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The Environmental Context of Gastropods on Western Laurentia (Basin and Range Province) During the Great Ordovician Biodiversification Event

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The Environmental Context of Gastropods on Western Laurentia (Basin and Range Province) During the Great Ordovician Biodiversification Event

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

Doctor of Philosophy

in

Geological Sciences

by

Robyn Mieko Dahl

December 2015

Dissertation Committee:
Dr. Mary Droser, Chairperson
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Committee Chairperson

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DEDICATION

I dedicate this work to my family, who has always supported me and encouraged me in my unexpected endeavors. To my parents, Karin Yamasaki and Ron Dahl, who believed in me even when I didn't, and to my grandmas, Solveig Dahl and Reiko Yamasaki, who's pride and love kept me motivated.

ABSTRACT OF THE DISSERTATION

The Environmental Context of Gastropods on Western Laurentia (Basin and Range Province) During the Great Ordovician Biodiversification Event

by

Robyn Mieko Dahl

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

Gastropods are a major component of modern marine ecosystems and can be found in nearly every type of marine ecosystem. Gastropods experienced their first radiation during the Great Ordovician Biodiversification Event (~470 Ma), during which their diversity tripled. This study examines the gastropod assemblage preserved in the Basin and Range Province of the Western United States to establish the environmental context for the Ordovician gastropod radiation. Gastropods are present within every facies examined, but their relative abundance and distribution varies. Gastropods are rare in normal marine settings and abundant in harsh (i.e., dysoxic, hypersaline) environments. Environmental context of Ordovician gastropods is shown to impact survivorship through the end-Ordovician extinction event and throughout the Paleozoic and Mesozoic.

Collecting accurate density data for fossil deposits can prove challenging, especially when beds are not exposed in plane view. In these cases, paleontologists are tasked with reconstructing shellbed density from cross section exposure. This study presents a mathematical model to calculate the density of fossil material within a bed from bedding cross section counts. The model is calibrated against an Ordovician biofacies comprised of oncoids, macluritid gastropods and receptaculitids exposed in the Arrow Canyon Range of Southern Nevada, where unique preservation provides both cross section exposures and plan view of fossil concentrations.

University Earth Science Departments seeking to establish impactful geoscience outreach programs often pursue large-scale, grant funded programs. While this type of outreach is highly successful, it is also extremely costly, and grant funding can be difficult to secure. Here, we present the Geoscience Education Outreach Program (GEOP), a small-scale, very affordable model tested over five years in the Department of Earth Sciences at UCR. GEOP provides a variety of outreach events and allows UCR Earth Sciences to participate in a wide range of community events. The GEOP model prioritizes simplicity, flexibility and affordability in order to best meet the educational needs of Riverside County, CA.

Table of Contents

Chapter 1: Environmental Analysis of Ordovician Gastropods in the Basin and Range Province

Chapter 2: Modeling the Density of Fossils from Cross-Section Exposures: An Example from the Ordovician of the Arrow Canyon Range, NV

Chapter 3: Building an Effective and Affordable K-12 Geoscience Outreach Program from the Ground Up: A Simple Model for Universities

APPENDICES

List of Figures

CHAPTER 1

CHAPTER 2

CHAPTER 3

List of Tables

CHAPTER 1

CHAPTER 3

CHAPTER 1:
ENVIRONMENTAL ANALYSIS OF ORDOVICIAN GASTROPODS IN THE BASIN AND RANGE PROVINCE

ABSTRACT

Gastropods are a major component of modern marine ecosystems and can be found in nearly every type of marine ecosystem. They experienced their first notable radiation during the Great Ordovician Biodiversification Event (~470 Ma), during which their diversity tripled. This study examines the gastropod assemblage preserved in the Basin and Range Province of the Western United States to establish the environmental context for the Ordovician gastropod radiation. Gastropods are present within every facies examined, but their relative abundance and distribution varies; they are rare in normal marine settings and abundant in harsh (i.e., dysoxic, hypersaline) environments. Environmental context of Ordovician gastropods is shown to impact survivorship through the end-Ordovician extinction event and throughout the Paleozoic and Mesozoic.

INTRODUCTION

Gastropods are the most diverse and ecologically successful invertebrate clade in the modern ocean (Fryda et al., 2008; Bouchet and Rocroi, 2005). Modern marine gastropod species diversity is estimated at 60-80k, with representatives in nearly every type of ecosystem from the deepest marine trenches to tidal flats (Bouchet and Rocroi, 2005; Hughes, 1986). The clade's latitudinal range extends from the tropics to the poles (Clark and Crame, 2010). Gastropods are well known for having adapted to nearly every marine mode of life, including suspension feeding, carnivory, herbivory, deposit feeding, and ectoparasitism, and have also evolved to possess an array of elaborate behavioral and chemical defenses and predation techniques, such as efficient drilling methods and venom, which have aided in their post-Paleozoic rise to ecological dominance (Hughes, 1986; Vermeij, 1977). Furthermore, gastropods comprise the largest of the molluscan classes and are a major component of the Modern Evolutionary Fauna (Sepkoski, 1981). Members of this important clade often occupy keystone positions within modern benthic marine ecosystems and are responsible for maintaining ecosystem health (Paine, 1969).

Gastropods experienced their first global radiation event during the Great Ordovician Biodiversification Event (GOBE) (Alroy, 2010; Fryda et al., 2008; Fryda & Rohr, 2004; Erwin and Signor, 1990) (Figure 1.1). During the GOBE, gastropod diversity increased by over 60% in a double-pulsed radiation, with peak diversity occurring during the Whiterockian (Novack-Gottshall and Miller, 2003). Despite this dramatic diversification, gastropods have remained underexamined in surveys of Ordovician paleoecology, with only passing mention made of the clade in seminal publications (Finnegan and Droser, 2008; Boyer and Droser, 2003; Harper, 2006; Miller, 1997; Droser et al., 1995; Sepkoski and Sheehan, 1983; Hintze, 1973; Walcott, 1884).

The lack of research focus on gastropods is likely due to the combination of several factors: (1) lack of biostratigraphic application due to relatively simple morphology resulting in high occurrences of homoplasy, (2) aragonitic shell mineralogy resulting in markedly poor preservation of most specimens, and (3) rarity compared to other more dominant Paleozoic clades like brachiopods and trilobites. These factors have influenced the past century of research on the GOBE, and have driven the assumption that gastropods are of little paleoecological importance in Ordovician fossil assemblages.

Our understanding of Ordovician gastropods is also influenced by collection and database biases. Because of their poor preservation, surveys of Ordovician gastropod diversity (Rohr, 1994, 1996) have focused solely on silicified assemblages. While silicification produces better-preserved specimens, it limits our ecological understanding of gastropods because sampling is restricted to environments in which silicification has occurred. This sampling bias is magnified by the reliance on databases like the Paleobiology Database, since database entries are dependent on published collections.

The environments in which animals originate impact evolution. Jablonski et al. (1983) and Sepkoski and Sheehan (1983) both demonstrated that most marine communities exhibit a strong onshore-offshore trend, in which benthic assemblages originate in shallow marine environments and radiate into deeper water environments. In these studies, onshore-offshore trends are examined from a community perspective, and gastropods are combined with other taxa. For example, Jablonski et al. (1983) combined gastropods with orthid brachiopods, trepostome and cryptostome bryozoans, crinoids, and ptychopariid trilobites to form the Ordovician Shelf Community, which exhibits an onshore-offshore radiation trend (Figure 1.2).

Gastropods were diversifying rapidly during the GOBE, and this event sets the stage for a long and atypical evolutionary trajectory. By the Middle Ordovician, gastropods on Laurentia were widespread and are found in all depositional environments present on the carbonate platform and shelf, defying the typical onshore-offshore trend. The environmental context of this first diversification is a necessary component for understanding the mechanisms that shaped gastropod evolution throughout the Phanerozoic. In this study, we turn to the rich Ordovician fossil assemblage preserved in the Basin and Range Province of the Western United States to quantify the environmental context of gastropods and analyze how this context impacts the evolutionary trajectory of this important marine clade. We find that the environments in which gastropods were adapted to influence their survivorship through the end-Ordovician mass extinction event and ultimately throughout the Phanerozoic.

Figure 1.1
Gastropod diversity (shown in red) throughout the (A) Phanerozoic (Alroy, 2010) and, (B) the Ordovician (Novack-Gottschall and Miller, 2003).

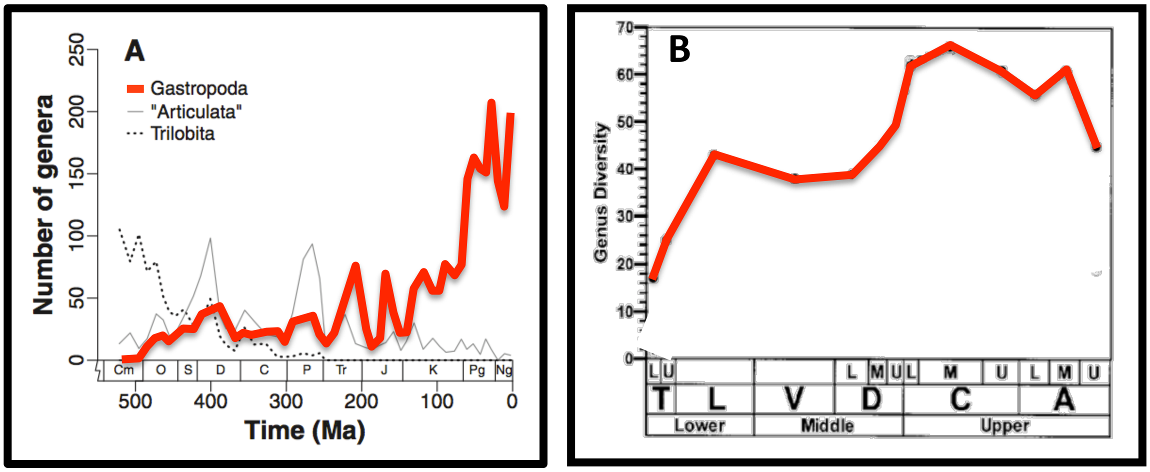


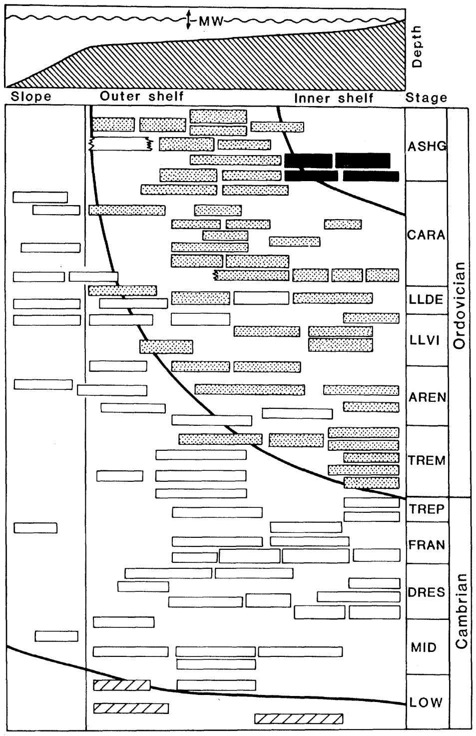
Figure 1.2

(page 9)

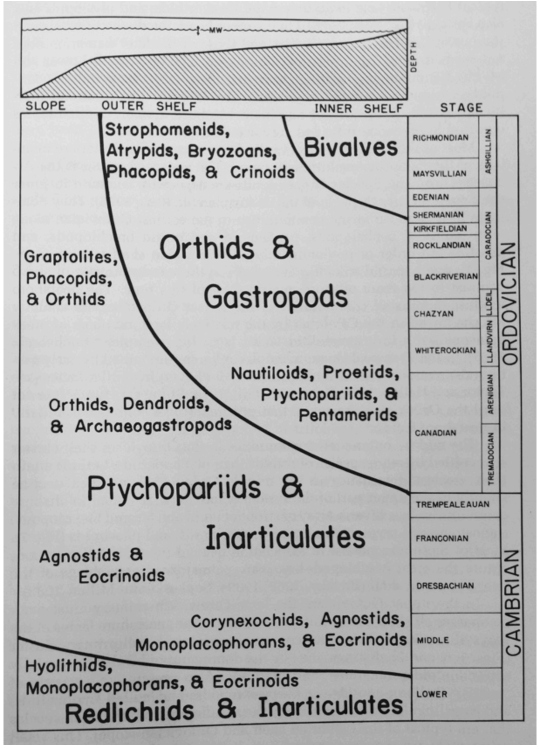
A. Time-environment diagram showing the distribution of four primary clusters of Cambro-Ordovician fossil communities. Each box in the diagram represents a single community; the horizontal position shows its approximate environment range. Cluster membership of each community is indicated by patterning (diagonal ruling, lower Cambrian shelf cluster unified by the joint possession of redlichiid trilobites, hyolithids, and inarticulate brachiopods; blank, Middle Cambrian to Lower Ordovician shelf and Ordovician slope cluster unifed by the joint possession of diverse ptychopariid trilobies and lingulid and acrotretid brachiopods; stippling, Ordovician shelf cluster unified by diverse orthid brachiopods, archaeogastropods, trepostome and crytostome bryozoans, crinoids, and some ptychopariid trilobites; solid black, Upper Ordovician inner shelf cluster distinguished by the dominance of bivalves, especially modiomorphoids, nuculoids, and pteriodes). Cluster boundaries strongly time-transgressive, indicating that major faunal associations originate in the nearshore environments and spread across the shelf. Stages from the bottom to top are as follows: Lower, Middle, Dresbachian, Franconian, Trempealeauan, Tremadocian, Arenigian, Llanvironian, Llandeilian, Caradocian, and Ashgillian. (figure from Jablonski et al., 1983)

B. A mapping of onshore-offshore pattens observed in principal Cambro-Ordovician benthic taxa. (figure from Sepkoski and Sheehan, 1983).

A


MW
Depth
Slope
Outer shelf
Inner shelf
Stage
ASHG
CARA
LLDE
LLVI
AREN
TREM
TREP
FRAN
DRES
MID
LOW
Ordovician
Cambrian

B


MW
DEPTH
SLOPE
OUTER SHELF
INNER SHELF
STAGE
Strophomenids, Atrypids, Bryozoans, Phacopids, & Crinoids
Bivalves
Orthids & Gastropods
Graptolites, Phacopids, & Orthids
Nautiloids, Proetids, Ptychopariids, & Pentamerids
Orthids, Dendroids, & Archaeogastropods
Ptychopariids & Inarticulates
Agnostids & Eocrinoids
Corynexochids, Agnostids, Monoplacophorans, & Eocrinoids
Hyolithids, Monoplacophorans, & Eocrinoids
Redlichiids & Inarticulates
RICHMONDIAN
MAYSVILLIAN
EDENIAN
SHERMANIAN
KIRKFIELDIAN
ROCKLANDIAN
BLACKRIVERIAN
CHAZYAN
WHITEROCKIAN
CANADIAN
TREMPEALEAUAN
FRANCONIAN
DRESBACHIAN
MIDDLE
LOWER
ASHGILLIAN
CARADOCIAN
LLDEIL
LLANDVIRN
ARENIGIAN
TREMADOCIAN
ORDOVICIAN
CAMBRIAN

BACKGROUND ON ORDOVICIAN GASTROPODS

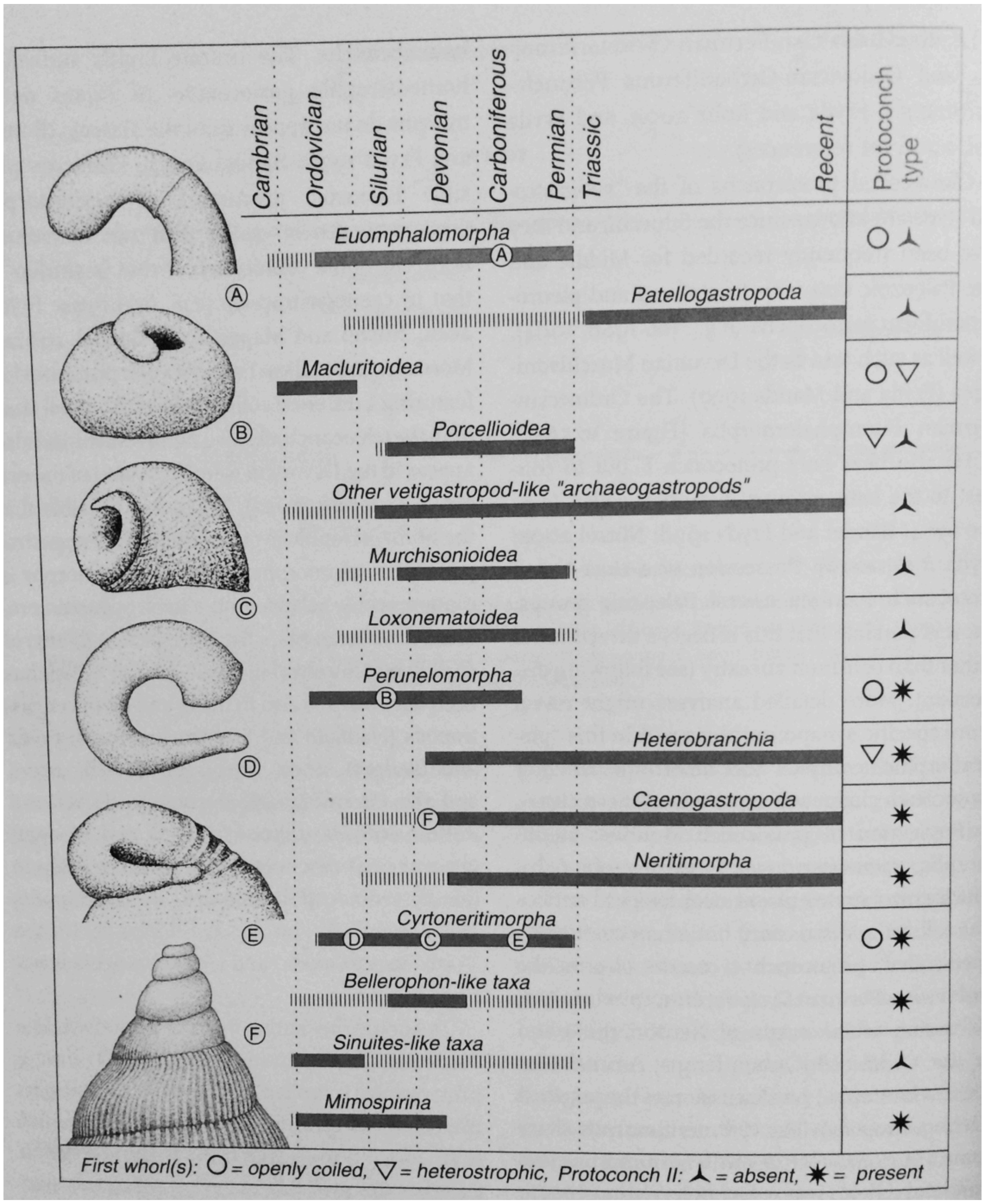
Gastropods evolved in the latest Cambrian and experienced their first major global radiation during the GOBE (Fryda et al., 2008). After this initial radiation, gastropods maintained steady diversity throughout the rest of the Paleozoic, an evolutionary trend so unusual for marine clades that Erwin and Signor (1990) dubbed gastropods an "extinction-proof" clade. In their examination of this trend, Erwin and Signor (1990) found that the apparent stasis in diversity throughout the Paleozoic was in fact a pattern of evolution at lower taxonomic levels (familial or generic). Early Paleozoic subclades suffered high extinction rates during the end Ordovician and Devonian mass extinction events, but were quickly replaced by new subclades and so the total diversity of gastropods appeared static (Erwin and Signor, 1990). Furthermore, while much work has been done in attempt to tease apart the complex phylogeny of this important marine clade (e.g., Fryda et al., 2008; Wagner and Erwin, 2006; Wagner, 2001) and several studies have examined the taxonomic diversity of Paleozoic gastropods (e.g., Rohr, 1996; Rohr, 1994), little examination of this clade's Paleozoic paleoecology has been undertaken.

Novack-Gottshall and Miller (2003) used the Paleobiology Database to examine geographic and environmental diversity dynamics for Ordovician gastropods and bivalves, and found that gastropods experienced a double-pulsed radiation, diversifying rapidly in the Early Ordovician (Tremadocian) and again in the late Middle Ordovician (Darwillian) (Figure 1.1). They found that gastropods were globally widespread and showed the highest generic diversity in shallow offshore settings. This pattern holds true for global and regional (Basin and Range) analyses. A more detailed paleoenvironmental analysis is not provided, likely due to the nature of databases. While databases can provide a massive number of specimens (often on the order of tens of thousands) and can useful in identifying large-scale evolutionary trends, database entries often lack detailed environmental or sedimentological context (Harnik, 2009). Depositional environment and sedimentological context must necessarily be very broadly categorized in order to accommodate the range of descriptions within the published literature.

Other studies of Ordovician gastropods, such as surveys of taxonomic diversity and phylogenetic analyses, also lack detailed paleoenvionmental analysis because they have relied on museum collections (isolated, well-preserved specimens) or have targeted field collections in silicified intervals, which produce well-preserved specimens but occur rarely in the Great Basin region and only in shallow carbonate settings (Fryda, 2012; Fryda et al., 2008; Rohr, 1996, 1994).

In their survey of Lower and Middle Ordovician shellbeds in the Great Basin region, Li and Droser (1999) found that mollusk-dominated shellbeds (including gastropods) accounted for only 7% of shellbeds examined, and more typical Paleozoic fauna like trilobites and brachiopods accounted for the majority (70%) of Lower and Middle Ordovician shellbeds. They also found that gastropod-dominated shellbeds tended to be thin (<10 cm) and occurred in pods, stringers or clumps rather than in laterally continuous beds. Finnegan and Droser (2005) also noted the tendency for gastropods to occur in discontinuous lenses in Middle Ordovician shellbeds.

Figure 1.3
Diagram illustrating the stratigraphic ranges of main gastropod groups based on protoconch morphology (gray bars). Shaded bars show stratigraphic ranges inferred from teleoconch features (based on Fryda [1999, 2005] and Fryda and Rohr [2004, 2006]). Characteristic protoconchs are drawn on the left side (A) Euomphalomorph protoconch of the Early Carboniferous *Serpulospira*. (B) Late Silurian perunelomorph larval shell. (C) Early Devonian cyrtoneritimorph *Vltaviela*. (D) Late Ordovician cyrtoneritomorph larval shell. (E) Larval shell of the Carboniferous *Orthonychia.* (F) Early Devonian subulitid larval shell. (figure from Fryda et al., 2008).



PALEOZOIC GASTROPOD PHYLOGENY

Paleozoic gastropod phylogeny is notoriously complicated, due primarily to frequent occurrences of homoplasy and poor preservation (Fryda, 2012; Wagner and Erwin, 2006; Wagner, 2001; Wagner 1995). Identification of a gastropod species can be almost impossible without preservation of the protoconch, evidence of soft anatomy such as muscle scars, or external ornamentation, all of which are rarely preserved in specimens from the Paleozoic (Fryda et al., 2012; Wagner and Erwin, 2006). Nevertheless, as more well-preserved specimens are collected, the gastropod phylogeny becomes better resolved, and gastropod researchers have arrived at a working phylogeny (Figure 1.4, Fryda et al., 2008). This phylogeny positions the Bellerophontoidea as a sister group to all other Paleozoic gastropods and highlights the close relationship of Macluritoidea and Euomphaloidea. These three groups are morphologically quite different from the rest of the groups in this working phylogeny, and this body style (nearly planispiral whorls, flat base) are unique to the Lower Paleozoic (Fryda et al., 2008). In this phylogeny, murchisoniiforms (common in the Ordovician) give rise to modern gastropod clades, including the Caenogastropoda (Fryda et al., 2008; Wagner, 1999)

One of the greatest disputes in Paleozoic gastropod phylogeny is the placement of the Bellerophontoidea. The Bellerophontoidea are isostrophic (planispiral, bilaterally symmetrical) and were long believed to be untorted (Wagner, 2001). Torsion, a twisting of the gut that gives gastropods their spiral morphology, is one of the defining characteristics of the clade, so the

Bellerophonotidea's lack of torsion brought their placement within the gastropod clade into question (Wagner, 2001). Well-preserved specimens, with muscle scars and protoconch preserved, have revealed that some bellerophonotoids are torted and others are not, thus further complicating their placement within the gastropod phylogeny (Fryda et al., 2008). "Consensus" gastropod phylogeny is based on basic teleoconch shell morphology first proposed by Knight et al. (1960) (Figure 1.2). In this phylogeny, the Bellerophontoidea are the most primitive gastropods and give rise independently to two subclades: the macluritoids + euomphaloids and the pleurotomarioids (Wagner and Erwin, 2006). Representatives of all subclades have been reported from the Ordovician of the Great Basin region (Rohr, 1994, 1996).

Figure 1.4
"Consensus" phylogeny implied by Knight et al. (1960), with two subclades (macluritoids + euomphaloids, and pleurotomarioids + descendants) derived from paraphyletic bellerophontoids, and at least two "advanced" groups derived from pleurotomarioids. Bars show the number of reductions in symmetry, some of which retain the primative aspidobranch condition, others of which involve the loss of the right gill. Arrows show the inferred inhalent and exhalent water flows. Gastropods modified from Knight et al. (1960). Figure from Wagner & Erwin (2006).

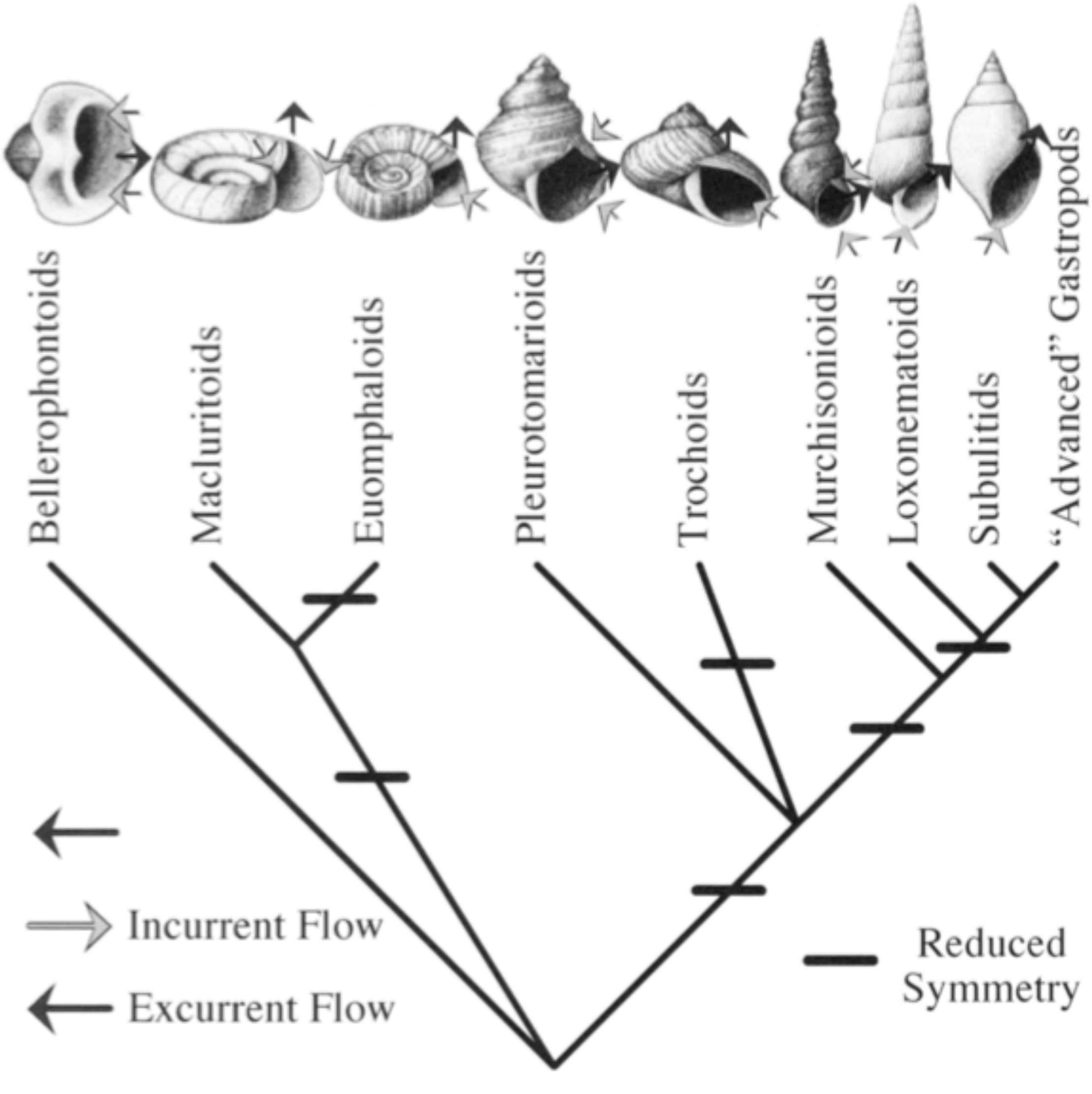
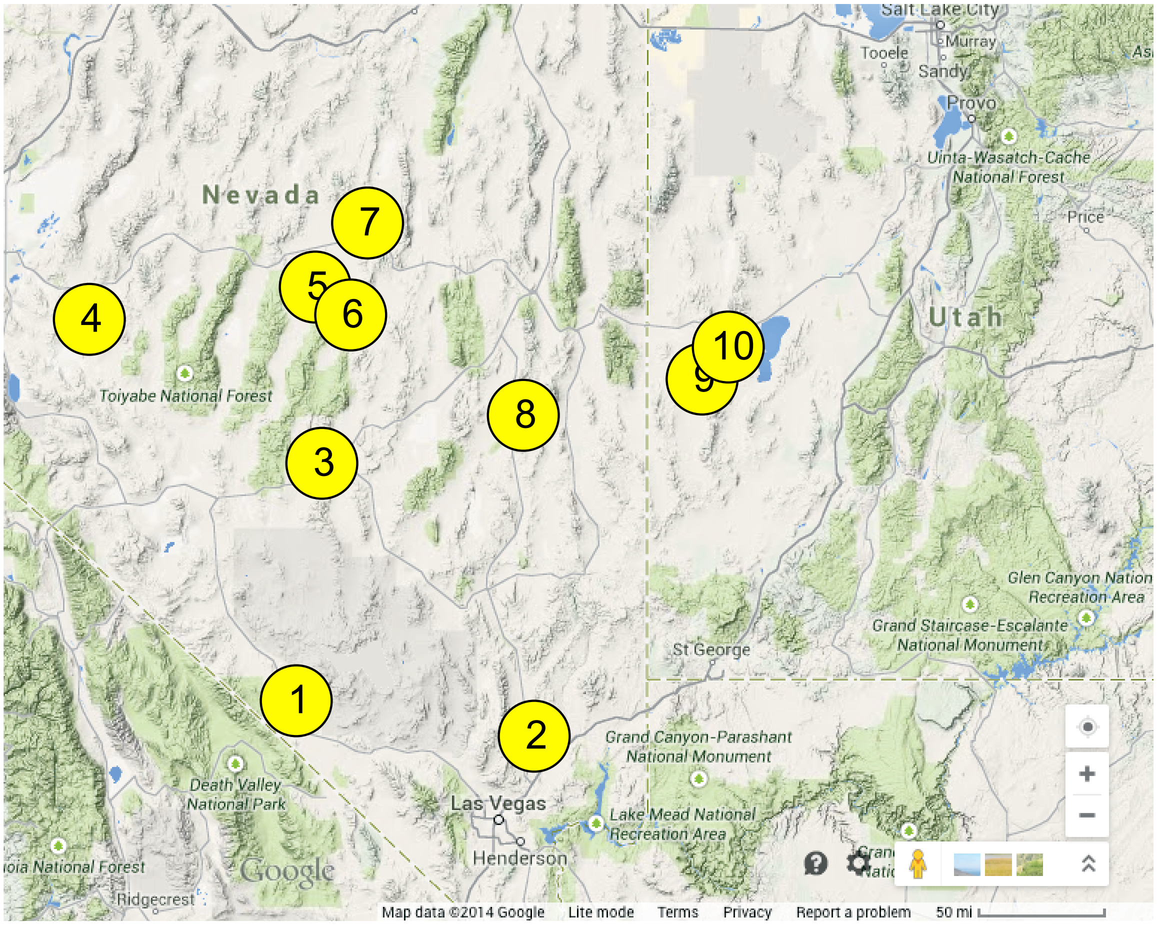


Figure 1.5
Map of localities spanning the Great Basin region:

1. Meikeljohn Peak
2. Arrow Canyon Range
3. Little Rawhide Mountain
4. Ikes Canyon
5. Martin's Ridge
6. Ninemile Canyon
7. Lone Mountain
8. Shingle Pass
9. Crystal Peak
10. Ibex Region



GEOLOGIC SETTING

Field collections were made at ten localities in the Great Basin region (Figure 1.5). This region was chosen for: (1) a nearly complete Lower Paleozoic succession, (2) a wide range of carbonate and mixed-carbonate-siliciclastic depositional environments that are well exposed and biostratigraphically well-constrained (Fortey and Droser, 1999; Ross et al., 1991; Ross, 1977; Hintze, 1973, 1951; Merriam, 1963), (3) a history of paleoecological surveys in the region that provide a baseline understanding of the Ordovician ecosystems preserved in the region (e.g., Finnegan and Droser, 2008; Boyer and Droser, 2003; Harper, 2006; Miller, 1997; Droser et al., 1995; Sepkoski and Sheehan, 1983; Hintze, 1973; Ross, 1967; Walcott, 1884), and (4) a well-established understanding of the taxonomic diversity of gastropods in the Great Basin region (Rohr, 1996, 1994). The ten localities, which have all been examined in previous studies, are biostratigraphically well-constrained (see below), and span the range of depositional environments present on the western passive margin of Laurentia during the Ordovician.

