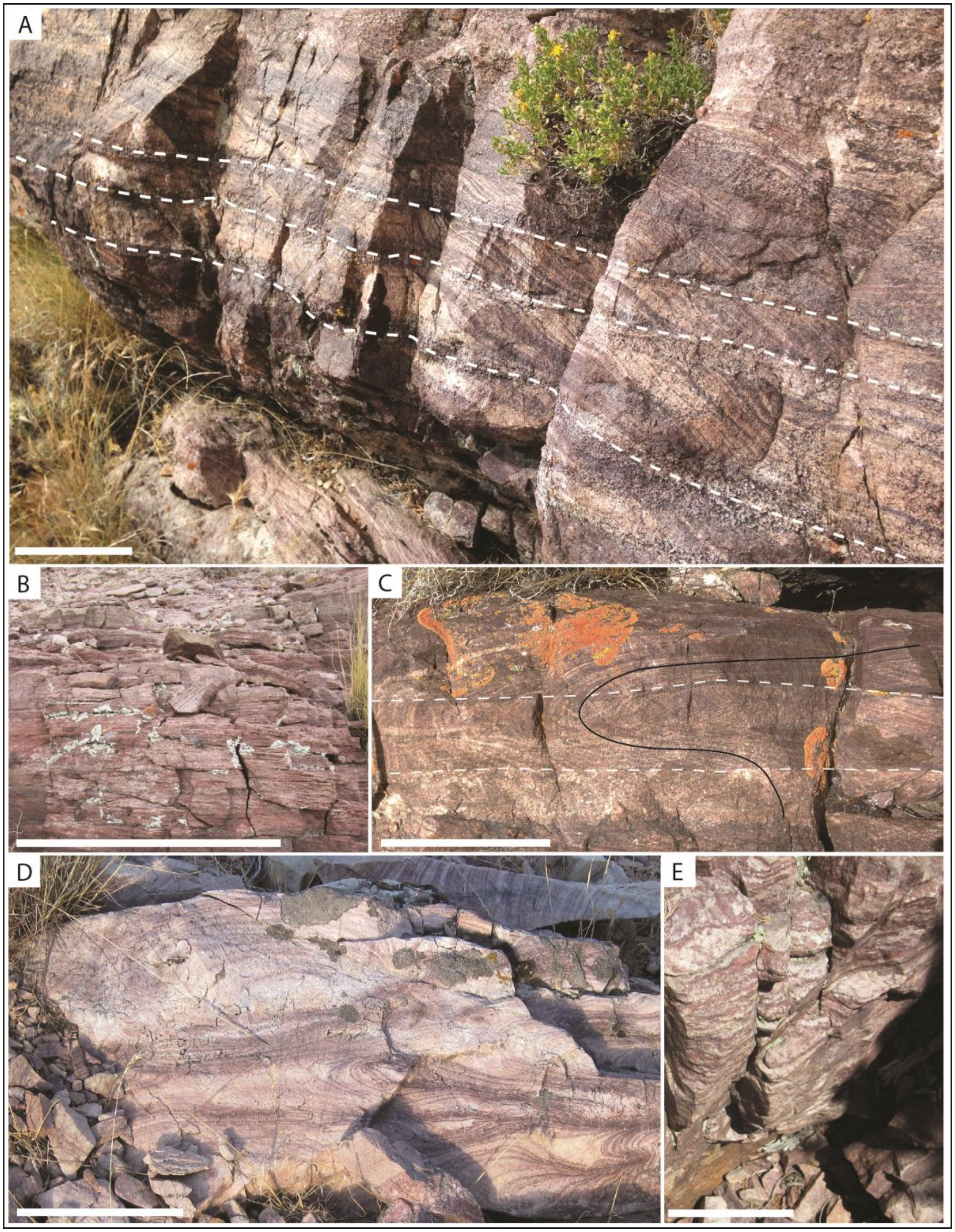


Figure 1.8. Facies E - A) Rip-up clast bearing sandstone in the Egan Range (Nevada) Scale bar is 10 cm. B) Weathered rip-up clast bearing sandstone in the southern Wah Wah Range. Note oxidation halo surrounding cavities formerly housing shale rip-up clasts. Scale bar is 1 m. C) Close up of weathered rip-up clast cavity showing thickness of surrounding oxidation halo (Wah Wah Range). Scale bar is 10 cm. D) Rip-up clast bearing sandstone with granular quartz concentrated around cavities of weathered shale rip-up clasts (Wah Wah Range). Scale bar is 10 cm. E) Rip-up clast bearing bed within concentrations of clasts along preserved portions of the bedding plane. Scale bar is 1 m. F) Cross sectional view of rip-up clasts in parallel laminated sandstone. Scale bar is 10 cm.

**Figure 1.8**

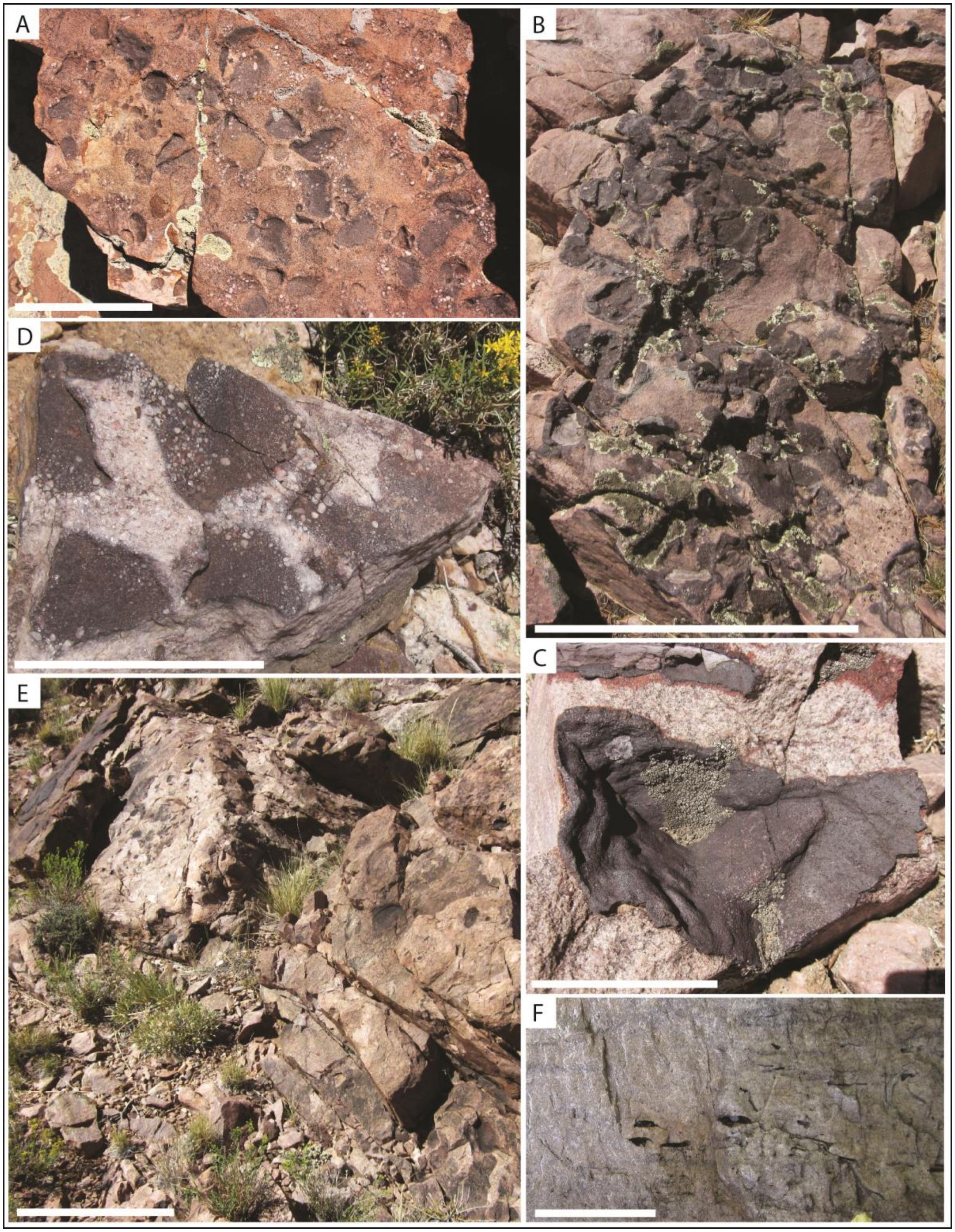


Figure 1.9. Facies F and G - A) Hummocky cross stratified sandstone (cross stratification highlighted with dashed black lines. “Up direction” indicated by black arrow) with interbedded shale (Ogden, UT). Scale bar is 10 cm. B) Thin shale interval between beds of _ne to medium grained sand (Logan, UT). Scale bar is 10 cm. C) Maroon shale interbed underlying cross bedded sandstone bed. Scale bar is 10 cm. D) Interbedded shale and sandstone laminae. Note laterally discontinuous sand beds highlighted by dashed white lines. Scale bar is 10 cm. E) Outcrop of sandstone and shale interbeds (Huntsville, UT). Scale bar is 1 m. F) Planar laminated sandstone interbed (Logan, UT). Scale bar is 10 cm.

**Figure 1.9**

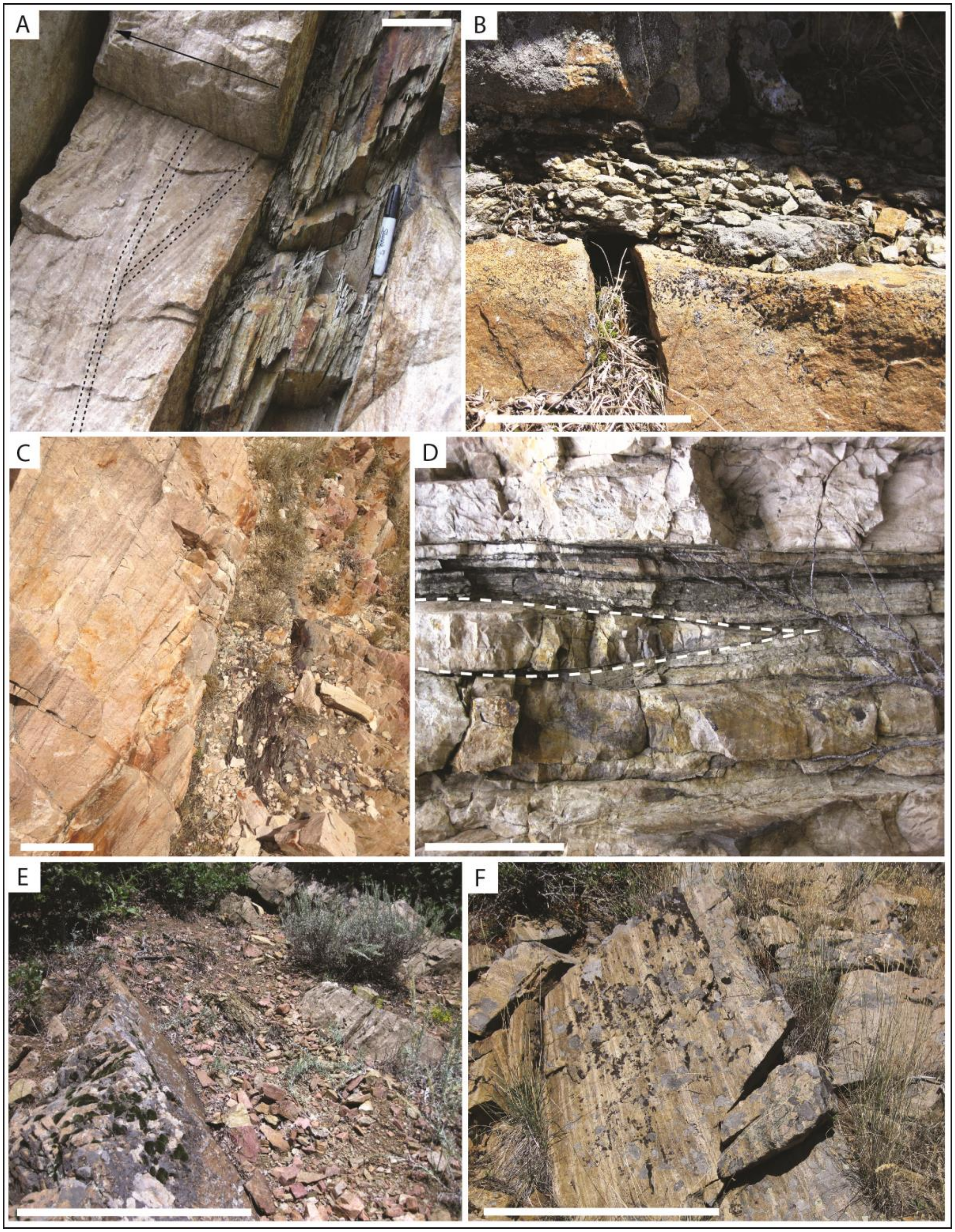


Figure 1.10. Facies H- A) Outcrop of volcanic flow in the southern Cricket Mountains. Scale bar is 1 m. B) Vesicular volcanic clast. Scale bar is 10 cm. C) Contact between volcanic flow and underlying sandstone. Note contact metamorphism in underlying sand. Scale bar is 20 cm. D) Outcrop of volcanic flow in the Frisco Mountains. Scale bar is 1 m. E) Volcanic flow exposed northeast of Logan, UT. Scale bar is 1 m. F) Volcanic clast. Scale bar is 10 cm. G and H) Exposures of basalt in the southern Wah Wah Range. Scale bars are 1 m.

**Figure 1.10**

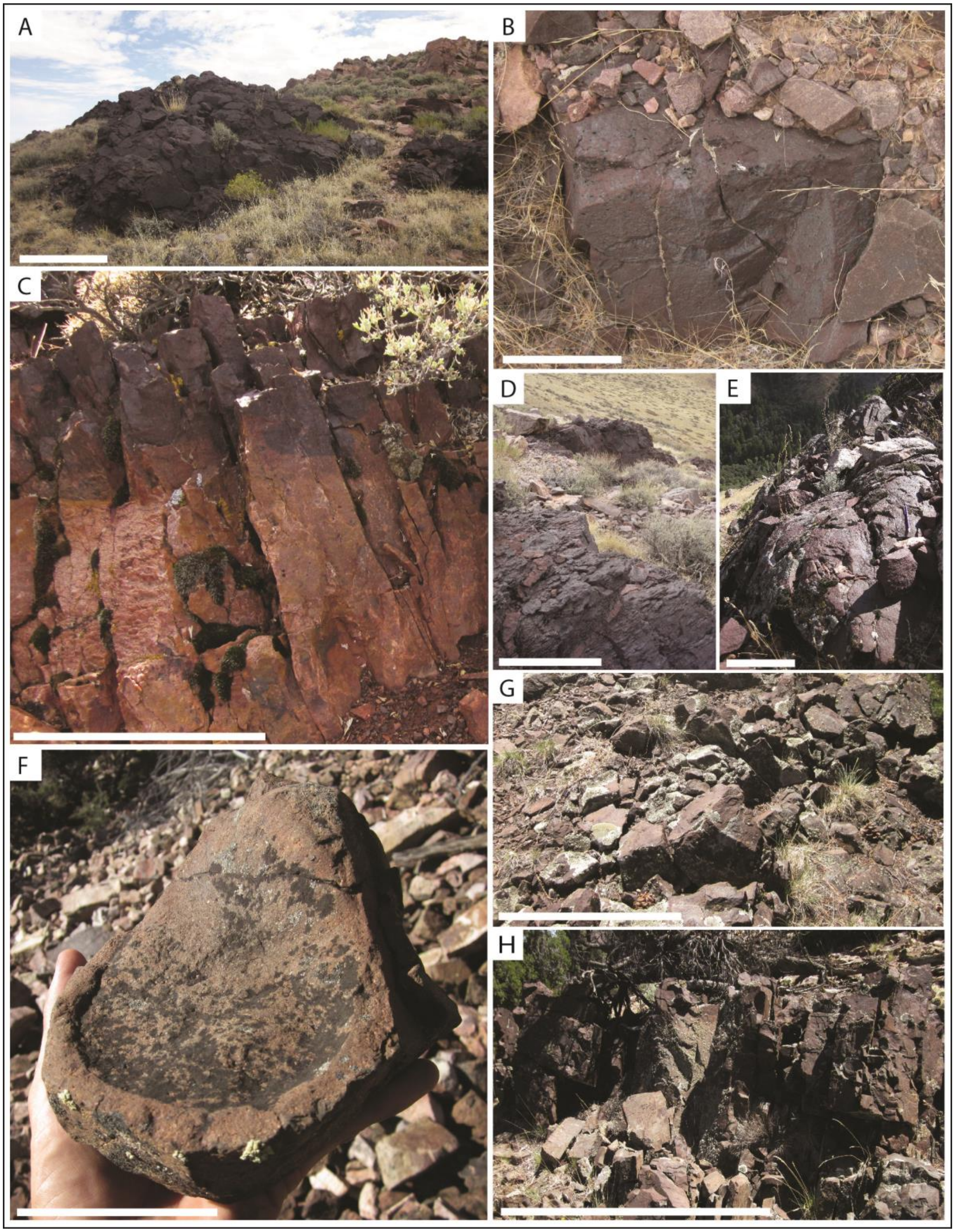


Figure 1.11. Trace fossils in Facies F and G - A) Epirelief view of Berguaeria burrows collected from an unknown locality (Magwood, 1996). Scale bar is 1 cm. B) Plagiogmus burrows weathering out of a sandstone bedding plane (Cricket Mountains) (Magwood, 1996). Scale bar is 10 cm. C) Diplocraterion burrow viewed in cross section. Scale bar is 10 cm. D) Hyporelief view of a fine-grained sandstone casting of an intensely bioturbated zone (Snake Range). Scale bar is 10 cm. E) Rusophycos and Palaeophycus burrows viewed in hyporelief. Note the juxtaposition of the medial axis of the rusophycos burrows and several Palaeophycus burrows indicated by white arrows (southern Cricket Mountains). Scale bar is 10 cm.

**Figure 1.11**

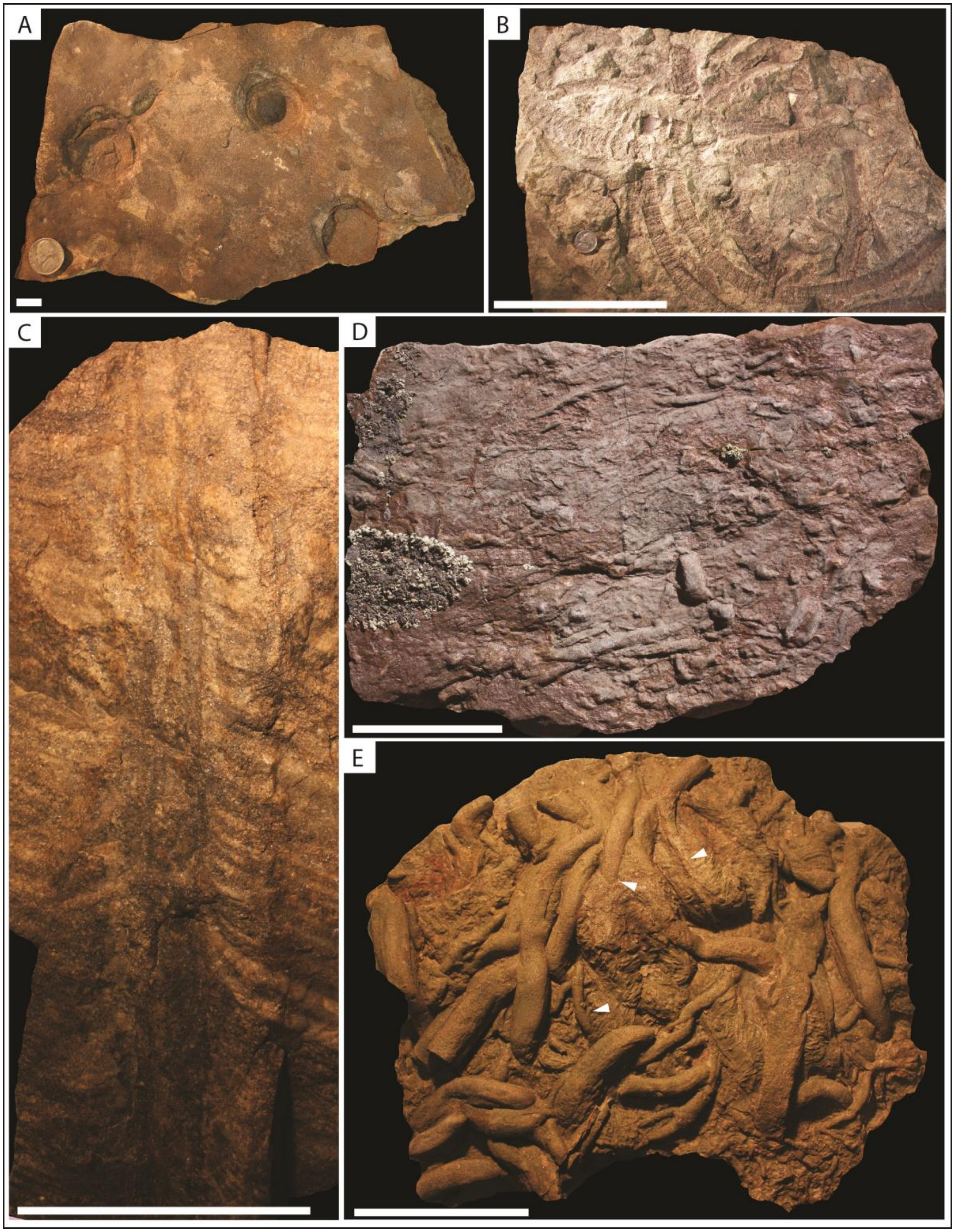


Figure 1.12. Skolithos burrows - A) Isolated Skolithos burrows in medium sand below densely bioturbated fine-grained sandstone bed (Huntsville, UT). Scale bar is 10 cm. B) Skolithos burrows weathering out of a sandstone bedding plane (Sheeprock Mountains). Scale bar is 10 cm. C) Dense Skolithos burrows viewed in cross section. Scale bar is 10 cm. D) Linear Skolithos burrows viewed in an isolated boulder (Wah Wah Range). Scale bar is 10 cm. E) Dense Skolithos burrows overlying massive and planar laminated sandstone bed (southern Cricket Mountains). Scale bar is 1 m.

**Figure 1.12**

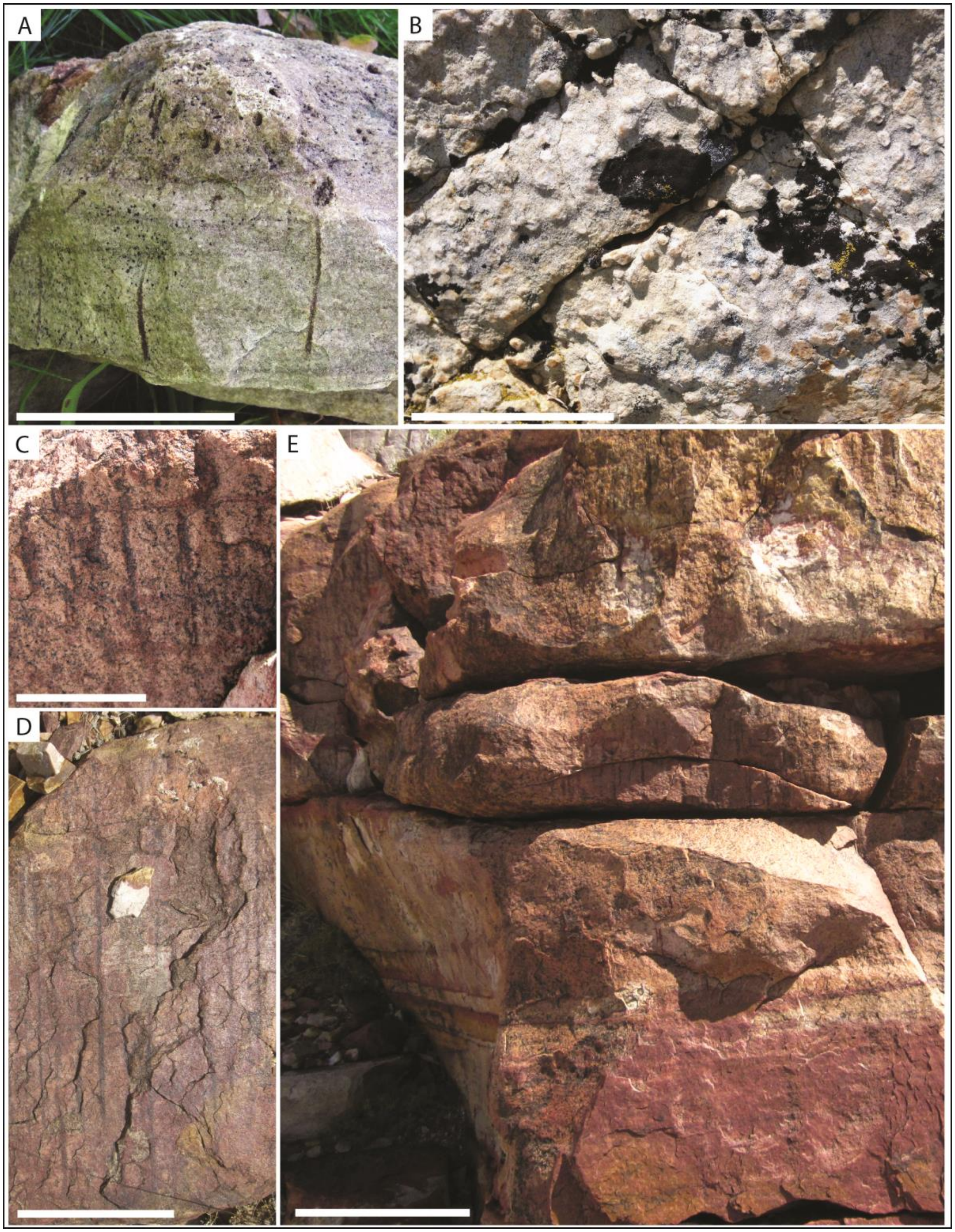


Figure 1.13. Arenicolites burrows - A) Arenicolites burrows with upper cones preserved in fine-grained sandstone (northern Wasatch Range). Scale bar is 1cm. B) Arenicolites burrows with upper “funneled” portion of burrows missing (Egan Range). Scale bar is 1 cm. C) Arenicolites fabric consisting of burrow bottoms preserved along the exposed bedding plane. Note that the terminus of these burrows correlates with coarse-grained, rip-up clast layer (southern Cricket Mountains). Scale bar is 10 cm. D) Arenicolites burrow in cross section (Wah Wah Range). Scale bar is 1 cm. E) Arenicolites fabric consisting of burrow bottoms preserved along the exposed bedding plane. Note that the terminus of these burrows correlates with coarse-grained, rip-up clast layer (Snake range). Scale bar is 10 cm. F) Exposed bedding plane containing abundant and large Arenicolites burrows. Scale bar is 1 m. G) Arenicolites fabric consisting of burrow bottoms preserved along the exposed bedding plane. Note that the terminus of these burrows correlates with coarse-grained, rip-up clast layer (southern Cricket Mountains). Scale bar is 10 cm.

**Figure 1.13**

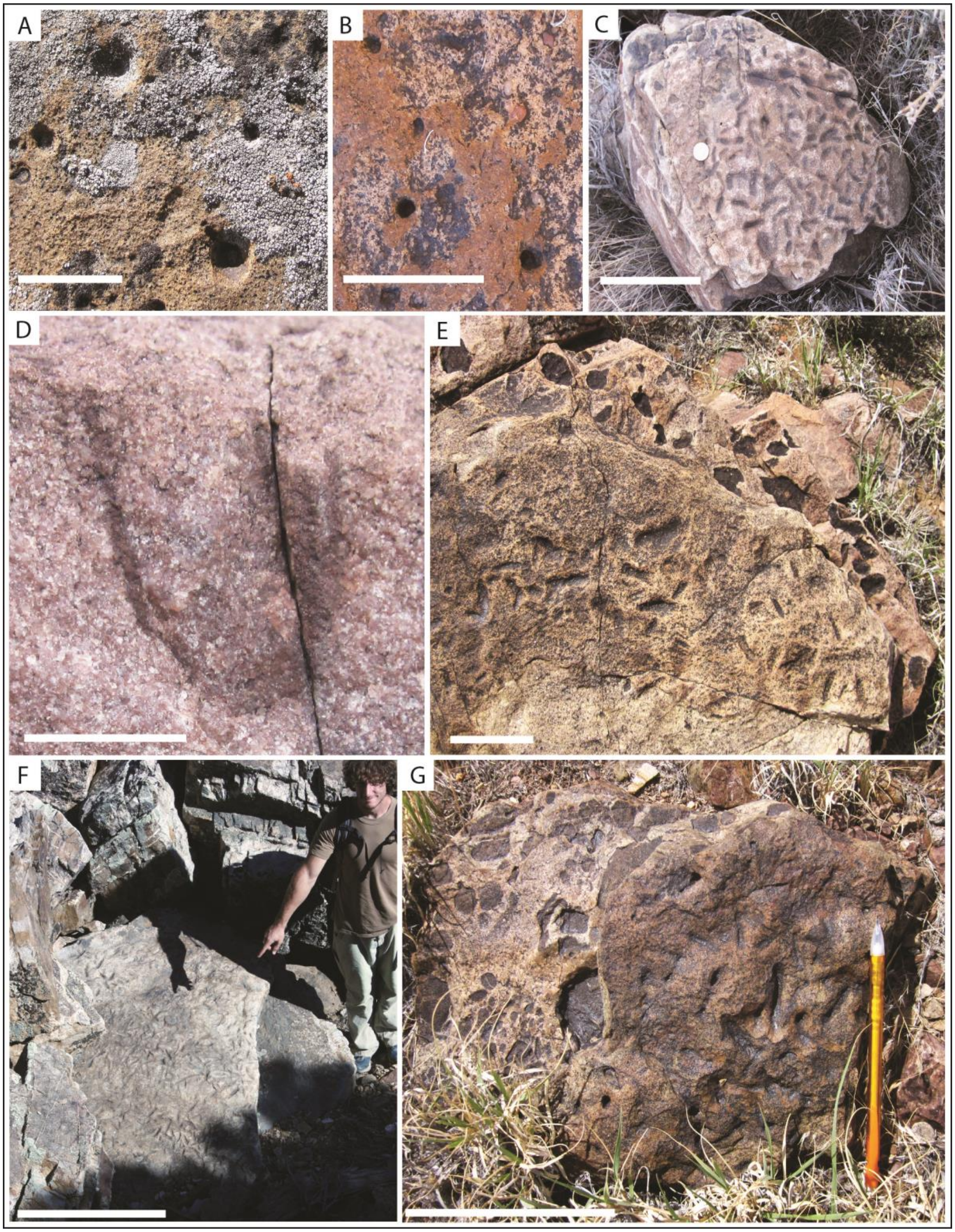


Figure 1.14. Generalized stratigraphic sections and correlation scheme for the craton margin.

**Figure 1.14**

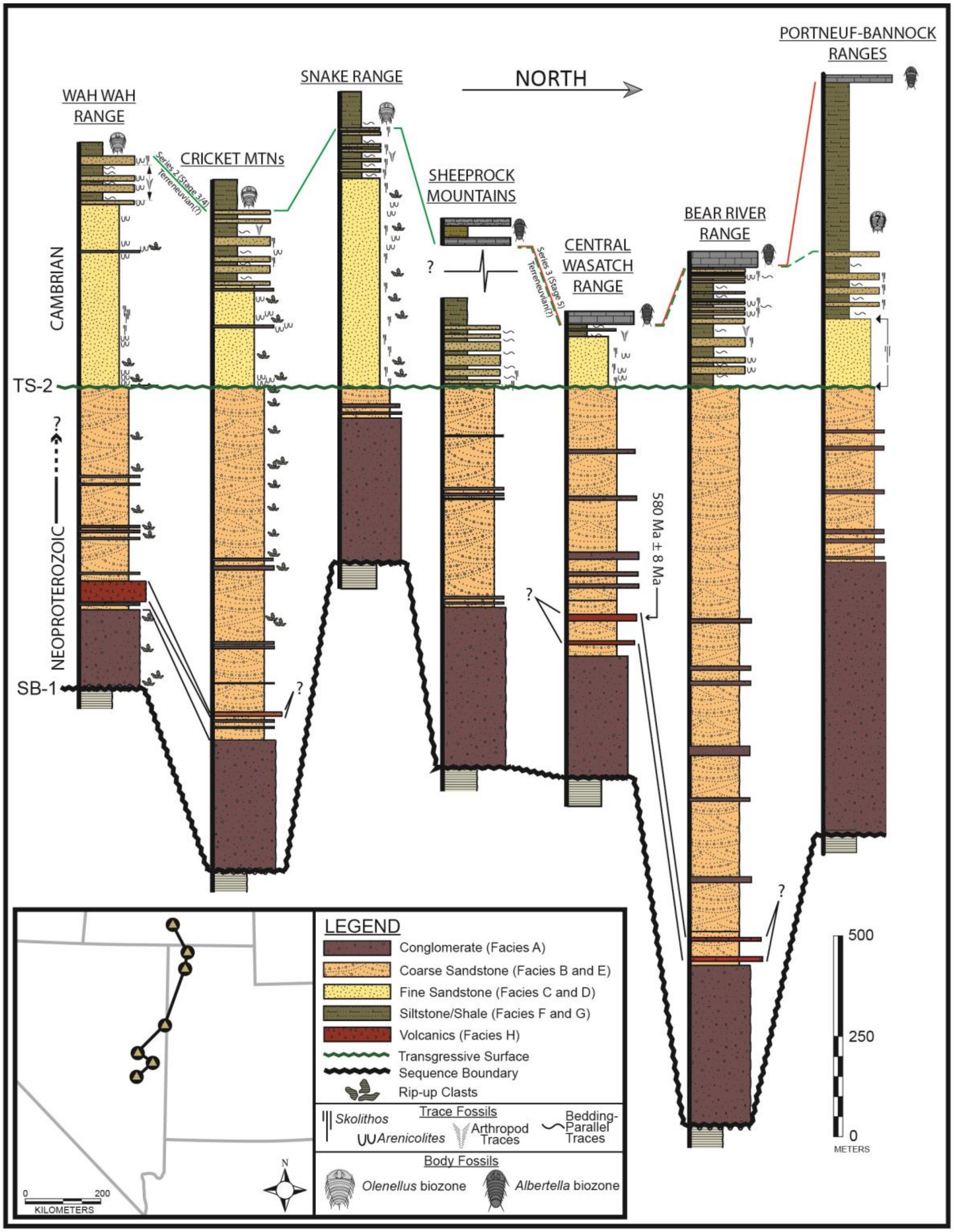
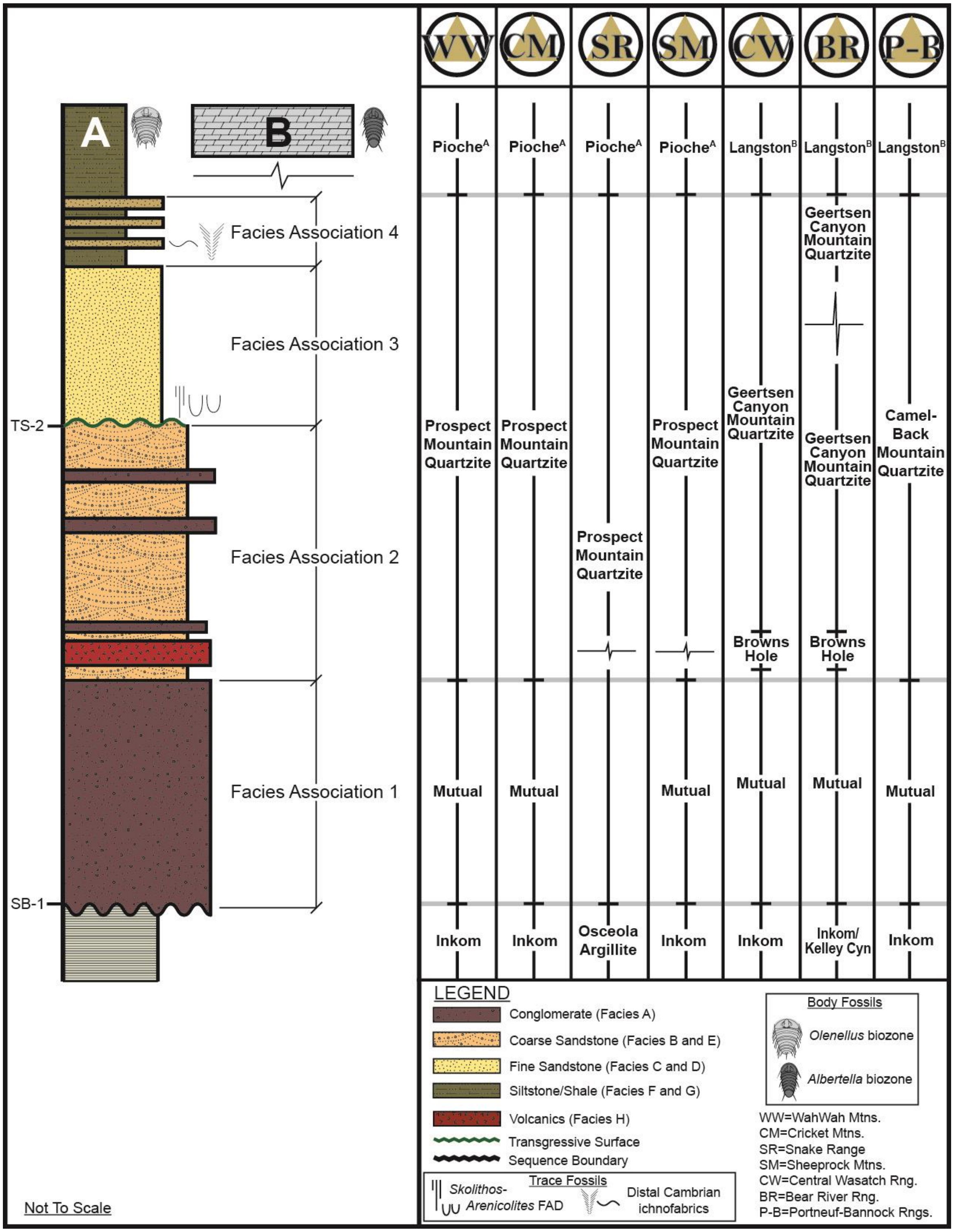