The Paleozoic succession in the Great Basin region is exposed in a generally north-south trending fault block which extends from the Wasatch Range in Central Utah across Nevada to the White-Inyo Mountains in Eastern California (Ross et al., 1991). This package of sediments was deposited off the western passive margin of Laurentia throughout the Paleozoic and into the early Mesozoic (Hintze, 1973). Throughout the Ordovician, Laurentia was situated just south of the paleoequator and its western margin was dominated by a large (several hundred kilometers wide) tropical ramp that deepened to the west and included a complex and shifting system of basins, oncolite shoals, and other bathymetric features (Ross, 1989, 1977) (Figure 1.6). This region was often swept by large tropical storm systems and received a high rate of terrestrial siliciclastic input (Finnegan and Droser, 2005; Siewers, 1995; Ross, 1989; Hintze, 1973). Much of the Paleozoic strata was uplifted and exposed through thrust faulting during the Sevier Orogeny in the Late Cretaceous (Hintze, 1973).

The Ibexian-Whiterockian stratigraphic boundary between the Lower and Middle Ordovician marks the initiation of the GOBE in the Great Basin region (Droser et al., 1995). This boundary is well constrained through the biostratigraphic framework established in the region since the mid-20th century (Ross et al., 1991; Ross, 1977; Hintze, 1973, 1951). The Ibexian and Whiterockian Series are divided into a series of lettered biozones (A-O) based on trilobite and brachiopod assemblages that can be recognized across the range of lithofacies present in the Great Basin region (Figure 1.7) (Fortey and Droser, 1999; Ross et al., 1993, 1991; Hintze, 1973, 1951). Field localities for this project cross the Ibexian-Whiterockian boundary and span biozones I-N.

While Great Basin stratigraphy varies range to range, biostratigraphy and lithology allow for correlation across the region (Figure 1.5). The ten localities included in this study fall into five stratigraphic successions correlated by Ross (1973): (1) Shingle Pass, (2) Ibex Area and Thomas Range, UT, (3) Toquima Range, NV, (4) Monitor and Antelope Ranges, NV, (5) Arrow Canyon Range, NV.

Figure 1.6
Middle Ordovician (470 mya) paleogeography. (A) global, (B) regional focused on Laurentia. The yellow lines in both indicate the paleoequator, the yellow star indicates position of field area (Blakely, 2014).

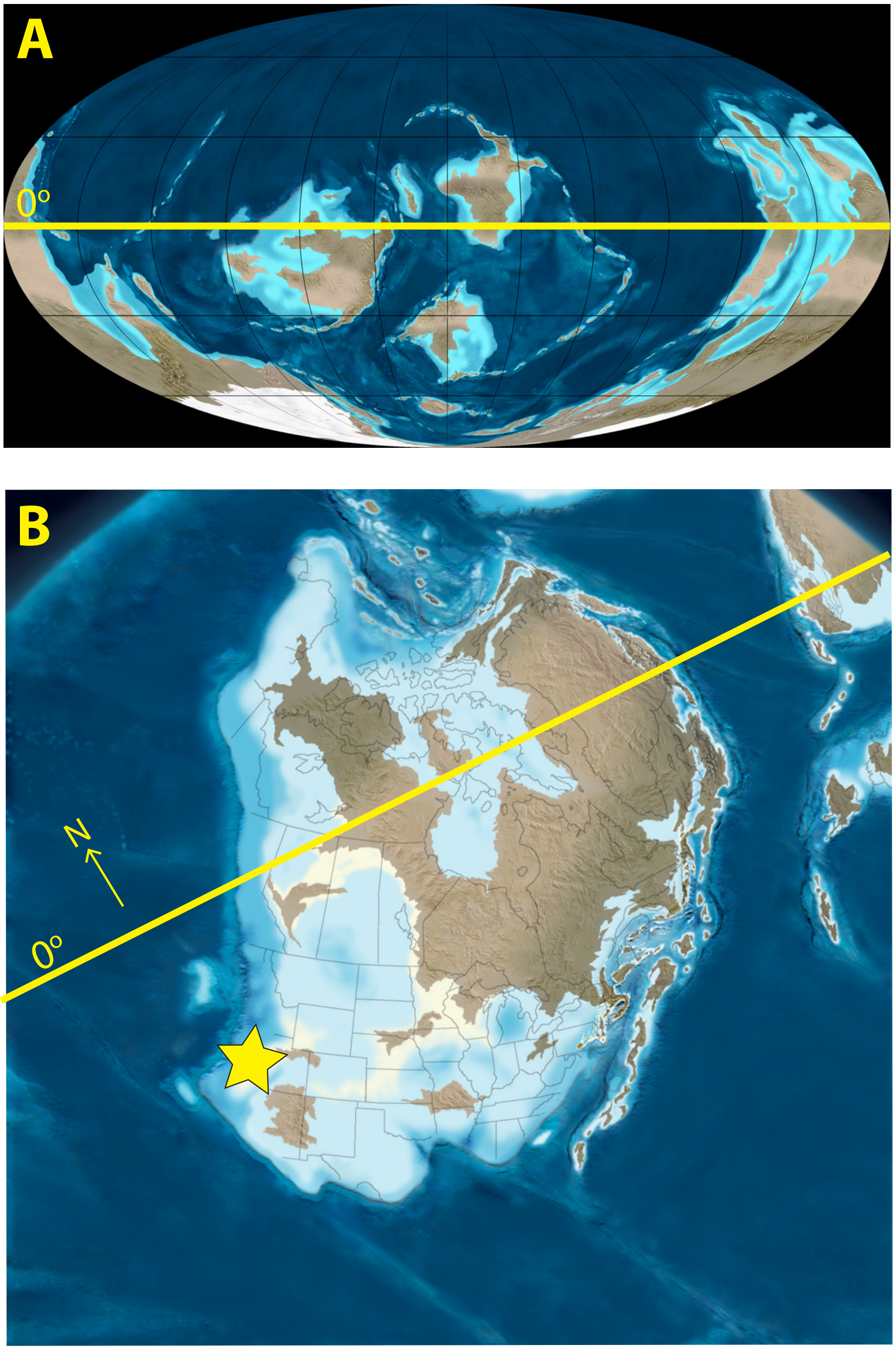
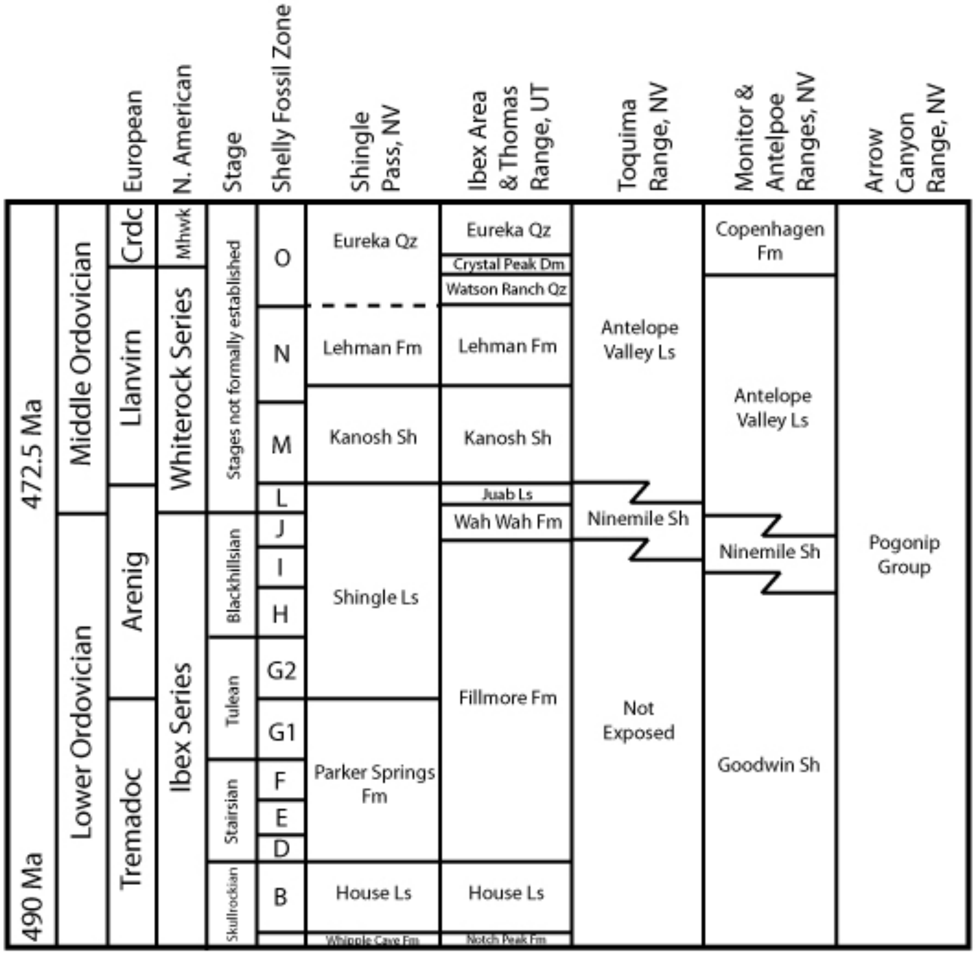


Figure 1.7
Correlated middle Ordovician stratigraphy of Great Basin ranges by Shelly Fossil Zones A-O. (after Ross, 1977).



METHODS

Facies Analysis

The Ordovician stata of the Basin and Range Province can be characterized by the class carbonate facies of Wilson (1974). These nine facies, ranging from the basin facies to the platform evaporite facies, have been used as the basis for sedimentological and paleontolgoical surveys in the Basin and Range Province (see Pruss et al., 2012; Finnegan and Droser, 2008; Boyer and Droser, 2003). In keeping with this tradition, we have opted to use the following facies designations of Wilson (1974). Though Wilson (1974) designated nine carbonate facies, only six were examined in this study (Figure 1.8). The remaining three were either too deep (deep shelf marin facies and foreslope facies) or too shallow (platform evaporite faices) and are not preserved at any of the localities examined. It should be noted that Ordovician carbonates in the Basin and Range Province contain up to 30% terrestrial siliciclastic input.

Basin facies -- starved or filled basin

Water is too deep and dark for benthonic prodution of carbonate, and deposition is dependent on the amount of influx of fine argillaceous and siliceous material and the rain of decaying plankton. Euxinic and hypersaline conditions may result. May also form within fault-bounded basins on the platform, such as the Kanosh Basin.

Shelf facies

Water with a depth of tens or even a few hundred meters, generally oxygenated and of normal marine salinity. Good current circulation. Deep enough to be below normal wave base but intermittent storms affect bottom sediments.

Organic reef or platform margin

Ecologic character varies dependent on water energy, steepness of slope, organic productivity, amount of frame construction, binding, or trapping, frequency of subaerial exposures, and consequent cementation. Three types of linear shelf margin organic buildup profiles may be discerned. Wilson (1974) designates three distinct "types" for this facies, but only one, Type I, is observed in the Ordovician stata of the Basin and Range Provice. Type I is formed by downslope carbonate mud and organic debris accumulations.

Winnowed platform edge sands

These take the form of shoals, beaches, offshore tidal bars in fans or belts, or dune islands. Depths of such marginal sands range from 4 or 10 m to above sea level. The environment is well oxygenated but not hospitable to marine life because of shifting substrate.

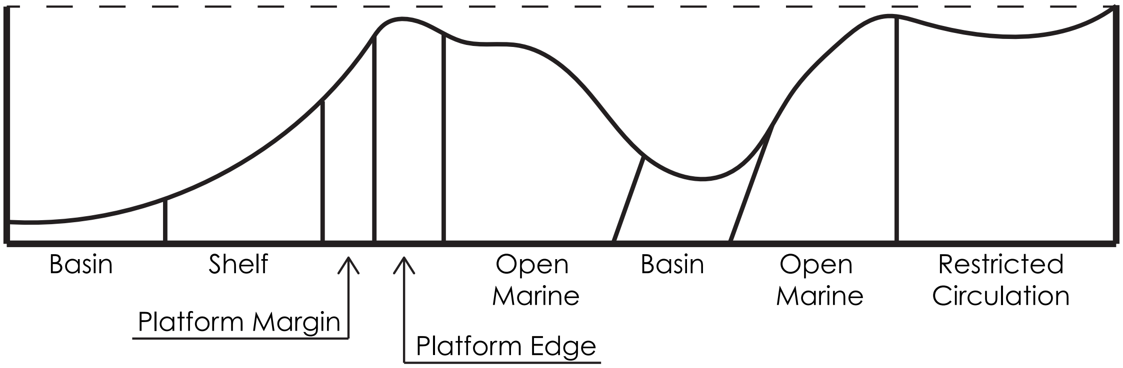
Open marine platform facies

Environments are located in straits, open lagoons and bays behind the outer platform edge. Water depth is generally shallow, a few tens of meters deep at most. Salinity varies from essentially normal marine to somewhat variable salinity. Circulation is moderate.

Facies of restricted circulation on marine platform

Includes mostly fine sediment in vary shallow, cut-off ponds and lagoons, coarser sediment in tidal channels an local beaches, and the whole complex of tidal flat environment. Conditions are extremely variable here and constitute a stress environment for organisms. Fresh, salt, and hypersaline water occur as well as areas of subaerial exposure, both reducing and oxygenated conditions and marine and swamp vegetation. Windblown terrigenous material may contribute significantly. Diagenetic effects are strongly marked in the sediment.

Figure 1.8
Carbonate facies, modified from Wilson (1974) for the Ordovician strata of the Basin and Range Province. Depths and extent of each facies is exaggerated, and the basin between the open marine facies is a fault-bounded basin.



Sampling

In the field, detailed sedimentological sections were logged at each of the ten localities. Lithology was characterized using the Dunham scale (mudstone, wackestone, packstone, grainstone; Dunham, 1962). The facies preserved at each locality were determined at the outcrop, as regional and geologic context are more accessible in the field than later, during sample analysis.

After measuring, bulk samples (weighing 7-8 kg) were taken of each facies, regardless of macrofossil content and presence/absence of gastropods. This was to ensure accurate relative abundance of gastropods within all depositional environments. After "blind sampling," additional bulk samples were taken at gastropod-rich intervals and individual collections were made of well-preserved specimens in order to fully capture gastropod diversity at each locality.

The majority of Ordovician localities in the Great Basin do not preserve silicified fossil material, but silicified material was present at the Ikes Canyon and Martin's Ridge localities. In addition to the sampling methods detailed above, gastropod-rich intervals were double sampled so that the bulk samples could be processed both through mechanical breakdown and dissolution.

Processing

Bulk samples were first slabbed, polished and photographed in order to capture macro-scale sedimentary fabrics and confirm the depositional environment designations made in the field. Then polished slabs were thin sectioned to analyze micro-scale sedimentary fabrics (grainsize, carbonate cements and other diagenetic fabrics, percent siliciclastic material compared to carbonate). If fossil material in a bulk sample was not silicified, we used a "crack out" method to quantify taxonomic diversity and establish relative abundance of gastropods for each bulk sample. Samples were broken down using a chisel and sledgehammer, and then all visible fossil material (>2 mm in long axis length) was identified to the finest taxonomic scale possible. If the fossil material in a bulk sample was silicified, we would process one of the two samples via the method described above and dissolve the other in highly dilute acid (10% formic or acetic) to release the fossil material from the carbonate matrix (Green, 2001). Then fossil material was identified to the finest taxonomic level possible.

RESULTS

Gastropod-Bearing Facies

Gastropods occur across the carbonate platform in all facies examined, but their distribution is not even or consistent, and varies due to lithology and energy. Of the nine designated carbonate facies, six were observed in this study.

1. Basin facies
2. Shelf facies
3. Platform margin facies
4. Oncolite facies (corresponding to Wilson's "winnowed platform edge sands facies")
5. Open marine platform facies
6. Restricted circulation facies

The criteria used to identify facies are shown in Table 1.1 and a diagram of these facies is shown in Figure 1.8. Specific descriptions of each facies follows:

Basin facies

The basin facies consists of laminated very thin to thin beds (<1 mm to 2 mm) of unfossiliferous, unbioturbated shales interbedded with medium to thick (5-15 cm) carbonate mudstones and wackestones and rare thick (20-30 cm) sandstone beds. We interpret this package reflect shallowing-up cycles. Carbonate interbeds contain rare ostracod, trilobite and bellerophontid gastropod fossils. This facies weathers easily and typically forms gentle slopes and must be excavated deeply to expose fresh shale. The basin facies is interpreted as forming within a deep, fault-bounded, restricted (likely disoxic) basin, indicated by the lack of bioturbation and macrofauna. The black shale facies occurs within the lowermost member of the Kanosh Shale at Crystal Peak.

Shelf Facies

The shelf facies consists of light grey, thick bedded (5-25 cm) gastropod-dominated packstones with a micritic matrix separated by orange-brown siliciclastic silty partings. The fossil material is silicified. While gastropods account for 84.8% of the fossil material within the packstones, rare trilobites and brachiopods are also present. The shelf facies is interpreted as forming beyond the platform margin, far below fair weather but above storm wave base. The shelf facies is uncommon in the Basin and Range Province, and was only examined at Ikes Canyon, within a 15 m interval of the Antelope Valley Limestone, just below a thick interval of the winnowed platform edge facies.

Platform Margin Facies

The platform margin facies consists of medium to thickly bedded (2-10 cm) fossiliferous limestones. Color ranges from light grey to orange-brown and the carbonate matrix contains up to 30% siliciclastics. Trilobites dominate the fossil assemblage preserved in this facies (accounting for 82.0% of the relative abundance). Other taxa, like brachiopods, gastropods, echinoderms, bryozoa, bivales and cephalopods are rare. While this facies and the open marine platform facies both represent deposition under normal marine conditions, this facies represents a more distal and deeper water depositional environment. This facies is common throughout the Ordovician succession of the Great Basin and occurs within the Shingle Limestone at Shingle Pass, the Wah Wah Formation and Juab Limestone in the Ibex Area, the Antelope Valley Limestone at Martin's Ridge, Lone Mountain and Little Rawhide Mountain, and the Ninemile Shale at Meiklejohn Peak and Little Rawhide Mountain.

Oncolite Facies

The oncolite facies consists of medium to thickly bedded oncolite-bearing limestones. Oncoids range from loosely to densely packed, roughly approximating the Dunham scale for fossiliferous carbonates (where loosely = oncolite wackestone, moderately = oncolite packstone, densely = oncolite grainstone). This facies is interpreted as forming in high energy, shallow water shoals, with the densely-packed oncoid intervals forming within the shoals and the loosely packed oncoid intervals forming in the protected lagoonal zone behind the shoal. Body fossil density varies throughout and macrofauna diversity within this facies is low and limited to macluritid gastropods, receptaculitids (an enigmatic Paleozoic group commonly interpreted as calcified algae), and small accumulations of trilobite and echinoderm skeletal hash. The platform edge facies is common throughout the Great Basin region and others have noted that the oncolite shoal responsible for the formation of this facies migrated across the Laurentian carbonate ramp throughout the Ordovician (Ross, 1989). It occurs within the Pogonip Group (member Opf) at the Arrow Canyon Range and within the Antelope Valley Limestone at Martin's Ridge, Lone Mountain, Little Rawhide Mountain, and Ikes Canyon.

Open Marine Platform Facies

The open marine platform facies consists of medium to thickly bedded wackestones, packstones, and grainstones, with up to 30% terrestrial siliciclastic input. Brachiopods dominate the assemblage (representing 56.3% of the macrofauna), though trilobites, ostracods, gastropods and cephalopods are also present. Though this facies represents deposition in a more proximal setting than the platform margin facies, deposition is still below fair weather wave base. The densely packed brachiopod shellbeds within this facies have been interpreted as storm-generated accumulations (Finnegan and Droser, 2008).

Restricted Circulation Facies

The restricted circulation facies consists of thin to medium bedded light to dark grey carbonate mudstones and wackestones. Macrofauna preserved within the restricted circulation facies consist primarily of gastropods, but also include ostracods, bivalves and trilobites. In this facies, shellbeds tend to be monospecific, regardless of taxonomic composition. For example, one bed may be composed completely of the gastropod *Clathrospira* while another stratigraphically distinct bed may be composed completely of the bivalve *Modiolopsis*. This pattern is not easily reflected in the total relative abundance for this facies.

The restricted circulation facies is interpreted as forming in a very shallow, hypersaline protected lagoon, indicated by the authigentic formation of carbonate muds (Flügel, 2010). Hypersalinity is also indicated by the unusual macrofauna assemblage, most notably the lack of typical Paleozoic faunal like brachipods and echinoderms and the occurrence of monospecific mollusk shellbeds (Boyer and Droser, 2003). No evidence of exposure or karsting is present within this facies. The restricted circulation facies occurs within the Lehman Formation at Crystal Peak and the Ibex Area and in the uppermost 20 meters of Pogonip Group, Member F in the Arrow Canyon Range.

Table 1.1

Characteristics used in identifying facies, including: lithology, grain type and depositional texture, bedding and sedimentary structures, terrigenous clastics admixed or interbedded, and biota (after Wilson, 1974).

Facies	*Basin* a) fine clasts b) carbonates	*Shelf* a) carbonates b) shale	*Platform margin* a) boundstone mass b) crust on accumulation of organic debris and lime mud	*Winnowed platform edge sands (Oncolite)* a) shoal lime sands	*Open marine platform* a) lime sand bodies b) wackestone-mudstone areas, bioherms c) areas of clastics	*Restricted platform* a) bioclastic wackestone, lagoons and bays b) litho-bioclastic sands in tidal channels c) lime mud-tide flats d) fine clastic units
Lithology	Dark shale or silt, thin limestone (starved basin), evaporite fill with salt	Very fossiliferous limestone interbedded with marls, well segregated beds	Massive limestone dolomite	Calcarenitic-oolitic-oncolitic lime sand or dolomite	Variable carbonates and clastics	Generally dolomite and dolomitic limestone
Grain type and depositional texture	Lime mudstone, fine calcisiltites	Bioclastic and whole fossil wackestones, some calcisiltites	Boundstones and pockets of grainstone; packstone	Grainstones well sorted, rounded	Great variety of textures; grainstone to mudstone	Clotted, pelleted mustone and grainstone, laminated mudstone, coarse lithoclastic wackestone in channels
Bedding and sedimentary structures	Very thin lamination, rhythmic bedding, ripple cross lamination	Thoroughly burrowed, thin to medium, wavy to nodula beds, bedding surfaces show diastems	Massive organic structure or open framework with roofed cavaties; lamination contrary to gravity	Medium to large scale crossbedding, festoons common	Burrowing traces very prominent	Birdseye, stromatolites, mm laminations, graded bedding, dolomite crusts on flats, cross-bedded sand in channels
Terrigenous clastics admixed or interbedded	Quartz silt and shale, fine grain siltstone, cherty	Quartz silt, siltstone, and shale, well segregated beds	None	Only some quartz sand admixed	Clatics and carbonates in well segregated beds	Clastics and carbonates in well segregated beds
Biota	Primarily nektonic-pelagic fauna preserved in local abundance on bedding planes	Very diverse shelly fauna preserving both infauna and epifauna	Major frame building colonies with ramoes forms in pockets; in situ communities dwelling in certain niches	Worn and abraded coquinas of forms living at or on slope; few indigenous organisms	Open marine fauna lacking (e.g., echino-derm, cephalopods, brachiopods); molluscs, sponges, forams, algae abundant, patch reefs present	Very limited fauna, mainly gastropods, algae, certain formas and ostracods

Localities Studied

Meiklejohn Peak.

Bare Mountain, Beatty, NV. Meiklejohn Peak is characterized primarily by a large bioherm ("mud mound") positioned within the Antelope Valley Limestone, which overlies the Ninemile Shale. The mound sits stratigraphically just above Ibexian-Whiterockian boundary, indicated by the appearance of basal Whiterockian trilobites (Fortey and Droser, 1999). The mound itself is easily identified by its large mounded shape and lithology, light grey limestone with zebra bands and stromatactis structures, indicating deepwater clathrate formation (Krause, 2001; Fortey and Droser, 1999). The macrofauna within the mound have been studied extensively (Ross, 1972), with special focus on the inarticulate brachiopods (Krause and Rowell, 1975).

Arrow Canyon Range

Arrow Canyon Range, NV. The 170 m section measured in the Arrow Canyon Range of Southern Nevada includes the uppermost portion of the Pogonip Group. The Pogonip Group is the regional name for a thick package of carbonates that are correlated with the Antelope Valley Limestone (Central Nevada) and the Middle Ordovician succession preserved in the Ibex Region of Confusion Range in Western Utah. The Pogonip Group is loosely divided into six members, A-F, and samples for this study were taken from the uppermost two members OPe and OPf. OPe is comprised primarily of medium to thinly bedded carbonate wackestones, packstones and grainstones and is interpreted to have been deposited on the inner shelf under normal marine conditions. OpF is comprised of oncolite, oolite and thinly bedded carbonate mudstones (ribbon rock) and wackestones. The oncolitic and oolitic facies represent shallow marine shoal and the thinly bedded carbonates were deposited in lagoonal conditions.

Little Rawhide Mountain

Hot Creek Range, NV. The 300 m section measured at Little Rawhide Mountain includes the Ninemile Shale and the lowermost Antelope Valley Limestone. The Ninemile Shale at Little Rawhide Mountain forms gentle slopes of highly weathered shale and contains very little fossil material. The Ibexian-Whiterockian boundary lies within the lowermost Antelope Valley Limestone, indicated by a bed of Olenid trilobites and the graptolite *Pseudotrigonograptus ensiformis* (Fortey and Droser, 1999). The Antelope Valley Limestone at Little Rawhide Mountain is exposed in a series of thick limestone benches of brachiopod-dominated shellbeds and resembles the Kanosh Shale in the Ibex Region. Exposure of the Antelope Valley Limestone continues above the measured section but is inaccessible due to steep vertical cliffs. Float material at the base of the slope suggests that inaccessible portion contains oncolite. Little Rawhide was visited only once during this study because the dirt road into the locality was washed out by storms in the 2010-2011, rendering the site inaccessible.

Ikes Canyon

Toquima Range, NV. Though the Antelope Valley Limestone is ~300m thick at the Ikes Canyon locality, measuring a continuous section is nearly impossible due to abundant faulting. The locality has not been examined in detail since Kay (1962) measured an 833 ft (254 m) section through the Stoneberger Shale and Antelope Valley Limestone. Kay (1962) designated eight "zones" throughout the Antelope Valley Limestone, including a 102 ft (30 m) thick *Maclurites-Girvanella Zone*. We measured a 20 m section through the accessible outcrop of this zone. Despite Kay's designation, this zone is not lithologically similar to the Maclurities-dominated oncolite shoals preserved at other localities (Arrow Canyon Range, Martin's Ridge, Lone Mountain). This zone is characterized by medium to thickly bedded limestones with abundant gastropod shellbeds.

Martin's Ridge

Monitor Range, Antelope Valley region NV. The Martin's Ridge locality was chosen because it was the main collection site for Rohr's seminal survey of Ordovician gastropod diversity. The ridge is located along the western margin of the Antelope Valley and provides a large (210 m) exposure of the Antelope Valley Limestone, though the complete thickness of the Antelope Valley Limestone in this region is much greater (Merriam and Williams, 1956). While the lithology is primarily dominated by densely packed oncoids, the section also includes intervals of mudstone, wackestone, packstone and grainstone reminiscent of the Wah Wah and Juab Formations of the Ibex Region. Fossil material is silicified.

Lone Mountain

Monitor Range, Antelope Valley region NV. Lone Mountain, and isolated peak in the northern Antelope Valley, is located just North of the Martin's Ridge and

Ninemile Canyon localities. Lone Mountain is stratigraphically similar to Martin's Ridge. The Antelope Valley Limestone is well exposed on the mountain's western slope. We measured a 210 m section through the Antelope Valley Limestone, which was dominated by a series of shallowing-up sequences characterized wackestones and packstones capped by grainstones and oncolite. Like at Martin's Ridge, fossil material at Lone Mountain is silicified.

Ninemile Canyon

Monitor Range, Antelope Valley region NV. The Ninemile Canyon locality is located on the eastern side of the Antelope Valley, across the valley from the Martin's Ridge locality. The 75 m section measured at Ninemile Canyon sits completely within the lowermost Antelope Valley Limestone, which is sedimentologically distinct from the Antelope Valley Limestone exposed across the valley at Martin's Ridge and Lone Mountain (Ross, 1977; Merriam and Williams, 1956). At Ninemile Canyon, the Antelope Valley Limestone is comprised of light grey, thinly bedded, argillaceous limestones and is notably less fossiliferous than at Meiklejohn Peak and Little Rawhide Mountain. At this locality, the Antelope Valley Limestone is ~335m thick but there are several hundred meters of unexposed slope between the lowermost exposure and the upper exposure. Because the upper Antelope Valley Limestone forms sheer cliffs in Ninemile Canyon, we were unable to measure and collect from that unit at this locality.

Shingle Pass

Southern Egan Range, NV. The Shingle Pass locality, which is roughly 130 km southwest of the Ibex Region, was originally chosen because of the potential access to outcrops of the Kanosh Shale and Lehman Formation. Outcrops of these units were much more remote than reported and thus were not feasible field sites. We instead measured a 20 m section through the lowermost Shingle Limestone. The Shingle Limestone's total thickness in the Southern Egan Range is 450 m (Kellogg, 1963). The Shingle Limestone is comprised of thinly to thickly bedded, cliff-forming dark grey limestone. Sedimentologically, the Shingle Limestone is similar to the Wah Wah Formation and Juab Limestone, which underlie the Kanosh Shale and Lehman Formation in the Ibex Region. The Ibexian/Whiterockian boundary sits within the Shingle Limestone, above the section measured in this study (Kellogg, 1963; Sweet and Tolbert, 1997; Finnegan and Droser, 2005).

Ibex Region

Southern Confusion Range, UT. The Ibex Region in western Utah is one of the most well-studied Ordovician successions in the Great Basin, having the been the focus of Lehi Hintze's detailed stratigraphic and paleontological surveys in the mid-20th century and several subsequent studies in the following decades. We measured two sections at Hintze Localities, "Section J" and "Camp." Section J (154 m) includes the upper Wah Wah Formation, Juab Limestone and lowermost Kanosh Shale. Section J is characterized by a series of small (1-5 m) cliffs in the Wah Wah Formation, light grey weathered mudstones, wackestones and packstones in the

Juab Limestone, and gently sloping brown weathered shale in the lowermost Kanosh Shale. The Ibexian-Whiterockian boundary falls within the upper Wah Wah Formation (Finnegan and Droser, 2005; Hintze, 1951). Camp (96 m) includes the middle and upper Kanosh Shale and entire Lehman Formation and is characterized by densely packed brachiopod shellbeds throughout the Kanosh Shale and thin to medium bedded dark grey limestones in the Lehman Formation. The boundary between the Kanosh Shale and the Lehman Formation is marked by a 3 m thick sandstone bench, and the top to the Lehman Formation grades into the Eureka Sandstone.

Crystal Peak

Northern Wah Wah Mountains, UT. Like Section J and Camp in the Ibex Region, Crystal Peak is one of Hintze's Ordovician localities and therefore has been well examined in several paleontological surveys (Boyer and Droser, 2003; Li and Droser, 1999; Wilson et al., 1992; Hintze, 1951). The section lies just north of Crystal Peak itself, which is a striking volcanic intrusion that stands out in white against surround the Paleozoic carbonate strata. The Crystal Peak section (225 m) encompasses the entire Kanosh Shale and Lehman Formation. The Crystal Peak section is the only section included in this study that includes the black shale member of the Kanosh Shale. Sampling at Crystal Peak was focused in the black shale member of the Kanosh Shale.

Gastropod Taxa

Eighteen gastropod taxa were identified (see Table 1.2). Of the eighteen, twelve were identified to Genus. Due to poor preservation, the remaining six taxa were unidentifiable beyond Order and are indicated as "Unidentified Euomphaloid A-F." Gastropod distribution across facies is shown in Figure 1.9.

Order Bellerophontida

Family Bucaniidae: One genus (*Bucania* Hall 1847) was identified from the Family Bucaniidae. *Bucania* was collected from the basin facies within the Kanosh Shale at the Crystal Peak locality and thus represents the deepest gastropod occurrence recorded in this study. This genus is very long lived, with a record that extends into the Triassic.

Order Euomphalina

Family Euomphalidae: One genus (*Straparollus* de Montfort 1810) was identified from the Family Eomphalidae. *Straparollus* was collected from the platform margin facies within the Shingle Limestone at the Shingle Pass locality, and represents the only fossil material collected from that section. This is the first report of *Straparollus* from the Basin and Range Province during the Ordovician, though this genus has been reported from the Ordovician of Canada (Miller et al., 1954).

Family Ophiletidae: Four genera were identified from the Family Ophiletidae: *Barnesella* Bridge and Cloud 1947, *Lecanospira* Butts 1926, *Malayaspira* Kobayashi 1958, and *Rossospira* Rohr 1994. The Ophiletidae are characterized by a flat "base" with nearly planispira whorls, creating a sturdy, disk-like morphology (see Figure

1.6). These four genera are most common within normal marine depositional environments (the open marine platform facies and the platform margin facies), though *Lecanospira* also occurs within the deeper water shelf facies. All four taxa go extinct by the end-Ordovician.

Family Macluritidae: Two genera were identified from the Family Macluritidae: *Monitorella* Rohr 1994 and *Palliseria* Wilson 1924. These two taxa occur predominately within the oncolite facies, but are also present in very low relative abundance in the shelf facies and the open marine platform facies. Like the Ophiletidae, the Macluritidae are characterized by flat bases and nearly planispiral whorls and go extinct by the end-Ordovician.

Order Murchisoniina

Family Eotomariidae: Two genera were identified from the Family Eotomariidae: *Clathrospira* Ulrich and Scofield 1897 and *Liospira* Ulrich and Scofield 1897. *Clathrospira* forms monospecific shellbeds within the restricted circulation facies. *Liospira* was collected from the platform margin facies in the Wah Wah Formation, where it accumulated in dense but discrete lenses. *Clathrospira* went extinct at the end-Ordovician and *Liospira* persists through the Silurian.

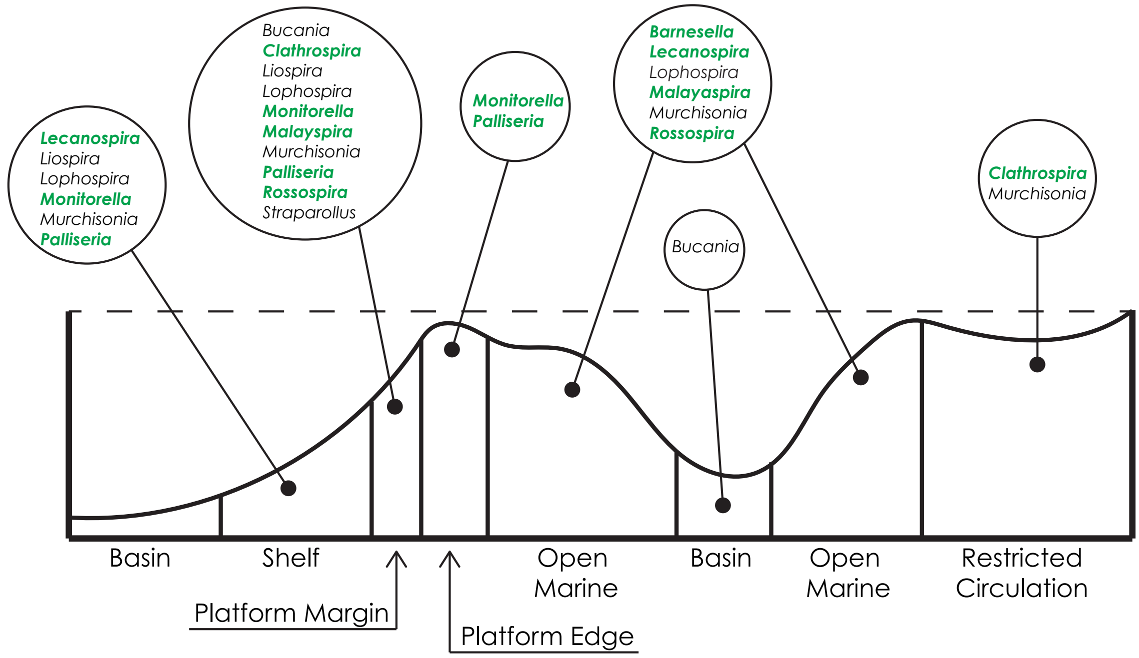
Family Lophospiridae: One genus, *Lophospira* Whitfield 1886, was identified from Family Lophospiridae. *Lophospira* was one of two dominant gastropod taxa within the gastropod-dominated packstones in the shelf facies. *Lophospira* persists through the end-Ordovician before going extinct in the Silurian.

Family Murchisoniidae: One genus, *Murchisonia* d'Archiac and de Vernuil 1841, was identified from Family Murchisoniidae. *Murchisonia* is the more environmentally widespread gastropod identified in this study, occurring within four of six facies (shelf, platform margin, open marine platform, and restricted circulation) and spanning the entirety of the carbonate platform. *Murchisonia* is also one of the most long-lived genera identified in this study, persisting through the Paleozoic and most of the Mesozoic before going extinct in the early Cretaceous.

Table 1.2
Taxonomic affinity and age range of all identified gastropods.

Class	Gastropoda	Age Range
Order	Bellerophontida	
Family	Bucaniidae	
Genera	*Bucania* Hall 1847	Ord - Tri
Order	Euomphalina	
Family	Euomphalidae	
Genera	*Straparollus* de Montfort 1810	Ord - Cret
Family	Ophiletidae	
Genera	*Barnesella* Bridge and Cloud 1947	Ord
	Lecanospira Butts 1926	Ord
	Malayaspira Kobayashi 1958	Ord
	Rossospira Rohr 1994	Ord
Family	Macluritidae	
Genera	*Monitorella Rohr 1994*	Ord
	Palliseria Wilson 1924	Ord
Order	Murchisoniina	
Family	Eotomariidae	
Genera	*Clathrospira* Ulrich and Scofield 1897	Ord
	Liospira Ulrich and Scofield 1897	Ord - Sil
Family	Lophospiridae	
Genera	*Lophospira* Whitfield 1886	Ord - Sil
Family	Murchisoniidae	
Genera	*Murchisonia* d'Archiac and de Verneuil 1841	Ord - Cret

Figure 1.9
Distribution of gastropod genera by facies. Green text indicates extinction by the end-Ordovician, black indicates survival. Water depth and extent of carbonate platform is exaggerated and does not reflect actual platform topography.



Results by Locality

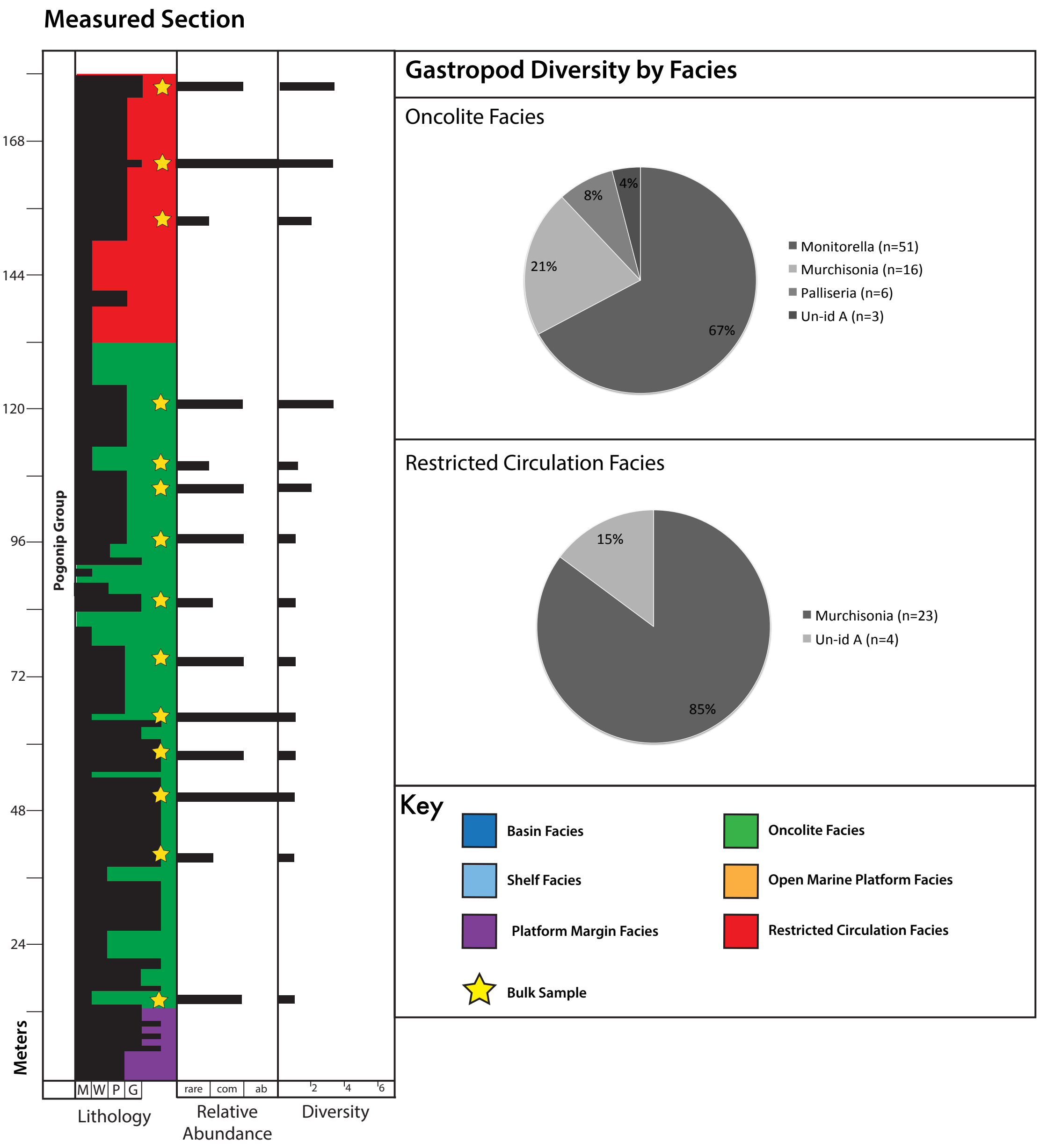
The following plates include data guides to each of the localities examined in this study (Figures 1.10-1.19). Each locality figure shows the measured section, gastropod diversity, and taxonomic diversity. Each plate is paired with an analysis of the relationship between depositional environment and gastropod diversity. Because of the very small sample size (often 0-5 gastropods per bulk sample), we were unable to do statistical analyses of relative abundance. Gastropod diversity measurements show diversity within each facies rather than bulk sample for this same reason.

Arrow Canyon Range

A 170 m section was measured in Arrow Canyon Range through the Ordovician Pogonip Group members E and F (OPe and OPf) (Figure 1.8). As described above, OPe was deposited on the platform during normal marine conditions while OPf was deposited in shallower environments, grading from an oncolite shoal (oncolite facies) up to a protected lagoon (restricted circulation facies). Fourteen bulk samples were collected at this locality. Gastropods account for 95% of the taxa collected in bulk sample, and half (55%) of the gastropods are macluritids (*Monitorella* and *Palliseria*). These macluritid gastropods were collected from the oncolite within the oncolite facies of OPf. The only other taxa collected in bulk sample from OPf are receptaculitids and trilobite and echinoderm hash. Receptaculitids are very rare in bulk sample, accounting for only 5% of the overall taxonomic diversity. More gastropods and receptaculitids are visible in bedding plane and cross-section exposures, but bulk sampling was impossible due to the hardness of the carbonate.

There is a facies shift in uppermost 30 m of the measured section as the oncolite facies grades into the restricted circulation facies, indicating shallowing into a lagoonal environment. Like in the Lehman Formation at Ibex, fossil material occurs in monospecific shellbeds and is dominated by mollusks (gastropods and bivalves). Gastropod taxa in this facies at this locality include *Murchisonia* and an unidentified euomphalid (Unidentified Euomphalid A).

Figure 1.10
Arrow Canyon Range measured section and gastropod diversity by genus. Columns in measured section indicate carbonate lithology, relative abundance of gastropods in each bulk sample (rare, common, abundant), and gastropod diversity.

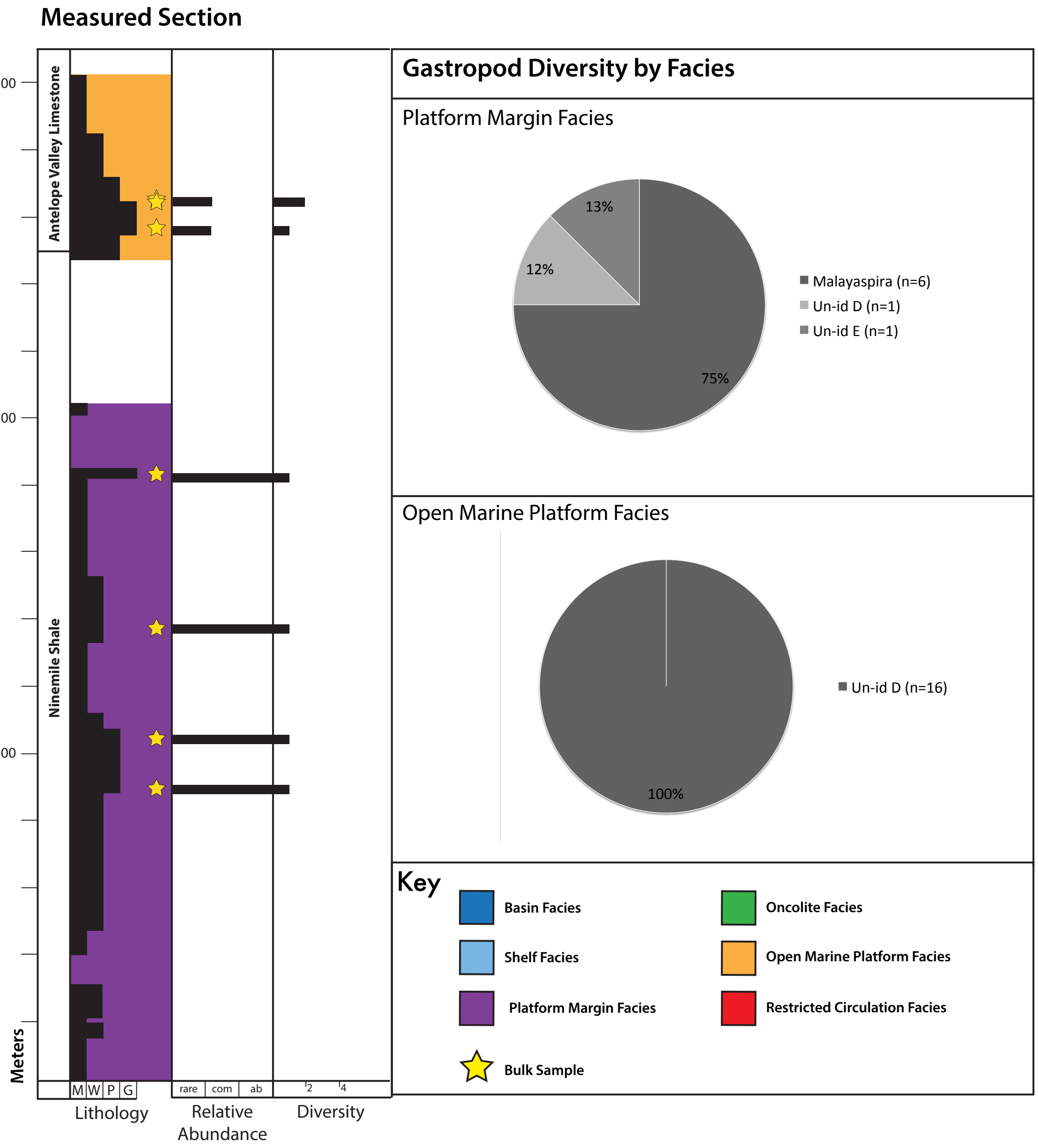


Little Rawhide Mountain

The 300 m section measured at Little Rawhide Mountain includes the Ninemile Shale (0-203 m) and the lowermost Antelope Valley Limestone (250-300 m), with ~40 m of unexposed slope between the two units. Seven bulk samples were collected, four from the Ninemile Shale and three from the Antelope Valley Limestone. Very few bulk samples were collected in the Ninemile Shale because this unit contains very little fossil material, and bulk samples were taken whenever gastropod were sighted. The Ninemile Shale is comprised of the platform margin facies. In the four Ninemile Shale bulk samples, gastropods were the only taxa. The preservation these specimens were very poor, so identification was impossible, but all 17 specimens collected were clearly the same taxa and this taxa has been designated Unidentified Euomphalid D (Un-ID D).

The lowermost Antelope Valley Limestone at Little Rawhide, comprised of the open platform facies, is dominated by brachiopod packstones and greatly resembles the Kanosh Shale of the Ibex Region. This unit contains abundant fossil material and gastropods account for <10% of the overall taxonomic assemblage. In addition to brachiopods, trilobites are common. The gastropods collected from this unit include *Malayaspira* and another unidentified Euomphalid, "Un-ID E."

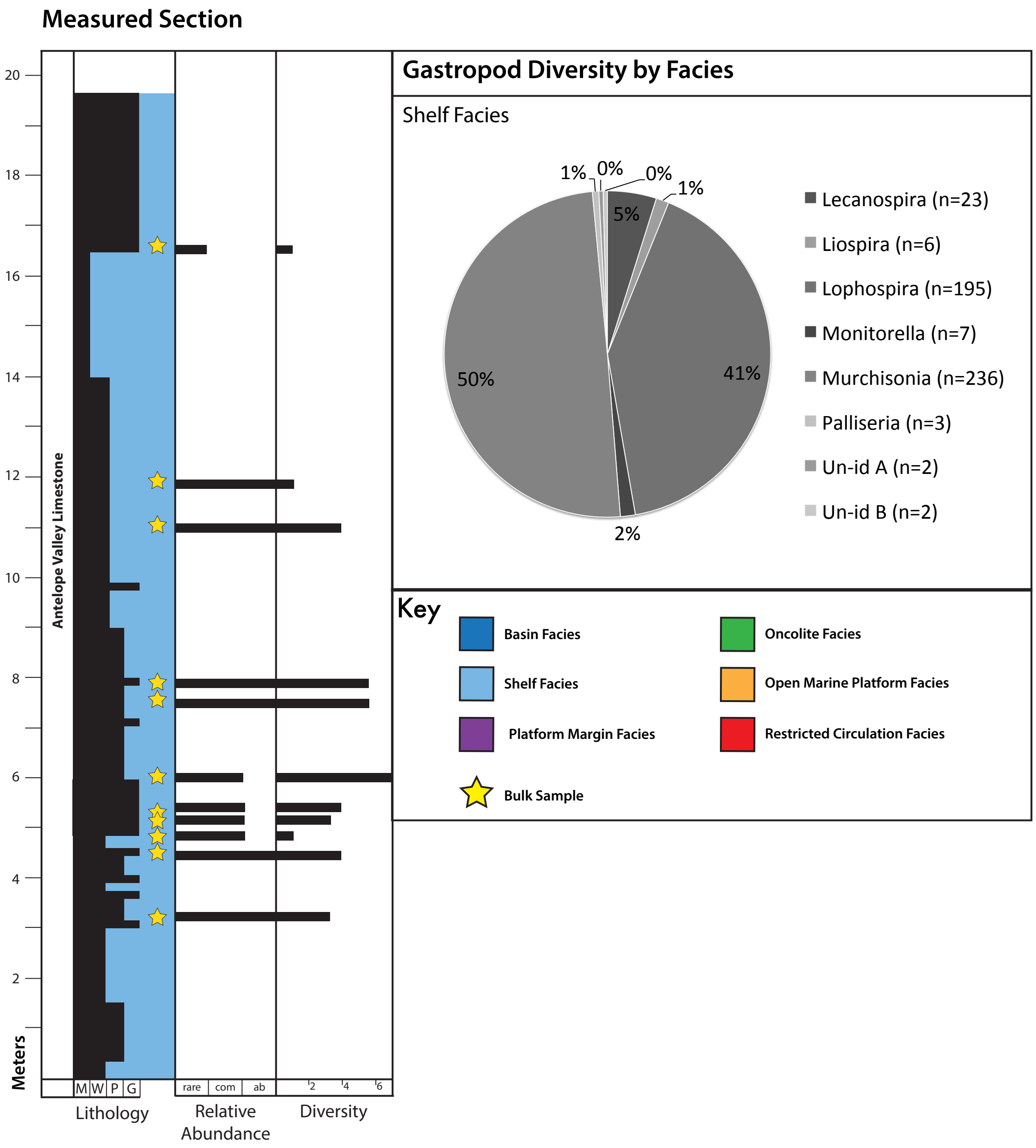
Figure 1.11
Little Rawhide Mountain measured section and gastropod diversity by genus. Columns in measured section indicate carbonate lithology, relative abundance of gastropods in each bulk sample (rare, common, abundant), and gastropod diversity.



Ikes Canyon

The Ikes Canyon locality is heavily faulted and measuring a continuous section though the Antelope Valley Limestone was not possible. The 20 m section measured through the shelf facies within the Antelope Valley Limestone at this locality sits stratigraphically below the platform edge facies. Ikes Canyon represents the most distal, deepest portion of the carbonate platform, and this is the only locality at which the shelf facies occurs. The locality description follows the facies description closely. Ten bulk samples were collected and produced 474 gastropod specimens representing eight taxa.

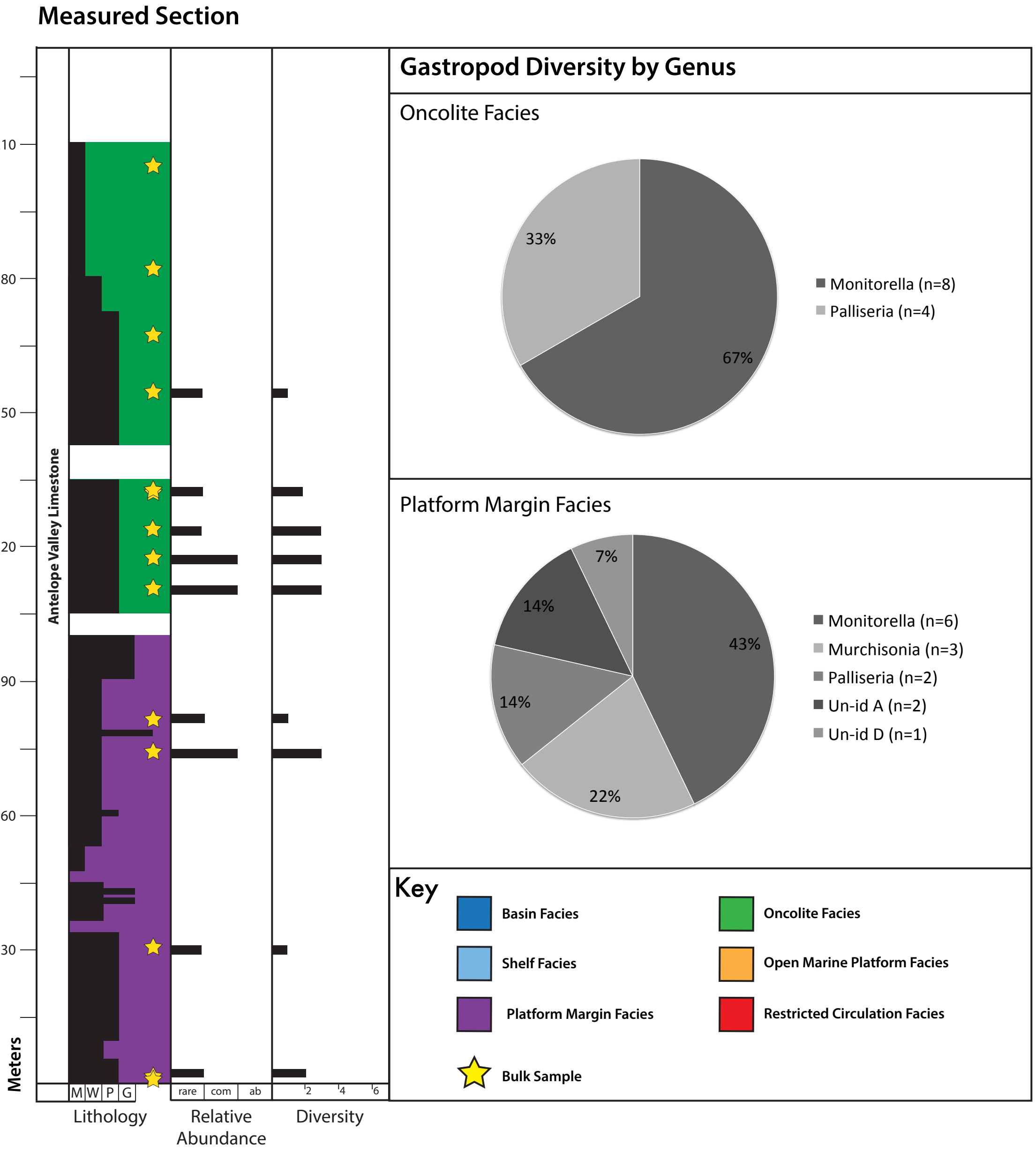
Figure 1.12
Ikes Canyon measured section and gastropod diversity by genus. Columns in measured section indicate carbonate lithology, relative abundance of gastropods in each bulk sample (rare, common, abundant), and gastropod diversity.



Martin's Ridge

The 210 m section measured at Martin's Ridge includes the open marine platform facies and the oncolite facies. As mentioned above, this locality was chosen because it was the main collection site for the Rohr (1994, 1996) survey of Whiterockian gastropods of Nevada. Fossil material at Martin's Ridge is silicified. Gastropods are rare in the packstones and grainstones. Of the three taxa in this facies, one was identified to genus (*Murchisonia*) and two were identified to family (Unidentified Euomphalid A and D). The oncolite facies at Martin's Ridge, dominated by densely packed oncoids, resembles the oncolite facies in the Arrow Canyon Range, at Lone Mountain, and at Little Rawhide Mountain. Both *Monitorella* and *Palliseria* were collected from the oncolite facies. These macluritid gastropods were the only macrofauna besides receptaculitids found in this facies at Martin's Ridge.

Figure 1.13
Martin's Ridge measured section and gastropod diversity by genus. Columns in measured section indicate carbonate lithology, relative abundance of gastropods in each bulk sample (rare, common, abundant), and gastropod diversity.

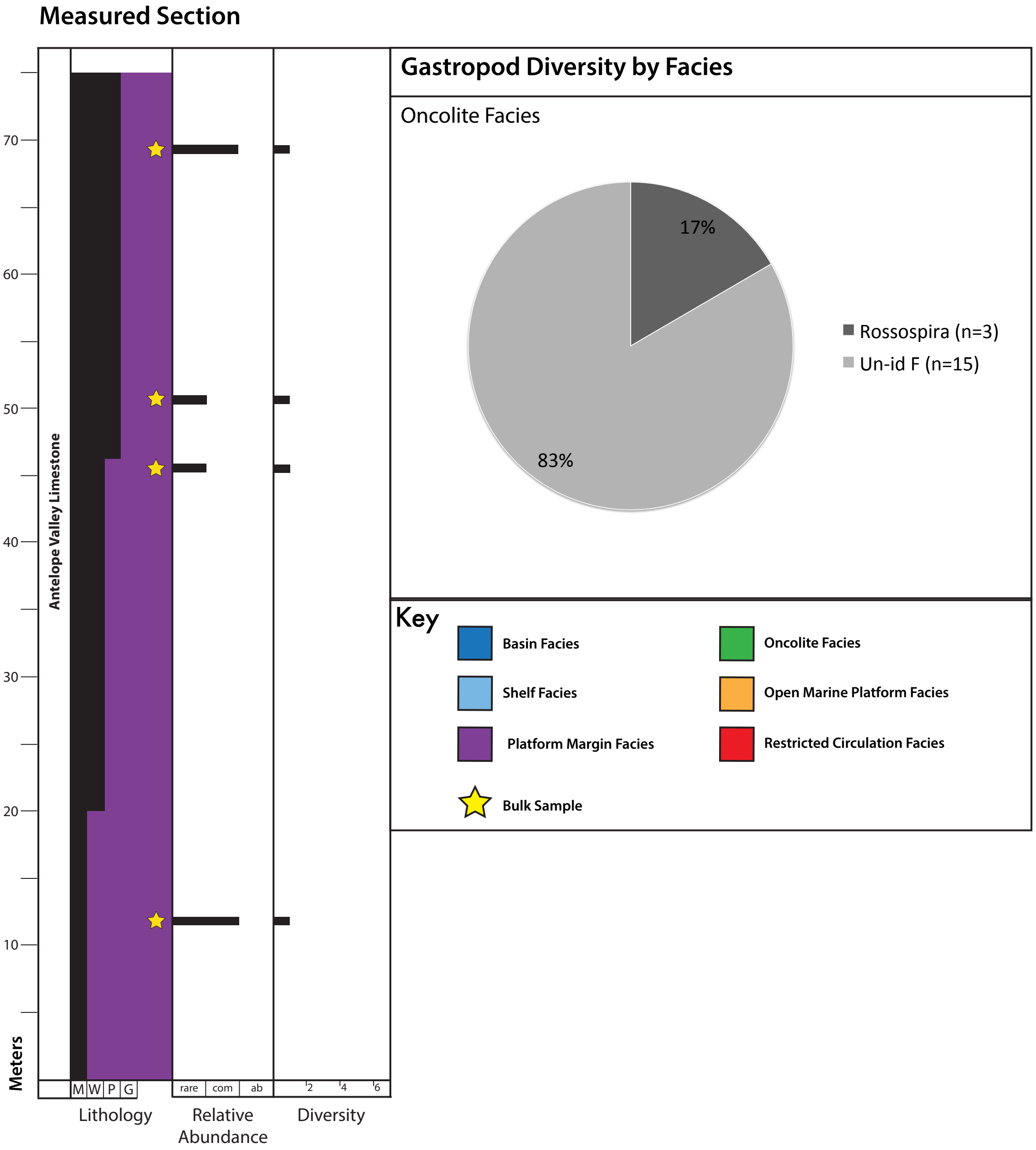


Ninemile Canyon

The 75 m section measured through the platform margin facies in the lowermost Antelope Valley Limestone at Ninemile Canyon did not produce abundant fossil material. The Antelope Valley Limestone at Ninemile Canyon is much more thinly bedded and markedly less fossiliferous than the exposures at Martin's Ridge and Lone Mountian, and we interpret this locality to have deposited on the platform margin rather than on the inner shelf or at the oncolite shoal. In addition to trilobite sclerites, 18 gastropod specimens were collected. Two taxa were represented, *Rossospira* and an unidentified euomphalid (Unidentified Euomphalid F).

Figure 1.14

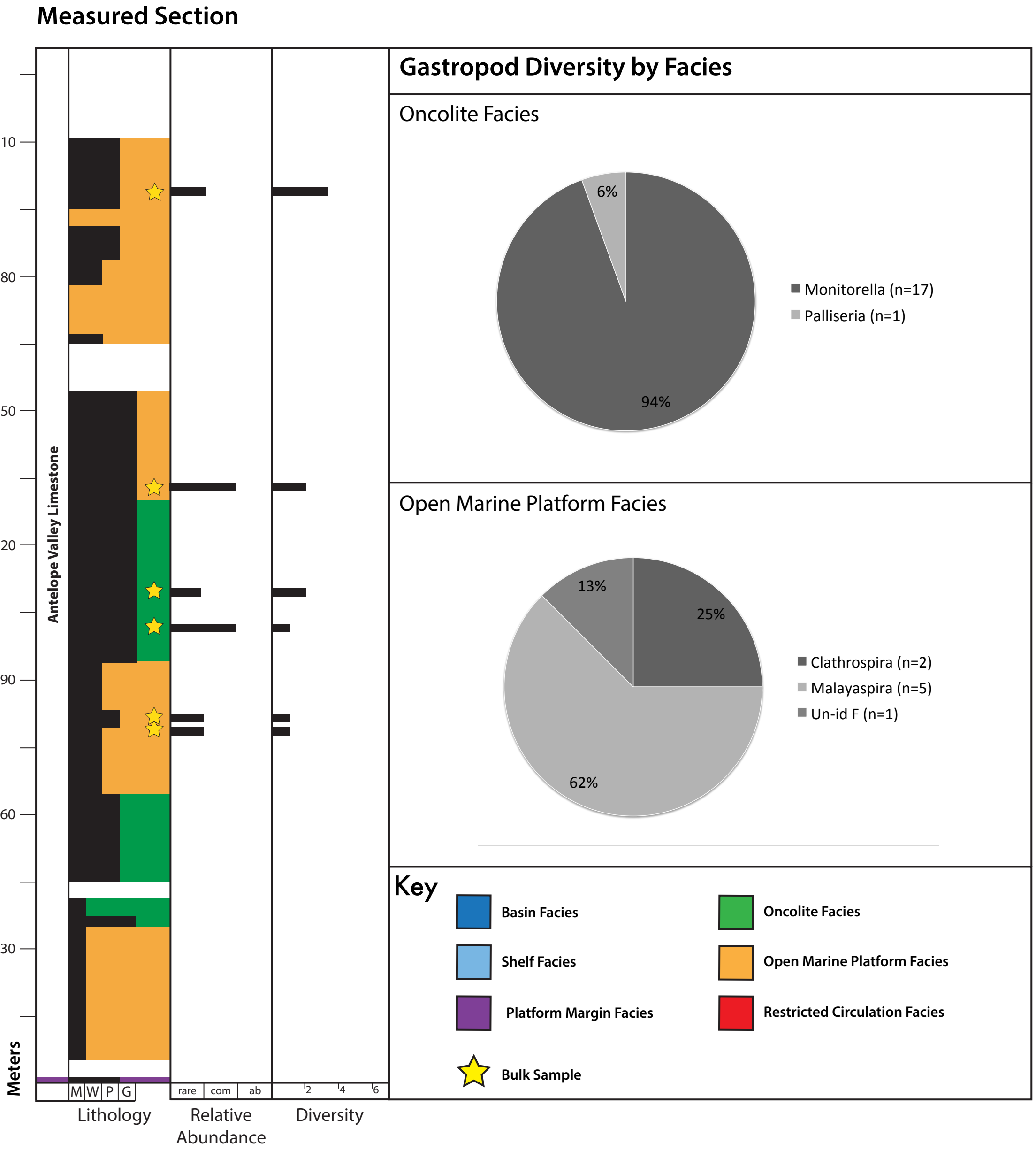
Ninemile Canyon measured section and gastropod diversity by genus. Columns in measured section indicate carbonate lithology, relative abundance of gastropods in each bulk sample (rare, common, abundant), and gastropod diversity.



Lone Mountain

The 210 m section measured at Lone Mountain strongly resembles the section measured at Martin's Ridge, as it starts with the open marine platform facies and then transitions to the oncolite facies. Gastropods are rare in both facies at Lone Mountain, with three taxa identified from the brachiopod-dominated packstones and grainstones of the open marine platform facies facies (*Clathrospira, Malayaspira* and Unidentified Euomphalid F) and two from the oncolite facies (*Monitorella* and *Palliseria*). Gastropods comprise a small percentage of the assemblage in the packstones and grainstones in the open marine platform facies. Trilobite sclerites, brachiopods and echinoderm hash comprise the bulk of this facies at Lone Mountain. Gastropods do comprise a significant portion (roughly half) of the relative abundance of macrofauna in the oncolite facies, with receptaculitids being the only other macrofauana identified from this locality.