WAH WAH RANGE
CRICKET MTNs
SNAKE RANGE
NORTH
SHEEPROCK MOUNTAINS
CENTRAL WASATCH RANGE
BEAR RIVER RANGE
PORTNEUF-BANNOCK RANGES
Series 2 (Stage 3/4)
Terreneuvian(?)
Series 3 (Stage 5)
Terreneuvian(?)
CAMBRIAN
NEOPROTEROZOIC
TS-2
SB-1
?
580 Ma ± 8 Ma
LEGEND
Conglomerate (Facies A)
Coarse Sandstone (Facies B and E)
Fine Sandstone (Facies C and D)
Siltstone/Shale (Facies F and G)
Volcanics (Facies H)
Transgressive Surface
Sequence Boundary
Rip-up Clasts
Trace Fossils
Skolithos
Arenicolites
Arthropod Traces
Bedding-Parallel Traces
Body Fossils
Olenellus biozone
Albertella biozone
500
250
0
METERS
0
200
KILOMETERS
N

Figure 1.15. Generalized stratigraphic section for the craton margin showing relationships between Facies Associations identified during this investigation. Note that the section breaks at the contact with overlying shales or dolomite to coincide with the regional variability in the lithofacies of overlying Cambrian units. Table on right depicts disparity and overlap in the applied lithostratigraphic nomenclature of correlative units. Section breaks indicate missing lithofacies. Refer to Figure 1.2 for section locations.

**Figure 1.15**


A
B
Facies Association 4
Facies Association 3
Facies Association 2
Facies Association 1
TS-2
SB-1
Not To Scale
WW
CM
SR
SM
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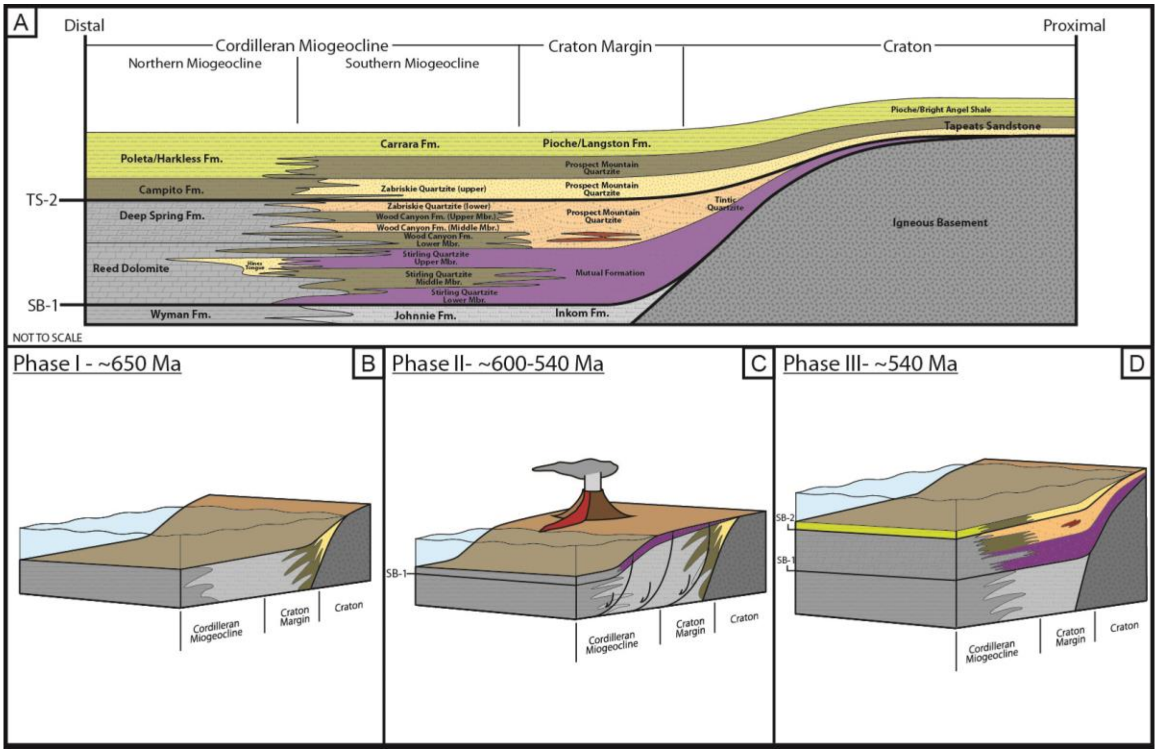
BR
P-B
Pioche^A
Langston^B
Geertsen Canyon Mountain Quartzite
Prospect Mountain Quartzite
Camel-Back Mountain Quartzite
Browns Hole
Mutual
Inkom
Osceola Argillite
Inkom/ Kelley Cyn
LEGEND
Conglomerate (Facies A)
Coarse Sandstone (Facies B and E)
Fine Sandstone (Facies C and D)
Siltstone/Shale (Facies F and G)
Volcanics (Facies H)
Transgressive Surface
Sequence Boundary
Trace Fossils
Skolithos-Arenicolites FAD
Distal Cambrian ichnofabrics
Body Fossils
Olenellus biozone
Albertella biozone
WW=WahWah Mtns.
CM=Cricket Mtns.
SR=Snake Range
SM=Sheeprock Mtns.
CW=Central Wasatch Rng.
BR=Bear River Rng.
P-B=Portneuf-Bannock Rngs.

Figure 1.16. Regional correlation scheme and paleoenvironmental reconstruction. Legend for lithotypes depicted is available in Figure 1.14. A) Distal to proximal transect through the Great Basin showing hypothesized relationships between the Cordilleran Miogeocline, Craton Margin, and Craton. B) Paleoenvironmental reconstruction illustrating depositional processes following the initial phase of rifting associated with the breakup of the supercontinent Rodinia. C) Schematic representation of tectonic uplift and a westward shift in the paleoshoreline associated with the second phase of rifting in western Laurentia. Note that the listric faults and rift shoulders illustrated in this drawing are for demonstration purposes only as field exposures of these features for this younger rift event are currently unavailable. D) Illustration of passive margin sedimentation with ongoing basin subsidence at the onset of the Sauk Marine Transgression.

**Figure 1.16**



**Additional Supporting Materials Available on ProQuest**

# CHAPTER 2

## The oldest *Zoophycos* and implications for Early Cambrian deposit feeding

### Abstract

*Zoophycos*-group burrows are prevalent elements of the trace fossil record throughout the majority of the Phanerozoic and are among the most celebrated trace fossils in all of ichnology. Reported herein are the oldest definitive specimens of *Zoophycos* from Early Cambrian strata of the Lower Member Wood Canyon Formation in southeastern California. Eight specimens were collected approximately 40 m above the Precambrian-Cambrian boundary within the *Rusophycus avalonensis* zone, making them significantly older than any other purported occurrences of *Zoophycos*. These specimens are simple, basically two-dimensional forms occurring with well-defined mud-sand lamellae in the absence of a vertical axis and/or any evidence of vertical movement of sediment. They are interpreted as the product of a horizontal deposit feeder as has been suggested for other examples of *Zoophycos* (e.g. Seilacher, 1967, 2007). The discovery of these specimens not only expands the range of *Zoophycos* nearly to the base of the Cambrian but also reveals the presence of deposit feeding prior to the appearance of the trilobites, considerably earlier than has been suggested for the advent of this feeding style. This type of activity may have had a significant impact on levels of sediment mixing during the Precambrian-Cambrian transition, though the rarity and shallow tier position of these specimens suggests otherwise.

## Introduction

*Zoophycos* is among the most distinct and widely utilized trace fossils. As defined by Häntzschel (1975), *Zoophycos* is a complex spreite structure that can be arranged in simple lobes or highly complex spiral structures. The systematic probing of sediment suggested by the general morphology of *Zoophycos* has led workers to interpret this burrow as a classic fodinichnion, that is, it is produced, at least in part, by deposit feeding (Seilacher, 1967; Bromley and Hanken, 2003; Seilacher, 2007). The identity of the *Zoophycos* producer is unknown but is generally considered to be some sort of infaunal worm-like animal (Seilacher, 1967; Kotake, 1989; Bromley, 1991; Seilacher, 2007). *Zoophycos* has been considered by some to have an age range that extends to the Cambrian (e.g. Crimes, 1992; Lowemark and Shafer, 2002, etc.) based on two tentative reports of this burrow from Atdabanian strata of the Campito Formation in eastern California (Alpert, 1977) and the Mickwitzia Sandstone in Sweden (Jensen, 1997). However, these two specimens contain morphological features such as enlarged marginal tubes relative to the corresponding spreiten (Jensen, 1997) and pelleted laminae (Alpert, 1977) that are atypical of the ichnogenus (Simpson, 1970; Miller, 1991; Seilacher, 2007) yielding a temporal distribution of *Zoophycos* considered by most to extend only from the Ordovician to Recent (Wetzel and Werner, 1980; Bromley, 1991; Seilacher, 2007). Here reported are archetypal *Zoophycos* burrows from earliest Cambrian strata (*Rusophycos avalonesis* Zone) in the Wood Canyon Formation of southeastern California, significantly extending this age range nearly to the base of the Cambrian. Even when considering the other reports of Cambrian *Zoophycos* (Alpert, 1977; Jensen, 1997), there have been no reported examples of this burrow that predate skeletal elements of the Cambrian fauna prior to this discovery.

Of potentially greater significance than the novelty of these being the oldest examples of *Zoophycos,* these specimens provide robust evidence of deposit feeding in close proximity to the Precambrian-Cambrian boundary. The advent of deposit feeding and the potential to effectively mix sediment were key steps in the evolution of animals that fundamentally changed the nature of ecosystems and perpetually altered the physical and chemical characteristics of sediment. Prior to the discovery reported herein, no uncontroversial evidence for deposit feeding has been reported from strata older than the Ordovician (Butterfield and Jensen, 2001; Butterfield, 2002). Unlike body fossils or even other trace fossils that have been suggested as possible fodinichnia from the Early Cambrian (Crimes, 1992), the features within these *Zoophycos* provide clear evidence of Cambrian deposit feeders.

## Geologic Setting

The Wood Canyon Formation (WCF) is an Ediacaran-Early Cambrian unit cropping out from southeastern California to southwestern Nevada (Stewart, 1970). Specimens were recovered at Chicago Pass in the northern Nopah Range just west of the California-Nevada state line (Figure 2.1). At Chicago Pass, Proterozoic and Early Cambrian rocks of the Stirling Quartzite and WCF rest atop Middle Cambrian rocks of the Bonanza King Formation due to thrusting along the north-dipping Chicago Pass Thrust Fault.

The WCF is divided into three members with the Precambrian-Cambrian boundary placed within the Lower Member among a series of siliciclastic to carbonate capped parasequences of varying thicknesses (Horodyski et al., 1994; Corsetti and Hagadorn, 2000; Jensen et al., 2001). Lithofacies within the Lower Member of the WCF have been interpreted as representing a subtidal environment (Corsetti and Hagadorn, 2000) or possibly the distal edge of a braid-delta (Fedo and Cooper, 2001). Comprehensive reviews of the stratigraphy and sedimentology of these sections are provided by Stewart (1970) and Diehl (1976).

The Precambrian-Cambrian boundary is located just above the second parasequence of the series (Horodyski, 1991; Jensen et al., 2001) based on the earliest observed occurrence of the trace fossil *Treptichnus pedum* (Horodyski et al., 1994), the boundary defining ichnotaxon at the Global Stratotype Section and Point (GSSP) in Newfoundland (Narbonne et al., 1987). Ediacaran body fossils, including *Cloudina* and *Swartpuntia*, stratigraphically underlie this point (Hagadorn et al., 2000). Specimens of *Zoophycos* were located approximately 20 m above the top of the third parasequence (Figure 2.1) within the Early Cambrian *Rusophycus avalonensis* trace fossil zone (Jensen et al., 2001).

## Description of Zoophycos specimens

*Zoophycos* specimens are rare in the WCF and are concentrated in a stratigraphic interval that spans no more than 1 m in thickness. There is one complete specimen and 7 incomplete specimens. We utilize the established terminology of Simpson (1970) to describe the general morphology of these materials. Two morphological features, lamina and lamella, apply to these *Zoophycos* and are discussed in further detail below.

*Zoophycos* laminae are defined by Simpson (1970) as the spreite "lobes" or "plates" within the trace and are described by the general shape of their outline (Stewart, 1970; Bromley and Hanken, 2003). The laminae in the Wood Canyon *Zoophycos* are arcuate (Stewart, 1970, p. 508, figure 1b; Figure 2.2), preserving the "cocks-tail" or "cauda galli" morphology common in other specimens of *Zoophycos*. Lamellae are produced by sediment sorting by the animal within the burrow and define the internal structure of the laminae (Stewart, 1970, p. 507). In bedding-plane view, lamellae are expressed as subparallel lines (spreiten) radiating out from the apical portion of the trace. Lamellae are most abundant in the widest portions of the fossil with as many as 81 lamellae present in a single transect drawn perpendicularly to the margins of the trace fossil (Supplementary Materials). The ridges of the lamellae have an average spacing of approximately 1 mm with a standard deviation of approximately .3 mm (Supplementary Materials). In the narrowest portions of the fossil, fewer lamellae are present and spacing between individual lamella is greater. In cross-section, the collection of lamellae preserve the typical *Zoophycos* chevron pattern produced by the segregation of fine and coarse grained materials by the original organism (inset to Figure 2.2) . Chevron direction viewed in cross section suggests migration of the animal from the outer margin (i.e. the longest margin of the arcuate lobe) of the lamina inwards.

## Discussion

*Zoophycos* commonly have an apical tube in the narrowest portion of the trace fossil that the organism utilized for vertical migration in the sediment (Miller, 1991). This structure is not present in the Wood Canyon Formation specimens suggesting that either this feature was not preserved or that vertical movement was not accomplished by the progenitor of these burrows. Thus, only horizontal movement of the organism can be inferred from these specimens. *Zoophycos* burrows in late Paleozoic and younger sedimentary rocks are considered elite burrows; that is, they are deep tier or "elite" burrows (Bromley, 1996) making their preservation potential extremely high. In contrast, the lack of any vertical aspect within these Early Cambrian *Zoophycos* suggests that they were shallow, near-surface burrows well within the interpreted mixed layer of a maximum 1-2 centimeters in depth at this time (Droser et al., 2002). This is also consistent with the rarity of these burrows in the Wood Canyon Formation and the absence of definitive *Zoophycos* specimens until the Ordovician when the depth and extent of burrowing increased (Droser and Bottjer, 1989). Given that *Zoophycos* are easily identifiable in cross section, the lack of reported *Zoophycos* between the lower Cambrian and the Ordovician is consistent with a sediment surface to shallow burrow origin.

No specimens have been recovered that preserve the marginal tube that reflects the terminal active burrow of the organism prior to the abandonment of burrow activity. Häntzschel (1975) emphasized the importance of this feature in *Zoophycos*, however, the majority of workers no longer consider this a defining feature of the ichnogenus (Ekdale and Lewis, 1991; Miller, 1991; Uchman, 1995; Olivero, 2007). The preservation of a differentiated marginal burrow would require that the burrow remain open long enough to be infilled with sediment. Thus, taphonomy more than ethology may contribute most significantly to the presence or absence of this feature.