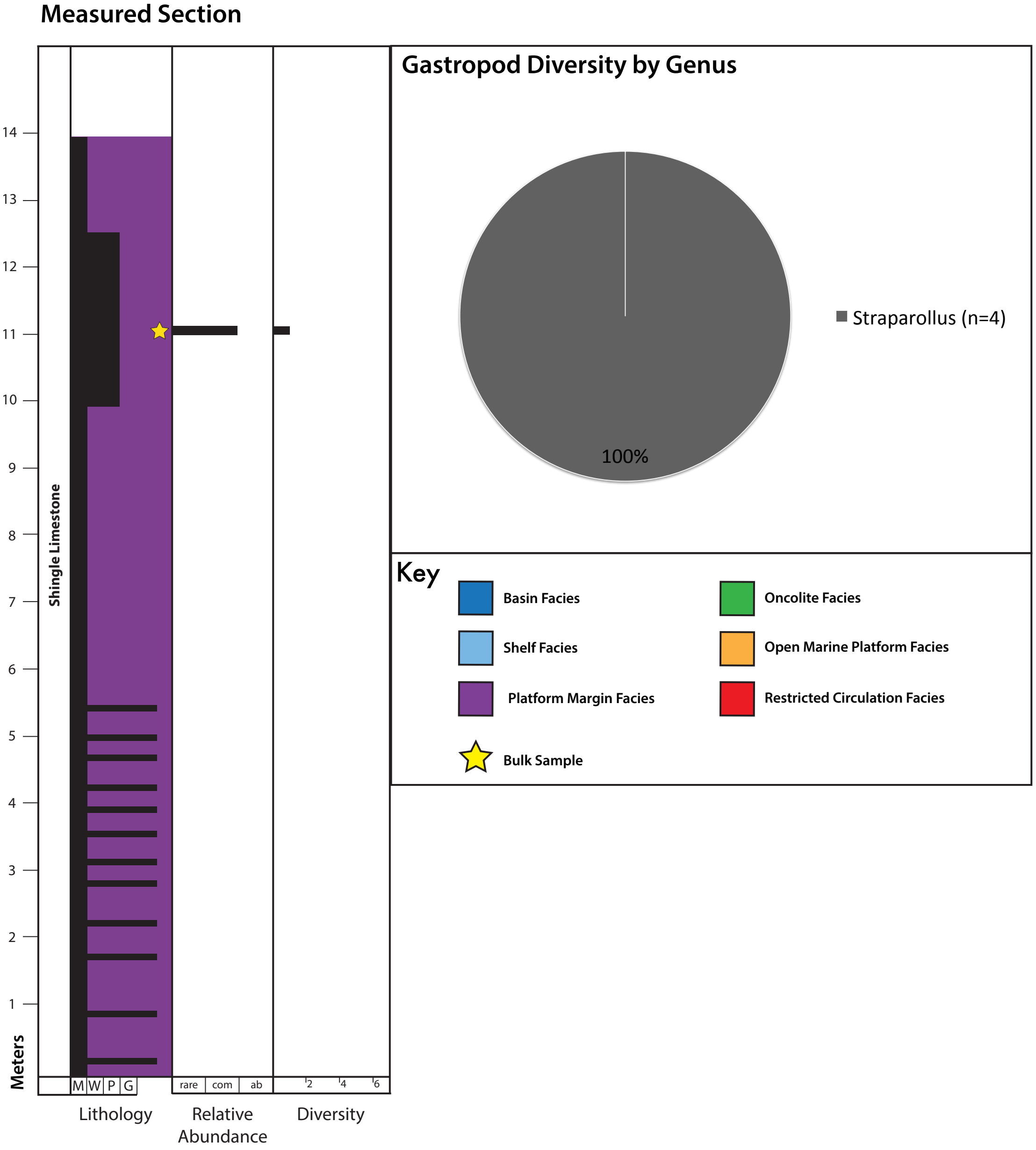
Figure 1.15
Lone Mountain measured section and gastropod diversity by genus. Columns in measured section indicate carbonate lithology, relative abundance of gastropods in each bulk sample (rare, common, abundant), and gastropod diversity.



Shingle Pass

The 14 m section measured at the Shingle Pass locality is positioned stratigraphically within in the lowermost Shingle Limestone, a unit that is roughly correlative to the Wah Wah Formation in the Ibex Region. This section is comprised completely of the platform margin facies. Though the Shingle Limestone is very thick (350 m) at Shingle Pass, much of it is poorly exposed. The four gastropod specimens (all *Straparollus*) collected from this section represent the only fossil material collected.

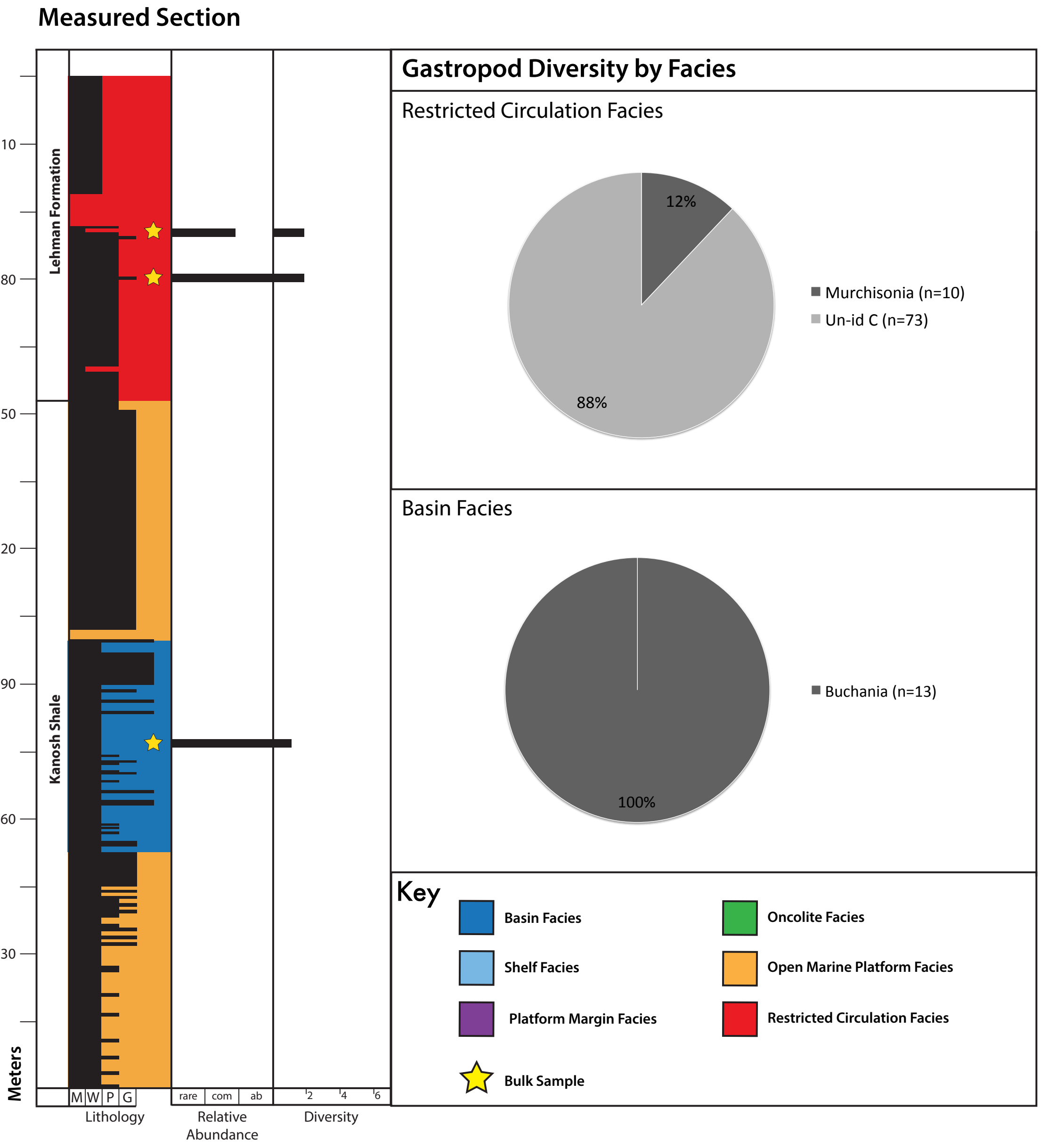
Figure 1.16
Shingle Pass measured section and gastropod diversity by genus. Columns in measured section indicate carbonate lithology, relative abundance of gastropods in each bulk sample (rare, common, abundant), and gastropod diversity.



Crystal Peak

The Crystal Peak section is the only locality at which the black shale facies in the lower Kanosh Shale is well exposed. The 225 m section measured at Crystal Peak includes the entire Kanosh Shale and Lehman Formation. Sampling was focused on two facies: the basin facies in the Kanosh Shale and the restricted circulation facies in the Lehman Formation. One taxon of gastropod, the bellerophontid *Bucania*, was collected from the basin facies in the Kanosh Shale and two taxa, *Murchisonia* and an unidentified micrograstropod "Unidentified Euomphalid C" were collected from the restricted circulation facies in the Lehman Formation. *Buchania* accounts for 73% of the relative abundance in black shale facies, suggesting that this gastropod was specially adapted to the dysoxic conditions in the deepest depositional environment within the restricted Kanosh Basin. The microgastropod and *Murchisonia* form densely-packed, discrete lenses within the Lehman Formation.

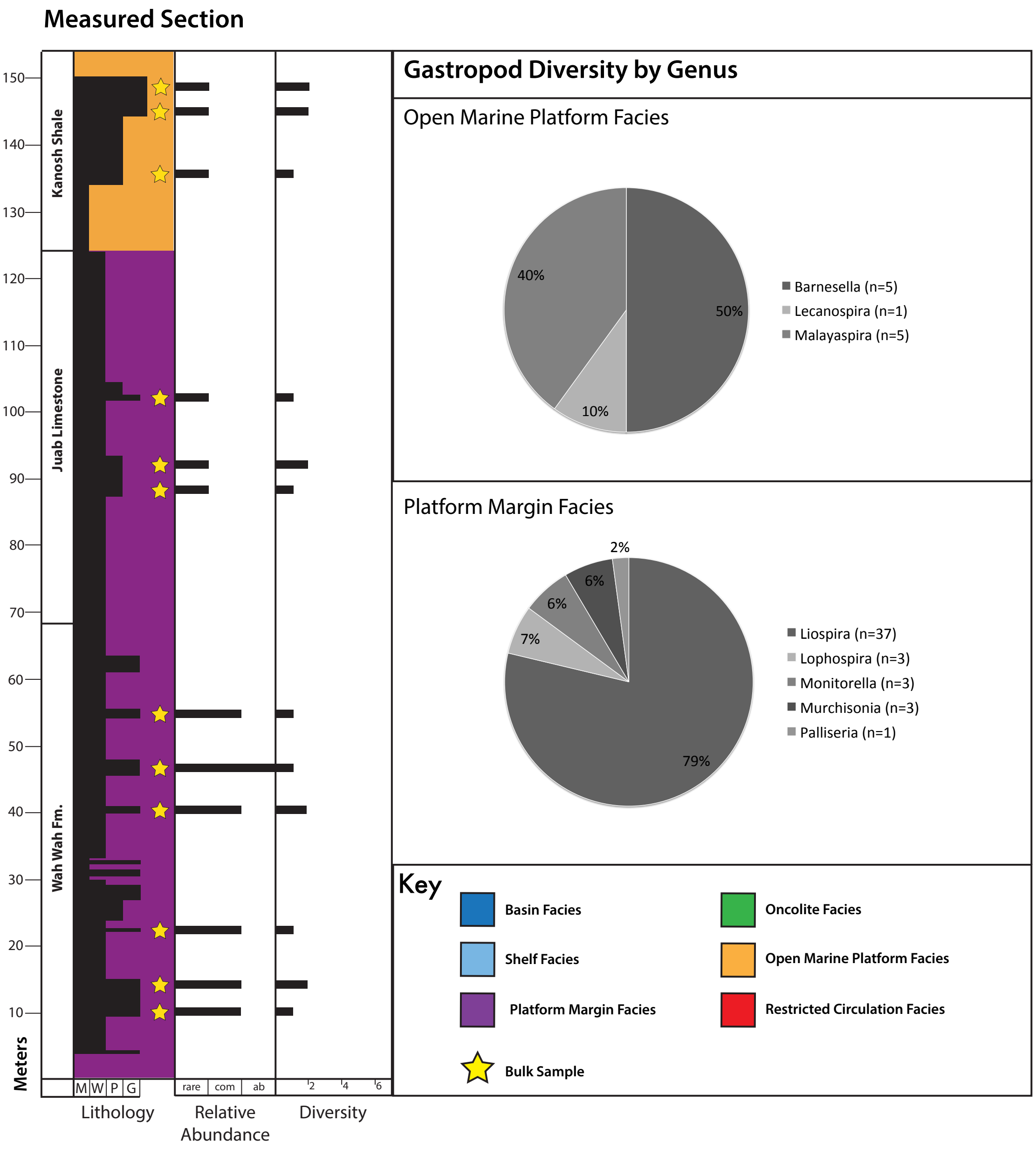
Figure 1.17
Crystal Peak measured section and gastropod diversity by genus. Columns in measured section indicate carbonate lithology, relative abundance of gastropods in each bulk sample (rare, common, abundant), and gastropod diversity.



Section J, Ibex Region

The 155 m section measured at Hintze's Section J in the Ibex Region begins in the upper Wah Wah Formation, continues through the Juab Limestone and ends in the lowermost Kanosh Shale. The Wah Wah Formation and Juab Limestone, dominated by the open marine platform facies, are interpreted to represent deposition on the platform margin under normal marine conditions while the Kanosh Shale represents deposition within a large restricted basin. Due to lithology, sampling was very difficult in the Wah Wah Formation and Juab Limestone. Six bulk samples were taken in the Wah Wah Formation and three were taken in the Juab Limestone. The six gastropod taxa identified from the Wah Wah Formation and Juab Limestone (*Lecanospira, Liospira, Lophospira, Monitorella, Murchisonia,* and *Palliseria*) account for less than 10% of the relative abundance measured in these formations, and gastropods tended to occur either as lone specimens within a brachiopod or trilobite dominated shellbed or as small monospecific lenses (most common for *Liospira*). Three bulk samples were taken from the Kanosh Shale. The lowermost member of the Kanosh Shale is dominated by the basin facies and characterized by carbonate hardground horizons interbedded with shale. Hardgrounds in the lowermost member of the Kanosh are better developed at Section J than at the Crystal Peak locality. The hardgrounds at Section J are heavily encrusted by bryozoa and echinoderm holdfasts with abundant ostracods, and gastropods are rare. Three gastropod taxa (*Barnesella, Malayaspira,* and *Murchisonia*) were identified from the Kanosh Shale at Section J.

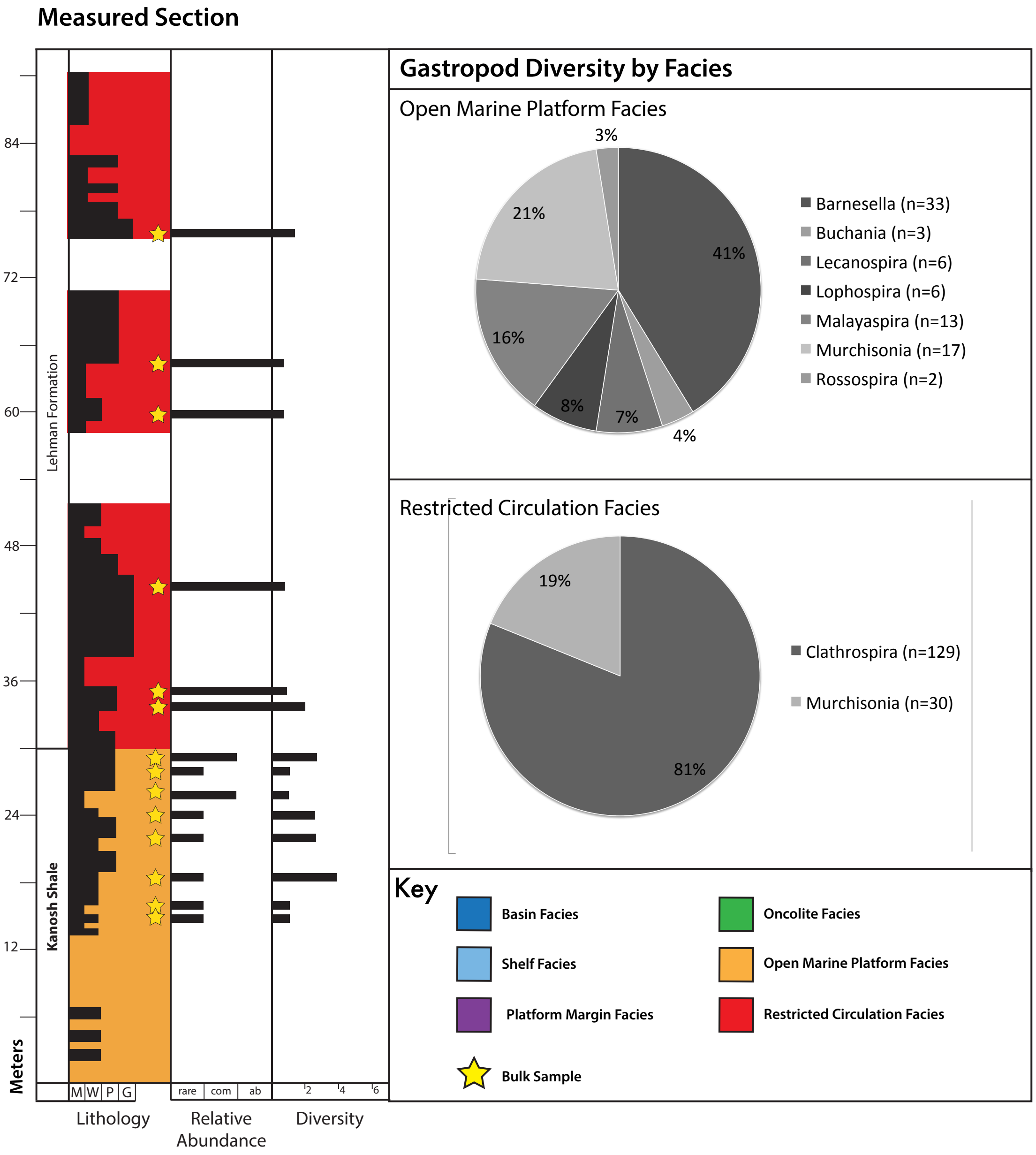
Figure 1.18
Ibex Region, "Section J" measured section and gastropod diversity by genus. Columns in measured section indicate carbonate lithology, relative abundance of gastropods in each bulk sample (rare, common, abundant), and gastropod diversity.



Camp Section, Ibex Region

The 90 m section measured at Hintze's Camp locality in the Ibex Region begins in the upper Kanosh Shale and includes the full Lehman Formation. The open marine platform facies in the upper Kanosh Shale is composed of brachiopod-dominated packstones and grainstones. Ostracods and trilobite sclerites are also common in the upper Kanosh Shale, with rare gastropods and cephalopods present. Though gastropods account for less than 10% of the relative abundance in this facies, the gastropod assemblage is rich and seven gastropod taxa were identified (*Barnesella, Buchania, Lecanospira, Lophospira, Malayaspira, Murchisonia* and *Rossospira*). The Lehman Formation is composed of the restricted circulation facies, with monospecific mollusk shellbeds. The shellbed-forming gastropods include *Clathrospira* and *Murchisonia*.

Figure 1.19
Ibex Region, "Camp" measured section and gastropod diversity by genus. Columns in measured section indicate carbonate lithology, relative abundance of gastropods in each bulk sample (rare, common, abundant), and gastropod diversity.



DISCUSSION AND CONCLUSIONS

The relative abundance of each facies is shown in Figure 1.19. Taxa are classified broadly as: gastropod, brachiopod, trilobite, ostracod, bryozoan, cephalopod, bivalve, and receptaculitid. Gastropod diversity by facies is shown in Figure 1.20. Gastropod taxa are identified to the genus level when possible, but poor preservation has rendered six gastropod taxa unidentifiable beyond the family level and these are identified as "Unidentified Eumphalid A-F." The taxonomic affinities and age ranges of identified genera are shown in Table 1.2. The twelve identified genera represent three orders of gastropod (Bellerophontida, Eomphalina, and Murchisoniina). Nine of the twelve genera are limited in age to the Ordovician or the Ordovician and Silurian, while three have much larger age ranges. The bellerophontid gastropod *Bucania*'s age range extrends from the Ordovician through the Triassic and both the euomphalid *Straparollus* and the Murchisoniina *Murchisonia* range from the Ordovician through the Creteceous.

Gastropods account for 72.7% of the relative abundance of bulk samples collected from the basin facies. Ostracods account for 22.7% and trilobite sclerites account for 4.5% of the relative abundance in this facies. It should be noted that the ostracod and trilobite shell material was much smaller than the gastropod shells and relative abundance may not accurately represent ecology in this facies. Furthermore, this facies has very little fossil material and the sample size for all taxa is small (n=22). Only one genus of gastropod, *Bucania*, occurs in this facies. *Bucania* is a bellerophontid gastropod, and its position within the gastropod phylogeny is not well resolved. *Bucania* represents the only in situ macrofauna occuring within this facies, suggesting that this genus was specialized to the harsh environmental conditions present in the deepest portion of Kanosh Basin, a large fault-bounded basin within the platform. The genus *Bucania* persists through the Paleozoic into the Triassic before going extinct.

Gastropods account for 77.2% of the relative abundance of bulk samples taken in the shelf facies. The remainder of the assemblage is comprised of trilobite sclerites (14.2%) and brachiopods (8.6%). Fossil material within in this facies was silicified, with better preservation than at most other localities. Eight gastropod taxa were identified. Six were well-preserved enough to identify to genus (*Lecanospira, Liospira, Lophospira, Monitorella, Murchisonia,* and *Palliseria*) and two were only able to be identified to family (Unidentified Euomphalids A and B). Though eight taxa occur within this facies, the assemblage was dominated by two genera: *Lophospira* and *Murchisonia* (38.9% and 52.5% relative abundance of gastropods). Both genera have a high-spired morphology (an atypical morphology for Paleozoic gastropods; Fryda et al., 2012) and are interpreted to have been mobile grazers. Both genera survived through the end-Ordovician mass extinction. *Lophospira* goes extinct in the Silurian and *Murchisonia* survives to the Cretaceous.

The densely-packed gastropods within the packstones in the shelf facies show little evidence of significant transport. We interpret these packstones as storm-generated accumulations (Finnegan and Droser, 2008; Kidwell, 1986). The lack of transport suggests that a diverse assemblage of gastropods was thriving along the shelf during the Ordovician. This contradicts traditional onshore-offshore pattern hypothesis (Jablonski et al., 1984), as the shelf facies is the most offshore examined in this study.

Due to the size difference between gastropods and other taxa, this breakdown may not accurately represent the ecological dominance of gastropods within this facies. The gastropod shells and fragments were much larger than the trilobite sclerites and brachiopod shells.

Trilobites account for 82.0% of the relative abundance of bulk samples taken from the platform margin facies. The remainder of the assemblage is comprised of gastropods (7.5%), brachiopods (4.8%), echinoderms (3.7%), bryozoans (1.7%), and cephalopods (0.3%). The platform margin facies is a deeper, more distal open marine depositional environment than the open marine platform facies. Rare gastropods account for less than 10% of the total relative abundance and occurred in one of every three bulk samples. The gastropod assemblage is most diverse of all six facies examined in this study. Fourteen gastropod taxa were identified from this facies, ten of which could be identified to the genus level (*Barnesella, Buchania, Lecanospira, Liospira, Lophospira, Monitorella, Malayaspira, Murchisonia, Rossospira,* and *Straparollus*), and four of which could only be identify to family (Unidentified Euomphalids A, D, E, and F).

Six of these taxa have the typical early Paleozoic gastropod morphology of macrluitids and euomphalids. They are nearly planispiral with flat, sturdy bases. Seven other taxa are high-spired pleurotomarids, trochids, and murchisonioids, and the remaining taxon is a bellerophontid gastropod. The diversity of morphologies of this gastropod assemblage suggest a diversity of life modes. Macluritids and euomphalids were likely sessile and filter feeders, while the pleurotomarids, trochids, murchisoniods and bellerophontids were likely mobile grazers. Gastropods tended to occur either as lone specimens or in monospecific "pockets" or "lenses" within shellbeds. This facies was clearly dominated by brachiopods and trilobites, suggesting that while gastropods were present and diverse, they were not dominant in open-shelf, normal marine conditions.

Of the ten gastropod genera identified, five go extinct by the end-Ordovician, and two more go extinct in the Silurian. The remaining three (*Bucania, Murchisonia,* and *Straparollus*) persist until the Mesozoic. As with the gastropods of the shelf facies, the high diversity of gastropods in this more distal, deeper water facies contradicts the traditional onshore-offshore radiation patterns observed in benthic marine assemblages.

Gastropods account for 75% of the relative abundance of bulk samples taken from the oncolite facies. The remainder of the assemblage is comprised of receptaculitids (13%), trilobites (9%), and echinoderms (3%). Two genera of Macluritid gastropods, *Monitorella* and *Palliseria* occur within this facies. When compared to the density of the oncoids, the Macluritid gastropods occurred more abundantly in the loosely to moderately packed oncoid intervals rather than the densely packed intervals. We interpret the loosely to moderately packed oncoid intervals to represent a calm, shallow depositional environment positioned shoreward from and protected by the oncolitic shoal. This interpretation suggests that macluritid gastropods preferred to live in the calm, protected proximal side of the shoal rather than directly within the high-energy shoal environment.

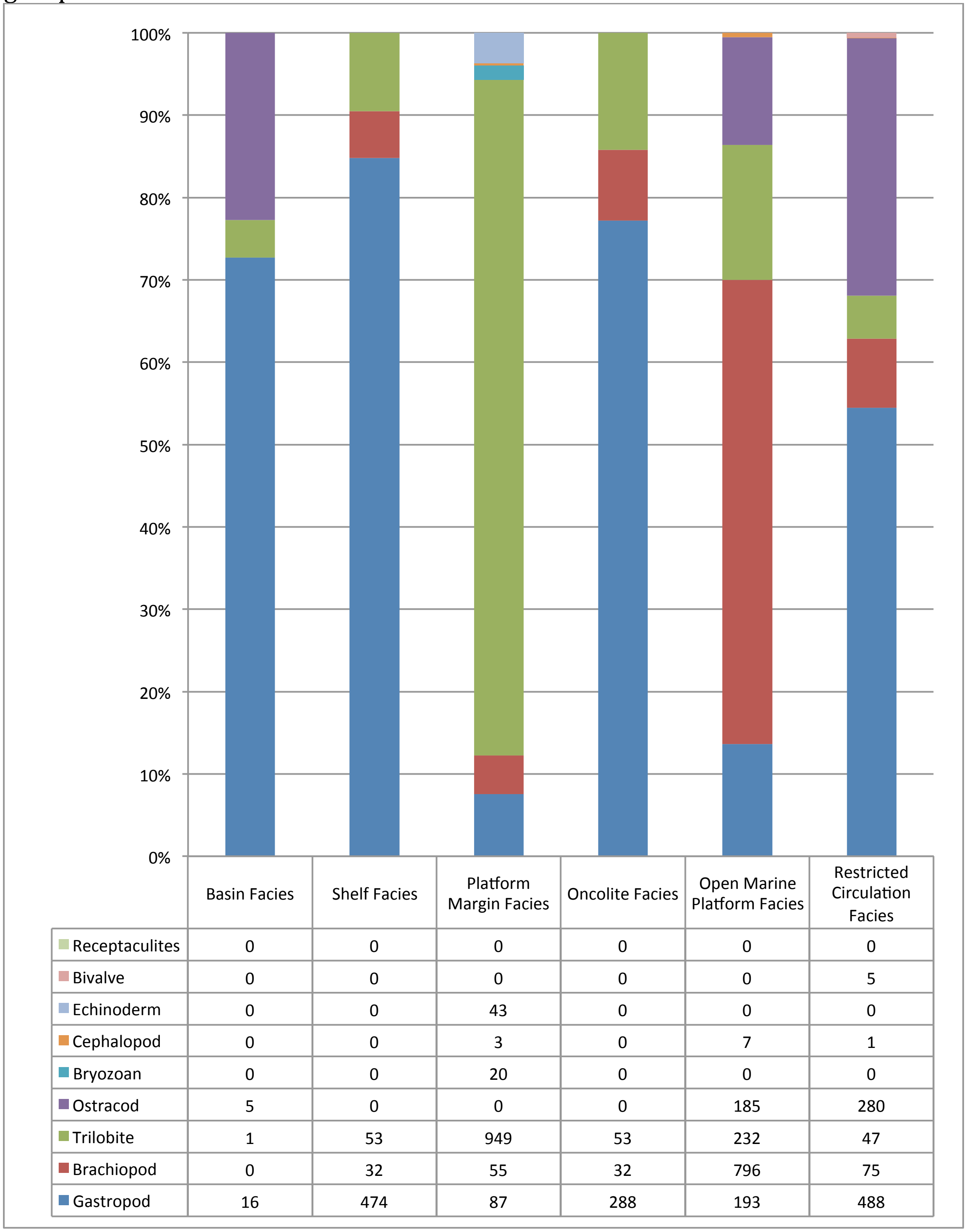
Gastropods account for 54.5% of the relative abundance of bulk samples taken in the retricted circulation. The remainder of the assemblage is comprised of ostracods (31.3%), brachiopods (8.4%), trilobites (5.2%), and bivalves (0.1%). As described above, taxa within this facies tend to occur in monospecific shellbeds, so when gastropod occurrences account for 100% of the relative abundance in individual shellbeds.

Three gastropod taxa were identified from the restricted circulation facies: *Clathrospira, Murchisonia*, and an unidentified microgastropod (1-2 mm in diameter) designated as "Unidentified Eumphalid C." The occurrences of monospecific shellbeds (specificially of mollusks rather than more typical Paleozoic fauna) suggest that the macrofauna found within this facies were specially adapted for life in harsh conditions. Hypersalinity within the lagoon would have been taxing for the typical Paleozoic fauna like echinoderms, brachiopods and trilobites. Rather than compete, these gastropod taxa adapted to the hypersalinity.

Brachiopods comprise 53.3% of the relative abundance of bulk samples collected from the open marine platform facies. The remainder of the relative abundance is comprised of trilobites (16.4%), gastropods (13.7%), ostracods (13.1%) and cephalopods (0.5%). The gastropod assemblage occurring within this facies closely resembles that of the platform margin facies, though only eight taxa were identified within in this facies. Six taxa were identified to genus: *Barnesella, Lecanospira, Lophospira, Malayaspira, Murchisonia* and *Rossospira*. The remaining two are classified as "Unidentified Eomphaloids D and E."

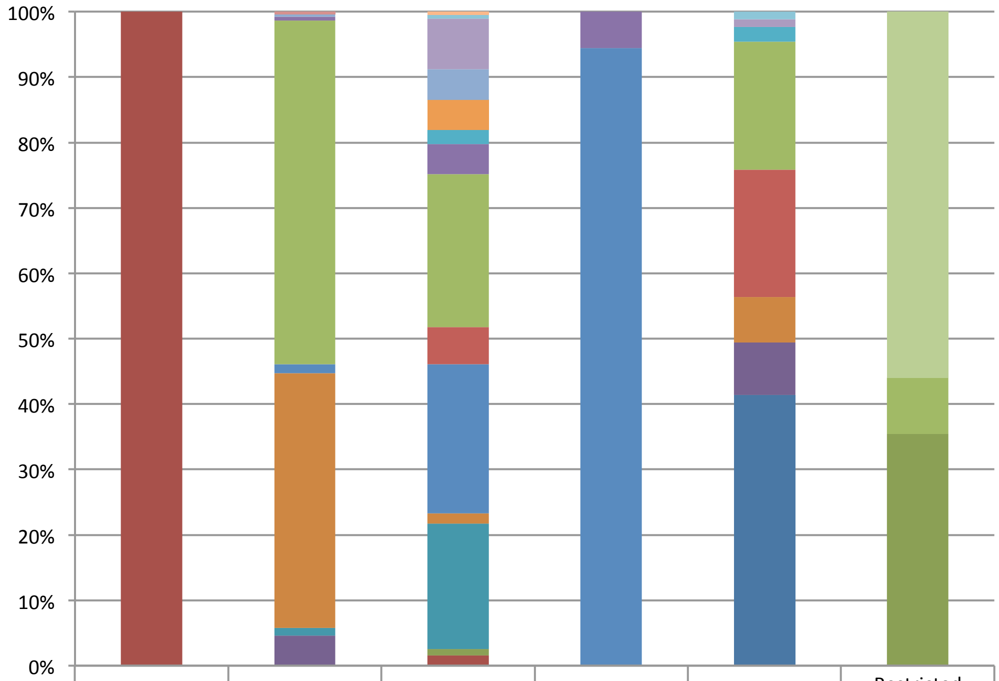
Figure 1.20

Taxonomic diversity by facies. Bars indicate the taxonomic composition of fossils collected from each facies. Data table shows individual counts for each taxonomic group and facies.



	Basin Facies	Shelf Facies	Platform Margin Facies	Oncolite Facies	Open Marine Platform Facies	Restricted Circulation Facies
Receptaculites	0	0	0	0	0	0
Bivalve	0	0	0	0	0	5
Echinoderm	0	0	43	0	0	0
Cephalopod	0	0	3	0	7	1
Bryozoan	0	0	20	0	0	0
Ostracod	5	0	0	0	185	280
Trilobite	1	53	949	53	232	47
Brachiopod	0	32	55	32	796	75
Gastropod	16	474	87	288	193	488

Figure 1.20
Gastropod diversity within each facies.