While the lamellae within these specimens follow a fairly regular pattern, they are not well organized nor do they contain minor (branching) lamellae as in some other specimens of *Zoophycos*. Localized cross-cutting of lamellae in bedding plane view is a common feature among Wood Canyon specimens. Cross-cutting of the lamellae within the WCF specimens (supplementary material) on a bedding plane suggests multiple passes by the organism through the same area. This interpretation is supported by the uneven lamellae in the narrow portion of the fossil while becoming more parallel and evenly spaced as the trace becomes wider. The narrowest portions of the burrow would have to have been visited multiple times to create the arcuate laminae in these *Zoophycos*. In these areas, older lamellae would have been "cut" as the organism propagated through to exploit new materials in the more distal regions of the trace.

## The Advent of deposit feeding

The problems associated with constraining feeding strategies from fossilized remains, even in exceptionally preserved materials, suggest that the trace fossil record provides the only robust proxy for interpreting these types of behaviors (Butterfield and Jensen, 2001; Butterfield, 2002). For example, body fossils of the Cheng Jiang biota containing sediment filled guts have been used as the primary evidence of Cambrian deposit feeding (Bergström, 2001), however, taphonomic evidence and detailed morphological analysis of these taxa has revealed that they could not have been deposit feeders (Butterfield, 2002). Prior to the discovery of these *Zoophycos*, no putative deposit feeding trace fossils had been reported from prior to the Ordovician (Butterfield, 2002).

Early Cambrian trace fossils including *Treptichnus pedum, Teichichnus* and *Rhizocorallium* have been considered by some to be evidence of deposit feeding (Alpert, 1977; Lowemark and Shafer, 2002; Seilacher, 2007). However, this interpretation is problematic as these are morphologically indiscreet burrows not exclusive to a single behavior (Seilacher, 2007). That is, these burrows may have been utilized for a diverse set of infaunal activities that may or may not have included deposit feeding (Seilacher, 2007). While additional behaviors have been proposed for *Zoophycos* that may augment interpretations of the trace maker as strictly a deposit feeder (Bromley, 1991), an aspect of deposit feeding is present in all current models. The *extent* to which deposit feeding is expressed among *Zoophycos* burrows is interpreted from the overall morphology and internal characteristics of the burrow on a case by case basis.

The general morphology of these specimens is consistent with their construction by a horizontal strip miner as suggested by Seilacher (2007). Lamellae are most likely to have been produced by backfilling as an organism excavated new materials and placed those materials in the previously open portion of the burrow. It is unlikely that closely spaced, well sorted and regularly arranged lamellae would suggest detritus feeding or some other selective feeding strategy as the organized and repetitive nature of these backfilled burrows do not represent a selective means of processing sediment.

## Summary and Conclusions

These Wood Canyon Formation *Zoophycos* are currently the oldest reported examples of this celebrated burrow. These burrows substantiate previous claims that deposit feeding was utilized as a feeding strategy by Cambrian organisms. Deposit feeding is a prevalent feeding style among disparate freshwater, marine, and terrestrial invertebrates and is the most effective means of biologically mixing sediment (Rhoades and Young, 1970; Lopez and Levinton, 1987). Thus, the robust evidence of deposit feeding near the Precambrian-Cambrian boundary that these specimens provide has direct and significant evolutionary implications for both the biosphere as well as the lithosphere

Biologically mediated sediment mixing has been credited for a variety of ecological and environmental changes near the Precambrian-Cambrian boundary including the disappearance of the Ediacara biota (Seilacher and Plüeger, 1994), changes in ocean chemistry (Canfield and Farquhar, 2009), and the eventual radiation of the Cambrian Fauna (Seilacher and Pflüeger, 1994). Placed in this temporal context and given the extent to which deposit feeding can evoke change in the substrate, it is tempting to cite the advent of deposit feeding as contributing to the severe ecological and environmental changes occurring at this time. While these *Zoophycos* burrows demonstrate that deposit-feeding organisms were present during the Early Cambrian, the lack of any vertical aspect in these burrows precludes any interpretation that this behavior occurred any deeper than the depth of penetration observed in the lunate lamellae. Evidence suggesting that the Early Cambrian mixed layer was already a few centimeters deep (Droser et al., 2002) and the lack of any evidence suggesting that these burrows extended any deeper, limits the impact that this feeding strategy can be concluded to have had.

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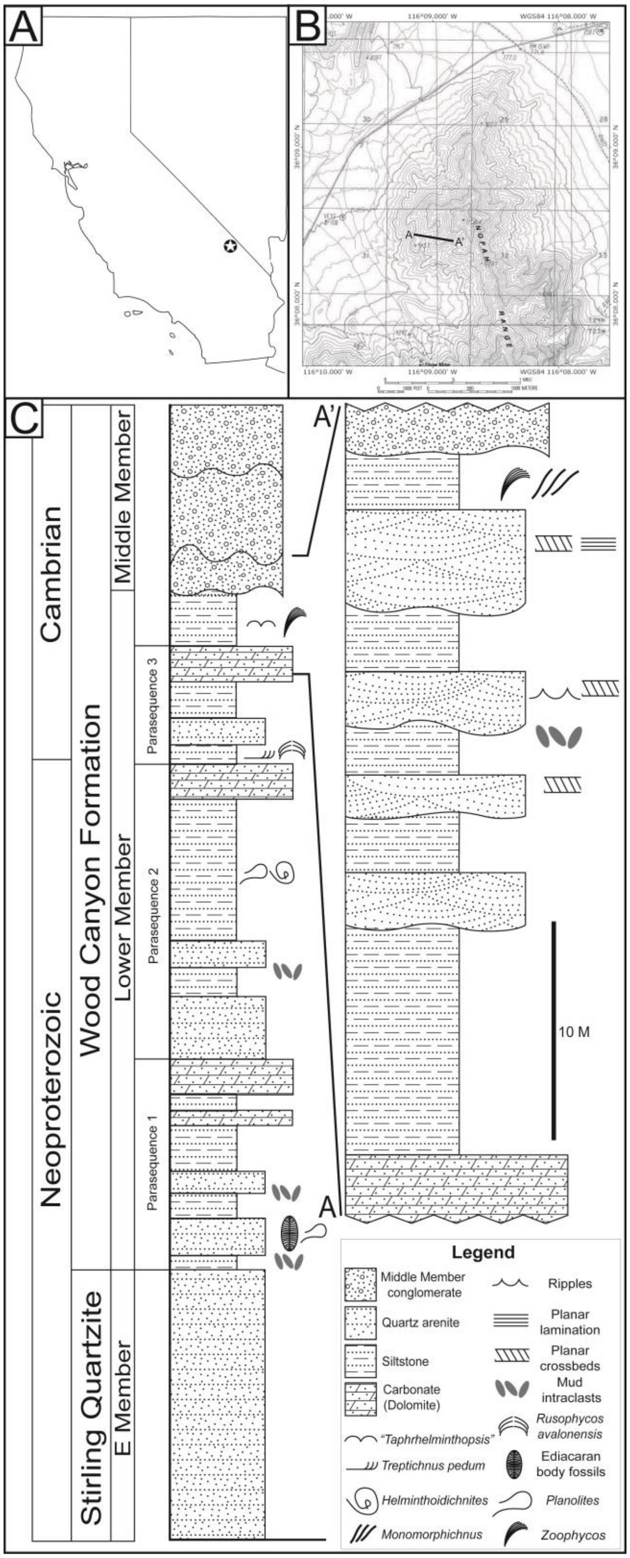
**NOTE 1:** While there are now several ichnogeneric names available for trace fossils that this describes (e.g. *Spirophyton*, *Fucoides*, *Glossophycus*) these are generally treated as synonyms (Uchman, 1995; Olivero, 2007) and the ichnogenus *Zoophycos* is commonly applied to a morphologically diverse set of trace fossils containing lobate or spiraling spreiten structuring (cf. Bromley and Hanken, 2003).

## Figures

Figure 2.1. Locality map and stratigraphic context for portions of the Wood Canyon Formation in the Death Valley region. A and B: Regional context for field locality. A to A' transect line in B shows location of actual stratigraphic section depicted in inset of C. C: Generalized stratigraphic section for Precambrian to Early Cambrian strata of the Stirling Quartzite and Wood Canyon Formation. Inset shows actual stratigraphic section obtained at the Chicago Pass locality. The trace fossils indicated in these sections show only first occurrences.

**Figure 2.1**


A
B
116°10.000' W
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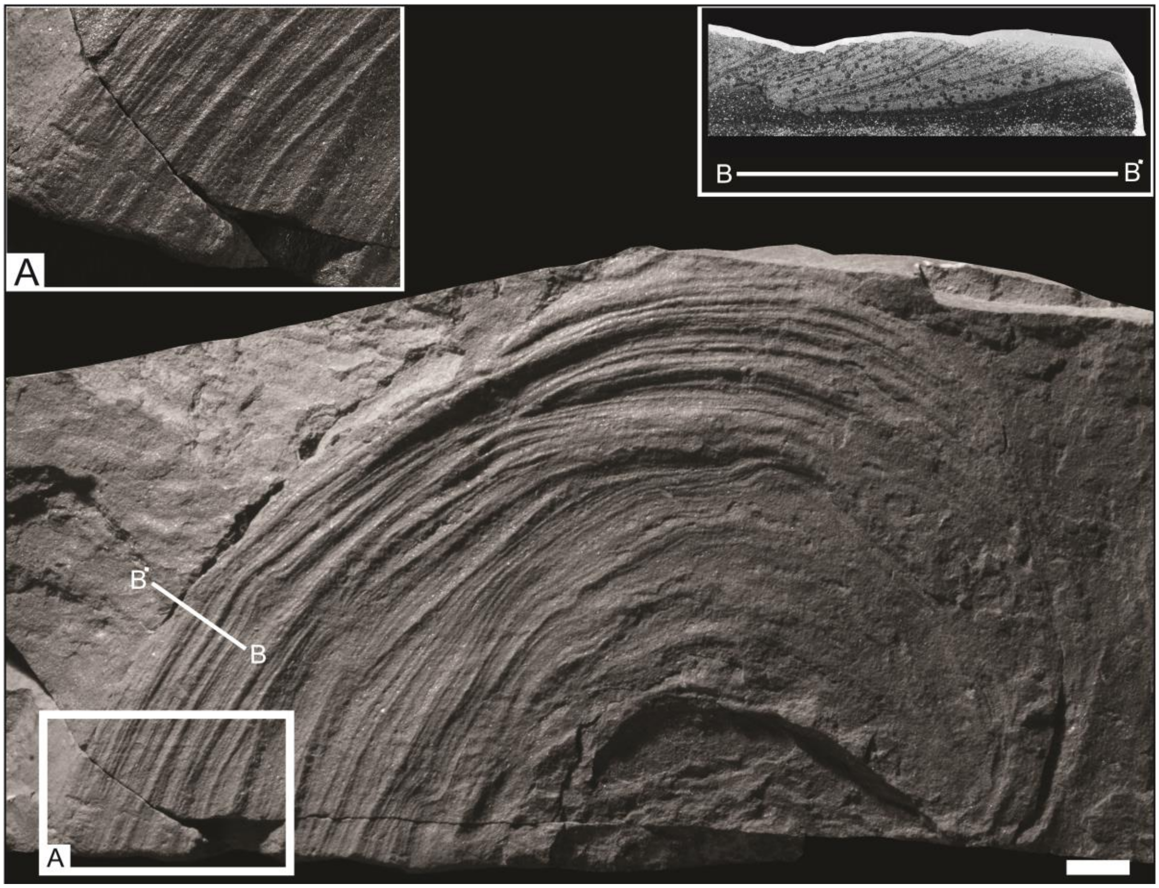
WGS84 116°08.000' W
36°09.000' N
36°08.000' N
A
A'
NOPAH
RANGE
C
Cambrian
Neoproterozoic
Wood Canyon Formation
Stirling Quartzite
Middle Member
Lower Member
E Member
Parasequence 3
Parasequence 2
Parasequence 1
A'
A
10 M
Legend
Middle Member conglomerate
Quartz arenite
Siltstone
Carbonate (Dolomite)
"Taphrhelminthopsis"
Treptichnus pedum
Helminthoidichnites
Monomorphichnus
Ripples
Planar lamination
Planar crossbeds
Mud intraclasts
Rusophycos avalonensis
Ediacaran body fossils
Planolites
Zoophycos

Figure 2.2. Zoophycos specimen (UCR10966/1) from the Lower Member of the Wood Canyon Formation. Main photo is bedding plane (epirelief) view of the specimen. Inset shows thin section of the specimen cut along the transect labeled as B to B'. A: Close-up bedding plane view of lamellae in the distal portion of the fossil.

**Figure 2.2**



**Additional Supporting Materials Available on ProQuest**

# CHAPTER 3

## Paleobiological and taphonomic implications of Earth's oldest fossil medusae

### Abstract

Discoidal macrofossils reported herein from the lower Cambrian Zabriskie Quartzite (Great Basin, western United States) represent soft-bodied organisms transported and preserved along the top of a medium- to coarse-grained sandstone bedding plane. The general morphology, internal structure, local abundance and biostratinomy of these fossils suggest that they may represent the earliest fossil evidence of medusozoans and, moreover, the oldest example of a metazoan mass stranding event currently on record.

In addition to insights regarding the potential phylogenetic affinities of early Cambrian medusozoans, the Zabriskie fossils advance reconstruction of the environmental and taphonomic dynamics responsible for the preservation of soft-bodied macrofauna in nearshore facies through the Precambrian-Cambrian transition. The taphonomic model presented herein examines and revises previously outlined biostratinomic models for the preservation of stranded medusozoans through additional comparison with modern medusa strandings and full consideration of the large-scale environmental and ecological conditions present along early Cambrian shorelines. Further, fossils of soft-bodied marine macrofauna preserved in coastally deposited sandstone are largely restricted to Ediacaran and Cambrian strata. Ediacara-type soft-bodied taxa all but disappeared from and preservation of soft-bodied fossil assemblages in sandy facies of coastal paleoenvironments became increasingly rare roughly concurrent with the Precambrian-Cambrian transition. The question of whether this shift in the soft-bodied fossil record reflects a preservational bias or records a real extinction event remains a topic of strong debate. We compare, in detail, the taphonomic requirements for the preservation of stranded Cambrian medusae to those required for the preservation of soft-bodied Ediacara organisms and find key secular disparities in the taphonomic history of this mode of preservation. This disparity implies that a preservational bias may have been introduced near the onset of the Phanerozoic, shifting the predominant environment for soft-bodied preservation in sandstone from subtidal facies to the supralittoral zone.

## Introduction

The juxtaposition of terrestrial and marine environments along the ocean’s shores and the abundance and diversity of modern life observed there allude to the ecological and evolutionary significance of this environmental setting. Representatives of all major animal phyla spend some portion of their lives in intertidal settings and, despite the relatively small global surface area represented by these environments, littoral sequences are well represented in the geologic record. However, soft-bodied macrofossils recording life in ancient littoral settings are almost entirely absent from the fossil record. This dichotomy between living abundance and fossil rarity emphasizes the preservational biases associated with the erosional and biodegradational processes characteristic of the vast majority of coastlines. Background wave and tide energy, punctuated by periodic storm events, results in repeated high-energy deposition and reworking of poorly consolidated substrates.  Soft organic tissues transported and/or exhumed by these events are, with rare exception, quickly broken apart by wave energy and/or are consumed by marine and terrestrial scavengers, and thus an unusually small proportion of organic matter is buried in littoral sediments.  Additionally, the elevated porosity and permeability associated with most coastal substrates results in heightened flow of oxygenated pore fluids, enhancing the rapid decomposition of any remaining organic detritus.  Due to the rarity with which fossilization of nonmineralized taxa occurs in these settings, those few nonmineralized beach inhabitants which do eventually make it to the fossil record provide exceptional windows in the paleobiology and taphonomy of intertidal biotas.  Conspicuously, fossils of Cambrian medusozoans, or “jellyfish”, are a substantial portion of this otherwise sparse record, suggesting that unusual preservational pathways, resulting from the interaction of medusozoan tissues with a unique set of environmental and ecological variables were operating along early Paleozoic shorelines.

To supplement and foster further evaluation of the nature and qualities of the fossil record of Cambrian jellyfish, we describe a new medusa-bearing locality from the lower Cambrian Zabriskie Quartzite of the southern Nopah Range in the Death Valley region (southeastern California, U.S.A.) (Figure 3.1).  Discoidal structures, occurring on a single bedding plane at this locality were examined; paleobiologically, sedimentologically and taphonomically characterized; and compared to both modern and other fossilized examples of medusozoan remains.  This analysis suggests that the Zabriskie fossils provide the oldest macrofossil evidence of cnidarian medusae from the

Phanerozoic. Further, the sedimentological context and *en masse* occurrence of these fossils indicate that this assemblage records the oldest reported example of a metazoan mass stranding event. Further, the taphonomic character of the Zabriskie specimens suggests that previous preservational models for Cambrian medusozoans may be further refined by integrating conceptual models for Cambrian Earth system dynamics with uniformitarian sedimentological principles. Comparison to broadly similar preservational modes characteristic of Ediacaran Lagerstätten also highlights important distinctions between Ediacaran and Cambrian taphonomic pathways, with important implications for the preservational, as well as evolutionary dynamics of the Precambrian-Cambrian transition (see Butterfield, 2003).

## Geologic Setting

Precambrian-Cambrian sediments are well-exposed in western North America, largely as a result of protracted subsidence of the ocean basin following separation of Laurentia from the supercontinent Rodinia (Stewart, 1970, 1972). Rifting and the ensuing tectonic subsidence was initiated and hinged along a sinuous craton margin that essentially traced what is now the southern and eastern perimeter of the Great Basin, continuing north-northwestward into Canada (Stewart, 1972; Fedo and Cooper, 2001). Nearly coincident with this tectonic activity, sea level rise associated with the onset of the Sauk Marine Transgression resulted in further expansion of available sediment accommodation space (Sloss, 1963; Stewart, 1970, 1972). A sedimentary succession nearly 9 km thick accumulated in portions of the basin, resulting in an extensive and largely continuous record of the Precambrian–Cambrian transition, today well-exposed throughout the western Cordillera (Stewart, 1970, 1972). This succession is commonly referred to as the Cordilleran Miogeocline (Stewart, 1970). Deposition in the Cordilleran Miogeocline persisted nearly uninterrupted until at least the late Devonian and the onset of the Antler Orogeny (Roberts et al., 1958). Sediments deposited in the Cordilleran Miogeocline form a westward thickening, 4000 km long wedge of mixed siliciclastic and carbonate sediments exposed from western Canada to northern Mexico (Stewart, 1970; Stewart, 1972; Stewart and Poole, 1974; Fedo and Cooper, 2001). The succession is largely dominated by siliciclastic detritus with carbonate units being most prevalent in exposures in western portions of the Great Basin (Stewart, 1970, 1972).