	Basin Facies	Shelf Facies	Platform Margin Facies	Oncolite Facies	Open Marine Platform Facies	Restricted Circulation Facies
Un-id F	0	0	1	0	0	0
Un-id E	0	0	1	0	1	0
Un-id D	0	0	15	0	1	0
Un-id C	0	0	0	0	0	273
Un-id B	0	2	0	0	0	0
Un-id A	0	2	9	0	0	0
Straparollus	0	0	9	0	0	0
Rossospira	0	0	4	0	2	0
Palliseria	0	3	9	16	0	0
Murchisonia	0	263	45	0	17	42
Malayaspira	0	0	11	0	17	0
Monitorella	0	7	44	272	0	0
Lophospira	0	195	3	0	6	0
Liospira	0	6	37	0	0	0
Lecanospira	0	23	0	0	7	0
Clathrospira	0	0	2	0	0	173
Buchania	16	0	3	0	0	0
Barnesella	0	0	0	0	36	0

Ordovician gastropods are widespread by the Middle Ordovician and occur in all depositional environments examined in this study. Gastropods are present on the across the platform, within the shallow and high energy oncolite shoal, in extremely shallow lagoonal environments and even at the bottom of a deep, oxygen-restricted basin. All of the gastropods identified in this study originated within the Ordovician, so the clade's widespread environmental distribution suggests a rapid radiation and contradicts the nearshore origination patterns observed by Jablonski et al. (1983). While gastropods are present in all these depositional environments, their abundance and diversity is uneven.

Ordovician gastropods thrived when they adapted to specific environments that may have been more taxing (either in terms of nutrients, ocean chemistry or energetics) for typical Paleozoic fauna. For example, gastropods dominated the hypersaline depositional environment of the restricted circulation facies, the high-energy and loose substrate of the oncolite facies, and oxygen-limited bottom waters of the basin facies. All three of these facies were deposited in environments that were either oxygen limited, non-normal marine chemistry (hypersaline), or very high energy (oncolite shoal). Because the gastropod taxa living in these environments were likely specialized to atypical environmental conditions, they were able to thrive without competition from other fauna. In these environments, gastropod diversity was low but relative abundance was very high (75-100%).

Ordovician gastropods were most diverse in normal marine conditions. Gastropod diversity was high (eight taxa or more) at all of the normal marine facies (shelf facies, platform margin facies, and open marine platform facies). The high relative abundance of gastropods within the shelf facies suggest that they were more ecologically successful in this deep water environment than typical Paleozoic fauna like trilobites, brachiopods, echinoderms and bryozoa. This trend may have been driven by the muddy substrates present along the platform shelf. The very low relative abundance of gastropods within the other two normal marine facies suggest that gastropods were outcompeted in most normal marine conditions.

Patterns in relative abundance for gastropods within normal marine conditions are difficult to discern. Gastropods comprise 85% of the relative abundance in the shelf facies and yet they only comprise ~10% of relative abundance in the platform margin and open marine platform facies. All eight gastropod taxa present within the gastropod-dominated grainstone facies are also present within the platform margin and open marine platform facies, though diversity is almost double in the platform margin facies. Because the shelf facies only occurs at one locality, Ikes Canyon, there may have been unique environmental conditions that caused gastropods to thrive and outcompete typical Paleozoic fauna. Furthermore, the gastropod-dominated grainstones at Ikes Canyon are storm generated accumulations so smaller shell material may have been winnowed away, thus inflating the relative abundance of gastropods within this facies.

The taxonomic assemblages of all gastropod-bearing facies noticeably lack abundant echinoderms. While minor accumulations of echinoderm hash are present at the Arrow Canyon Range, one would expect echinoderms to be much more ubiquitous in Paleozoic assemblages. This pattern, in which gastropods and echinoderms do not appear to coexist, can be explained by substrate. Echinoderms require a hardground on which to attach and were likely unable to find a footing in any of the gastropod-bearing facies examined in this study. There is a correlation between high gastropod abundance and muddy or loose substrates, which are the types of substrates that preclude echinoderm attachment. Furthermore, echinoderms require normal marine salinity and temperature, hence they would have been unable to live in the conditions present in the hypersaline lagoon and the oxygen-restricted bottomwaters of the Kanosh Basin.

The environmental context of Ordovician gastropods in the Basin and Range Province sets the stage for gastropod evolution throughout the Phanerozoic. This study shows that the gastropod genera adapted to ecological harsh environments were both more successful within the Ordovician and survived through the end-Ordovician mass extinction. The gastropod genera that were adapted to normal marine conditions were not only more rare, but also were extinct by the end-Ordovician.

Of the gastropod orders that survive the end-Ordovician mass extinction, one gives rise to modern gastropods, the Caenogastropoda, in the Middle Paleozoic. This order, the Murchioniina, includes genera that are specially adapted to life in harsh environments rather than normal marine, shallow environments, as would be predicted by trends observed in other marine clades. Another order, the Bellerophontida, is adapted to a deep, oxygen-restricted environment in the Middle

Ordovician, yet diversifies into shallow marine environments by the Late Paleozoic. This contradicts onshore-offshore patterns observed in other clades, and adds to the evidence that gastropods are an atypical marine clade.

The rise of gastropods to the level of ecological dominance observed in the modern ocean was initiated by a rapid radiation into a wide range of depositional environments in the Ordovician. Iconic early Paleozoic gastropod groups, such as the Macluritidae and Euomphalidae, are most common in normal marine environments and are extinct by the end of Paleozoic, whereas gastropod groups specially adapted to harsh environments where other clades are absent persist through the Paleozoic and give rise to modern gastropods.

CHAPTER 2:

MODELING THE DENSITY OF FOSSILS FROM CROSS-SECTION EXPOSURES: AN EXAMPLE FROM THE ORDOVICIAN OF THE ARROW CANYON RANGE, NV

ABSTRACT

Collecting accurate density data for fossil deposits can prove challenging, especially when beds are not exposed in plane view. In these cases, paleontologists are tasked with reconstructing shellbed density from cross section exposure. This study presents a mathematical model to calculate the density of fossil material within a bed from bedding cross section counts. The model is calibrated against an Ordovician biofacies comprised of oncoids, macluritid gastropods and receptaculitids exposed in the Arrow Canyon Range of Southern Nevada, where unique preservation provides both cross section exposures and plan view of fossil concentrations.

INTRODUCTION

Collecting accurate density data for low-concentration fossil deposits can prove challenging. Paleontologists are often tasked with reconstructing bed density from bedding cross section, especially when beds are not exposed in plane view. In these situations, low-concentration and patchy fossil material can easily be underestimated or missed completely. This problem can be addressed through bulk sampling at high-frequency intervals, though this method is not always practical. Bulk sampling might be impeded by lithology, restricted or regulated by volume, or the locality might be too remote to transport bulk samples.

While models such as Kidwell's R-Sediment models are excellent in modeling the accumulation of fossil concentrations from sedimentation rate (Kidwell, 1986), no model exists to estimate the density of fossil material within a bed from cross-section exposure. Fortunately, geospatial modeling issues like this have long been considered in mathematics, and we can build off of existing thought experiments and basic geometry to create a workable model for paleontological applications. For example, Buffon's Needle Problem (developed by French naturalist and mathematician Georges-Louis Leclerc, Comte de Buffon, 1777) models the probability that a randomly tossed needle of length l will land on a line, given a floor with equally spaced parallel lines a distance d apart. Perhaps more applicable to fossil assemblages, the Buffon-Laplace Needle Problem (refined by Laplace, 1812, 1820) models the probability that a tossed needle of length l will land on at least one line, given a floor with a grid of equally spaced parallel lines distances a and b

apart, with $l < a, b$. These types of models can be adapted to modeling the occurrence of fossil material within a shellbed by counting cross-section occurrences.

Here we present a model using simple geometry to calculate the density of fossil material within a bed from bedding cross section counts. Our model is adapted from Buffon's studies and calibrated against a unique Ordovician biofacies comprised of oncoids, macluritid gastropods and receptaculitids. This biofacies is recognized globally in shallow carbonate settings and is particularly well represented in the Middle Ordovician succession of the Basin and Range Province of the western United States, occurring in the Antelope Valley Limestone (AVL), Pogonip Group and Juab Limestone. The varied modes of exposure of this biofacies in the Arrow Canyon Range of Southern Nevada provide an ideal dataset with which to calibrate this model. Within a 120 meter stratigraphic interval, fossil material is frequently exposed in large, meter-scale bedding planes and in cross section, thus providing several "snapshots" of fossil distribution on the seafloor. Our equation can thus be tested against real world fossil deposits.

GEOLOGIC SETTING

The development of this model stems from a paleoecological examination of the association between oncoids, macluritid gastropods and receptaculitids. This is association has been reported from Ordovician shallow carbonate settings in the Basin and Range province of the Western United States (Merriam, 1963; Ross et al., 1989; Ross, 1994; Droser et al., 1995; Kaya and Friedman, 1997), the Precordillera of Western Argentina (Cañas and Carrera, 1993), the Duwibong formation of Korea (Banks and Johnson, 1957; Kano and Fujishiro, 1997), Sonora, Mexico (Beresi et al., 2012), and the Croisaphuill Formation of Scotland (Raine, 2010) (Figure 2.1). This apparent biofacies is typically defined both by environment (shallow carbonate shoal, indicated by the formation of oncoids) and taxonomic composition (presence of large macluritoid gastropods and receptaculitids, to the near-exclusion of any other macrofauna) (Figure 2.2).

Oncoids, centimeter-scale coated grains, are rare in modern marine settings but common throughout the Paleozoic and Mesozoic (Peryt, 1981, 1983a). These grains, which form in active subtidal environments via bacterially-mediated carbonate accretion, accumulate in large, meter-scale shoals (Peryt, 1983b). Throughout the Middle Ordovician, oncolitic shoals migrated across a vast carbonate ramp, tracking the passive margin shoreline of western Laurentia (Ross, 1977; Ross et al., 1989). Within the Antelope Valley Limestone and the Pogonip Group (regional distinctions between correlative packages of Middle Ordovician carbonates), the oncolitic facies represents deposition in a shallow, subtidal environment and typically crops out between an open-water, inner shelf facies and a lagoonal facies. In the Arrow Canyon Range, the field locality of this study, this shallowing sequence from open water to lagoon is preserved within the Ordovician Pogonip Group, members E and F (OPe and Opf). The oncolite occurs within Opf, and 41 m constitute the macluritid-receptaculid-oncoid biofacies.

Figure 2.1
Map of global occurrences of the Macluritid-Receptaculitid-Oncoid biofacies during the middle Ordovician, indicated by red dots. Green dots indicate occurrences of macluritid gastropods, according to the Paleobiology Database (source: Paleobiology Database).

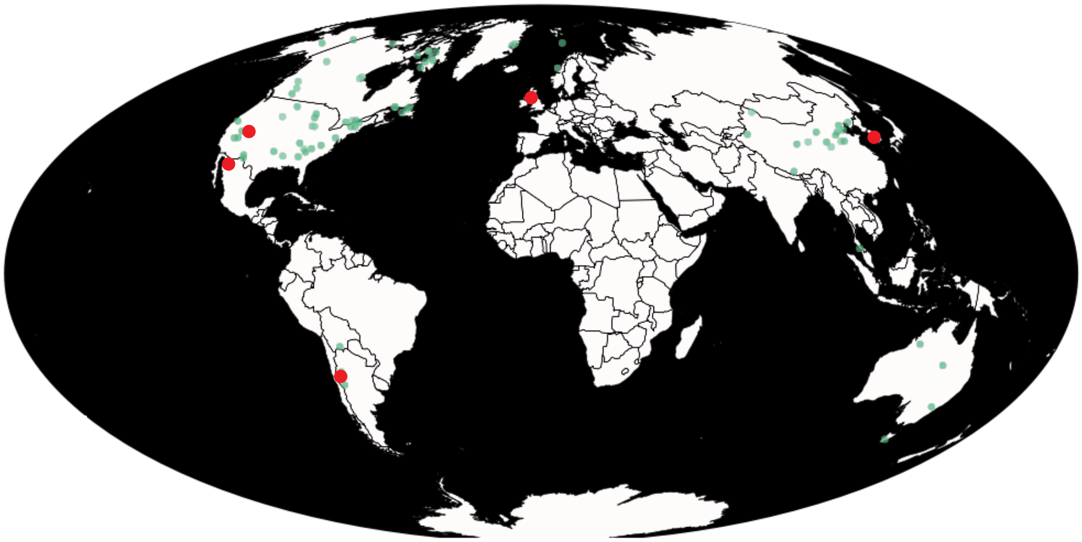


Figure 2.2
Macluritid-receptaculitid-oncoid biofacies in the Arrow Canyon Range. 5 cm scale on bottom right.

The iconic Ordovician gastropod family Macluritoidea includes the genera *Maclurites* Le Seur, 1818*, Maclurina*, Ulrich and Scofield, 1897*, Palliseria*, Wilson, 1924 and *Monitorella*, Rohr, 1994. This family is characterized by "large dextral shells with a flat or protruding base and a nearly radial aperture with no re-entrants" and calcified opercula (Rohr, 1994). The Macluritoidea gained status as icons of the Ordovician because of their size (they were the largest of the Paleozoic gastropods, with one specimen of *Maclurina* reaching 25 cm in diameter; Rohr et al., 1992). While the Macluritoidea have long been interpreted to have been sedentary filter feeders (Yochelson, 1990; Salter, 1859), recent morphometric examination of *Maclurites* and *Maclurina* ontogeny has shown that juveniles may have been mobile algae grazers before transitioning to filter feeding adults (Novack-Gottshall and Burton, 2014).

Occurrences of macluritids are limited to the Ordovician and range from Ibexian to Cincinnatian (491 to 443.7 Ma; Paleobiology Database). Macluritoids are reported globally in the Paleobiology Database, with occurrences on Laurentia, Gondwana, Baltica, and Avalonia (Figure 2.1). In the Middle Ordovician strata of the Basin and Range Province, macluritids have been reported from the Antelope Valley Limestone, the Pogonip Group and the Juab Limestone (Yochelson, 1986; Rohr, 1994). Macluritoids in the Basin and Range Province often occur within the oncolitic facies, with one notable exception: *Monitorella auricula* was collected from the inner shelf facies of the Juab Limestone in the Ibex Region of western Utah.

Receptaculites, the third component of this apparent biofacies, occur commonly throughout the Ordovician and Devonian. The clade's taxonomic affinity is still under debate and receptaculitids have been tentatively classified as sponges, calcareous green algae, and even as an extinct clade of problematic organisms unrelated to other taxa (Nitecki et al., 1999). In the Basin and Range Province, receptaculitids always occur within the oncolitic facies, but receptaculitids are reported from a variety of shallow marine environments across Laurentia during the Ordovician (Paleobiology Database). Receptaculitids are easy to recognize by the Fibonacci-like arrange of meroms that spiral outwards along their outer surface.

Field data for this study was collected from Member F of the Ordovician Pogonip Group (OPf), exposed in the Arrow Canyon Range of Southern Nevada (Figure 2.3). This outcrop serves as an ideal natural laboratory in which to develop a bed density model because it provides 120 meters of nearly continues cross-section exposure through the oncolitic facies as well as several square meters of bedding plane exposure. These exposures provide two vantage points from which to study shellbed composition. The bedding plane exposures were essential in developing this model, as we were able to compare actual bed density to density visible in cross-section.

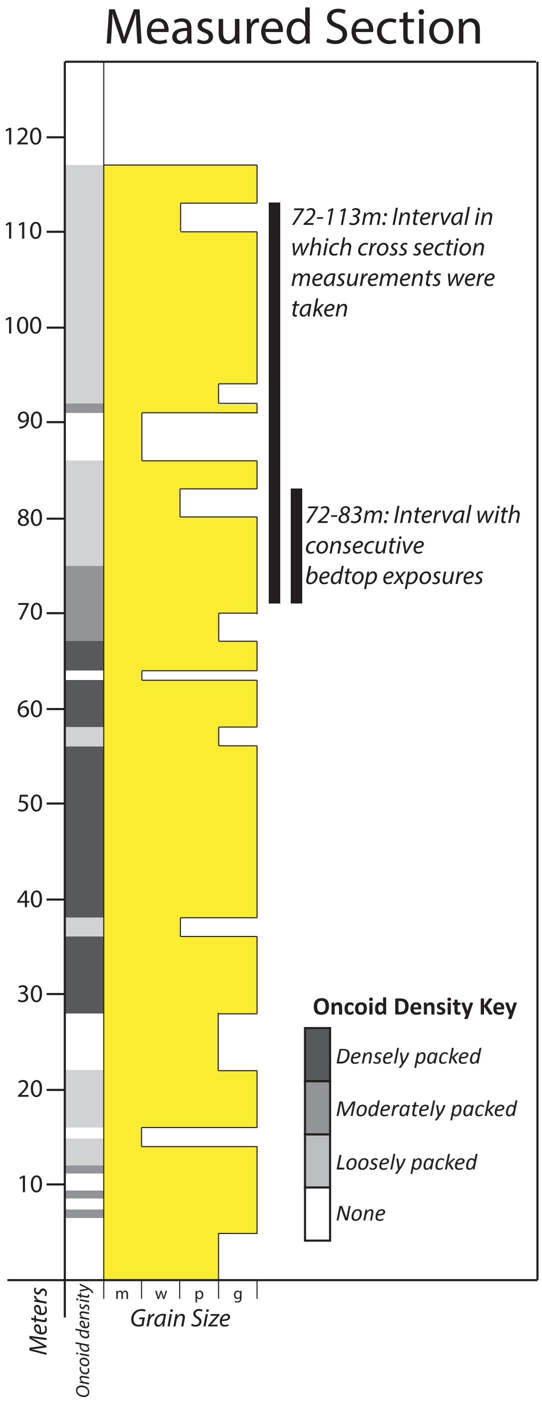
The model was calibrated against macluritid occurrences throughout OPf. A detailed 120 meter sedimentological section was measured through OPf (Figure 2.4). Environmental interpretations were made on site. The OPf member has long been characterized as oncolitic, but a closer examination reveals a more complex sedimentological story. While OPf is dominated by the oncolitic facies, oncoid density fluctuates from densely packed (oncoid grainstones) to absent. We interpret this to reflect the shifting oncolite shoal and associated shallow water environments, described below:

Meter	Description
0 - 28	*Thinly bedded carbonate packstone and grainstone facies.* Oncoids are rare. Fossil material (averaging 5-10mm in long axis length), is common and is comprised of trilobite sclerites, brachiopods, disarticulated crinoid columnals and gastropods. *Environmental interpretation:* inner shelf, normal marine, distal from the oncolite shoal.
28 - 72	*Ocolite facies.* Densely packed, large (5-15mm) oncoids, many nucleated around shell fragments. Fossil material is common and is comprised of trilobite sclerites, brachiopods, disarticulated crinoid columnals and gastropods. *Environmental interpretation:* Oncolitic shoal, very shallow, normal marine (above wave base).
72 - 83	*Bedtop exposure interval.* Oncolitic facies similar to the 28-72 m interval, with moderate to densely packed oncoids. Weathering through this interval has exposed several (11) large bedtops on which oncoids and maculuritid gastropods are preserved. Other fossil material, including receptaculities, is very rare. *Environmental interpretation:* proximal side of the oncolitic shoal (still within the shoal).
83 - 86	Oncolite facies, as described above. *Environmental interpretation:* Oncolitic shoal, very shallow.
86 - 91	Oolitic facies. Devoid of fossil material, very poor exposure. *Environmental interpretation:* oolitic shoal, very shallow.
91 - 113	Receptaculitid facies. Loosely to moderately packed oncoids. Large (10-20cm) receptaculitids and large (5-10cm) maculuritid gastropods are commonly exposed in cross section throughout this interval. Nearly devoid of any other fossil material. *Environmental interpretation:* Proximal to the oncolitic shoal, protected, lagoonal. Oncoids preserved within this facies were transported in from the oncolite shoal.
113 - 118	Lagoonal facies. Thinly bedded carbonates mudstones ("ribbon rock"). Devoid of fossil material, bioturbated (ii 2-3). *Environmental interpreation:* lagoonal, protected by the oncolite shoal.

Upon close examination of OPf sedimentology, we found that the macluritid-receptaculid-oncoid biofaces does not occur in densest portion of the oncolite. While oncoids occur in varying density throughout the 120 m measured section, macluritid gastropods and receptaculitids occur only in a distinct interval from 72-113 m, where oncoid packing is loose or moderate. This suggests that macluritids and receptaculitids were living on the shoreward, protected side of the oncolite shoal.

Figure 2.3
Location of the Arrow Canyon Range, Southern NV, USA, indicated by the red marker (Source: Google Maps).

Figure 2.4


Measured Section
120
110
100
90
80
70
60
50
40
30
20
10
72-113m: Interval in which cross section measurements were taken
72-83m: Interval with consecutive bedtop exposures
Oncoid Density Key
Densely packed
Moderately packed
Loosely packed
None
Meters
Oncoid density
m
w
p
g
Grain Size

COLLECTION OF FIELD DATA

A 50x50cm quadrat was used to measure macluritid density on bedtops. To measure density, the quadrat was placed randomly onto the bedtop, then photographed, then all macluritids within the square were counted, measured (diameter), and described. Oncoids, if present and/or visible, were described (average size, shape) and oncoid density was measured using a semi-quantitative 3-point scale (1 = loosely packed, clasts not touching; 2 = moderately packed, some clasts touching; 3 = densely packed, clasts touching). Cross-sectional views were exposed nearly continuously throughout the upper 46 m of the section. The same width as the quadrat (50 cm) was used to measure macluritid gastropod occurrences in cross section.

Ninty-six bedtop quadrats were analyzed on bedding planes exposed from 72-83 m in the Arrow Canyon measured section (Figure 2.5). Macluritid gastropods abundance in quadrats ranged from 0 to 19 (mean = 2.9). The average macluritid gastropod radius was 9.77mm (272 total macluritids observed).

Seventy-eight cross section measurements were taken throughout the upper 46m of the section. Macluritid occurrences in cross section measurements ranged from 0 to 4 (mean = 0.62). Macluritid gastropods occurrences appear to increase up-section (Figure 2.6). In the lower portion of the section (72-96 m), 0-1 gastropods were observed in cross section while in the upper portion (97-113 m), 2-4 gastropods were observed.

Figure 2.5
Macluritid gastropod abundance and size distribution.

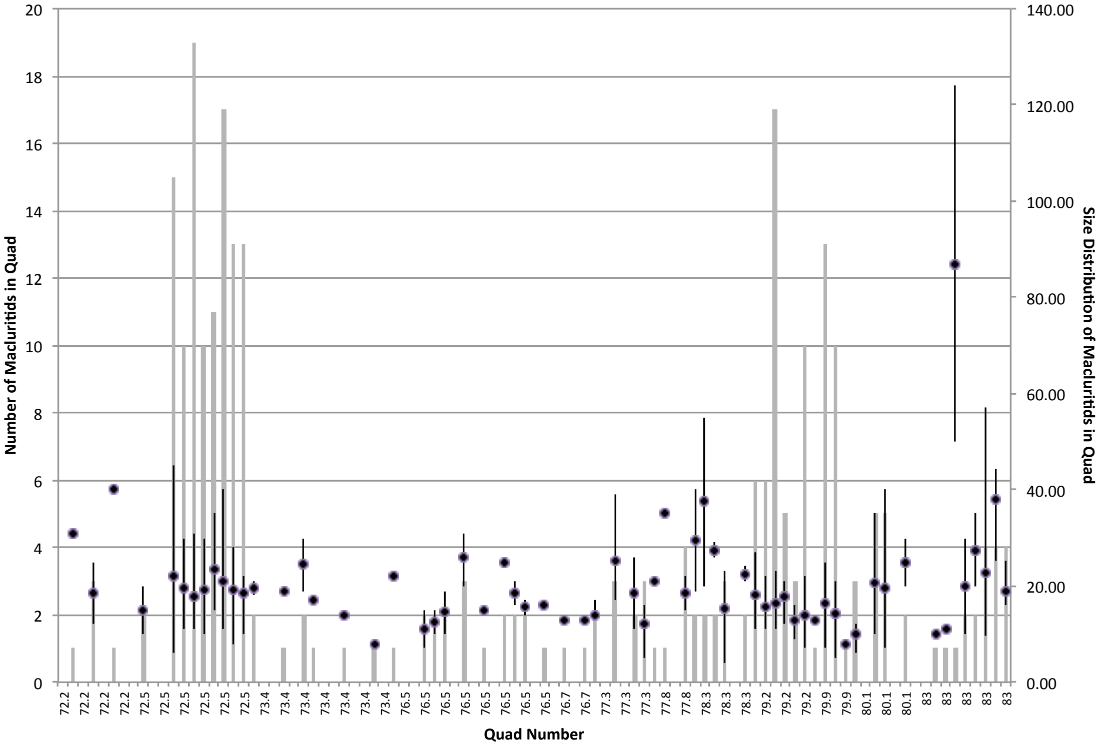
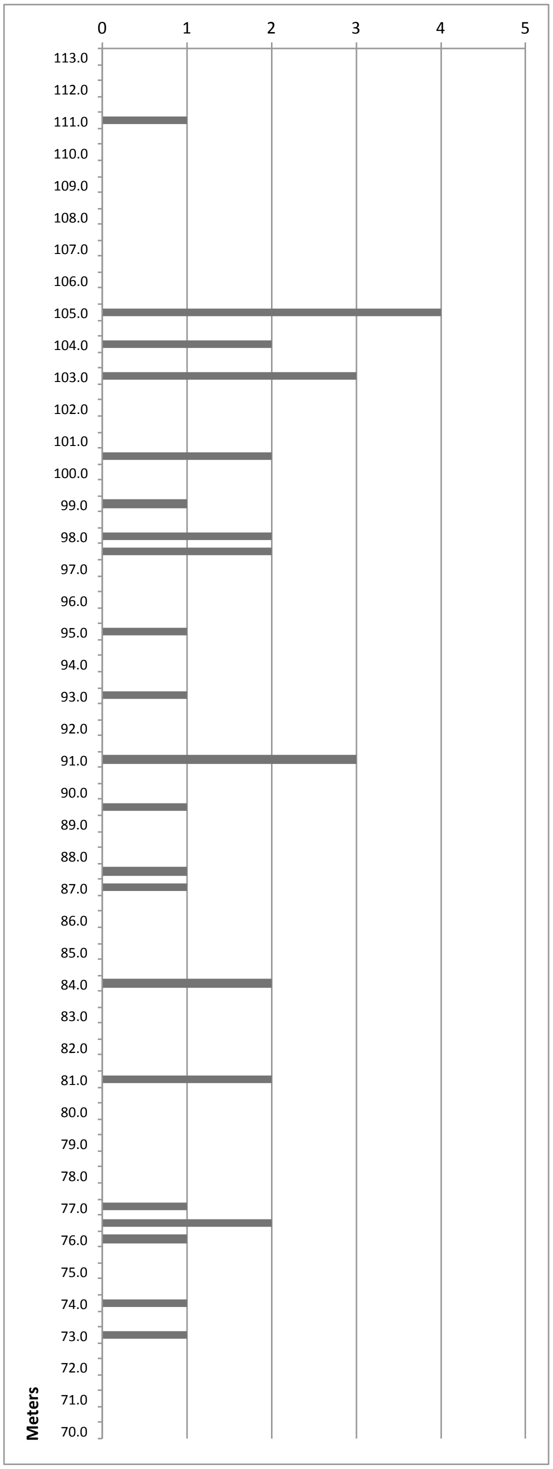


Figure 2.6
Number of macluritid gastropods exposed in cross section along a 50 cm length of beds throughout the Arrow Canyon Range section.



BUFFON'S MODELS

Buffon's Needle Problem (Figure 2.7) developed from a common 18th century coin toss game, in which players would bet on whether or not a tossed coin would land on the lines between square flooring tiles. Buffon realized that the probability of a coin intersecting a tile border could be calculated using geometry and probability, and thus developed his Clean Tile Equation, in which the probability P that a coin of diameter d will lie entirely on a single tile on a square grid with tile length l:

$$P_1 = \frac{(l-d)^2}{l^2} = \left(1 - \frac{d}{l}\right)^2$$

Buffon then realized that this equation could be adapted for more complex shapes, such as polygons or even needles, and could also be adapted for other flooring patterns, such as long thin floorboards (Figure 2.8). He then developed a set of models for calculating the probability that a tossed needle of length l would intersect a line between floorboards, given a floor with equally spaced floorboards with width d. For short needles ($l < d$), the model is quite simple. First, Buffon defined the size parameter x by:

$$x \equiv \frac{l}{d}$$

Then derived the following equation:

$$P(x) = \int_0^{2\pi} \frac{l|cos\theta|}{d}\frac{d\theta}{2\pi}$$

$$= \frac{2l}{\pi d} \int_0^{\pi/2} cos\theta \, d\theta$$

$$= \frac{2l}{\pi d}$$

$$= \frac{2x}{\pi}$$

The equation is more complex for long needles, in which $l > d$:

$$P(x) = \frac{2}{\pi}\left(x - \sqrt{x^2 - 1} + sec^{-1}x\right)$$

Fortunately, this situation, in which a fossil fragment (the "needle") is longer than the distance across the shellbed (the "floorboards") does not have real world paleontological applications. As an interesting aside, a special situation arises when $l = d$. In this case, $x = 1$ and the equation becomes an opportunity to experimentally solve for π, and was used as such in the 18th century.

$$P(x) = \int_0^{2\pi} \frac{l|cos\theta|}{d} \frac{d\theta}{2\pi}$$

$$= \frac{2l}{\pi d} \int_0^{\pi/2} cos\theta \, d\theta$$

$$= \frac{2l}{\pi d}$$

$$= \frac{2}{\pi}$$

Figure 2.7
Diagram of Buffon's Needle Problem, showing the relationship of needle length to floorboard width.

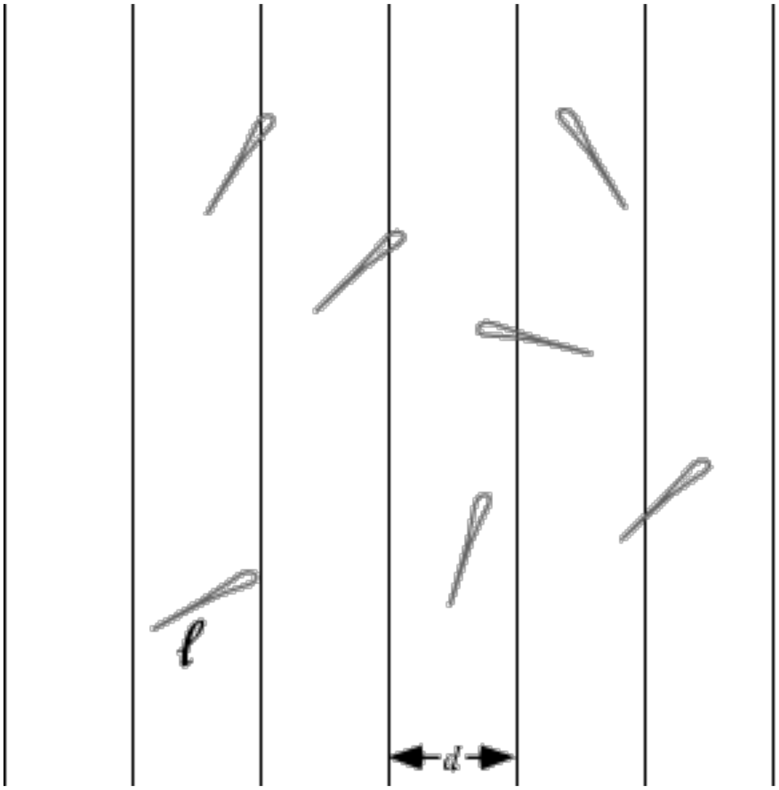
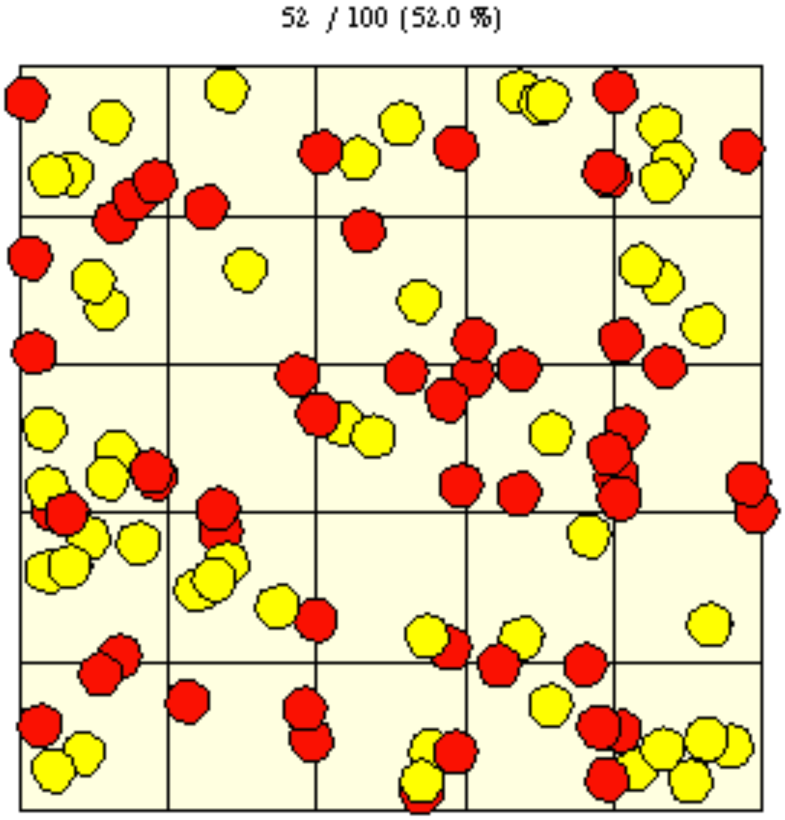


Figure 2.8
The Clean Tile Game, popular in the 17th Century, was played by guessing the likelihood that a coin tossed onto a grid of floor tiles would intersect the lines of the grid. Buffon was able to calculate this likelihood, given the radius of the coin and the length of the side of the tiles. In the diagram, yellow circles represent coins that do not intersect a line and red tiles represent coins that do.



DEVELOPMENT OF THE MODEL

Buffon's thought experiments and models were carried out without the fossil record in mind, and thus must be adapted in order to be applied to shellbed density estimates. Some characteristics, such as the geometric calculations necessary to predict if a disc will intersect a line along the border of a defined area still apply. Other conditions, such as the realities of exposure at *in situ* shellbeds are quite different from objects like coins and needles tossed onto floorboards or tiles. Because our model was to be calibrated against the macluritid gastropod distribution within the Ordovician Pogonip Group exposed in the Arrow Canyon Range, we kept certain basic assemblage characteristics in mind: macluritid gastropods were modeled as circular discs with variable radii, bedding plane exposure area in the model was defined by the size used to measure actual density on the outcrop (0.25 m^2).

Modeling Real Data

We began by analyzing actual bedding plane quadrats measured in the Arrow Canyon Section. To do this we analyzed photos of each quadrat in ImageJ in order to calculate the radius of each macluritid gastropod ("disk") and plot the centroid of the disks onto a 0.25 m^2 Cartesian plane. We then digitally mapped the quadrat in R (see Appendix A for script).

The model uses the data contained in a designated spreadsheet to build a digital plot of the bedding plane quadrat (Plot A), as shown in Figure 2.9. We then used this digital plot to calculate the expected number of disks within a 0.25 m^2

quadrat based on the number of disks visible in 50 cm of bedding cross section (see Appendix B for script).

In this script, the length of the side of the plane (L) is defined as 0.5 m, the area of the plane is defined (L*L) and calculated as 0.25 m^2. Then the significance level (alpha, α) is defined as 0.05 and the standard deviation (sigma, σ) for disk density is defined (assuming Poisson distribution) and calculated using the Arrow Canyon Range bedding planes datasheet.

In order to calculate the expected number of disks, the script draws sequential lines through the plane (the number of lines is defined as "nsamp"), counts the number of disks that are intersected (Figure 2.10), then calculates the expected linear density along a 1.0 meter line. This linear density is then used to calculate the expected areal density of disks within a 1.0 m^2 plane via the formula: $\lambda = 2\sigma\bar{r}$, where lambda (λ) equals the linear density, sigma (σ) equals the areal density, and $\bar{r}$ equals the range of radii (see Appendix C for derivation). The model then creates a second plot (Plot B), showing the number of intersections (linear density) observed along each 0.5 m long cross section and the corresponding expected areal density per 1.0 m^2 portion of bedding plane.

This type of analysis is plotted for the example quadrat 72.5F in Figure 2.11. This plot shows that the number of intersections (linear density) along a 0.5 m cross section ranged from 0-4, and so the expected areal density for 1.0 m^2 bedding plane ranged from 0-300 (with 95% confidence intervals calculated). The linear density falls exactly within in the range of observed linear densities throughout the 46 m of the Arrow Canyon Range section, but the massive range of areal density estimates are unwieldy and confidence intervals show that differences in areal density estimates are not significant, due to the small sample size.

Modeling Synthetic Bedding Planes

The model can also be used to generate synthetic or hypothetical bedding planes from real data. For example, the Arrow Canyon data can be used to input average density and distribution of measured radii of macluritid gastropods to create a much larger synthetic bedding plane than the 0.25 m^2 quadrats measured in the field (see Appendix D for script).

Mathematically, this script functions similarly to the original script. The primary difference is that areal density and bedding plane area are defined by the user instead of calculated from observed data. The user can input a realistic areal density based on observation, or can increase or decrease the density. The user can also adjust the area of the bedding plane to create increasingly larger bedding planes, as shown in Figure 2.12. The model assumes random distribution of fossil material and references the complete Arrow Canyon dataset, with 93 quadrats analyzed and 273 gastropods measured, to insure an accurate distribution of radii.

Just as with the original model, two plots (A and B) are generated by this model. The first (Plot A) is a digital map of the synthetic bedding plane, and the second (Plot B) uses the linear density (observed on Plot A) of the fifty consecutive lines drawn along the x-axis to calculate the corresponding expected areal density for a 1.0 m^2 bedding plane. Plot B includes 95% confidence intervals. As the user increases the area of the synthetic bedding plane, the expected areal density and corresponding confidence intervals shrink (see Figure 2.12). Because the model assumes random distribution of disk centroids, different plots and numbers will be generated each time the model is run.

Figure 2.9
(A) Field photograph of one of the bedtop quadrats, 72.5F, with yellow arrows highlighting three areas with macluritid gastropod fossils, and (B) Plot A (the digital map) created by the model from the same quadrat.

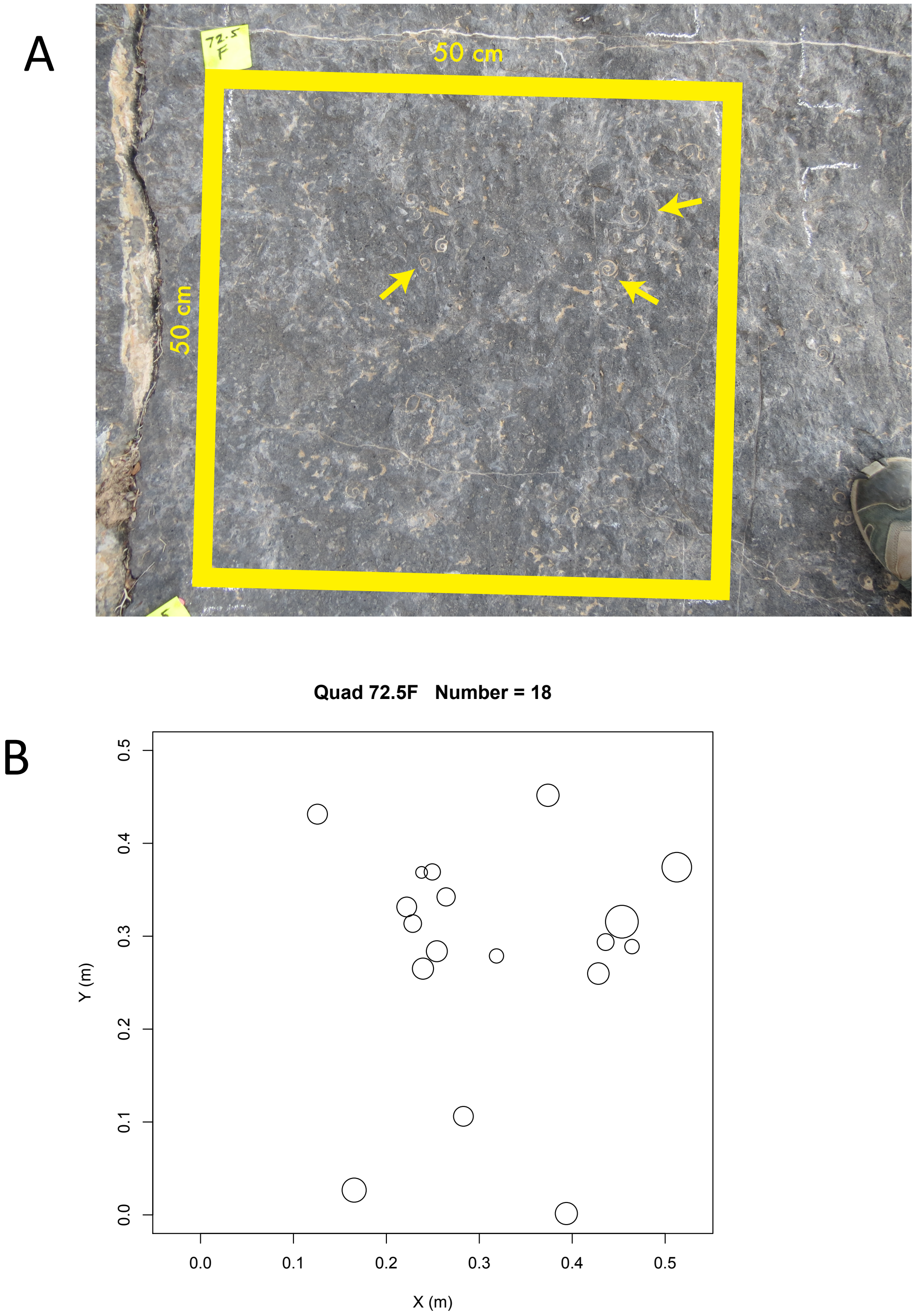


Figure 2.10

Plot A (a digital map of macluritid gastropods observed) for Quadrat 72.5F, with analysis lines drawn every centimeter along the x-axis. Lines that intersect gastropods (circles) are color coded by the number of intersections: grey - 0, blue - 1, green - 2, orange - 3, red - 4. These intersections are used by the model to calculate linear density and areal density for a 1.0 m^2 bedding plane.

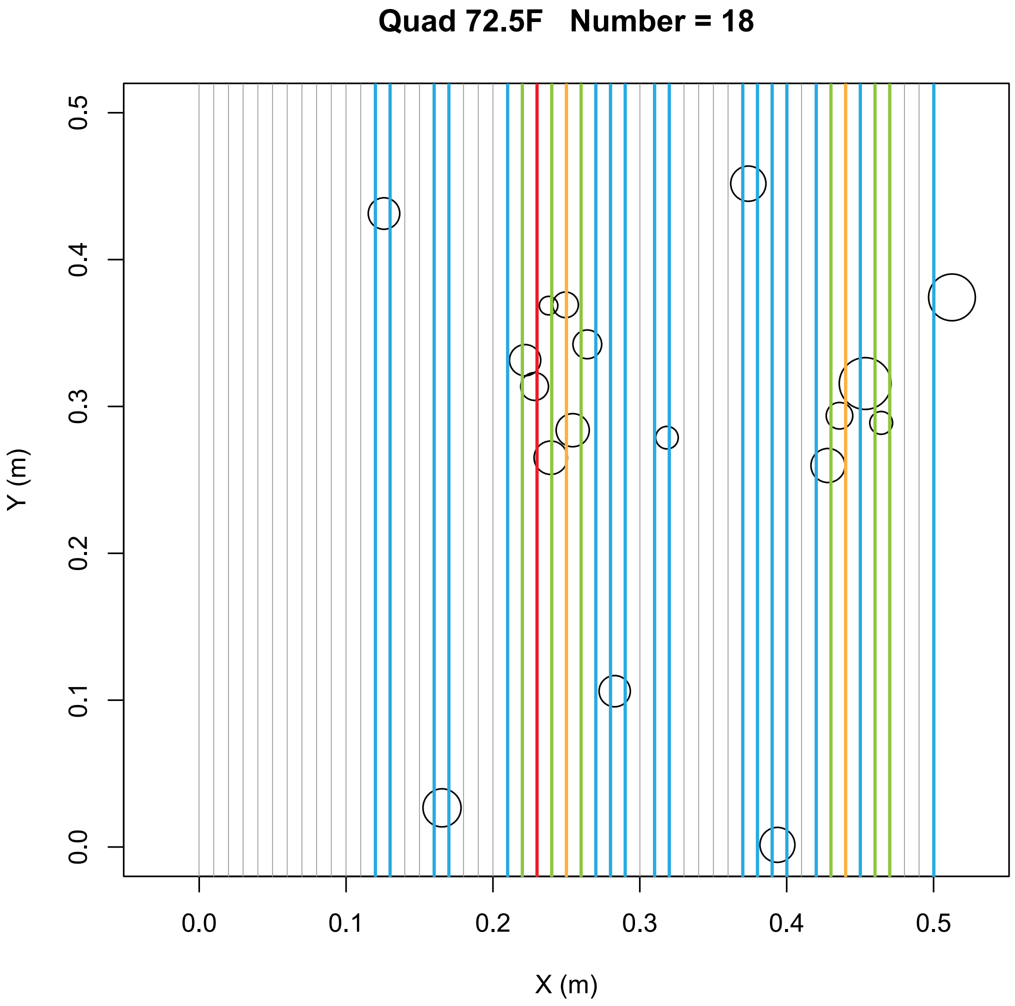


Figure 2.11
Plot B (estimating areal density from linear density) for Quadrat 72.5F. In the plot, circles indicate the expected areal density based on the linear density measured at that x-value. Because linear density in quadrat 72.5F ranged from 0-4, areal densities are estimated for 0, 1, 2, 3, and 4. Error bars represent 95% confidence intervals.

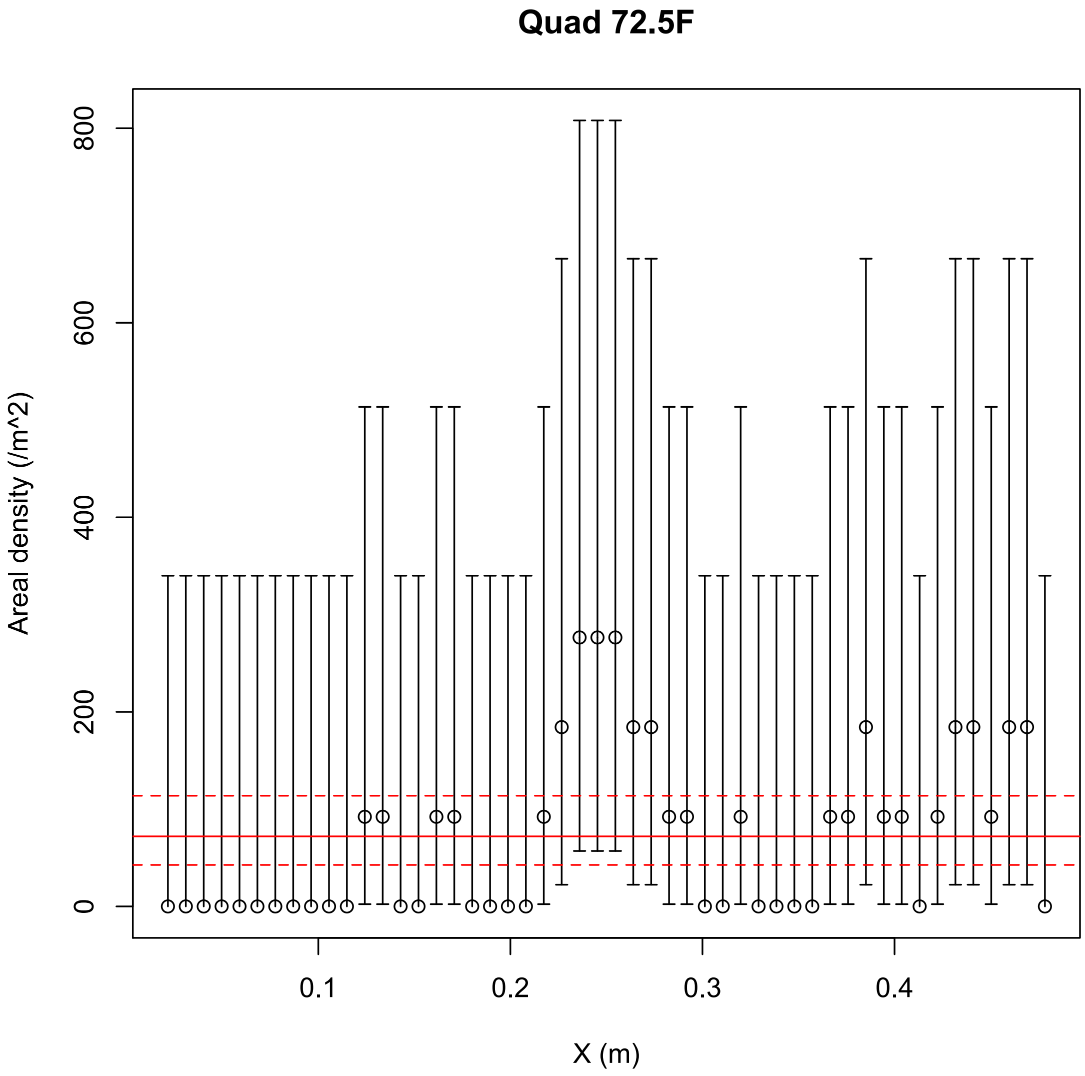
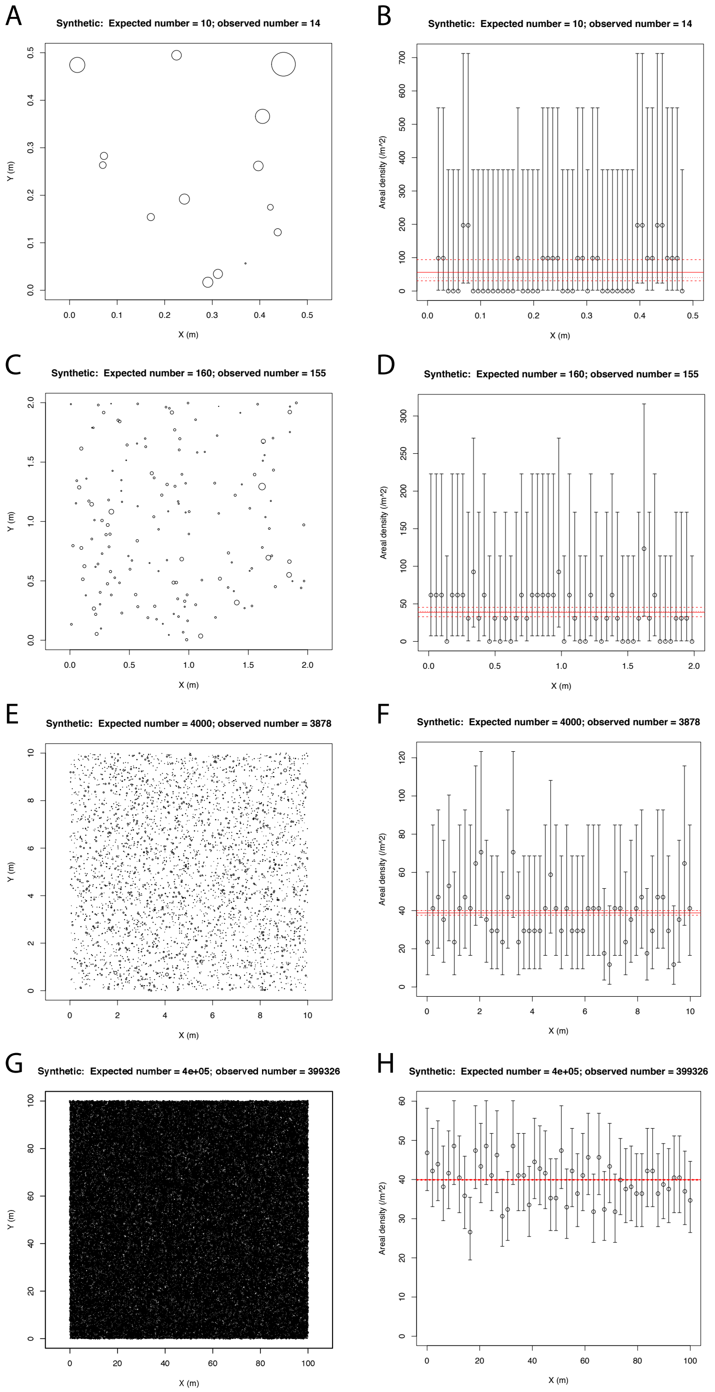


Figure 2.12
Plots for synthetic bedding planes of increasing area with realistic density and radii: A-B) 0.25 m^2, C-D) 4 m^2, E-F) 100 m^2, G-H) 10000 m^2



DISCUSSION

Analysis of Arrow Canyon Range

Data collected during cross section analysis in the field suggest that macluritid gastropod density increases up section (Figure 2.5). In the lower portion of the measured section (72-83 m), cross section measurements ranged 0-1 gastropods per 50 cm, while cross section occurrences the upper portion (97-113) ranged from 2-4. When applied to the Arrow Canyon Range bedding plane dataset, the model accurately predicts that cross section exposures will range from 0-4 and then suggests that the density of macluritid gastropods does not vary significantly throughout the section.

Upon first consideration, this may seem to suggest that the model is not useful in producing information that cannot be obtained from field analysis, but the strength of the model as analytical tool is in its ability to create synthetic bedding planes from field data. The "realistic" density (realistic can be defined in several ways, i.e., average, plus or minus one or two standard deviations, maximum observed) of macluritid gastropods in a 0.25 m^2 quadrat and the distribution of measured radii can be used to create increasingly large synthetic bedding planes. These synthetic bedding planes can then be used to analyze subtle differences in cross section exposure when the observed dataset is too small to return significant results.

As an example of this method, we have created increasingly larger synthetic bedding planes (L = 0.5 m, area = 0.25 m^2; L = 2 m, area = 4 m^2; L = 10 m, area = 100

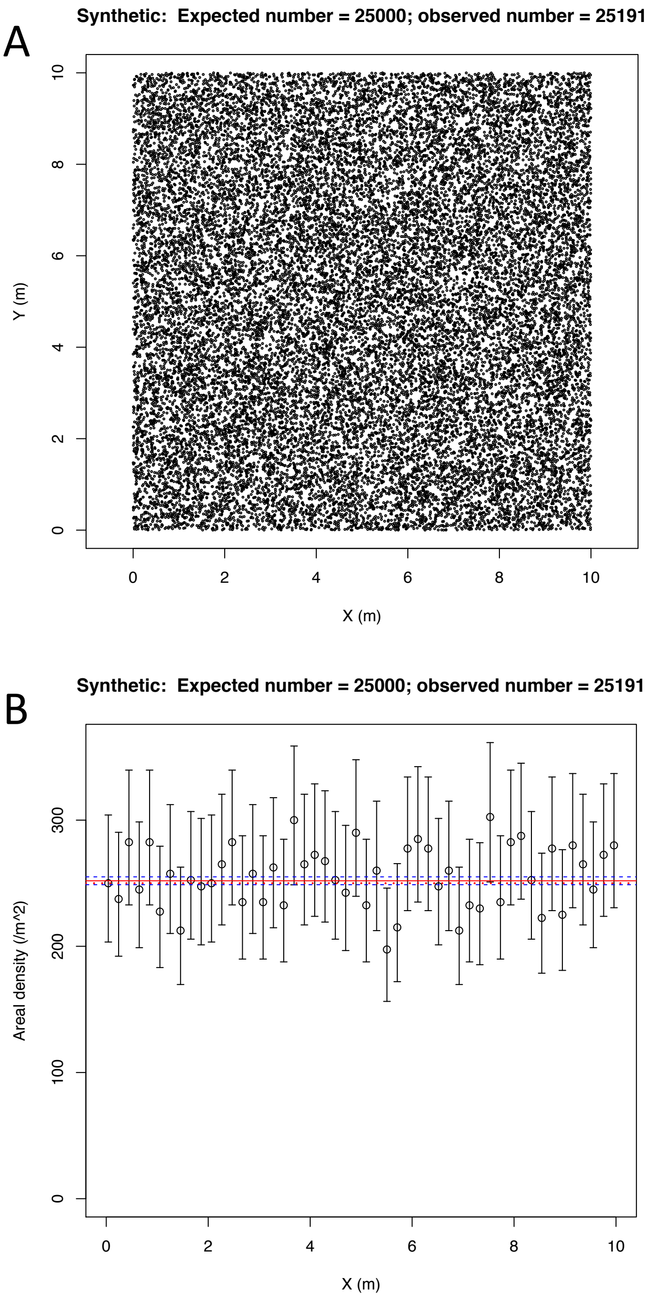
m^2; L = 100 m, area = 10000 m^2) from the Arrow Canyon Range dataset (Figure 2.13G,H). The smallest synthetic bedding plane is the same size as the actual quadrats measured in the Arrow Canyon Range and this run returns similar outputs to actual observations; cross section exposures along a 0.5 m length ranges from 0-3 and areal density within 1 m^2 ranges from 0-200 (+/- 500). As with the analysis of observed data, the error in this prediction is so large that this synthetic bedding plane is not usable. The 4 m^2 synthetic bedding predicts areal density per 1 m^2 to range from 0-125 (+/- 175). The size of the error in this run is also too large to provide any useful information. The much larger 100 m^2 synthetic bedding plane predicts areal density per 1 m^2 to range from 10-70 (+/- 30), which is a much more reasonable range and a manageable, if not ideal, margin of error. The largest synthetic bedding plane (100,000 m^2) predicts that areal density per 1 m^2 will range from 25-50 (+/- 10).

Applications of the Model

There are certain situations in paleontology which applying a model is easier or more appropriate than traditional collection and analytical techniques. This example for the Arrow Canyon Range is one such situation. Bulk sampling throughout the entire measured section was impossible because of the lithology, so we have used this model to take advantage of the unique exposures and were able to analyze the density of macluritid gastropods throughout the section. Though the specific morphology of macluritid gastropods (they are circular disks) are easy to accurately model, other common taxa like brachiopods, trilobites, or ammonites could also be analyzed.

It is also likely that the model would produce more precise results (with smaller margin of error) when modeling more densely packed shellbed or accumulations. For example, the synthetic bed scrip can be programed to model a brachiopod shellbed by plotting densely packed disks of the same radius, shown in Figure 12.14. In this simulation, disk radius was set at 20 mm, density was set at 250 per m^2, and the bedding plane area was set at 100 m^2.

Figure 2.14


A
Synthetic: Expected number = 25000; observed number = 25191
Y (m)
0
2
4
6
8
10
X (m)
0
2
4
6
8
10
B
Synthetic: Expected number = 25000; observed number = 25191
Areal density (/m^2)
0
100
200
300
X (m)
0
2
4
6
8
10

CHAPTER 3:

BUILDING AN EFFECTIVE AND AFFORDABLE K-12 GEOSCIENCE OUTREACH PROGRAM FROM THE GROUND UP: A SIMPLE MODEL FOR UNIVERSITIES

ABSTRACT

University Earth Science Departments seeking to establish impactful geoscience outreach programs often pursue large-scale, grant funded programs. While this type of outreach is highly successful, it is also extremely costly, and grant funding can be difficult to secure. Here, we present the Geoscience Education Outreach Program (GEOP), a small-scale, very affordable model tested over five years in the Department of Earth Sciences at the University of California, Riverside (UCR). GEOP provides in-class presentations for local K-8 classrooms, STEM mentoring for middle and high school students, and day-long events on UCR campus for middle and high school students, and it allows UCR Earth Sciences to participate in a wide range of community events. The program is managed by UCR graduate students, impacts ~4,000 people (K-12 students, UCR students, the Riverside community at large) and operates for less than $3,000 annually. The GEOP model prioritizes simplicity, flexibility and affordability in order to best meet the educational needs of Riverside County, CA.

INTRODUCTION

In 2009, members of the Department of Earth Sciences at the University of California, Riverside (UCR) made a collective decision to engage more effectively with the Riverside community at large. Riverside County, where UCR is located, is one of the most densely populated and socio-economically disadvantaged counties in California. According to the 2010 U.S. Census, 46.7% of Riverside County's 2.3 million residents are Hispanic and 39.8% of households are non-English speaking., Riverside County's median household income is 10% lower than the California average and children are highly likely to attend a Title 1 (High Poverty) school. Communities like these are more vulnerable to dangerous geologic events such as earthquakes (common in Southern California) and the local impacts of climate change (such as extreme heat waves and drought) because they lack both access to important geoscience information and the economic ability to recover from damaging events (Morello-Frosch et al., 2009). As geoscience experts, we were in an ideal position to improve geoscience communication in Riverside County.

We acted in response to our social responsibility as geoscientists and to the necessity of geoscience education and outreach in K-12 classrooms that has been further highlighted by several recent studies. These studies project a severe workforce shortfall in the coming decades and a failure to successfully recruit new geoscience students (see National Research Council, 2010; National Research Council, 2011; Zeigler and Camarota, 2014; Wilson, 2014). This failure to recruit has several causes. School districts across the nation have been reducing or eliminating geoscience curriculum, thereby removing the opportunity for K-12 students to gain exposure to geoscience. In California, public school science course offerings are largely dictated by the University of California admissions requirements. Students are required to take "two years (three years recommended) of laboratory science providing fundamental knowledge in two of these three foundational subjects: biology, chemistry and physics" (UC Admissions Requirements). Because Earth Science is not a University of California approved laboratory science course, high school students have little incentive to enroll in Earth Science courses, even if they are offered. Riverside Unified School District (RUSD), the district in which UCR is located, is gradually eliminating Earth Science courses. Consequently, students only gain exposure to the geosciences if they elect to take AP Environmental Sciences.

The reduction in course offerings from public school science curriculum is not unique to the Earth Sciences and not unique to California, and in fact was recognized in two of five "hidden" threats facing science education by Huntoon et al. (2012), namely state educational standards not emphasizing key concepts and limited course options. The lack of high school level course offerings in the Riverside area have likely contributed to low recruitment. Similarly, a lack of exposure to a discipline at the high school level has a negative impact on that discipline's ability to attract outstanding students to college majors and careers (Huntoon et al., 2012).

These geoscience recruitment woes are further compounded by a severe lack of diversity within the field. According to the *2014 Status of the Geoscience Workforce* from the American Geosciences Institute (AGI), geoscience programs are the least diverse in science, technology, engineering and mathematics (STEM) fields, with only 7% of students from underrepresented minorities compared to 30% across all STEM fields (NSF, 2012; Wilson, 2014). And despite the fact that studies have identified the underlying causes of the geosciences' failure to recruit students (factors such as lack of awareness of career opportunities, under-preparation in STEM coursework, lack of familial support, and fewer opportunities for engagement in outdoor activities such as hiking and camping; Stokes et al., 2014; O'Connell and Holmes, 2011), our field has continuously failed to recruit young geoscientists from minority communities. As national demographics grow increasingly diverse, we must develop effective recruitment strategies targeted toward minority students if we are to avoid the projected worker shortfall. Without an increase in recruitment, AGI predicts that this shortfall may grow as large as 135,000 by the year 2022 (Wilson, 2014).

To address these issues, the UCR Department of Earth Sciences established the Geoscience Education Outreach Program (GEOP). GEOP is organized by Earth Science graduate students, operates on a budget of less than $3000 annually, and impacts thousands of Riverside County residents (K-12 students and adults). While the majority of outreach events in GEOP are in-class presentations to K-8 classrooms, the program is designed with enough flexibility to accommodate the wide range of needs in Riverside County. The program provides mentoring for middle and high school students, activities and education for school groups, visits to the UCR campus, community events, and easy access to geoscience experts. Our success proves that GEOP is a workable model that can be recreated in many university Earth Sciences departments and easily tailored to different types of audiences (underrepresented minority students, rural communities, etc.).

Program Objectives

In designing GEOP, we identified five primary objectives:

1. Provide geoscience content to supplement existing K-12 STEM curricula
2. Expose K-12 students to geoscience content (K-8) and career opportunities (6-12)
3. Provide opportunities for high school students to engage in geoscience research
4. Strengthen the geoscience education pipeline in the region by building connections between school districts, community colleges and UC Riverside
5. Strengthen connections with local school districts and the Riverside community at large so that our department can provide necessary geoscience information on relevant topics (earthquakes and other natural hazards, global climate change) and improve science literacy in our surrounding community

INSTITUTIONAL BACKGROUNDS

University of California, Riverside

UCR is a federally-designated Hispanic-serving research university in Southern California with a student body population of 21,200. Institutions are designated Hispanic-serving when they serve a study body population that is at 25% Hispanic and over 50% low income; (Bordes and Arredondo, 2005). UCR is the most diverse of the ten University of California campuses (Table 3.1) and has developed several highly effective programs to ensure the success of underrepresented minority students (41.3% of student body), first generation college students (45% of student body) and low income students (56% of student body, based on Pell Grant Awards). Because of these programs, UCR is a national leader in successfully graduating underserved students. At UCR, graduation rates for these historically disadvantaged groups are equal to graduation rates overall and to national graduation rates for all students (Dept. of Education, 2015 College Scorecard). Washington Monthly's annual list of Top Universities, which measures social mobility and community service in addition to academic research, ranked UCR second overall in 2015. The majority of UCR undergraduates, like the majority of the inhabitants of the City of Riverside, come from Southern Californian communities (Riverside, San Bernardino, Los Angeles, Orange and San Diego Counties).

University of California is fully committed to meeting the educational needs of Californians and has cemented this commitment in the UC Board of Regents *Policy* *on University of California Diversity Statement*, noting that "The University particularly acknowledges the acute need to remove barriers to the recruitment, retention, and advancement of talented students, faculty, and staff from historically excluded populations who are currently underrepresented." In the UCR Department of Earth Sciences, we consider a thriving outreach program to be a part of the university's commitment.

Riverside Unified School District and Other Surrounding Districts

Riverside Unified School District (RUSD) is bordered by several other districts (Moreno Valley School District, Val Verde School District, Jurupa School District, Alvord School District). All of these local school districts are majority Hispanic and serve a high population of low-income students (see Table 3.1). Though STEM education is valued and promoted in these districts, schools are underfunded and students lack opportunities to engage in STEM learning. GEOP has been designed to best serve the student populations in these local districts and therefor all events and activities are free of cost and public education events are presented in English and Spanish.

Table 3.1
Demographic breakdown by ethnicity for Riverside County, UCR, the State of California, and the United States, showing the high Hispanic population of Riverside County compared to California and the United States (1U.S. Census Bureau, 2010; 2UCR Office of Admissions).

Ethnicity	Riverside County[1]	UCR[2]	CA[1]	USA[1]
Hispanic or Latino	46.9%	32.1%	38.4%	17.1%
White, not Hispanic	38.0%	17.0%	39.0%	62.6%
African American	7.0%	8.7%	6.6%	13.2%
Asian or Pacific Islander	7.1%	35.4%	14.6%	5.5%
Native American	1.9%	0.5%	1.7%	1.2%
Other	3.3%	8.7%	3.7%	2.4%

Table 3.2
Breakdown of annual spending by event type. Annual costs average $2055.00 ($0.66 per person). Because GEOP events are scheduled by request, the number of events fluctuates each year depending on the number of requests. The 2014-2015 budget is not final as of the writing of this paper and is expected to match the budget of 2013-2014.

Event Type	Total Number of People Impacted				
	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
In-class presentations	1440	2250	2250	720	480
On-campus groups	0	0	300	300	300
Other school outreach	100	100	100	100	525
Mentoring	0	35	2	2	5
Community Events	0	0	5400	6200	5200
Total Number	1540	2385	8052	7322	6509
Total Budget	$950.00	$1,775.00	$2,800.00	$2,900.00	$1,850.00
Per Person Spending	$0.62	$0.74	$0.35	$0.40	$1.23

PROJECT DESIGN

In developing the GEOP model, our goal was to provide the most services possible on our very limited budget. GEOP is designed around several project-based learning activities. Project-based learning has been shown to be highly effective in conveying geoscience, as geologic processes occur on long time scales (e.g., evolutionary change, mountain range orogeny) and/or on large spatial scales (e.g., plate tectonics, global climate change) (Libarkin and Brick, 2002; McConnell et al., 2003). We also considered the demographics of our target audiences and designed outreach products that best served the largely Hispanic and often low-income student population of Riverside County. And finally, we wanted GEOP to benefit everyone involved in the program, so we considered how the program would impact not only K-12 students but also their teachers and the volunteers presenting GEOP programming.