The establishment of passive margin sedimentation in the early Phanerozoic coupled with Sauk-associated rising sea levels likely resulted in, beginning in the early Cambrian, an eastward march of the paleoshoreline (Sappenfield and Droser, in prep). One interval of the shoreline's migration is recorded in the widespread and laterally continuous sandstones and siltstones assigned to the upper portions of the Zabriskie Quartzite (Prave, 1992; Sappenfield and Droser, in prep). The Zabriskie Quartzite is a texturally mature siliciclastic unit exposed over 36,000 square kilometers in southeastern California and portions of southern Nevada (Barnes and Klein, 1975). The formation ranges from 3 to approximately 300 meters in thickness, thickening from southeast to northwest, and is generally composed of massive to cross-bedded, fine- to medium-grained quartz arenite with interbedded mudstone (Stewart, 1970; Prave, 1992). The underlying Wood Canyon Formation and the overlying Carrara Formation have both yielded *Bonnia-Olenellus* faunas (Stewart, 1970; Diehl, 1979), thus constraining the age of the Zabriskie Quartzite to the early Cambrian (Series 2). Exquisite examples of diagnostic early Cambrian *Skolithos* piperock, for which the Zabriskie Quartzite is best known, are readily apparent in the majority of exposures of the formation. Localized assemblages of *Arenicolites* and *Planolites* burrows are also present. Prior to this investigation, body fossils had not been reported from the Zabriskie Quartzite.

## Paleoenvironmental Setting

Detailed facies analyses and sequence stratigraphic evaluation in the Zabriskie Quartzite suggest that deposition occurred in a range of coastal marine and terrestrial environments (Prave, 1984; Prave, 1992). Prave (1984) originally described 18 lithofacies within multiple exposures of the formation. These lithofacies are entirely composed of siliciclastic detritus of varying textural and mineralogical maturity. Observation of the lateral and vertical distribution of lithofacies cropping out in California and Nevada suggest that the thickest exposures of the Zabriskie Quartzite consist of two distinct sequence tracts separated by a regional unconformity in the upper portion of the unit (Prave, 1992). Facies associations in the lower portion of the Zabriskie Quartzite are indicative of a transition from marine to terrestrial deposition during a sea level lowstand, where densely burrowed nearshore marine and coastal lithofacies gradually give way to prograding braidplain deposits (Prave, 1992). This succession is capped by a regionally persistent transgressive lag which marks the onset of sea level rise and associated coastal onlapping of marine facies (Prave, 1992). Consistent with the division of these systems tracts, the Zabriskie Quartzite is divided into the Resting Spring Member and the Emigrant Pass Member (Figure 3.1). The fossils reported herein were recovered from the Emigrant Pass Member, approximately 20 meters above the base of the transgressive lag marking the base of this subunit (Figure 3.1).

Portions of the Zabriskie Quartzite have been directly correlated to various other quartz arenite units in western North America including the Prospect Mountain Quartzite and equivalent strata in Nevada, Idaho and portions of Utah (Prave, 1992; Sappenfield and Droser, in prep). These arenaceous units record a global phenomenon, largely limited to Precambrian and lower Paleozoic strata, of deposition of laterally continuous and geographically widespread sandstone bodies, collectively referred to as “sheet quartzites” (Dott, 2003). Petrologic data, coupled with the late Precambrian–Cambrian age of these successions suggest that the cosmopolitan deposition of sheet quartzites likely reflects anactualistic erosional processes resulting from the absence of terrestrial vegetation (Clemmensen and Dam, 1993; Dott, 2003). In the absence of extensive terrestrial vegetation, unstabilized sand-rich coastal systems and alluvial plains are thought to have been far more widespread, and erosion rates correspondingly higher, than are commonly observed today (Lindsey and Gaylord, 1992). Coarse siliciclastic sediment derived from these sources is interpreted to have been transported onto the shelf by a combination of eolian input and tidal- and storm-influenced shelf currents (Lindsey and Gaylord, 1992). These anactualistic sedimentological dynamics, coupled with passive margin development along the western limits of Laurentia, likely account for the fairly homogenous and laterally persistent masses of sand exposed over much of western North America today (Johnson and Baldwin, 1986).

Beaches are generally high energy environments characterized by sequential episodes of rapid deposition and erosion. This alternation, paired with the abundance and proliferation of infaunal and epifaunal communities, results, in modern littoral systems, in a highly dynamic and typically unstable substrate. Lacking a terrestrial biotic component, the early Cambrian coastline was likely to have been fundamentally distinct from the majority of modern beaches. Microbial communities were likely far more widespread in nearshore marine environments at this time (Hagadorn and Bottjer, 1997; Gehling, 1999; Noffke et al., 2002; Gehling and Droser, 2009). The proliferation of microbially-bound substrates, in conjunction with the deposition of sheet quartzites is recorded by the globally widespread occurrence of microbially induced sedimentary structures (MISS) or textured organic surfaces (TOS) in Precambrian through lowermost Paleozoic strata (Hagadorn and Bottjer, 1997; Gehling, 1999; Noffke et al., 2002; Gehling and Droser, 2009). Animals expanded into the infaunal life mode during the early Phanerozoic and, even by the late early Cambrian, infaunalization was well advanced (Tarhan and Droser, 2014), as evidenced by the abundance and size of *Skolithos* and *Arenicolites* burrows in marine facies of the Zabriskie Quartzite. However, concurrently, littoral sediments subject to exposure and desiccation were less well colonized by infauna, permitting denser communities of microbes to thrive relatively undisturbed. MISS or TOS are thus not uncommon in many early Cambrian littoral quartzite successions in the Great Basin. In the Zabriskie Quartzite these structures include wrinkle marks, pustules and “elephant skin” textures.

## Materials and Methods

The Zabriskie medusozoan specimens reported herein occur along a single, east-dipping, sandstone bedding plane exposed in the southern Nopah Range (Figure 3.1). The specimens are preserved within an approximately 9 meter thick flat-laminated to ripple cross-laminated sandstone interval in the upper portion (Emigrant Pass Member) of the Zabriskie Quartzite (Figure 3.1). The specimen-bearing bed was examined and excavated *in situ*, exposing approximately 6 $m^2$ of fossiliferous bedding plane (Figure 3.2). The fully excavated bed was divided into 25 cm x 25 cm grids and the location, size, orientation, and morphological features of all discoidal fossils occurring on the bed were recorded (Figures 3.2 and 3.3). Similar structures observed in adjacent (within a 5 m radius) float were also catalogued; these specimens bear a marked lithologic similarity to the *in situ* fossiliferous bedding plane, strongly suggesting that these loose clasts were weathered from the immediately adjacent outcrop. Measurements taken in the field were supplemented using ImageJ image-processing and analysis software (Rasband, 1997-2008) on digital photographs. Latex molds were also made in order to facilitate laboratory analysis, including the production of replicate casts.

A total of thirteen specimens were identified from the excavated surface and associated talus. Of these, nine were recorded along the *in situ* bedding plane and four were identified in immediately adjacent float. Specimens range from 3 cm to greater than

21 cm in diameter (Figures 3.2 and 3.3) with fossil margins preserved in both convex and concave epirelief of no more than 2-3 mm. Specimens were systematically measured along the shortest axis; measurements thus represent a minimum size. All of the specimens are slightly ovoid, with the elongated axis roughly parallel to the predominant orientation of ripple crests preserved along the bedding plane (Figure 3.2). Similarly, specimens are also characterized by variable topographic relief; variation in relief occurs in the largest specimens, along an axis parallel to that of the surrounding ripple crests and troughs (Figure 3.2).

Select fossils were removed from the exposure and transported back from the field for sectioning. This material was cut using an automated oil saw and subsequently polished in a vibrating lap in multiple stages, using a series of successively finer silicon carbide grits. Polished surfaces were scanned while submerged in a water reservoir to enable high-resolution photographic analyses of sedimentological features preserved in the fossils and surrounding horizons. Thin-sections were generated from these materials for further petrologic evaluation. In the case of each analyzed specimen, continuous, undisturbed laminae occurred directly below the fossil.

Specimens typically occur as high-relief and topographically variable sandstone molds. Positive-relief (convex) portions of each of these fossils are distinctly lighter-colored, allowing these fossils to be readily distinguished from the dark desert varnish that coats the remainder of the bed. This disparity in color does not result from differences in either composition or grain size, but instead likely reflects differential weathering of cements due to the elevated topography of these fossils.

In addition to the discoidal to elliptical shape, association with laminated sediments and high relief described above, the Zabriskie specimens are characterized by a number of additional differentiated features. Three general preservational motifs characterize the Zabriskie specimens: 1) convex discoidal ridges, 2) concave discoidal moats encircling a flat or low positive-relief interior, and 3) convex mounds characterized by second-order elements of highly variable relief, indicative of plastic deformation Specimens are commonly characterized by one or more of these motifs, and may occupy a continuum between them.

Discs preserved as convex discoidal ridges include both the largest and smallest of the Zabriskie specimens. These specimens are characterized by a general discoidal shape, without additional embellishment. Ripples preserved in the interior of the largest specimen (Figure 3.3.3) are consistent in orientation, size and general morphology with those present on the surrounding bedding plane.

Several specimens are characterized by concentric convex rings separated by a concave depression or 'moat' (Figures 3.3.4, 3.3.5 and 3.3.6). The central portions of these fossils are characterized by low positive relief and contain evidence of deformation (Figures 3.3.4, 3.3.5 and 3.3.6). This preservational style was represented among all specimens ranging from approximately 10 to 15 cm in diameter. Some evidence of folding within the interior mound was observed in each of these specimens. Faint concentric rings were observed within the concave moat of at least two specimens (Figures 3.3.4 and 3.3.5).

Several specimens are distinctively preserved in convex relief with abundant rills and striations indicative of plastic deformation.  One particularly well-preserved example (Figures 3.3.1, 3.3.2, and 3.3.4), collected from the *in situ* bedding plane, contains abundant striations of considerable relief both within the interior and along the perimeter of the fossil.  The striations associated with the specimen margins are characterized by similar relief to the striations associated with the specimen interior (Figures 3.3.2 and 3.4.2).  Cross sections cut and polished orthogonal to bedding indicate that the laminae underlying the specimens are entirely undisrupted (Figures 3.3.7 and 3.3.8).

## Interpretation

Discoidal structures generally comparable to the Zabriskie specimens are common elements of the rock record.  This commonality reflects the frequency with which ring-like impressions are produced by both biotic and abiotic processes. Hypotheses surrounding discoidal rock impressions have repeatedly been reconsidered and revised as new materials are uncovered or as new perspectives take hold (Pickerill, 1982, 1990; Hagadorn and Miller, 2011).  Interpretation of the origin of the Zabriskie specimens thus requires consideration of a wide spectrum of alternative hypotheses, including both abiogenic and alternative biogenic structures.  Interpretations of affinity must be consistent with at least five distinctive features characteristic of individual specimens and shared among the assemblage.  These are as follows: 1) Sediments immediately underlying these fossils remain undisturbed, 2) Specimens are preserved in both concave and convex epirelief, 3) “Wrinkling” along the margins of the fossils suggest isolated, plastic deformation of the sandy substrate, 4) Individual specimens are deformed parallel to the paleocurrent, and 5) The specimens are non-uniform in size, distribution, and preservational style.

Circular features observed on bedding planes are most commonly interpreted as scratch circles (Jensen et al., 2002), trace fossils (Mata et al., 2012), gas/fluid escape features (Hagadorn and Miller, 2011) and concretions (Seilacher, 2001), as well as being attributed to a variety of radially symmetrical body fossils (e.g. Gehling et al., 2000). The characteristics of each of these potential affinities are described and the Zabriskie specimens evaluated according to these criteria below.

Scratch circles (Kullingia) are discoidal features produced by currents which induce a passive interaction between ‘tethered’ (e.g. stalked and attached to the substrate by means of a holdfast) epibenthic organisms and the substrate (Jensen et al., 2002). Most commonly, these structures are produced when currents spin tubular organisms attached to the seafloor along the sediment-water interface, producing a series of low-, negative-relief concentric rings in the substrate (Jensen et al., 2002). This often produces a series of concentric “rings” that reflect repeated annulations or ornamentation along the stalk of the scratch circle-producing organism. A conical depression, representing the organism’s attachment site, is sometimes present at the center of scratch circles and, very rarely, some portion of the tubular organism may also be preserved (Jensen et al., 2002). It has been observed that the temporal distribution of scratch circles in normal marine strata is non-uniform and that there is an unusual abundance of scratch circles in Neoproterozoic and lower Paleozoic strata, potentially reflecting the firm and cohesive substrate conditions resulting from the lack of intensive bioturbation through this interview (Tarhan et al., 2015; Droser et al., 2002; Jensen et al., 2002). Given that the Zabriskie Quartzite was deposited concurrent with the peak of the scratch circle record, we have carefully evaluated the likelihood that the Zabriskie specimens might be analogous to scratch circles.

However, the features described above for the Zabriskie specimens are in stark contrast to those characteristic of scratch circles. The Zabriskie specimens are largely asymmetrical rather than perfectly circular. This asymmetry is not uniformly distributed along the bed nor is evidence of tectonic deformation observed in immediately adjacent beds. A tectonic origin for this asymmetry is therefore unlikely. Moreover, trace fossils (e.g. *Skolithos* and *Arenicolites*), body fossils (e.g. trilobites, *Harlaniella confusa*, hyolithids, etc.) and abiotic sedimentary structures observed in strata above and below the fossil-bearing bed are not characterized by evidence of tectonic deformation on the scale required to produce the alignment observed in the Zabriskie fossils. Additionally, the variable internal morphology (e.g. folds and rilling) characteristic of the Zabriskie fossils is entirely dissimilar from the smooth surface of Kullingia. The positive relief of the ridges and raised central mounds observed in the Zabriskie fossils (Fig 3.3) also suggest that a scratch circle origin is improbable, as the rotation of a tethered stalk would be expected to produce, as preserved in epirelief, a very low-relief structure with concentric furrows, rather than ridges.

Animal burrows (e.g. *Berguaeria*), gas/fluid escape structures (e.g. Astropolithon), and concretions are commonly preserved as discoidal structures along bedding planes. Such structures can be quite large, can contain considerable ornamentation and often occur *en masse* and have thus been repeatedly mistaken for fossilized medusae (Pickerill and Harris, 1979; Seilacher, 2000; Hagadorn and Miller, 2011; Mata et al., 2012). Distinguishing true medusozoan body fossils from either discoidal trace fossils or abiotic sedimentary structures is discussed collectively below, as both of these processes involve perturbation of sediment at depth, resulting in the formation of discoidal structures. Thus, distinguishing structures produced by these processes from body fossils is largely contingent upon three-dimensional data obtained from viewing materials in both bedding-plane and cross-sectional views.

Slabbed specimens reveal that laminae immediately below the Zabriskie fossils remain undisturbed (Figures 3.3.7 and 3.3.8), indicating that these structures did not form through either passive (abiotic) or active (infaunal) sediment disturbance. Sand volcanoes collected from a separate outcrop of the Zabriskie Quartzite in the Montgomery Mountains (Figure 3.3.9) contain ample evidence of sediment disruption, including fluidization and upward migration of sediments. Viewed in cross section (Figure 3.3.9), laminae are continuously interrupted for centimeters below the surface expression of each sand volcano. Sectioned Zabriskie medusa samples, however, contain undisrupted laminae within millimeters of each fossil specimen (Figures 3.3.7 and 3.3.8). In bedding plane view, the folds and asymmetry of the Zabriskie fossils provide further evidence excluding a trace fossil or non-biogenic sedimentary origin.

As radial symmetry is characteristic of the baupläne of many groups of organisms, the attribution of fossilized discoidal impressions ought to be carefully considered. Discoidal holdfasts, associated with the remains of frondose organisms, are a common component of the terminal Ediacaran-aged Ediacara Biota; structures such as *Aspidella* are broadly morphologically comparable to the Zabriskie fossils, and likewise typically occur *en masse* (Gehling et al., 2000). Precambrian holdfasts may be preserved as positive relief casts on either the tops or the bases of beds, are characterized by regular relief and pronounced external margins and may also contain concentric rings, which have been observed to incrementally gain relief toward the center of the fossil (Gehling et al., 2000).

However, the styles of preservation and general morphology of Ediacaran holdfasts make a comparable origin for the Zabriskie fossils unlikely. Evidence of an attached stalk, as might be expected from an epirelief composite holdfast (Tarhan et al., 2014), is absent from the Zabriskie specimens. Further, the margins of the Zabriskie fossils are irregular and show signs of significant biostratinomic deformation, inconsistent with the preservation of Ediacaran holdfasts which, as previously noted, are typically characterized by regular margins with pronounced relief (Gehling et al., 2000). The absence of disrupted laminae immediately beneath these fossils, as well as the absence of unidirectional strain marks—in spite of the evidence of alignment characterizing the Zabriskie fossil assemblage (Figure 3.2)—is inconsistent with a pullout origin for these fossils (Tarhan et al., 2010), as the forcible removal of a stalked organism from the substrate would disturb the immediately underlying sediment.

The features observed within individual Zabriskie specimens and characteristic of the assemblage as a whole are most characteristic of medusozoan strandings recorded in

Cambrian strata. Medusozoans are, among modern groups, considered to be among the oldest and most widespread macrofaunal zooplankton groups (Collins, 2002; Peterson and Butterfield, 2005). Phylogenetic and molecular clock data are consistent with a Precambrian origin for the Medusozoa (Collins, 2002; Peterson and Butterfield, 2005; Peterson et al., 2008) and previous reports of definitive medusa body fossils, likely representing extant crown-group lineages, extend as far back as the middle to upper Cambrian (Furongian) (Hagadorn et al., 2002; Hagadorn and Belt, 2008; Young and Hagadorn, 2010; Erwin et al., 2011). Incontrovertible fossils of mass strandings of Cambrian jellyfish have also been previously reported from the Potsdam Group of New York (Hagadorn and Belt, 2008) and the Elk Mound Group of Wisconsin (Hagadorn et al., 2002; Tarhan, 2008).