GEOP project design was guided by the theoretical frameworks of Levine et al. (2007) and Nora (2005), which both suggest methods for improving recruitment and retention of underrepresented minority students in STEM fields. The Levine Framework, which focuses specifically on the geosciences, examines K-16 students' critical incidents of engagement with the geosciences in order to determine what factors influence decision making at education junctures (high school to college, two year college to university, university to graduate school or workforce). They find that factors such as course selection, extracurricular activities, familial involvement, geoscience awareness, and effective instruction were most important for K-12 students. The Levine Framework also suggests that effective interventions at each stage of education could improve recruitment into the geoscience education pipeline. The Nora Framework, which considers STEM fields as a whole rather than specifically focusing on a single field, suggests that Hispanic students are more likely to bring pre-college characteristics to college. Pre-college experiences like prior academic achievement or first-generation status function like "pull factors" and cause students to either "pull away" or get "drawn in" to a STEM major. Both frameworks suggest that exposure to and engagement with STEM fields early in a student's academic career can influence their interest in that field when they reach college.

Several studies have examined the impact of different types of interventions included in GEOP, such as short duration classroom outreach events and mentoring (see Tsui, 2007). For example, Laursen et al. (2007) evaluated the impact of short duration classroom outreach events through interviews with teachers, students and presenters. When asked about changes in interested and engagement in science, 88% of teachers and 92% of students reported positive gains. When asked about new views of science and scientists, 44% of teachers and 100% of students reported positive gains. And finally, when asked about student understanding of science concepts and their relevance to real life, 38% of teachers and 33% of students reported positive gains. When evaluating the impact of these events on the presenters, Laursen et al. (2007) found that 83% reported a gain in skills (teaching communication and management), 92% reported a gain in understanding (particularly in issues surrounding education and diversity), 83% reported a person gain (such as growth in confidence and intrinsic or emotional rewards), and 96% reported career gains (such as transferable knowledge and skills or resume building). Andrews et al. (2005) also found that outreach providers benefited from participation and graduate student participants were often motivated by the opportunity to improve teaching and communication skills. The NSF GK-12 Program, which connected Graduate Teaching Fellows (who are training to become research scientists) from SUNY Binghamton with 3-6 grade classrooms in the Binghamton City School District, showed that this connection benefits all involved (Stamp and O'Brien, 2005). Teachers learned new content, students' attitudes towards science improved, and Graduate Teaching Fellows gained teaching experience.

Mentoring has been proven repeatedly to increase student engagement and success in STEM fields (see Charlevoix and Morris, 2014; Griffin et al., 2010; Cole and Espinoza, 2008; Huntoon and Lane, 2007; Bordes and Arredondo, 2005; Santos and Reigadas, 2002). This is especially true for minority students, who often feel alienated or unfit to pursue an education or a career in the sciences. Several studies have documented the benefits mentoring has provided to minority students, including higher grade point averages, lower attrition, increased self-efficacy, and better defined academic goals (Santos and Reigadas, 2002; Schitzer and Thomas, 1998; Arnold, 1993; Thile and Matt, 1995). In an examination of the role of mentoring in Latina/o students' success in college, Bordes and Arredondo (2005) reported that mentoring improved student experiences during their first year of college by increasing feelings of cultural congruity. Furthermore, while previous studies have suggested that mentors are more effective if they share the same cultural background (e.g., Charlevoix and Morris, 2014; Santos and Reigadas, 2002), Bordes and Arredondo (2005) found that the cultural background of the mentor had no significant difference in student success. In a meta-analysis of 55 evaluations of youth mentoring programs, DuBois et al. (2002) found that when empirically derived best-practices are employed and when strong relationships between mentor and student are formed, mentoring programs can have a strong positive effect on a student's success. This effect was strongest for students from disadvantaged backgrounds.

GEOP is overseen by the Chair of the Department of Earth Sciences and a graduate student program manager. The program manager, who is selected yearly, is responsible for handling incoming requests from K-12 teachers, school administrators and community event organizers. While in-class presentations are standardized, other events may require personalization, so the program manager works with organizers and other community liaisons to determine how to best meet their needs. The program manager is also responsible for recruiting and training outreach volunteers (UCR graduate and undergraduate students), maintaining outreach kits and other teaching materials, and publicizing the program within local school districts and on the department's website.

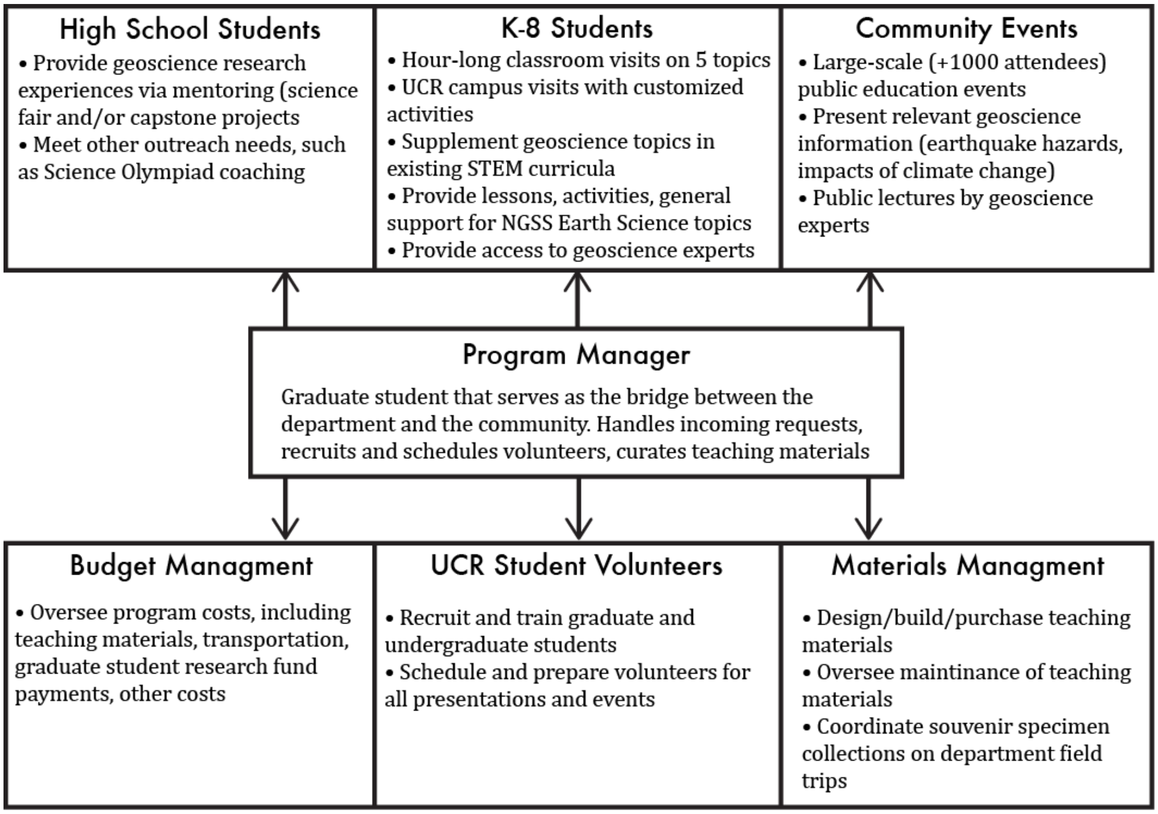
The program manager ultimately serves as the link between the university and the outreach audiences (see Figure 3.1). Because the graduate student program manager serves such a crucial role, the Department of Earth Sciences has awarded the program manager one quarter of Department Fellowship for each year that he or she servers as manager. The manager does not receive monetary compensation during the remaining two quarters of service but graduate students serving in this role have been willing to volunteer their time for the experience and professional development they receive while in this position. (See "Implementation" below for alternative funding models).

UCR Participant Recruitment and Training

GEOP relies heavily on graduate and undergraduate student involvement. At the beginning of each academic year, the program manager recruits graduate students through direct conversations with new graduate students, announcements at department meeting and seminars, and email messages. Undergraduate student recruitment is focused on upper level geology majors (typically juniors and seniors) who are recruited by the program manager through announcements given in upper division geology classes and at meetings of the Geology Club.

Over the past six years, nearly all (89%) Earth Science graduate students and most faculty (66%) have participated in GEOP events. This extremely high level of participation is likely due to the overall culture of service that permeates the department, UCR and the University of California. GEOP has been supported and promoted by all three department chairs (Mary Droser, Richard Minnich and current chair David Oglesby) and faculty encourage their graduate students to participate in the program. Incidentally, GEOP’s success has served as excellent leverage in garnering monetary donations to the department, which are then used to fund the program.

Figure 3.1
GEOP design. The Program Manager functions as the link between outreach communities and the department.



GEOP presenters are trained by the program manager. Training is always personalized and varies for each type of outreach event. For in-class presentations and campus visits, the program manager will acquaint the presenter with tailored educational materials, including presentation slides, specimens, activities and souvenirs. The program manager will also brief the presenter on the grade level and background knowledge the class may possess and on any special requests made by the teacher. First time presenters may request to be scheduled with an experienced partner. Finally, presenters are encouraged to adapt the presentation as they see fit. GEOP does not provide a script for presentations; they are designed to be flexible enough to meet each classroom's specific needs. Mentors to individual students are briefed on the student's academic background, interests and mentoring needs (science fair or capstone project). Throughout the mentoring relationship, the program manager will track progress and can provide resources and suggestions on an as-needed basis. For large-scale community events, volunteers are trained as a group, and first-time volunteers are paired or placed in a team with experienced volunteers so that they can also learn during the course of the event.

In-Class Presentations (K-8)

Hour-long in-class outreach presentations form the basis of GEOP. These presentations serve three purposes: 1) to expose elementary school students to the geosciences, 2) to supplement teachers' existing STEM curriculum, 3) to raise students' awareness of career opportunities in the geosciences and to foment the possibility of future recruitment of geoscientists. Engagement in STEM topics early in a student's academic career has been shown to be crucial in the later recruitment of STEM majors and professions, especially for Hispanic students (Tyson et al., 2007; Crisp et al., 2009). GEOP in-class presentations serve as an engagement opportunity, especially as geoscience course offerings are removed from districts in Riverside County.

In-class presentations are given by UCR graduate and undergraduate students. Teachers select one of five prefabricated presentation topics (Rocks and Minerals, Fossils, Earthquakes, Volcanoes, or Climate Change). These topics were chosen to provide a wide range of geoscience material that can be broadly applied to K-8 curriculum, as suggested by UCR faculty and an informal survey of RUSD teachers. Presentations are adjusted to grade level, each class's background knowledge and each teacher's STEM curriculum. The program manager communicates with teachers to assess these factors. Because of this tailoring, a rocks and mineral presentation for first grade students would be much simpler than it would be for fifth grade students, who would have prior knowledge of the structure of the Earth and the rock cycle. All five presentations are structured around experiential activities, which have been shown to be highly effective in engaging students in the geosciences (Van der Hoeven Kraft et al., 2011). Each presentation's activities and learning outcomes are detailed in Table 3.3. As California public schools have begun to transition to the Next Generation Science Standards (NGSS), we have adjusted our presentations to better meet NGSS curricula.

Teachers are often actively engaged in the presentations because they are tailored to each teacher's specific requests. Not only do teachers watch the presentation with their students, examine specimens and participate in learning activities, they also include the presentation in their own teaching by asking the class follow up questions and assigning written reflections about the presentation.

At the beginning of each presentation, the presenter introduces him or herself and gives a brief personal history on their love of science, education and career goals. At the end of each presentation, the presenter gives a short plug for the geosciences by suggesting that if students enjoyed the presentation, they should consider taking a geology class or even pursuing a career in the geosciences. The presenter points out that there are many excellent opportunities available in Southern California for students with degrees in geology. This final moment is key in raising awareness, as suggested by Levine et al. (2007). Finally, students are given a small specimen as a souvenir to launch their rock and mineral collection (see Table 3.4). UCR geology students collect the program's souvenir specimens on department field trips. We have collected serpentinite from fault zones in Northern California, scoria and obsidian from Inyo County in Eastern California, sulfur from Mono County in Eastern California, and tourmaline and quartz from San Diego County. We also receive mineral and fossil donations from amateur collectors. Collecting specimens from Californian localities has the benefits of being low cost (department field trips already visit these sites each year) and of creating a place-based connection for the students who receive them as souvenirs.

In-class presentations are offered free-of-cost to local classrooms (within 20 miles of UCR campus). Graduate student presenters receive $25 per presentation. This fee is placed in a research fund that can be used to purchase lab or field equipment or reimburse conference fees or other research costs. In this way, GEOP also helps to promote and fund graduate student research in the department. Undergraduates participate on a purely volunteer basis. If no students are available to do the presentation, the program manager will step in. We have found that $25 per presentation provides enough incentive to recruit graduate students without exhausting our small budget. This program costs $1875 annually (75 presentations per year) (see Table 2). We have also found that the double benefit of funding outreach and student research has made securing donor funding for the program easier, as donors feel their money is going twice as far.

Presentation 1: Rocks and Minerals

The Rocks and Minerals Presentation is designed to introduce students to basic geologic concepts, including the structure of the Earth (crust, mantle, core), plate tectonics, the three rock types (igneous, sedimentary, metamorphic), the rock cycle, minerals and their role in creating common objects and materials. The presentation begins with a very short PowerPoint presentation to introduce the structure of the Earth and the three rock types. During the presentation, hand samples of igneous, sedimentary and metamorphic rocks are passed around the classroom. Then a "show and tell" session of ~25 mineral specimens are displayed, described, and passed around the classroom. Students are allowed to handle all specimens in the teaching kit. Depending on time and grade level, students may get to learn basic mineral identification by testing mineral hardness and streak color. The presentation concludes with a final question and answer session. Then students receive a mineral specimen souvenir. The Rocks and Minerals presentation is the most popular of our presentations (requested ~50% of the time) because it fits easily into existing K-6 STEM curricula.

Presentation 2: Fossils

The Fossils presentation is designed to use a specimen collection of ~25 fossil to introduce students to history of life on Earth. The presentation begins with a short (~10 minute) lecture on what fossils are, how fossils form and where paleontologists find fossils. The remainder of the presentation is spent doing a hands-on investigation of the fossil specimens. Some fossils are presented and passed around the classroom in a "show and tell" style. Others are presented to the students without description and students are asked to make interpretations based on what they see (morphology, structure, similarity to familiar or living organisms). During the examination, students are presented with five fossil teeth (*Tryannosaurus, Charcharodon, Smilodon, Mammuthus* and *Equus*) and asked to interpret what type of diet each animal would have had. Students examine tooth morphology, serration and size before making interpretations. The presentation ends with a final question and answer session and then students are given a small fossil souvenir (typically a brachiopod or crinoid columnal).

Presentation 3: Earthquakes

The Earthquakes presentation is designed to introduce students to earthquake processes (where they occur and what causes them) and hazards. The presentation begins with a discussion of personal earthquake experiences ("Have you ever felt an earthquake?" "What did it feel like?" "What did you do during the earthquake?"). Since they live in the San Andreas Fault Zone, all students have some personal experiences with earthquakes. After this discussion, the presentation continues with a short lecture on the structure of the Earth, plate tectonics. and earthquake processes. Students then learn about the four major types of energy waves generated by earthquakes (P-wave, S-wave, Raleigh wave, and Love wave) by creating wave movement with a slinky. Younger students (K-3) demonstrate the waves by linking hands and moving the wave down the chain of students. After this demonstration, students learn about historic and recent earthquakes (San Francisco 1906, Loma Prieta 1989, Northridge 1994, Haiti 2010, Nepal 2015). The presentation is concluded with a discussion of earthquake hazards. Students learn about the potential for a large earthquake in the San Andreas Fault Zone and practice what to do during an earthquake. Projections and drills are based on The Great California Shakeout (Earthquake Country Alliance, 2015).

Presentation 4: Volcanoes

The Volcanoes presentation is designed to introduce students to volcanic processes (where and how they form), the major types of volcanoes (shield, composite, caldera, cinder cone), historic/famous volcanoes (Mt. St. Helens, Mt.

Vesuvius, Mauna Loa), and volcanic hazards. Students examine six examples of volcanic rock and are asked to draw conclusions about their formation (cooling rate, intrusive/extrusive). The presentation is concluded with a discussion of volcanoes in the Western United States (especially Northern California) and a question and answer session.

Presentation 5: Global Climate Change

The Global Climate Change presentation is designed to introduce the evidence for global climate change, the greenhouse effect and important greenhouse gases, human civilization's role in modern climate change, the concept of a carbon footprint, likely local impacts of global climate change, and ways that students can get involved in mitigation efforts. The concepts presented in this presentation are more advanced and complex than the other four presentations, and the presentation has proven more successful among older students (5-8 grade). The topics addressed in this presentation are conveyed via a combination of place-based discussion and experiential activities. For example, the climate in Riverside County is hot and dry (Mediterranean), with several +100°F days in the summer months. Students relate well to everyday examples of the greenhouse effect (a car on a summer day will heat up quickly because heat cannot escape out closed windows; see Table 3) and albedo (light grey cement is cooler on bare feet than black asphalt). Students can also study the relative albedo of different colored surfaces by measuring the temperature of black, white, green, and blue metal plates. If time permits, students can calculate their carbon footprint. This presentation is concluded with a discussion on solutions. Students are asked to think of changes they can make in their daily lives to reduce their carbon footprint.

Table 3.3
Prefabricated presentations for K-6 classrooms, showing each subject's activities and anticipated learning outcomes.

Presentation Topic	Activity	Learning Outcome
Rocks & Minerals	1. Examine and handle samples of the 3 rock types (igneous, sedimentary, metamorphic)	Students learn to identify the three rock types based on characteristics (composition, texture)
	2. Compare mineral specimens to classroom objects that contain those minerals	Minerals are an important resource, students interact with minerals every day
Fossils	1. Compare five fossil teeth (Charcharodon, Tyrannosaurus, Smilodon, Mammuthus, Equus)	Tooth structure can be used to interpret the diet of extinct animals
	2. Examine fossil specimens representing the major stages of evolution of life (marine invertebrates, dinosaurs, Pleistocene megafauna)	Fossils can be used to interpret ancient life, life has evolved greatly throughout the Phanerozoic, fossils are more than just dinosaur bones
Earthquakes	1. Discussion of personal earthquake experiences	Earthquakes are common in Southern California, earthquakes are a natural hazard that must be understood by people living in active fault zones
	2. Generate energy waves with a slinky	The waves generated by earthquakes move differently and are felt differently when they impact surfaces/structures
	3. Quake Catcher Network demonstration	Earthquakes can be tracked using very simple technology managed by students (citizen science)
	4. Earthquake drill	Students should drop, cover and hold on during an earthquake
Volcanoes	1. Examine specimens of volcanic rock (obsidian, pumice, scoria, granite)	Rock characteristics (grain size, cleavage, composition) can indicate the formation history of that rock
Climate Change	1. Discussion of climate vs. weather in Riverside County	Weather is the current atmospheric conditions and can change rapidly (hourly, daily) while climate is a long-term average of weather and changes very slowly
	2. Test the temperature of different colored surfaces	Color correlates with albedo, and surfaces with a high albedo reflect away solar energy before it can be absorbed and heat the surface
	3. Calculate your carbon footprint	Everyday activities consume energy, which leads to emissions of GHGs. Small changes in daily behavior can reduce GHG emissions
	4. Bottle Atmospheres	When sodium bicarbonate is added to water, it produces carbon dioxide. Increased carbon dioxide causes temperature in the bottle to rise in comparison to the control bottle

Table 3.4
Components of dedicated teaching kits for each in-class presentation topic and for community outreach events.

Topic	Kit Components
Rocks & Minerals	Rock samples: granite, obsidian, limestone, sandstone, coal, metamorphics Mineral samples: biotite, bornite, calcite, feldspar, galena, garnet, gypsum, halite, hanksite, hornblende, kyanite, labradorite, lepidolite, magnetite, malachite, muscovite, quartz, serpentine, sulfur, tourmaline Mineral identification kit (scratch kit, hardness scale, acid bottle, magnet) Souvenir specimen: any local rock or mineral currently available
Fossils	Sedimentary rock samples: sandstone, limestone Vetebrate specimens: *Albertosaurus* foot (cast), dinosaur caudal vertebra, dinosaur skin (cast) Invertebrate specimens: ammonite (Cretaceous), trilobite (Ordovician), sea urchin (Cretaceous), oyster (Cretaceous), orthocone cephalopods (Devonian) Teeth: *Carcharodon megalodon*, *Tyrannosaurus rex, Equus, Smilodon, Mammuthus jeffersonii* Other specimens: coprolite, trace fossils Souvenir specimen: small fossil (usually a brachiopod, gastropod, crinoid columnal)
Earthquakes	Fault demonstration table Slinky Quake Catcher Network demonstration Souvenir specimen: serpentinite (formed in fault zones)
Volcanoes	Volcanic rock specimens: obsidian, pumice, scoria, granite, pegmatite Souvenir specimen: obsidian, scoria, or pumice
Climate Change	Albedo demonstration (black, white, blue, green plates and laser thermometer) Pizza box solar oven Souvenir specimen: any rock or mineral specimen currently available
Community Events	Posters (climate change, earthquakes, other local natural hazards, in English and Spanish) Educational games (Drought Limbo, Tornado Twister, The Carbon Price is Right) Interactive Activities (Test the Albedo, Lightbulb Comparisons)

School Trips to UCR Campus

Campus visits are an opportunity to expose a large number of students to a range of geoscience topics in a short amount of time. GEOP hosts 2-5 school group visits to our department annually. School groups are typically ~100 middle school students from a local school, but GEOP has also hosted elementary school students, afterschool groups, and girl scout troops. Groups spend 2-4 hours on campus. Each of these events is tailored to the needs of the visiting students, and each visit often has a focus (global climate change, earthquakes, paleontology). Large school groups are divided into small groups of 10-15 students, then the small groups rotate through 5-7 "activity stations," spending 30 minutes at each. Activity stations focus on specific topics, so an example event that focused on paleontology may have six stations: 1) Hands-on examination of the fossil kit (used for in-class presentations), 2) Museum scavenger hunt, 3) Tour of the paleontology labs, 4) Rocks and minerals, 5) Climate Change in Southern California - what lived here during the last ice age?, 6) Paleontology Jeopardy. A climate change focused event would consist of six different stations: 1) What are greenhouse gases and where do they come from?, 2) Calculate your carbon footprint, 3) Games (Tornado Twister and Drought Limbo), 4) Bottle atmospheres, 5) Test the Albedo, 6) Climate Change Jeopardy. Campus visits are typically staffed by a combination of undergraduate student volunteers and graduate students. Graduate students receive $25-50 for their participation depending on the length of the event.

Mentoring

Mentoring has been shown to be highly impactful and effective in recruiting and retaining STEM students from underrepresented groups (DuBois et al., 2002; Griffin et al., 2010). These one-on-one interactions allow high school students to engage in high level research projects, become familiarized with formal research settings like university laboratories, and build personal relationships with scientists. All these activities have been shown to promote further engagement in the geosciences, such as choosing a geoscience-related major in in university, pursuing advanced degrees, and pursuing geoscience careers (Huntoon and Lane, 2007; Wilson et al., 2012).

GEOP has worked to provide mentors to local high school students in whatever capacity teachers and school administrators deem most needed or useful. Most GEOP mentors have worked with high school students on science fair projects on geoscience topics, but we have also provided mentors for year-long capstone projects and provided research opportunities in UCR Earth Science laboratories for interested high school students.

Participation in Community Events

As part of GEOP's objective to strengthen our department's connections with the Riverside community-at-large and to improve science literacy in the region, we have committed to participating in a wide range of community events. Examples include the City of Riverside's *Long Night of Arts and Innovation,* a public event to showcase the best STEM and creative arts projects from local institutions; UCR's

ScotFest, an annual homecoming festival for UCR students, alumni and families; and UCR's *Odyssey of the Mind*, an education fair for elementary and middle school students to explore the connections between STEM and art. Each of these events have thousands of participants and provide an excellent opportunity to educate the local community about relevant geoscience topics and issues, such as earthquakes and natural hazards or the impacts of climate change.

GEOP has designed a permanent set of teaching materials for community events. Having a dedicated teaching kit for these types of events simplifies organization and reduces costs to the one-time cost of building the kit. We spent $1000 on laminated (durable) posters and interactive games and activities (see Table 4 for detailed breakdown of kit). Community outreach events are staffed primarily by undergraduate student volunteers, though larger scale events such as the *Long Night of Arts and Innovation* (+10k visitors) may require graduate student staff as well. In these cases, graduate students are compensated $25-50 depending on length of time.

Other Outreach

GEOP's flexibility is a key factor in its success. The program prioritizes an ability to meet the needs and requests of teachers, schools, school districts, and the community at large, and as a result GEOP interacts with the citizens of Riverside County in a wide range of venues and capacities. For example, through GEOP, UCR Earth Sciences was able to provide four UCR graduate student coaches for the 2014-2015 academic year Science Olympiad team at the Riverside STEM Academy (they coached three subjects: Fossils, Dynamic Planet, and Geologic Mapping). Because the GEOP infrastructure was already in place, the GEOP coaches had abundant geoscience teaching materials readily available and received the standard $25 per coaching session.

OUTCOMES

In the past six years, GEOP has visited 238 K-8 classrooms, provided mentors to 41 high school students, and hosted 900 students on field trips to the Earth Science Department. The program has sustained a presence at events hosted by the City of Riverside and community groups, and has provided coaches for RUSD Science Olympiad teams (for the Fossils, Dynamic Planet and Geologic Mapping events). Ultimately, GEOP has engaged over 5,000 people per year in the geosciences, and most of those engagements have been with underserved K-12 students. The program is well known among teachers in RUSD and other local school districts. In addition to bringing geoscience to the Riverside community, GEOP has proven a valuable resource for our department by providing opportunities for our graduate and undergraduate students to hone their teaching and science communication skills and to engage with a diverse community.

Because GEOP is comprised of several different types of outreach events (many of which are unique or stand-alone events), evaluation data has been difficult to collect. We have conduced surveys at large public outreach events (Refresh Riverside and Long Night of Arts and Innovation) and we surveyed UCR undergraduate and graduate student presenters. Both datasets are discussed below. For other types of outreach, we have provided case studies from the perspective of individual participants in order to illustrate the impact of each participant's interactions with GEOP. These case studies highlight the types of success GEOP has shown over the past six years.

Case Studies

Edgar Rodriguez - 6th Grade Science Teacher

Edgar Rodriguez is the 6th grade science teacher at the Riverside STEM Academy (RUSD). After arranging GEOP presentations in 2011, Mr. Rodriguez decided to increase the geoscience component of his curriculum and worked with the GEOP program manager to design specialized activities for his classroom. These included a guided nature walk through the Box Springs Mountains Reserve above his campus among highlights of local geology and annual class field trips to the UCR Department of Earth Sciences. We have worked with Mr. Rodriguez every year since, and our involvement in his Earth Science curriculum has increased each year.

Raquel Mendoza-Cabral - High School Science Fair

By the time Raquel Mendoza-Cabral was in her junior year at Ramona High School (RUSD), she knew she wanted to pursue a college degree in engineering. She wanted to participate in science fair, but her high school did not host the competition. Through GEOP's science fair mentoring program, Raquel was partnered with a UCR graduate student to design and complete a science fair project that examined the effects of rising ocean temperature on marine ecosystems. Her project "The Heat is On, Will the *Halimeda* Survive?" won the district science fair and progressed to the California State Science Fair finals, where it helped Raquel earn a scholarship to study engineering at Worchester Polytechnic Institute in Massachusetts. And because of Raquel's dedication and success, Ramona High School now hosts an annual science fair competition.

Riverside STEM Academy Capstone Project

Two high school students at the Riverside STEM Academy (RUSD) have been mentored by a UCR graduate student for two years (sophomore and junior year). As part of their STEM-focused curriculum, they were required to complete a year-long capstone research project. Since they had competed on the rocks and minerals Science Olympiad team for three years already, they chose to design a geology capstone project. Because Earth Sciences is not offered at RUSD schools, they turned to UCR for guidance. Through GEOP they were paired with a graduate student mentor who helped them design a project that examined the geological structure and mineralogy of the Box Springs Mountains Reserve, which abuts their school campus. Their project is ongoing and they plan to enter it in the district science fair in 2016 (when they are high school juniors), thereby turning a capstone project into a multiyear research project. As a result of this project, they have both expressed an interest in pursuing college degrees in geology.

Noah Planavsky - Graduate Student & Mentor

As a graduate student at UCR, Noah Planavsky used geochemical analysis of ancient rocks to study the rise of oxygen in Earth's early atmosphere. As a recipient of the NSF Graduate Research Fellowship, Noah was self-funded and did not have an opportunity to teach in the classroom during his graduate studies. Noah wanted to develop teaching skills, so he signed up to mentor two juniors from Martin Luther King, Jr. High School on their science fair project, "Developing a Toolkit to Track Oxygen Depletion in Past Oceans." Noah met with his students once per week through the Fall Quarter, and together they created a sophisticated science fair project that progressed to the California State Science Fair. Noah's time as a mentor provided him with teaching experience and helped him learn how to communicate complex science to a high school audience. Noah has since joined the Geology and Geophysics faculty at Yale University.

Noah's experiences as a mentor are typical of UCR student participants in GEOP. In a survey conducted of graduate and undergraduate participants in GEOP, 100% (18/18) reported a gain in both teaching and science communication skills, while 77.78% (14/18) reported a gain in understanding of issues surrounding education and 55.55% (10/18) reported a gain in understanding of issues surrounding diversity. Participants also benefitted through experiencing gains in confidence or other intrinsic/emotional rewards (83.33%, 15/18) and through resume/*Curriculum vitae* enhancement (72.22%, 13/18).

Community Outreach Events

In 2011 and 2012, GEOP participated in UCR's *Refresh Riverside: A Community Climate and Sustainability Fair*, which brought local middle and high school students and their families to UCR campus to learn about the science of climate change and the importance of living sustainably in a vulnerable region. Each year over 700 people attended the fair. GEOP hosted several booths with information, interactive demonstrations, and educational games designed to teach fairgoers about local and global climate change. *Refresh Riverside* was the first large community outreach event that GEOP participated in, and the materials produced for this event were evaluated via surveys (see below) and have been reused several times at other community outreach events.

Refresh Riverside fairgoers (adults and children) were surveyed about their experiences at the fair in 2011 and 2012. The survey was offered in English and Spanish and respondents received little instruction so that they would write whatever was most salient to them on the day they responded. In both years, roughly half of adults (55% in Year 1 and 46% in Year 2) mentioned something related learning, teaching or information. Other common topics mentioned in surveys include fun, conservation, hands on learning, and suggestions for improvement. There were a total of 71 child responses (all in English). The children's survey consisted of three short questions: 1) Something I already know about climate change..., 2) Something that I learned today about climate change..., 3) What I liked most about today. There were 70 responses to the question, "What I already knew about climate change..." 48 of these 70 responses (69%) mentioned something directly related to climate change. Since this survey was not distributed to children before they visited the fair, it is likely that some of these responses about climate change were facts that the children learned at the fair. Of the 59 responses to the question "What I learned about climate change today...", the majority of children (58%) described something related to climate change or the actions that can be taken to mitigate climate change. Of the statements that were not directly related to climate change, greenhouse gases, or global warming, 6 of them (10%) mentioned learning some other scientific or environmental fact.

In 2012, the City of Riverside began hosting an annual event called *The Long Night of Arts and Innovation* to showcase the best STEM and creative arts projects in Riverside. Local universities, colleges and K-12 schools, as well as private design firms and technology development companies were all asked to participate. The event lasts from 4pm to midnight and receives over 10,000 visitors. Since its inception, GEOP has hosted several booths at *Long Nights* designed to teach the citizens of Riverside about geosciences in their daily lives. We have focused on earthquake hazards and the impacts of global climate change. Visitors to *Long Nights* can talk to geoscience experts, simulate earthquakes using the Quake Catcher Network, play educational games like "The Carbon Price is Right!," and calculate their household's carbon footprint. In addition to these interactive booths, GEOP has arranged for Earth Science professors to give public lectures on earthquake hazards and global climate change.

IMPLEMENTATION

If a department wishes to establish an outreach program like GEOP, it can take simple steps to maximize impact on a small budget. Here we list the steps and best practices for implementing a program like GEOP at another university.

Step 1: Designate a Program Manager

The graduate student Program Manager of your outreach program is crucial. As described above (see Program Design), the Program Manager is responsible for coordinating day-to-day operations, scheduling presentations and events, and assigning volunteers to each event. In six years of GEOP, we have had four program managers; each manager served for 1-2 years.

Step 2: Evaluate existing resources

Every university department has a wealth of existing resources. Most Earth Science departments possess collections that can be used to construct teaching kits for a Rocks and Minerals or Fossils presentation. While few departments or universities have official natural history museums, many have permanent display cases in hallways. These can be incorporated into activities and presentations when school groups visit campus. Research laboratories are also excellent stops for tour groups and provide an opportunity for K-12 students to meet and chat with geoscientists.

Graduate and undergraduate students are a department outreach resource as well. They will form the basis of your outreach program's team of volunteers. At UCR, we found that a small group of dedicated volunteers (6-10 reliable graduate and undergraduate students) can easily accommodate 75-100 outreach events per year.

Finally, take account of existing STEM outreach programs at your university. While another department's outreach program may have different goals or methods, there will likely be several opportunities to collaborate at events or on projects. Better communication among your university's various outreach programs will strengthen STEM education in your region and provide K-12 students with abundant opportunities to become engaged in STEM fields.

Step 3: Use funding to create reusable teaching materials

Once you have evaluated your existing resources, spend a portion of your budget on durable, reusable teaching materials. For GEOP, we used $1000 of departmental money in Years 1 and 2 to build educational games and activities and to print laminated posters on important topics. These materials have been used in nearly every type of outreach event, from in-class presentations for elementary school students to large-scale community events targeted at adults. Nearly all of GEOP's reusable teaching materials are tailored for residents of Riverside. For example, our laminated climate change posters highlight the impacts and projections for Riverside County. Earthquake posters highlight hazards related to the San Andreas Fault Zone. Paleontology materials highlight fossils found in Riverside County. This place-based approach gives the audience a personal connection to the material and allows them to engage more easily.

Step 4: Build and maintain a STEM education network

Your Program Manager should be responsible for communicating directly with local schools, community leaders and other campus outreach programs. GEOP's greatest successes have been the result of repeated interactions with individual teachers or students year after year (such as Edgar Rodriguez's 6th grade curriculum or the RSA students working on the Box Springs research project).

CONCLUSIONS

As the geosciences face a severe worker shortfall in the near future, we must develop new methods for engaging and recruiting new students, especially those from historically underrepresented minorities and other communities without easy access to the geosciences. Many university Earth Science Departments seek to address this issue but have difficulty launching a new program. The GEOP model presented here allows departments to establish a working, impactful program without a large start up budget or grant support. The simplicity and flexibility of the program allows departments to adapt to the unique needs of their local communities. Ultimately, university departments can launch outreach programs following the GEOP model, which then may serve as pilot programs for large-scale and grant-funded outreach projects.

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REFERENCES

Alroy, J., 2010. The shifting balance of diversity among major marine animal groups. Science, 329:1191:1194.

Andrews, E., Weaver, A., Hanley, D., Shamatha, J. and Melton, G., 2005. Scientists and public outreach: Participation, motivations, and impediments. Journal of Geoscience Education, 53(3):281-293.

Arnold, K.D., 1993. The fulfillment of promise: Minority valedictorians and salutatorians. Review of Higher Education, 16(3):257-283.

Banks, M.R. and Johnson, J.H., 1957, Maclurites and Girvanella in the Gordon River Limestone (Ordovician) of Tasmania: Journal of Paleontology, v. 31, p. 632-640.

Batten Hender, K.L. and Dix, G.R., 2006, Facies, geometery and geological significance of Late Ordovician (early Caradocian) coral bioherms: Lourdes Formation, western Newfoundland: Sedimentology, v. 53, p. 1361-1379.

Beresi, M.S., Cabaleri, N.G., Buitrón-Sánchez, B.E., Rodríguez, M.C., Heredia, S.E. and Tortello, M.F., 2012, Microfacies, biota y paleoambientes sedimentarios del Ordovícico temprano-medio del Cerro Salazar, Sonora central, México: Revista Mexicana de Ciencias Geológicas, v. 29, p. 330-345.

Biddle, K.T., 1983, *Girvanella* oncoids from the Middle to Upper Triassic allochthonous boulders of the Dolomite Alps, Northern Italy: Coated Grains, Springer, Berlin, p. 390-397.

Blakey, R. 2015. Colorado Plateau Geosystems, Arizona, USA.

Bordes, V. and Arredondo, P. 2005. Mentoring and 1st-year Latina/o college students. Journal of Hispanic Higher Education, 4(2):114-133.

Bouchet, P. and Rocroi, J.P. 2005. Classification and nomenclature of gastropod families. Malacologia, 47(1-2):1-368.

Boyer, D.L. and Droser, M.L. 2003. Shellbeds of the Kanosh and Lehman Formations of western Utah: Paleoecological and paleoenvironmental interpretations. Brigham Young University Geology Studies, 47:1-16.

Bridge, J. and Cloud, P.E, Jr. 1947. New gastropods and trilobites critical in correlation of Lower Ordovician rocks. American Journal of Science, 245:545-559.

Buffon, G. 1777. Essai d'arithmétique moral. Histoire naturelle générale er particuliére, Supplément 4, 46-123.

Butts, C. 1926. The Paleozoic rocks. Geological Survey of Alabama, Special Report No. 14:41-230.

Cañas, F. and Carrera, M., 1993, Early Ordovician microbial-sponge-receptaculitid bioherms of the Precordillera, Western Argentina: Facies, v. 29, p. 169-178.

Charlevoix, D.J. and Morris, A.R. 2014 Increasing diversity in geoscience through research internships. EOS, 95(8):69-76.

Clark, A. and Crame, J.A. 2010. Evolutionary dynamics at high latitudes: Speciation and extinction in polar marine faunas. Philosophical Transactions of the Royal Society B, 365:3655-3666.

Cole, D. and Espinoza, A. (2008) Examining the academic success of Latino students in Science Technology Engineering and Mathematics (STEM) majors. Journal of College Student Development, 49(4):285-300.

Crisp, G., Nora, A. and Taggart, A. 2009. Student characteristics, pre-college, college, and environmental factors as predictors in majoring in and earning a STEM degree: an analysis of students attending an Hispanic Serving Institution. American Educational Research Journal, 46(4):924-942.

d'Archaic, E.J.A. and de Verneuil, E.P. 1841. Note sur le genre Murchisonia. Bulletin de la Société Géologique de France, 12:154-169

de Montfort, P.D. 1810. Conchyliologie sytématique et classification méthodique des coquilles 2, pp. 1-676.

Droser, M.L., Fortey, R.A. and Li, X., 1996, The Ordovician Radiation: American Scientist, v. 84, p. 122-131.

Droser, M.L., Sheehan, P.M, Fortey, R.A. and Li, X. 1995. The nature of diversification and paleoecology of the Ordovician Radiation with evidence from the Great Basin. In *Ordovician of the Great Basin: Fieldtrip Guidebook and Volume for the Seventh International Symposium on the Ordovician System,* ed. J. Cooper, pp. 405-408.

Droser, M.L. and Sheehan, P.M., 1997, Paleoecology of the Ordovician Radiation: Resolution of large-scale patterns with individual clade histories, paleogeography and environments: Geobios, v. 20, p. 221-229.

DuBois, D.L., Holloway, B.E., Valentine, J.C. and Cooper, H. 2002. Effectiveness of mentoring programs for youth: a meta-analytic review. American Journal of Community Psychology, 30(2):157-197.
Dunham, R.J. 1962. Classification of carbonate rocks according to depositional textures. AAPG Special Volumes, A038:108-121.

Earthquake Country Alliance, 2015. The Great California Shakeout Drill Manual for K-12 Schools. Available at http://www.shakeout.org/california/downloads/ShakeOutDrillManualSchools_v2.pdf (accessed 28 April 2015)

Erwin, D.H. and Signor, P.W. 1990. Extinction in an extinction-resistant clade: The evolutionary history of the Gastropoda. In *The Unity of Evolutionary Biology*, ed. E.C. Dudley, pp. 152-160.

Finnegan S. and Droser, M.L. 2005. Relative and absolute abundance of trilobites and rhynchonelliform brachiopods across the lower/middle Ordovician boundary, eastern Basin and Range. Paleobiology, 31(3):480-502.

Finnegan S. and Droser, M.L. 2008. Reworking diversity: Effects of storm deposition on evenness and sampled richness, Ordovician of the Basin and Range, Utah and Nevada, USA. Palaios, 23(2):87-96.

Flügel, E. 2010. Microfacies of Carbonate Rocks: Analysis, Interpretation and Application. Springer Science and Business Media.

Fortey, R.A. and Droser, M.L., 1999, Trilobites from the base of the type Whiterockian (Middle Ordovician) in Nevada: Journal of Paleontology, v. 73, p. 182-201.

Fryda, J. 2012. Phylogeny of Paleozoic gastropods inferred from their ontogeny. In *Earth and Life: Global Biodiversity, Extinction Intervals and Biogeographic Perturbations Through Time,* ed. J.A. Talent, pp. 395-435.

Fryda, J., Nützel, A. and Wagner, P.J. 2008. Paleozoic gastropoda. In *Phylogeny and Evolution of the Mollusca,* eds. W. Ponder and D.R. Lindberg, pp. 239-270.

Fryda J. and Rohr, D.M. 2004. Gastropods. In *The Great Ordovician Biodiversification Event*, eds. B.D. Webby, F. Paris, M.L. Droser and I.G. Percival, pp. 184-195.

Green, O.R. 2001. *A Manual of Practical Laboratory and Field Techniques in Paleobiology.* Springer.

Griffin, K.A., Pérez, D., Holmes, A.P.E. and Mayo, C.E.P. 2010. Investing in the future: The importance of faculty mentoring in the development of students of color in STEM. New Directions Institutional Research, 148:95-103.

Gubanov, A.P. and Rohr, D.M., 1995, Paleobiogeography of the Macluritidae (Ordovician-Gastropoda): Ordovician Odyssey: Short Papers for the Seventh International Symposium on the Ordovician System, SEPM, p. 461-646.

Gunn, S., 1998, Paleoenvironments and paleoecology of the Ordovician Pogonip Group Member F, University of CA, Riverside, unpublished MS thesis, 143 p.

Hall, J. 1847. Containing descriptions of the organic remains of the lower division of the New York system (equivalent of the Lower Silurian rocks of Europe). Paleontology of New York, 1:1-338.

Harnik, P.G. 2009. Unveiling rare diversity by integrating museum, literature, and field data. Paleobiology, 32(2):190-208.

Harper, D. 2005. The Ordovician biodiversification: Setting an agenda for marine life. Palaeogeography, Palaeoclimatology, Palaeoecology, 232:148-166.

Hintze, L.F. 1973. Lower and Middle Ordovician stratigraphic sections in the Ibex Area, Millard County, Utah. Brigham Young University Geology Studies, 20:3-36.

Hughes, R.N. (1986). *A Functional Biology of Marine Gastropods.* London: Croom Helm.

Huntoon, J.E. and Lane, M.J. 2007. Diversity in the geosciences and successful strategies for increasing diversity. Journal of Geoscience Education, 55(6):447-457.

Huntoon, J.E., Buchanan, R., Buhr, S.M., Krist, S., Newton, S. and Van Norden, W. 2012. "Hidden" threats to science education. EOS, 93(17):170-171.

Kano, A. and Fujishiro, N., 1997, Facies and paleoecology of the Late Ordovician (Caradoc-Ashgill) stromotoporoid bioherms of Tasmania, Australia: Facies, v. 37, p. 17-19.

Kay, M. 1962. Classification of Ordovician Chazyan shelly and graptolite sequences from Central Nevada. GSA Bulletin, 73:1421-1430.

Kaya, A. and Friedman, G.M., 1997, Sedimentation and facies analysis of the *Girvanella*-constituted oncolitic shoals and associated lithofacies of the Middle

Ordovician Antelope Valley Limestone, Central Nevada, USA: Carbonates and Evaporites, v. 12, p. 134-156.

Kidwell, S.M. 1986. Models for fossil concentrations: Paleobiologic Implications. Paleobiology, 12(1):6-24.

Kidwell, S.M. and Aigner, T. 1985. Sedimentary dynamics of complex shell beds: Implications for ecologic and evolutionary patterns. In *Sedimentary and Evolutionary Cycles*, pp. 382-395.

Kidwell, S.M. and Brenchley, P.J. 1994. Patterns in bioclastic accumulation through the Phanerozoic: Changes in input or destruction? Geology, 22:1139-1143.

Kidwell, S.M., Fürsich, F.T. and Aigner, T. 1986. Conceptual framework for the analysis and classification of fossil concentrations: Palaios, v.1, p. 228-238.

Knight, J.B., Batten, R.L. and Yochelson, E.L. 1960. Description of Paleozoic gastropods. In *Treatise on Invertebrate Paleontology, Pt. I, Mollusca*, pp. 169-331.

Kobayashi, T. 1958. Some Ordovician fossils from the Thailand-Malayan borderland. Japanese Journal of Geology and Geography, 29:223-231.

Krause, F.F. 2001. Genesis and geometry of the Meiklejohn Peak lime mud-mound, Bare Mountain Quadrangle, Nevada, USA: Ordovician limestone with submarine frost heave structures -- a possible response to gas clathrate hydrate evolution. Sedimentary Geology, 145:189-213.

Krause, F.F. and Rowell, A.J. 1975. Distribution and systematics of the inarticulate brachiopods of the Ordovician carbonate mud mound at Meiklejohn Peak, Nevada. University of Kansas Paleontological Contributions, Article 61.

Laplace, P.S. 1812. Théorie analytique des probabilités. Paris: Vueve Courcier.

Laplace, P.S. 1820. Théorie analytique des probabilités, 3rd rev. ed. Paris: Vueve Courcier.

Laursen, S., Liston, C., Thiry, H. and Graf, J. 2007. What is a good scientist in the classroom? Participant outcomes and program design features for a short-duration science outreach intervention in K-12 classrooms. Cell Biology Education – Life Sciences Education, 6:49-64.

Lee, Y.I., Hyeong, K. and Yoo, C.M., 2001, Cyclic sedimentation across a Middle Ordovician carbonate ramp (Duwibong Formation), Korea: Facies, v. 44, p. 61-74.

Levine, R., González, R., Cole, S., Fuhrman, M. and Carlson Le Floch, K. 2007. The geoscience pipeline: A conceptual framework. Journal of Geoscience Education, 55(6):458-468.

Li, X. and Droser, M.L. 1999. Lower and Middle Ordovician shell beds from the Basin and Range Province of the Western United States (California, Nevada, and Utah). Palaios, 14(3):215-233.

Libarkin, J.C. and Brick, C. 2002. Research methodologies in science education: Visualization and the geosciences. Journal of Geoscience Education, 50(4):449-455.

McConnell, D.A., Steer, D.N. and Owens, K.D. 2003. Assessment and active learning strategies for introductory geology courses. Journal of Geoscience Education, 51(2):205-216.

Merriam, C.W and Williams, J.S. 1963. Paleozoic rock of Antelope Valley Eureka and Nye Counties Nevada. Geological Survey Pofessional Paper No. 423.

Miller, A.I. 1997. Dissecting global diversity patterns: Examples from the Ordovician Radiation. Annual Review of Ecological Systems, 28:85-104.

Miller, A.K., Youngquist, W. and Collinson, C., 1954, Ordovician cephalopod fauna of Baffin Island: Geological Society of America Memoirs, no. 62.

Morello-Frosch, R., Pastor, M., Sadd, J. and Shonkoff, SB. 2009. The Climate Gap: Inequalities in How Climate Change Hurts Americans and How to Close the Gap. University of California, Berkeley.

National Research Council. 2010. Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5. Washington, DC: National Academies Press.

National Research Council. 2011. Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads. Washington, DC: National Academies Press.

National Science Foundation, National Center for Science and Engineering Statistics. 2015. Women, Minorities, and Persons with Disabilities in Science and Engineering: 2015. Special Report NSF 15-311. Arlington, VA. Available at http://www.nsf.gov/statistics/wmpd (accessed 23 April 2015)

National University Rankings. 2015. Washington Monthly. Available at http://www.washingtonmonthly.com/college_guide/rankings-2015/national-universities-rank.php (accessed 18 October 2015)

Nitecki, M.H., Mutvei, H., and Nitecki, D.V. 1999. Receptaculitids: A Phylogenetic Debate on a Problematic Fossil Taxon. Kluwer Academic/Plenum Publishers, New York, NY, 241 p.

Nolan, T.B, Merriam, C.W. and Williams, J.S. 1956. The Stratigraphic Section in the Vicinity of Eureka, NV. Geological Survey Professional Paper, No. 276.

Nora, A. 2005. Access to higher education for Hispanic students: Real or illusory? 2005. The Majority in the Minority: Expanding Representation of Latina/o Faculty, Administrators and Students in Higher Education. Sterling, VA: Stylus. Pp. 47-70.

Novack-Gottshall, P.M. and Burton, K. 2014. Morphometrics indicates giant Ordovician Macluritid gastropods switched life habit during ontogeny: Journal of Paleontology, v. 88, p. 1050-1055.

Novack-Gottshall, P.M. and Miller, A.I. 2003. Comparative geographic and environmental diversity dynamics of gastropods and bivalves during the Ordovician Radiation. Paleobiology, 29:576-604.

O'Connell, S. and Holmes, A. 2012. Obstacles to the recruitment of minorities into the geosciences: A call to action. GSA Today, 21(6):52-54.

Paine, R.T. 1969. A note on trophic complexity and community stability. American Naturalist, 103:91-93.

Patzkowsky, M.E. and Holland, S.M., 1996, Extinction, invasion, and sequence stratigraphy: Patterns of faunal change in the Middle and Upper Ordovician of the Eastern United States: Paleozoic Sequence Stratigraphy: Views from the North American Craton, Geological Society of America Special Publications No. 306, p. 131-142.

Peryt, T.M., 1981, Phanerozoic oncoids - an overview: Facies, v. 4, p.197-214.

Peryt, T.M., 1983a, Classification of coated grains: Coated Grains, Springer, Berlin, p. 3-6.

Peryt, T.M., 1983b, Oncoids: Comment to recent developments: Coated Grains, Springer, Berlin, p. 273-275.

Raine, R.J., 2010, The Durness Group of NW Scotland: A stratigraphical and sedimentological study of a Cambro-Ordovician passive margin succession: unpublished PhD dissertation, University of Birmingham p. 270.

Rohr, D.M. 1994. Ordovician (Whiterockian) gastropods of Nevada: Bellerophontoidea, Macluritoidea, and Eumphaloidea. Journal of Paleontology, 68(3):473-486.

Rohr, D.M. 1996. Ordovician (Whiterockian) gastropods of Nevada, Part 2. Journal of Paleontology, 70(1):56-63.

Rohr, D.M., Blodgett, R.B. and Furnish, W.M., 1992, *Maclurina manitobensis* (Whiteaves) (Ordovician Gastropoda): The largest known paleozoic gastropod: Journal of Paleontology, v. 66, p. 880-884.

Rohr, D.M., Norford, B.S. and Yochelson, E.L., 1995, Stratigraphically significant Early and Middle Ordovician gastropod occurrences, Western and Northwestern Canada: Journal of Paleontology, v. 69, p. 1047-1053.

Rohr, D.M. and Yochelson, E.L., 1990, An unusual new Bellerophontacean gastropod from the Ordovician (Whiterockian) of Nevada: Journal of Paleontology, v. 64, p. 956-960.

Rohr, D.M. and Yochelson, E.L., 1999, Life association and operculum of Middle Ordovician gastropod Maclurites: Journal of Paleontology, v. 73, p. 1078-1080.

Ross, R.J. Jr., 1964, Middle and Lower Ordovician formations in southernmost Nevada and adjacent California: Geological Survey Bulletin 1180-C.

Ross. R.J., Jr. 1976. Ordovician sedimentation in the Western United States. Rocky Mountain Association of Geologists, 1976 Symposium.

Ross, R.J. Jr., 1977, Ordovician paleogeography of the western United States, p. 19-38 in J.H. Stewart, C.H. Stevens, A.E. Fritshe, eds., Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography, Symposium 1.

Ross, R.J. Jr., James, N.P., Hintze, L.F. and Poole, F.G., 1989, Architecture and evolution of a Whiterockian (Early Middle Ordovician) carbonate platform, Basin Ranges of Western U.S.A., p. 167-185, in P.D. Crevello, J.L. Wilson, J.F. Sarg and J.F. Read, Controls on Carbonate Platform and Basin Development: Society of Economic Paleontologists and Mineralogists, Special Publication No. 44.

Ross, R.J., Ethington, R.L., and Mitchell, C.E. 1991. Stratotype of Ordovician Whiterock Series. PALAIOS, 6(2):156-173.

Saint Martin, J.P., 2010, The *Girvanella*-like remains from Messinian marine deposits (Sardinia, Italy): Lagerstätten paradigm for microbial biota?: Annales de Paléontologie, v. 96, p. 33-50.

Salter, J.W. 1859. Figures and descriptions of Canadian organic remains. Geological Society of Canada, Montreal, Canada, p. 47.

Santos, S.J. and Reigadas, E.T. 2002. Latinos in higher education: An evaluation of a university faculty mentoring program. Journal of Hispanic Higher Education, 1(1):40-50.

Schwitzer, A.M. and Thomas, C. 1998. Implementation, utilization, and outcomes of a minority freshman peer mentor program at a predominately White university. Journal of the Freshman Year Experience and Students in Transition, 10:31-50.

Sepkoski, J.J. 1981. A factor analytic description of the Phanerozoic marine fossil record. Paleobiology, 7(1):36-53.

Sepkoski Jr, J. John, and Peter M. Sheehan. 1983. Diversification, faunal change, and community replacement during the Ordovician radiations. In Biotic Interactions In Recent And Fossil Benthic Communities. Springer US, 1983. Pp. 673-717.

Siewers, F.D., 1995, Origin and stratigraphic significance of limestone discontinuity surfaces, Ordovician (Whiterockian) of Nevada: Unpublished PhD thesis, University of Illinois at Urbana-Champaign, 246 p.

Stamp, N. and O'Brien, T. 2005. GK-12 partnership: A model to advance change in science education. BioScience, 55(1):70-77.

Stokes, P.J., Levine, R. and Flessa, K.W. 2014. Why are there so few Hispanic students in geoscience? GSA Today, 24:52-53.

Stricker, G.D. and Carozzi, A.V., 1973, Carbonate microfacies of the Pogonip Group (Lower Ordovician) Arrow Canyon Range, Clark County, Nevada, USA: Bulletin du Centre de recherches Pau, v. 30, p. 499-541.

Sweet, W.C. and Tolbert, C.M. 1997. An Ibexian (Lower Ordovician) reference section in the Southern Egan Range, Nevada, for conodont-based chronostratigraphy. US Geological Survey Profession Paper 1579-B:51:84.

Thile, E.L. and Matt, G.E. 1995. The ethnic mentor undergraduate program: A brief description and preliminary findings. Journal of Multicultural Counseling and Development, 23:116-126.

Tsui, L. 2007. Effective strategies to increase diversity in STEM fields: A review of the research literature. Journal of Negro Education, 76(4):555-581.

Tyson, W., Lee, R., Borman, K.M. and Hanson, M.A. 2007. Science, technology, engineering and mathematics (STEM) pathways: High school science and math coursework and postsecondary degree attainment. Journal of Education for Students Placed at Risk, 12(3):243-270.

University of California, Board of Regents. 2010. Regents Policy 4400: Policy on University of California Diversity Statement. Available at http://regents.universityofcalifornia.edu/governance/policies/4400.html (accessed 23 April 2015)

University of California, Riverside Office of Admissions. 2015. Available at https://www.ucr.edu/about/facts.html (accessed 23 April 2015)

University of California, Admissions Requirements, 2015. Available at http://admission.universityofcalifornia.edu/freshman/requirements/a-g-requirements/index.html#lab (accessed 18 October 2015)
Ulrich, E.O. and Scofield, W.H. 1897. The Lower Silurian Gastropoda of Minnesota. The Paleontology of Minnesota, 39(2):813-1081.

U.S. Census Bureau: State and County QuickFacts. 2010. Available at http://quickfacts.census.gov/qfd/states/06/06065.html (accessed 23 April 2015)

U.S. Department of Education, College Scorecard, 2015. Available at https://collegescorecard.ed.gov/school/?110671-University-of-California-Riverside (accessed 18 October 2015)

Van der Hoeven Kraft, K.J., Srogi, L., Husman, J., Semken, S. and Fuhrman, M. 2011. Engaging students to learn through the affective domain: A new framework for teaching in the geosciences. Journal of Geoscience Education, 59:71-84.

Vermeij, G.J. 1977. The Mesozoic Marine Revolution: Evidence from snails, predators and grazers. Paleobiology, 3(3):245-258.

Wagner, P.J. 1995. Testing evolutionary constraint hypotheses with early Paleozoic gastropods. Paleobiology, 21(3):248-272.

Wagner, P.J. 2001. Gastropods phylogenetics: Progress, problems, and implications. Journal of Paleontology, 75(6):1128-1140.

Wagner, P.J. and Erwin, D.H. 2006. Patterns of convergence in general shell form among Paleozoic gastropods. Paleobiology, 32(2):316-337.

Whitfield, R.P. 1886. Notice of geological investigations along the eastern shore of Lake Champlain, conducted by Prof. H.J. Seely and Pres. Ezra Brainerd, of Middlebury College, with descriptions of new fossils discovered. Bulletin of the American Museum of Natural History, 1(8):24-35.

Wilson, A.E. 1924. A new genus and a new species of gastropod from the Upper Ordovician of British Columbia. Canadian Natural History, 1:81-114.

Wilson, C. 2014. Status of the geoscience workforce 2014. American Geosciences Institute. Available at http://www.americangeosciences.org/workforce (accessed 4 May 2015)

Wilson, M.A., Palmer, T.J., Guensburg, T.E., Finton, C.D. and Kaufman, L.E. 1992. The development of an Early Ordovician hardground community in response to rapid seafloor calcite precipitation. Lethaia 25:19-34.

Wilson, Z.S., Holmes, L., deGravelles, K., Sylvain, M.R., Batiste, L., Johnson, M., McGuire, S.Y., Pang, S.S. and Warner, I.M. 2012. Hierarchical mentoring: A transformative strategy for improving diversity and retention in undergraduate STEM disciplines. Journal of Science Education and Technology, 21(1):148-156.

Workum, R.H., Bolton, T.E. and Barnes, C.R., 1976, Ordovician geology of Akpatok Island, Ungava Bay, District of Franklin: Canadian Journal of Earth Science, v. 13, p. 157-178.

Yochelson, E.L., 1986, Operculum of the Middle Ordovician gastropod *Palliseria robusta* Wilson: Journal of Paleontology, v. 60, p. 656-660.

Yochelson, E.L., 1989, Billings' second operculum: a late Early Ordovician *Maclurites* (Gastropoda) from western Newfoundland and the Canadian Arctic: Canadian Journal of Earth Science, v. 27, p. 669-676.

Yochelson, E.L., 1990. Billings' second operculum: A late Early Ordovician Maclurites (Gastropoda) from western Newfoundland and the Canadian Arctic. Canadian Journal of Earth Sciences, 27(5):669-676.

Yochelson, E.L., 1991, The late Early Ordovician gastropod *Teiichispira* at Port au Port, Newfoundland: Canadian Journal of Earth Science, v. 29, p. 1334-1341.

Zeigler, K. and Camarota, S.A. 2014. Is there a STEM worker shortage? A look at employment and wages in science, technology, engineering, and math. Center for Immigration Studies. Available at http://cis.org/no-stem-shortage (accessed 4 May 2015)

Appendix A

```
require(plotrix)

source("mkpdf.R")
source("readBedTopPlots.R") # loads up 'data' and 'Nmollusc'

quartz()
for (quad in unique(data$Quad))
{
  if (is.na(quad)) next # read.xlsx() adds extra rows for
some reason

  use = which(data$Quad == quad)
  symbols(data$x[use], data$y[use], circles=data$r[use],
asp=1,
          main=paste(quad, "  Number =", length(use)),
inches=F,
          xlab="X (m)", ylab="Y (m)", xlim=c(0,0.5),
ylim=c(0,0.5))
  readline("")
}

quartz()
quad = "72.5F"
#quad = "79.2C"
use = which(data$Quad == quad)
symbols(data$x[use], data$y[use], circles=data$r[use], asp=1,
        main=paste("Quad", quad, "  Number =", length(use)),
inches=F,
        xlab="X (m)", ylab="Y (m)", xlim=c(0,0.5),
ylim=c(0,0.5))
mkpdf(file=paste(quad, ".bedview.pdf", sep=""))
```

Appendix B

```
L = 0.5
area = L*L
alpha = 0.05
N = length(use)
sigma = N/area
sigma2.5 = 0.5*qchisq(alpha/2, 2*N)/area
sigma97.5 = 0.5*qchisq(1 - alpha/2, 2*N + 2)/area

rmean = mean(data$r[use])

nsamp = 50
x = seq(2*rmean, L - 2*rmean, length=nsamp)
n = rep(NA, nsamp)
for (i in 1:nsamp)
  n[i] = sum(abs(x[i] - data$x[use]) < data$r[use])
lambda = n/L
lambda2.5 = 0.5*qchisq(alpha/2, 2*n)/L
lambda97.5 = 0.5*qchisq(1 - alpha/2, 2*n + 2)/L

sigmaFromLambda = lambda/(2*rmean)
sigmaFromLambda2.5 = lambda2.5/(2*rmean)
sigmaFromLambda97.5 = lambda97.5/(2*rmean)

quartz()
lwd = 1
plotCI(x, sigmaFromLambda, li=sigmaFromLambda2.5,
ui=sigmaFromLambda97.5,
        err="y", xlab="X (m)", ylab="Areal density (/m^2)",
lwd=lwd, sfrac=0.005,
        main=paste("Quad", quad))
abline(h=sigma, col="red", lwd=lwd)
abline(h=c(sigma2.5, sigma97.5), lty="dashed", col="red")
mkpdf(file=paste(quad, ".sigmaFromLambda.pdf", sep=""))

print(sum(sigmaFromLambda2.5 < sigma & sigmaFromLambda97.5 >
sigma) / nsamp)
```

Appendix C

Calculating areal density from linear density.

Assume that discs are distributed independently and uniformly over the plane, with some density σ:	$\lim_{\lvert A\rvert\to\infty}\left(\frac{N(A)}{\lvert A\rvert}\right) = \sigma$
N(A) is the number of disc centers falling within a region of the plane A of area $\lvert A\rvert$. Then, because cross section exposure of macluritid fossils would occur if any portion of the fossil touched the line, refine the equation to include discs for which any portion fell within A (rather than just the centers) for some square region of side-length L.	$E[\hat{\sigma}'] = \sigma\left(1 + 4\frac{r_0}{L} + 4\left(\frac{r_0}{L}\right)^2\right)$
The line (where cross section exposure occurs) will intersect any discs whose centers are within r_0 of the line. For a section of the line of length *L,* there will be an area of $2\sigma r_0 L$. On average, $N(L) = 2\sigma r_0 L$ discs that intersect that part of the line. Define linear density $\leftthreetimes$ as the number of discs intersected per unit length along the line:	$\leftthreetimes \equiv \frac{N(L)}{L} = 2\sigma r_0$
r_0 varies because the radii of gastropods vary. To account for this, substitute r_0 with $\bar{r}$, the mean of the distribution of radii. The number of disc centers between r and $r + dr$ from a section of the line of length L is $2Ldr\sigma = 2\sigma Ldr$. A disc in this strip that will intersect the line is one with a radius greater than r, and the fraction of discs that have radii greater than r is:	$\int_r^\infty f(r')dr' = 1 - F(r)$
$F(r)$ is the cdf of the distribution:	$F(r) \equiv \int_0^r f(r')dr'$
The number of disks with centers in those two strips that intersect the line is:	$N(L) = \int_0^\infty 2(1 - F(r))\sigma Ldr$
The total number of discs that will intersect the line will be given by the integral of this quantity:	$N(L) = \int_0^\infty 2\big(1 - F(r)\big)\sigma Ldr$ $= 2\sigma L\int_0^\infty (1 - F(r))dr$
So that the linear density of disks that intersect the line is:	$\leftthreetimes = \frac{N(L)}{L} = 2\sigma\int_0^\infty (1 - F(r))dr$

Using integration by parts, the integral is equal to $\bar{r}$:	$\lambda = 2\sigma \int_0^\infty (1 - F(r))dr$ $= 2\sigma \left[r(1 - F(r))\vert_0^\infty - \int_0^\infty r(-f(r))dr \right]$ $= 2\sigma \left[0 + \int_0^\infty rf(r)dr \right]$ $= 2\sigma\bar{r}$

Appendix D

```
require(plotrix)
source("mkpdf.R")
source("readArrowCanyonData.R")

alpha = 0.05
sigma0 = 40
L = 100
area = L*L

syn = list(N=rpois(1, sigma0*L*L))
syn$x = runif(syn$N, min=0, max=L)
syn$y = runif(syn$N, min=0, max=L)
syn$r = sample(r.all, syn$N, replace=TRUE)/1e3

quartz()
symbols(syn$x, syn$y, circles=syn$r, asp=1,
        main=paste("Synthetic:  Expected number = ",
sigma0*area,
                   "; observed number = ", syn$N, sep=""),
        inches=F, xlab="X (m)", ylab="Y (m)", xlim=c(0,L),
ylim=c(0,L))
mkpdf(file=paste("synthetic.sigma0=", sigma0, ".L=", L,
".bedview.pdf", sep=""))

rmean = mean(syn$r)

nsamp = 50
x = runif(nsamp, min=0, max=L)
x = seq(2*rmean, L - 2*rmean, length=nsamp)
n = rep(NA, nsamp)
for (i in 1:nsamp)
  n[i] = sum(abs(x[i] - syn$x) < syn$r)
lambda = n/L
lambda2.5 = 0.5*qchisq(alpha/2, 2*n)/L
lambda97.5 = 0.5*qchisq(1 - alpha/2, 2*n + 2)/L

sigma = syn$N/area
sigma2.5 = 0.5*qchisq(alpha/2, 2*syn$N)/area
sigma97.5 = 0.5*qchisq(1 - alpha/2, 2*syn$N + 2)/area

sigmaFromLambda = lambda/(2*rmean)
sigmaFromLambda2.5 = lambda2.5/(2*rmean)
sigmaFromLambda97.5 = lambda97.5/(2*rmean)

quartz()
plotCI(x, sigmaFromLambda, li=sigmaFromLambda2.5,
ui=sigmaFromLambda97.5,
        err="y", ylim=c(0, max(sigmaFromLambda97.5)),
sfrac=0.005,
        xlim=c(0, L), xlab="X (m)", ylab="Areal density
(/m^2)",
        main=paste("Synthetic:  Expected number = ",
sigma0*area,
                   "; observed number = ", syn$N, sep=""))
```

```
abline(h=syn$N/area, col="red")
abline(h=sigma0, col="red", lty="dotted")
abline(h=c(sigma2.5, sigma97.5), lty="dashed", col="red")
mkpdf(file=paste("synthetic.sigma0=", sigma0, ".L=", L,
".sigmaFromLambda.pdf", sep=""))

print(sum(sigmaFromLambda2.5 < sigma0 & sigmaFromLambda97.5 >
sigma0)
/ nsamp)
```