Modern medusae are characterized by a highly cosmopolitan distribution throughout nearly all marine settings. Dense aggregations or “blooms” of medusozoans in modern coastal environments are common and can be associated with both reproductive and feeding behaviors (Hamner et al., 1994; Purcell, 2003; Purcell, 2005 Magome et al., 2007; Albert 2011). Inhabitation of wave-influenced, nearshore marine environments by modern medusae commonly results in mass strandings in the intertidal zone (Figure 3.4). Behavioral observations of the scyphozoan medusa *Aurelia* suggest that migration to tidally influenced portions of the shoreline may even be active as well as passive (Albert, 2011). Medusae will position themselves in the upper portion of the water column during incoming tides in order to be washed into the intertidal zone to forage, typically riding the ebb tide back out to sea (Albert, 2011). Medusae damaged by wave activity during the venture inland or trapped in coastal depressions following the ebbing of high tide or storm waters become stranded in the intertidal zone (Figure 3.4). This not infrequently results in portions of these aggregations washing ashore *en masse* (Figure 3.4). Unlike mineralized fossils such as trilobites which bear features that, even following biostratinomic degradation can commonly be readily identified, even to the species level, the simple, radially symmetrical body plan utilized by medusozoans is convergent with that of a number of disparate taxa. This, coupled with a lack of mineralized sclerites, can make even class- or phylum-level identification of discoidal fossils, let alone categorization to a more specific level, a challenging endeavor. Here, the presence of multiple fossils along a single bedding plane becomes a vital tool in interpreting these structures. The range and variability of detail provided by concurrent preservation of immediately spatially associated individuals under largely similar environmental conditions provides an essential tool for distinguishing anatomical from taphonomic structures, as well as shedding light on the behavioral implications of medusozoan mass accumulations. The occurrence of moderately dense, spatially associated assemblages of potentially monospecific and current-deformed discoidal fossils along a single bedding plane is most consistent with a cnidarian mass stranding interpretation (though some modern ctenophores have also been observed to form dense aggregates, albeit in deeper marine settings [Reisser et al., 2013]). The strong probability that this bedding plane is part of an intertidal facies, as indicated by our observation of oscillation ripples, an absence of subtidal trace fossils, and as supported by previous, detailed facies analyses by Prave (1992), lends further credence to interpretation of the Zabriskie fossil assemblage as a medusozoan mass stranding.

The anatomy of modern cnidarian medusae generally consists of a radially symmetrical, umbrella-shaped body or “bell”, reproductive organs, a ventrally located mouth attached to the tip of a stalk-like manubrium attached to, in certain groups, oral arms, as well as, among certain groups, tentacles trailing from the bell margin. Medusae are most hydrodynamically stable with their subumbrella (ventral side) down and thus most commonly come to rest with the subumbrella in direct contact with the substrate (Schäfer and Craig, 1972; Bruton, 1991). Other areas of a medusa carcass, conversely, will commonly be skewed by wave activity or heterogenous rates of desiccation. Anatomical and taphonomic features characteristic of the Zabriskie fossils, at both the individual and assemblage scale, are consistent with those observed in other medusozoan body fossil assemblages. Flat-topped or convex central mounds, consistent with those observed in modern medusae and with previous reports of fossilized medusae (Hagadorn et al., 2002; Hagadorn and Belt, 2008; Tarhan, 2008) are present in multiple of the Zabriskie specimens (Figures 3.2, 3.3.1, 3.3.3, 3.3.4, 3.3.5, 3.3.8 and 3.4). The best preserved example among the Zabriskie fossils (Figures 3.3.1, 3.3.2 and 3.4) contains a pronounced central convex mound, along with features strongly indicative of tissue deterioration and deformation (Figures 3.3.2 and 3.4). As discussed above, the lack of disturbance of sediments directly underlying these structures suggests that these structures were produced at the sediment-water interface rather than resulting from intra-sediment bile processes such as bioturbation, sediment fluidization or post-depositional concretion formation.  While generally ovate, all of the Zabriskie fossils are elongated parallel to the direction of ripple crests along the bedding plane (Figure 3.2).  Further, several of the Zabriskie specimens are characterized by a lack of perfect radial symmetry; for instance, the raised sediment mound in the best-preserved example of the Zabriskie fossils (Figures 3.3.1, 3.3.2 and 3.4) is not centralized, which is atypical for non-medusozoan discoidal structures.

The variety of preservational motifs characteristic of the Zabriskie fossils, even along a single bedding plane is a common theme among medusa body fossils (Hagadorn et al., 2002; Hagadorn and Belt, 2008; Tarhan, 2008; Young and Hagadorn, 2010).  The prevalence of modern medusozoan strandings suggests that, in spite of their gelatinous structure, medusa carcasses possess sufficient ductility to pass through the shore-break with their bells intact.  However, once stranded and subaerially exposed, their high water content and immobility make them particularly susceptible to desiccation and scavenging.

Several of the features common among the Zabriskie specimens and which (as discussed above) independently indicate a medusozoan affinity, rather than trace fossil or abiotic or diagenetic origin have also been invoked as key characters for the identification of other fossil medusa assemblages across the Phanerozoic fossil record (Young and Hagadorn, 2010).  Young and Hagadorn (2010) summarized these characters into the following categories: 1) Fossils have a general morphology consistent with that of modern cnidarian medusae; 2) Fossils display the influence of biostratinomic factors, including preburial transport and desiccation; 3) Fossils lack the perfect radial symmetry associated with abiotic sedimentary structures; 4) Fossiliferous strata are interpreted to have been deposited in a nearshore environment similar to settings in which modern medusa strandings are commonly observed; 5) specimens occur *en masse*; and 6) the absence, in either bedding-plane or cross-sectional views, of evidence suggesting an abiotic, trace fossil or other body fossil origin. These criteria were formulated on the basis of uniformitarian principles supported by a comprehensive review of reports in the literature of putative fossilized medusae and taphonomic studies of modern medusae (Schäfer and Craig, 1972; Norris, 1989). The independent observation of features of the Zabriskie specimens consistent with each of these criteria provides additional support for a medusozoan affinity for the Zabriskie specimens.

## Taphonomy

Given the rarity with which nonmineralized tissues are preserved in the fossil record, taphonomic models detailing the biostratinomic and diagenetic histories of those relatively few examples of fossilized soft-tissues are commonly the centerpiece about which new discoveries are described. Problematically, these models are often reliant upon comparison of fossilized forms to modern analogues in the context of an ancient and commonly non-actualistic depositional paleoenvironment and diagenetic conditions. Conversely, our model consciously seeks to disentangle the role of actualistic and non-actualistic processes responsible for formation of these fossils. A model that convincingly accounts for the preservation of these fossils must account for the following features: 1) Occurrence *en masse*, 2) Preservation in both concave and convex epirelief, 3)

Deformation of specimens parallel to the paleocurrent, and 4) Plastic deformation of the sediment immediately below the animal carcass. Previous reports of Cambrian cnidarians have thus placed considerable emphasis on explaining the variety of preservational motifs observed among these fossils in the gross context of a unique and evolving Cambrian shoreline. Common taphonomic features shared by the Zabriskie fossils and other medusozoan fossil deposits include the absence of a well-developed sedimentary mixed layer and evidence of subaerial exposure, including shrinkage and desiccation structures (cf. Hagadorn et al., 2002; Hagadorn and Belt, 2008; Tarhan, 2008; Young and Hagadorn, 2010). The discovery and analysis of the Zabriskie specimens thus not only enhances back and pushes deeper in time the known fossil record of this important group of taxa, but also tests several hypotheses concerning the biological, ecological, and environmental requirements for medusozoan preservation. This discussion thus considers the fossil record of Cambrian medusozoans at the individual, assemblage and composite stratigraphic scale in further refining a taphonomic model for this exceptional preservation.

As previously noted, coastal medusan blooms related to feeding and reproduction are common in modern oceans. The high abundance of specimens observed in the Zabriskie Quartzite, Potsdam Sandstone and Elk Mound Group suggest that the aggregation of medusozoans in nearshore modern environments was a strategy employed as early as the early Cambrian (Hagadorn et al., 2002). The apparently actualistic shoreward transport of medusozoans indicated by the preservation and facies associations of the Zabriskie fossils implies that the ductile and neutrally buoyant body plan of these organisms must have played an important role in their intact transport and preservation. Modern medusozoans are, in spite of their unmineralized anatomy, able to passively maintain their structural integrity in high energy conditions and under turbulent flow while, conversely, skeletonized carcasses are commonly broken apart. Given the high morphological disparity characteristic of the Zabriskie fossil assemblage, it is possible that these fossils represent multiple generations of strandings. However, the absence of cross-cutting relationships or overlap suggests that the morphological disparity characteristic of these fossils reflects variable rates of decay, disparity between individuals stranded live and those stranded post-mortem, and potentially post-stranding secondary transport, rather than time-averaging (Figure 3.5).

The morphology of the Zabriskie specimens, as well as that of other Cambrian medusozoan fossils, appears to have been strongly shaped by biostratinomic processes. Taphonomically mediated (rather than anatomically primary) features include striations—which we interpret to record fluid-mediated rilling (Figure 3.3.7) and/or folding (Figures 3.3.4 and 3.3.5), ripples within the central mound of the fossil (Figure 3.3.3), concentric rings interpreted to represent sequential stages in carcass desiccation (Figures 3.3.4 and 3.3.5) and striations at the fossil's margin potentially linked to folding of the organism's bell (Figures 3.3.1 and 3.3.4). The preservation of Cambrian medusae in both concave and convex epirelief suggests that disparate individuals were characterized by disparity in collapse, or disparity in accumulation of (within or immediately adjacent to a medusozoan) or winnowing of sediments associated with medusozoan carcasses. Disparity in topography both within and between specimens likely reflects some combination of: 1) Sediment buildup around the perimeter of the animal's carcass, 2) Sediment sealing by the body of the organism, 3) Sediment deposition during collapse of the sand-filled endodermal elements, 4) Active substrate disturbance by the attempts of the medusozoan to free itself from stranding, and 5) Desiccation of the body of the organism during subaerial exposure (Hagadorn et al., 2002; Young and Hagadorn, 2010). These scenarios are not mutually exclusive and thus, multiple conditions may and commonly do exist within a single fossil (Hagadorn et al., 2002; Tarhan, 2008).

The fossil margins of most medusa body fossils do not form distinct boundaries, but rather, are gradational making it difficult to discern where the carcass of the animal once laid in relation to the fossil perimeter. This is particularly true among specimens with their periphery preserved as a rounded convex ridge (Figure 3.3.3 and 3.3.8). Previous models have interpreted these ridges as resulting from sediment accumulation around the perimeter of the organism (Young and Hagadorn, 2010). However, in the absence of a well-defined fossil margin, it is difficult to discern whether sediment accumulated around and on top of the margins of the jellyfish or below the organisms as a result of their bodies sealing the substrate locally (Figure 3.6.2). Constraining this relationship is significant not only in evaluating the potential sizes of these animals, but also in evaluating the nature of the substrate at this time. It should be noted that burying of modern jellyfish does not typically result in additional sediment accumulation around the margins of the organism. Rather, most commonly, as waves wash over the organism, the speed of the retreating water increases as it is forced to move around the animal while water washing over the organism depresses the carcass further into the substrate. The heightened flow surrounding the animal increases the sediment carrying capacity of the water column, thus resulting in sediment erosion rather than deposition closest to the body of the organism. In some cases, the ridges produced by this process can extend several centimeters above the surrounding substrate. A potential exception to this condition would be atop a highly porous, firm foreshore where advancing wave energy may be slowed by the body of the organism, thus lowering the sediment carrying capacity of the water. Atop highly porous media on a gently sloping coastline, wave runup may infiltrate the substrate faster than it can recede, thus causing deposition of the suspended sediment load around the body of the animal. Convex peripheral ridges observed in the largest Zabriskie specimen are paired with separated ripples preserved within the fossil interior (Figure 3.3.3) suggesting that the carcass of the animal had been removed and oscillatory currents continued prior to final burial of the bedding plane (Figure 3.6). This observation is most consistent with the initial formation of a peripheral convex ridge below, rather than surrounding, individual specimens (Figure 3.6).

Concave discoidal moats, or grooves in the substrate between two ridges, are also common among medusae body fossils (Figures 3.3.4, 3.3.5, and 3.3.6). Previous models have attributed these features to the pulsating bell of a live stranded medusa (Norris, 1989; Bruton, 1991; Hagadorn et al., 2002; Tarhan, 2008; Young and Hagadorn, 2010). The inner and outer edges of the concave ring are interpreted to represent the proximal and distal reaches, respectively, of the bell (Figure 3.6). Supplementing this potential origin, the shrinkage of a medusa carcass may also produce moats during contraction of the organism's body (Figure 3.6). Shrinkage would presumably be due to desiccation; gradual desiccation would result in sequential shrinkage and, at each stage, sediment 'strand lines' would form at the new margins of the medusa. With continued decay, disparate portions of the body collapse, leading to deformation of the internal sediment mound. Multiple distinct, concentric, raised ridges within several of the Zabriskie specimens support at least a portion of these structures being related to desiccation (Figure 3.3.4).

The finest detail preserved in stranded medusa body fossils occurs in specimens preserved wholly in convex relief, commonly as a generally smooth surface bearing some impression of the ventral portion of the original organism (Figures 3.3.1, 3.3.2 and 3.3.4). These impressions are characterized by a mound of sediment near the center of the fossil with some examples preserving quadriradiate spurs extended from this mound (Hagadorn et al., 2002). Striations at the margins of these fossils suggest slight shrinkage of the carcass prior to fossilization (Figure 3.6.4). Previous models for comparable specimens collected from the Mt. Simon-Wonewoc Formation in Wisconsin have invoked ingestion of suspended sediment prior to stranding in a jellyfish's response to the perceived environmental stress (Hagadorn et al., 2002; Young and Hagadorn, 2010). This model is explained by the following critical path:

1) Prior to being washed onto shore, modern medusa transported to shallow, turbid water in the intertidal zone may pulse their bells in an attempt to escape stranding and, in so doing, ingest sediment.
2) Following stranding and deterioration of the medusa tissues, the sediment load carried by the animal may be distinctly mounded beneath the subumbrella.

3) The sediment mound may be augmented by excavation of the surrounding sediment by the bell of the medusa, if stranded alive. Striations of variable relief surrounding the sediment mound in the center of the fossil likely reflect folding in the interior of the body of the animal.

While sediment ingestion may explain mounding in some specimens (Figure 3.6.4), this model does not sufficiently account for the occasional preservation of neither subumbrella anatomy nor observations made in modern jellyfish strandings. If sediment deposition was occurring from the gastrovascular cavity, as proposed by the sediment ingestion model, deposition would follow the decay of the body of the animal. In this scenario, it is highly unlikely that the resulting deposition would produce structures mirroring the animal's original ventral morphology as those ventral features would no longer exist. Additionally, mounds comparable to those observed in the fossil record are commonly produced below modern jellyfish entirely as a result of sedimentological processes with little to no evidence of sediment ingestion. Similar to the model presented above for the genesis of peripheral ridges, wave energy washing over and around individual modern jellyfish preferentially removes the sediment surrounding the animal. During decomposition of the organism, the mucus lining the umbrella and tentacles forms a temporary sheath, filling the pore spaces and thus binding the immediately underlying substrate, making the area temporarily more resistant to erosion. The thickest portions of the mesoglea, typically at the central portion of the bell, desiccate last, thus result in a raised sediment mound occasionally preserving evidence of the ventral portion of the umbrella, in some instances including an apical mound representing the manubrium.

Given the reduction of terrestrial grazers along Cambrian beaches and the coinciding proliferation of microbial mats in nearshore settings, it is most likely that the binding agent provided by the medusozoan mucus was further supplemented by sediment binding via filamentous microbial mats dwelling in the sandstone pore space (Noffke et al., 2002; Gehling and Droser, 2009). This hypothesis is supported by abundant sedimentary structures of likely microbial origin preserved among several examples of medusozoan body fossils exposed in Wisconsin and New York (Hagadorn et al., 2002; Hagadorn and Belt, 2008; Tarhan, 2008).

The collective taphonomic history of these fossils is fundamentally distinct from other body fossils of nonmineralized forms in that their general morphology is largely a direct record of a response to sedimentological processes surrounding the animal rather than diagenetic processes occurring post burial involving decay of the animal tissue directly. The taphonomic framework listed herein suggests that dissimilar from carbonaceous films or permineralized forms, medusozoan fossils are produced by the accumulation and/or removal of sediment in response to changes in the water column’s sediment carrying capacity as waves wash over and around the original organisms, the recording of this passive interaction being directly reflective of anactualistic environmental and ecological conditions along the Cambrian shore.

## An Analogue for Ediacaran-Style Preservation?

Preservation of soft-bodied macrofauna in proximal sandstones is largely limited to the Neoproterozoic and early Paleozoic. Sandstones house some of the most exquisite and diverse fossil assemblages of Ediacaran metazoan communities in the fossil record (see review in Narbonne, 2005) and, as evidenced by the discussion herein, also contain exquisitely preserved Cambrian soft-bodied forms. As the vast majority of Ediacaran organisms disappear with the onset of the Phanerozoic Eon, comparisons of the requirements for soft-bodied preservation across the Precambrian-Cambrian transition are integral to the discernment of a potential mass extinction event from a preservational bias in the fossil record (Seilacher et al., 2005). The discovery of the Zabriskie specimens extends the record of Phanerozoic examples of soft-bodied preservation in sandstones considerably closer to the Precambrian-Cambrian boundary sparking a need for additional comparison of Neoproterozoic and early Paleozoic taphonomic models.

While the taphonomy of Cambrian medusa body fossils is generally comparable to that of Ediacaran-aged fossil assemblages, the preservational histories of these two groups are markedly distinct. Environmental conditions which may have heightened the preservation potential of soft-bodied organisms in nearshore settings across the Precambrian-Cambrian transition include limited scavenging and the absence of a well-developed mixed layer, which, if well developed, would have increased the oxygenation of seafloor sediments and thus rates of bacterial decomposition (Jensen et al., 2005; Bottjer et al., 2000; Droser et al., 2002 ; Dornbos et al., 2005; Seilacher et al., 2005; Dornbos, 2006). Ediacara-style preservation of soft-bodied organisms has long been attributed to unique diagenetic conditions resulting from the decomposition of extensive microbial matgrounds, which acted as seals and loci for authigenic mineralization (Gehling 1999; Mapstone and McIlroy 2006; Callow and Brasier 2009; Gehling and

Droser 2009;). This process resulted in highly-detailed casts and molds of a diverse array of organisms being preserved on the bases of sandstone beds deposited below wave base (Gehling, 1999; Gehling and Droser, 2013; Tarhan et al., 2015). In contrast, the indirect preservation of cnidarian medusae along bed tops does not indicate a direct role in diagenesis played by microbial mats, but rather, most importantly, requires a lack of erosional exhumation or disturbance by scavenging and bioturbating organisms. While microbial fabrics likely helped to bind the substrate and limit infaunal disturbance elsewhere in these settings (Seilacher and Pflüger, 1994; Jensen et al., 2005), the presence and decomposition of microbial mats does not appear to have exercised a direct control upon the diagenetic processes that led to the preservation of the Zabriskie medusae. Thus, while the preservation of medusozoans in Cambrian strata requires many of the same elements as required for Ediacaran styles of preservation (i.e. limited bioturbation/scavenging and microbial bound substrates), the taphonomic models for Precambrian and early Phanerozoic preservation in nearshore sandstones are fundamentally distinct. Therefore, it seems probable that, although the taphonomic window responsible for preservation of soft-bodied macrofauna in coarse-grained siliciclastics remained open, at least in certain nearshore settings, into the Cambrian, a major ecological transformation and/or an extinction event is not supported by the taphonomic implications of Cambrian medusae.

Perhaps the most intriguing preservational link between the Ediacara biota and Cambrian medusae is in the comparison between the predominant depositional settings housing each of these fossil groups. While fundamental components of Neoproterozoic taphonomic models including microbial mats and limited bioturbation are continued themes in Cambrian taphonomic models, the depositional setting of the Zabriskie fossils and similar Cambrian medusa-bearing deposits (e.g. Hagadorn et al., 2002), unlike the Ediacaran fossil record, is intertidal. Fossils of the Ediacara biota are exceedingly rare in shoreface sandstone facies (Gehling and Droser, 2013; Tarhan et al., 2015). The strict limitation of Cambrian soft-bodied preservation in sandstones to marginal marine facies suggests a significant migration of fossil preservation in nearshore sands from subtidal to intertidal environments. Thus, the Zabriskie fossils not only shed new light on the preservational history of this long-lived and ecologically significant clade of organisms, these fossils also yield insight into the taphonomic windows that fostered soft-bodied preservation in nearshore settings through the Precambrian–Cambrian transition.

## Significance

Medusozoans are considered among the oldest and most widespread macrofaunal zooplankton groups in modern oceans (Collins, 2002; Peterson and Butterfield, 2005; Collins et al., 2006) and yet, despite the abundance, ubiquity and deep evolutionary history of medusozoans, the fossil record of this subphylum is exceedingly sparse. The rarity of fossilized medusae, coupled with the importance of these animals in modern ecosystems, highlights the significance of expanding both the temporal and spatial distribution of the medusozoan fossil dataset. The discovery of these fossils not only extends the fossil record of cnidarian medusae back several tens of millions of years to the early Cambrian, but also further substantiates claims that jellyfish were abundant and widespread components of Cambrian marine ecosystems (Hagadorn et al., 2002; Hagadorn and Belt, 2008; Young and Hagadorn, 2010; Erwin et al., 2011). Given the simple body plans utilized by these organisms, distinguishable features are rarely preserved within individual specimens, a phenomenon most likely at least partially responsible for the previously mentioned misidentification of various disc-shaped impressions in rock. Rather, the interpretation of discoidal impressions as having been produced by stranded jellyfish requires consideration of the behavior and preservational history of these organisms in conjunction with the morphological details preserved within individual specimens.

In addition to providing evidence of the evolutionary history and ancient behavior of a critical component of the modern marine realm, these fossils contain a wealth of taphonomic information that may shed considerable light upon the anactualistic biostratinomic and diagenetic conditions present within nearshore settings at the onset of the Phanerozoic. Seeming to compound the general unlikelihood of preserving nonmineralized tissues (Gaines et al., 2005; Gaines et al., 2008 ; Garson et al., 2012), the high water content and near-neutral buoyancy of medusae would, at first glance, seem to be insurmountable biostratinomic hurdles. However, in light of the taphonomic evidence preserved among Cambrian medusae, the unique physiological properties of the medusozoa are likely what make these animals capable of remaining intact during transport to the shoreline to produce the sedimentary structures now preserved in the rock record.

While rare, the highest concentrations of putative medusae body fossils occur in early Phanerozoic strata. The concentration of medusae fossil-bearing intervals in Cambrian strata suggests that the taphonomic conditions conducive to their preservation were most widespread at this time. The preponderance of passive margins surrounding much of Laurentia through the Cambrian would have provided the ideal environmental setting for medusa stranding events to occur and be preserved over a wide geographic area. Thus, along the early Cambrian shoreline, the confluence between a significantly reduced terrestrial biosphere and an ocean teeming with complex metazoan life would have yielded a fundamentally distinct environment that, in rare instances, served as a preservational sanctuary for some medusozoans. Both notable and intriguing, this model also suggests that while several elements were required for the preservation of both Ediacaran and Cambrian forms, the taphonomic histories of these two groups are distinct, implying a shift in the preferred environments for soft-bodied preservation from subtidal to intertidal facies.

## Conclusions

As a whole, the lower Cambrian fossil record is critical to the understanding of environmental and ecological evolution during one of the most significant intervals in the history of life on Earth. Substantial alteration to ocean chemistry (Berner et al., 2007; Canfield and Farquhar, 2009), substrate conditions (Seilacher and Pflüger, 2004), sedimentology (Bottjer et al., 2000), and ecological structuring (Droser and Bottjer, 1988; Fortey and Owens, 1999; Butterfield, 2001; Droser and Li, 2001; Vannier, 2007) suggest that the early Cambrian was a pivotal time in the mutual development of metazoan ecosystems and environments. The sudden and global appearance of metazoan macrofossils in Ediacaran sandstones suggests a proliferation of mostly sessile life in shallow marine environments by at least ~555 million years ago (ma). Trace fossils observed in Cambrian littoral facies suggest that coastal marine life continued to flourish and became increasingly mobile during the transition into the Phanerozoic Eon. And making Ediacaran and Cambrian shorelines fundamentally unique to those present at any other time in Earth's history, these early metazoan ecosystems lacked a terrestrial counterpart and interacted with a substrate inhabited by dense and widespread colonies of microbes. The fossil record of cnidarian medusae thus provides a unique resource for reconstructing both environmental and paleobiological dynamics concomitant with the diversification of early metazoan life.

The taphonomic model presented herein for stranded Cambrian medusae can be summarized as follows (Figure 3.6):

1) Cambrian medusozoans aggregating adjacent to the shoreline were carried toward shore by either strong wave currents or changes in the tides. Wave turbulence was absorbed by the ductile bodies of these organisms while their near-neutral buoyancy facilitated continued shoreward transport. Sediment-laden water may have been ingested by some organisms; however, evidence for this phenomenon is sparse.
2) Medusae may have come to rest on the shoreline as live individuals or as corpses. Living organisms may have attempted to free themselves by

oscillating their bells while the bodies of other stranded organisms begin to desiccate. Either process may have etched concentric rings into the seafloor.

3) Continued wave activity likely resulted in the erosion and deposition of sediments surrounding the stranded organisms and progressive depression of the organism into the underlying substrate. The interior portions of these fossils likely record either: 1) Secondary transport of an individual resulting in the removal of the body of the organism, or 2) Protracted decomposition of the body of the animal and associated sediment binding.
4) Limited terrestrial scavenging and bioturbation left this portion of the substrate undisturbed during subaerial exposure. Microbial mats, or a similar binding agent, along the shoreline allowed the sand to record this plastic deformation following the full decay and/or removal of the body of the jellyfish.

This preservational pathway refines previous models for the preservation of Cnidarian medusae by deemphasizing the importance of sediment transport and diagenetic mechanisms involving the animals themselves and emphasizing the significance of sedimentological processes surrounding a gelatinous organism stranded along a microbially-bound substrate. Despite the modern shoreline being markedly distinct from the shores of the Cambrian Period, the similarities shared by both modern and ancient forms suggest that a uniformitarian approach can be applied to evaluating the origins of these features. While morphological aspects reported in the Zabriskie specimens and other Cambrian medusa fossils are commonly produced when jellyfish are stranded along modern shorelines, these structures are quickly eliminated by scavenging, bioturbation, waves, wind and sediment instability. In the absence of a pliable sediment binding agent, sand is inherently precluded from the types of plastic deformation observed within Cambrian jellyfish fossils. However, as evidenced by the spatiotemporal isolation of fossilized medusozoan strandings, anactualistic environmental conditions including a near absence of bioturbation and scavenging immediately upslope of the littoral zone are required for these features to be preserved in the rock record. While previous investigations have suggested that microbial mats likely played a role in the preservation of Cambrian medusae (Hagadorn et al., 2002), the evaluation presented herein suggests that their presence was likely a fundamental requirement for medusozoan preservation in unconsolidated Cambrian sands. Thus, a significant portion of the fossil record of cnidarian medusae is intricately linked to early Paleozoic substrate evolution (Tarhan et al., 2015). The spatiotemporal isolation of aggregate medusa body fossils is thus likely to be a response to changes in critical shear stress among coastal substrates through the onset of the Phanerozoic.

The sporadic nature of the medusa fossil record and the insights this record can provide into both the original organisms and their surrounding environments highlights the importance of future discoveries. Armed with a robust taphonomic model for medusozoans and a newfound awareness of their presence in Cambrian-aged intertidal facies, future goals should include identifying those units and localities most likely to house them. Cambrian sheet sandstones comparable to the Zabriskie Quartzite are globally distributed. The cosmopolitan distribution of Precambrian–Cambrian sheet sandstones (Dott, 2003) and the apparent proclivity for preservation of medusa fossils in such facies indicates that these units should be prime targets in the search for additional soft-bodied macrofossils. The discovery of the Zabriskie fossils is a prime example of soft-bodied preservation within a sedimentary package long considered to be devoid of macrofossils, emphasizing the importance of a detailed cataloguing of similar Cambrian lithofacies.

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## Figures

Figure 3.1. Location map (right) and stratigraphic sections (left) of the Zabriskie Quartzite: 1, type section for Zabriskie Quartzite in Resting Springs Range (adapted from Prave, 1992); 2, Nopah Range section showing approximate stratigraphic position of medusoid body fossils.

**Figure 3.1**

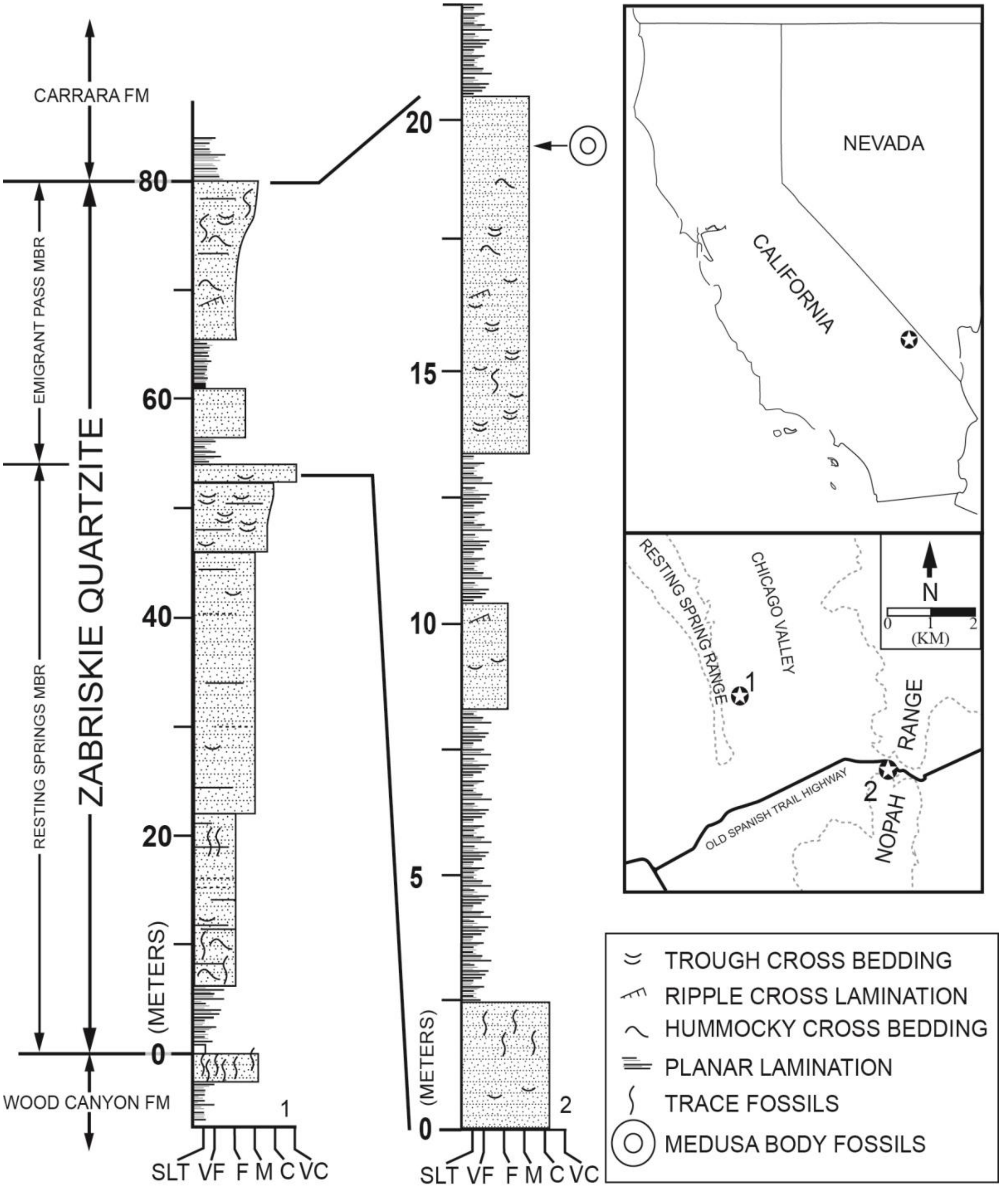

CARRARA FM
80
60
40
20
0
EMIGRANT PASS MBR
RESTING SPRINGS MBR
ZABRISKIE QUARTZITE
(METERS)
WOOD CANYON FM
1
SLT VF F M C VC
20
15
10
5
0
(METERS)
2
SLT VF F M C VC
NEVADA
CALIFORNIA
RESTING SPRING RANGE
CHICAGO VALLEY
N
0 1 2
(KM)
1
RANGE
2
NOPAH
OLD SPANISH TRAIL HIGHWAY
TROUGH CROSS BEDDING
RIPPLE CROSS LAMINATION
HUMMOCKY CROSS BEDDING
PLANAR LAMINATION
TRACE FOSSILS
MEDUSA BODY FOSSILS

Figure 3.2. Excavated fossiliferous bedding plane in the Zabriskie Quartzite: 1, Panoramic photo of excavated bedding plane following 25 cm x 25 cm grid application; 2, Line drawing of fossils mapped on bedding plane. Numbered boxes coincide with specimen labels in Figure 3.3. Scale bars are 25 cm.

**Figure 3.2**

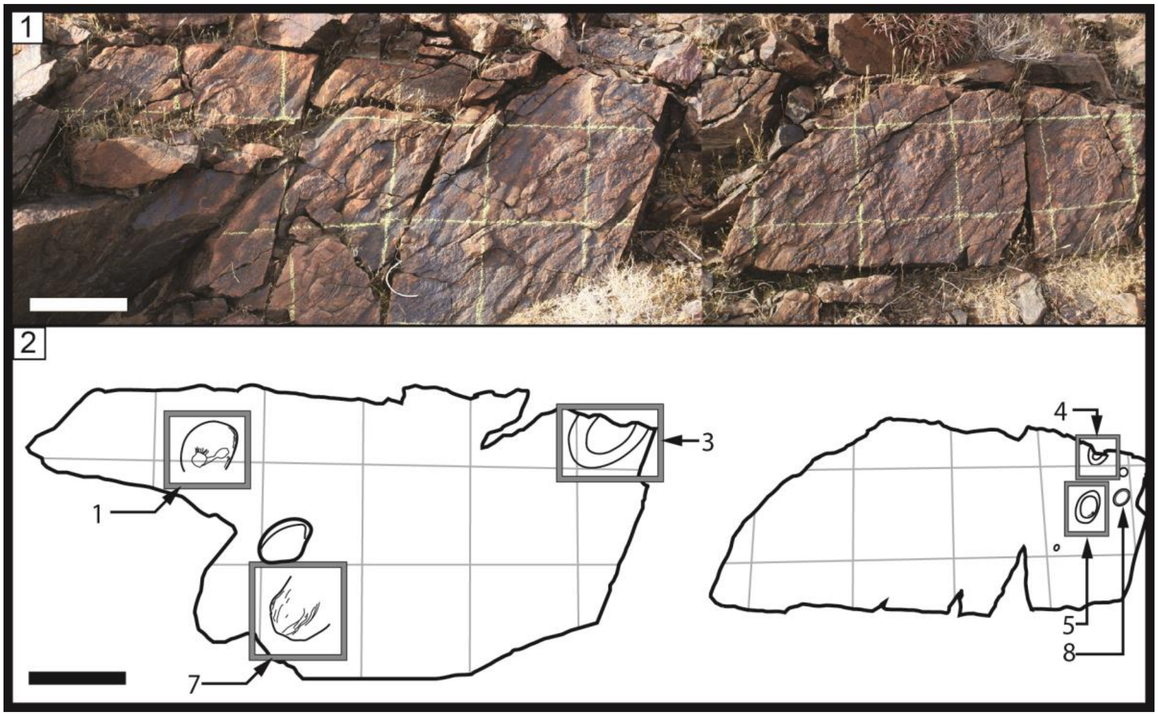


Figure 3.3. Lower Cambrian medusa fossils from the Zabriskie Quartzite: 1, (UCR11131-1), Specimen preserving evidence of sediment infill (white arrow); 2, (UCR11131-1), Close up of fossil shown in Figure 3.1 showing evidence of folding adjacent to the central mound and along the fossil's marginal furrow (A). "C" indicates bulbous structure projecting from the fossil's central mound; 3, (UCR11131-2), Large fossil containing ripples (white arrows indicate ripple crests) in the interior of the specimen, suggesting collapse of a portion of the carcass interior prior to burial; 4, (UCR11131-3), Discoidal specimen with 2 primary concentric ridges (A) and evidence of folding in the central mound of the fossil (B); 5, (UCR11131-4), Discoidal specimen with 2 primary concentric ridges (C) and evidence of folding in the central mound of the fossil (B); 6, (UCR11131-5), Discoidal specimen with 2 primary concentric ridges (a) and evidence of folding in the central mound of the fossil (B); 7, (UCR11131-6), Specimen showing evidence of preburial deformation ("rilling"). Scale bar is 1 cm. Corresponding image A-A'-A" shows cross sectional view through the specimen. Undisturbed laminae immediately underlying the specimen are indicated by the white arrows; 8, (UCR11131-7), Discoidal specimen with a single marginal ridge (white arrow). Corresponding image B-B' shows cross sectional view through the specimen. Undisturbed laminae immediately underlying the specimen are indicated by the white arrows; 9, (UCR11132-1), White arrows indicate abiotic sedimentary structures ("sand volcanoes") from an outcrop of the Zabriskie Quartzite in the Montgomery Mountains (western Nevada). Corresponding image C-C' shows cross sectional view through one of these structures. Note evidence of fluidization and upward migration of underlying sediments. Scale bars equal 5 cm in images 1-6 and 1 cm in images 7-9.

**Figure 3.3**

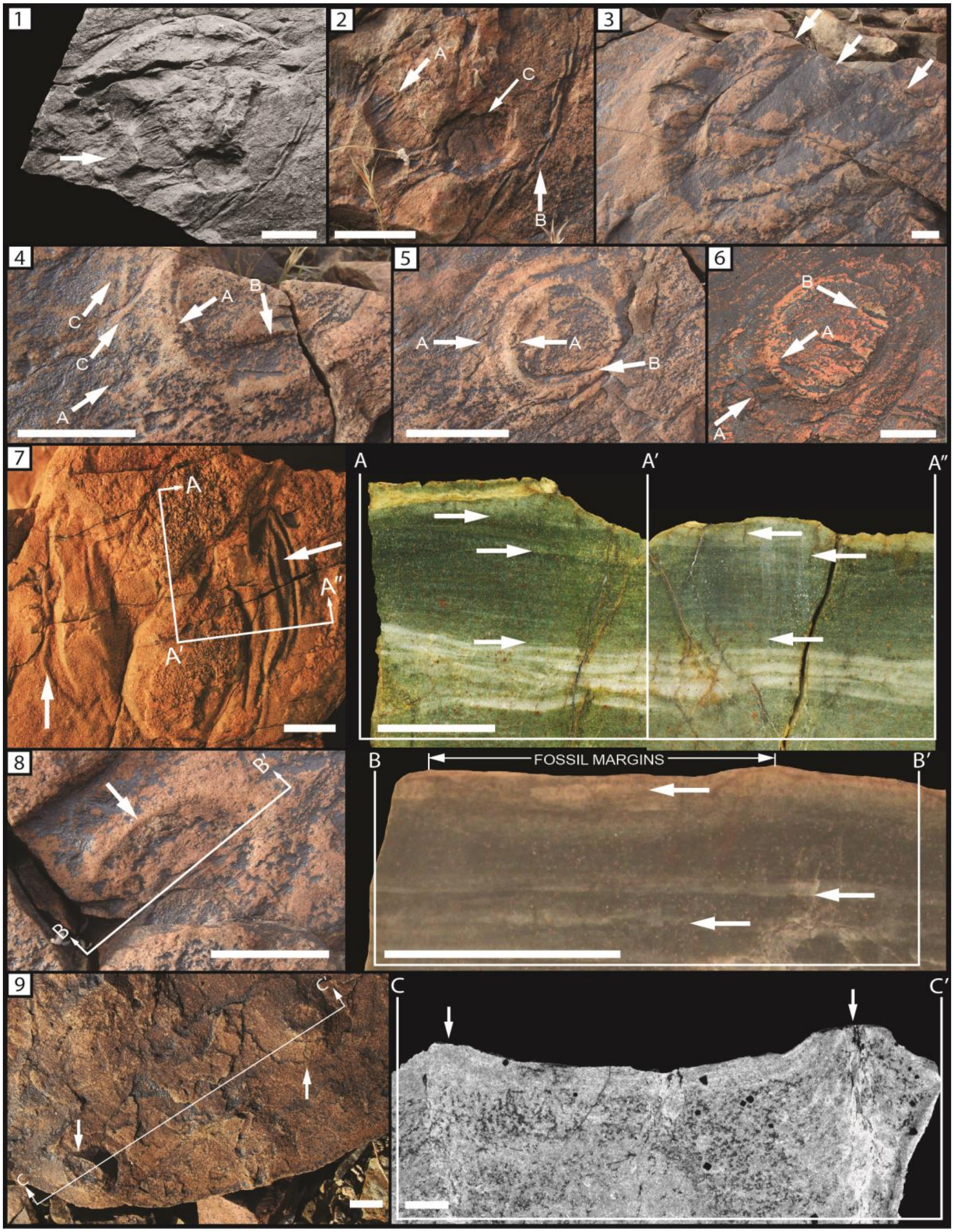

1
2
A
C
B
3
4
C
C
A
A
B
5
A
A
B
6
B
A
A
7
A
A'
A''
A
A'
A''
8
B'
B
B
FOSSIL MARGINS
B'
9
C'
C
C
C'

Figure 3.4. Photograph (1) and corresponding tracing (2) of major features observed in Zabriskie specimen (UCR11131-1). See also Figure 3.1 and 3.2. Scale bars equal 5 cm.

**Figure 3.4**

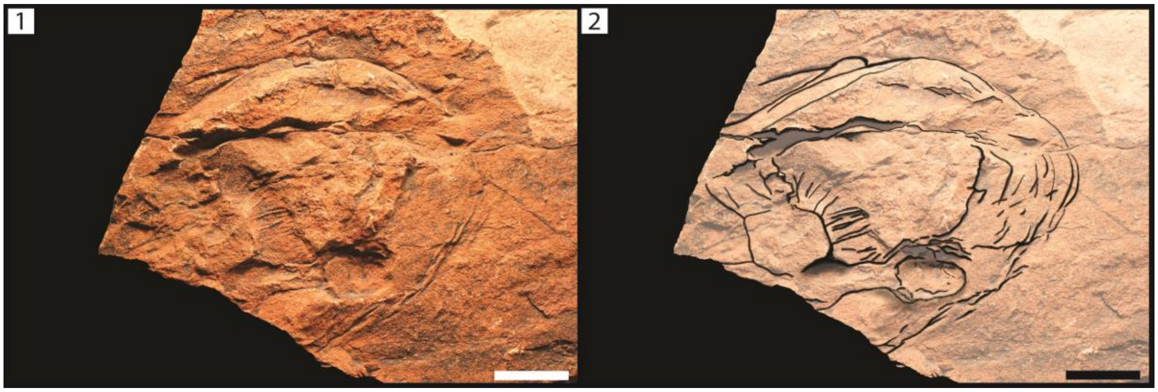


Figure 3.5—Transport model for the Zabriskie cnidarian medusa strandings: 1, Nearshore medusa bloom. Relatively undisturbed microbial mat (darker shading) in the intertidal zone; 2, High tide results in movement of the medusae to the upper portions of the water column, using the incoming tide to migrate further toward shore. Some individuals are damaged by wave activity; 3, Receding tide results in stranding and subaerial exposure of some of the medusae. Numbers correspond to taphonomic models outlined in Figure 3.6.

**Figure 3.5**

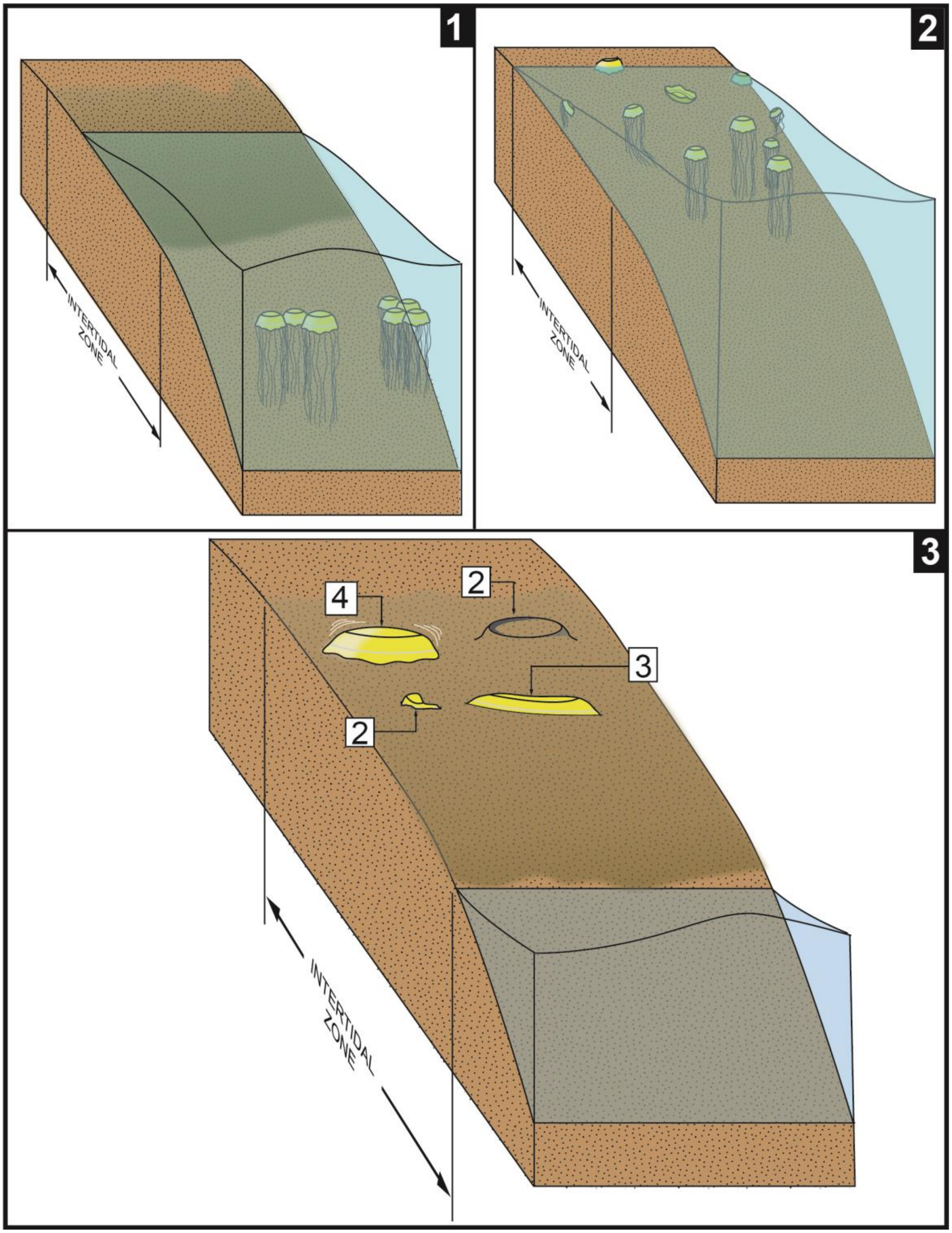
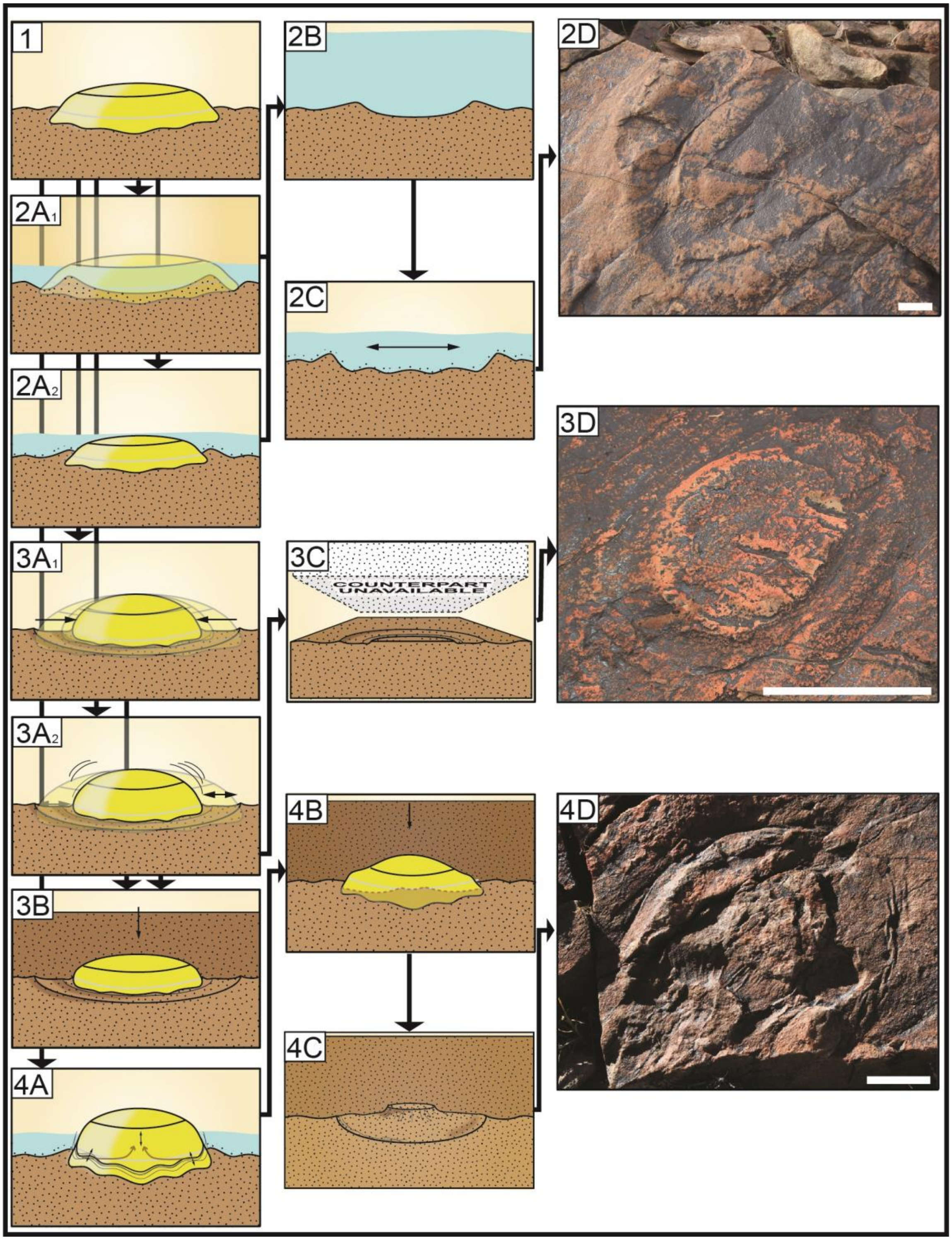


Figure 3.6—Taphonomic model schematics for the various preservational modes observed in Zabriskie cnidarian medusae. Note that these preservational models are not mutually exclusive and that cnidarian medusa fossils are capable of preserving steps along any or multiple of these preservational pathways. Also note, the bells of modern medusae will typically experience significant flattening and widening upon stranding. For clarification of taphonomic features observed in the Zabriskie fossils, vertical relief in these medusa schematics has been exaggerated: 1, Initial medusa stranding; 2A1, Tide-mobilized sediment is removed from the margins of the medusa or, 2A2, Tide-mobilized sediment begins accumulating at the margins of the medusa; 2B, Medusa carcass either collapses or is completely removed by wave activity; 2C, Sedimentation continues, resulting in ripple formation in the depression left by the collapsed or removed medusa carcass; 2D, (UCR11131-1), Example of this preservational style from the Zabriskie Quartzite; 3A1, Stranded medusa begins to desiccate, sequentially excavating a moat between two prominent ridges representing the distal (outer ridge) reach of the bell and intermittent phases of dessication, or 3A2, Stranded medusa begins to pulsate, excavating a moat between two prominent ridges representing the proximal (inner ridge) and distal (outer ridge) reaches of the bells; 3B, Medusa is buried and collapses; 3C, Collapsed or flattening of the medusa results in deformation or flattening in the interior of the fossil; 3D, (UCR11131-2), Example of this preservational style from the Zabriskie Quartzite; 4A, Wave activity presses on a stranded medusa deforming the plastic substrate below it, resulting in sediment mounding beneath the subumbrella and production of a well-defined marginal furrow; 4B, Medusa burial causes collapse of the organism; 4C, Lithification of the underlying sediments prior to complete decay of the organism results in casting of the desiccated and deformed carcass; 4D, (UCR11131-5), Example of this preservational style from the Zabriskie Quartzite. Scale bars are 5 cm.

**Figure 3.6**


1
2A₁
2A₂
3A₁
3A₂
3B
4A
2B
2C
3C
COUNTERPART UNAVAILABLE
4B
4C
2D
3D
4D