AFTER THE RAIN: USING PALEOCLIMATIC AND PALEOECOLOGICAL METHODS TO INFORM ARCHAEOLOGICAL INVESTIGATION IN BAJA CALIFORNIA AND RANGE CREEK CANYON, UTAH

by

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STATEMENT OF DISSERTATION APPROVAL

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ABSTRACT

This dissertation reports the work I have completed with two research projects, using paleoecological methods to compare precipitation histories to inform archaeological investigation at two sites. The first chapter will present an analysis of the population history of leporids (rabbits and hares) from Abrigo de los Escorpiones, a shell midden site on the coast of northern Baja California, over the past 10,000 years. Comparison of that population history to sedimentary-based records of the frequency and intensity of El Niño events over the same time period reveals strong correlations between precipitation and overall abundance, taxonomic composition, and age structure of the leporid population at the site.

The second chapter of this dissertation reports the results of a multiproxy paleoenvironmental reconstruction of climate during the past 2000 years at a site in Range Creek Canyon, in the Tavaputs Plateau region of eastern Utah. Results from the analysis of fossil pollen, macroscopic charcoal, sediment loss on ignition, magnetic susceptibility, and stable carbon isotope analysis of sediments demonstrate the site was used by human horticulturalists as a maize field during the Fremont occupation of the canyon between roughly AD 800 and AD 1100. Additionally, the paleoenvironmental proxies reveal the period of Fremont occupation of the canyon likely saw less summer precipitation than today, very likely necessitating irrigation of fields for maize horticulturalists.

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CHAPTER 1

INTRODUCTION

This dissertation is made up of two chapters: a study of how Holocene variation in precipitation influenced rabbit and hare populations of Baja California, and a study of pollen abundance and other paleoecological proxies from a sediment core in the Tavaputs Plateau region of central Utah. The central theme uniting these two topics is the development and use of paleoecological and paleoclimatic datasets to inform archaeological investigations. The ultimate goal for both of the studies presented in this dissertation is to provide baseline paleoclimatic and paleoecological records to facilitate further archaeological investigation in the two regions using the framework of behavioral ecology. Although the specific contexts of the two chapters are distinct, they both underscore how an understanding of precipitation variation is key to generating and testing a range of hypotheses related to past human behavior.

Abrigo de los Escorpiones

The first chapter of this dissertation deals with the effects that the frequency of El Niño events had on the lagomorph (rabbit and hare) populations of northern Baja California for the past 10,000 years as reconstructed from materials from Abrigo de los Escorpiones (hereafter Escorpiones), a well-dated, trans-Holocene vertebrate fauna from northern Baja California, Mexico. The El Niño/Southern Oscillation (ENSO) is a major source of climatic variation worldwide, with significant impacts on modern human and animal populations. However, few detailed records exist on the long-term effects of ENSO on prehistoric vertebrate populations. In this chapter, I examine how lagomorph deposition rate, population age structure and taxonomic composition from Escorpiones vary as a function of the frequency of wet El Niño events and eastern Pacific sea surface temperatures (SSTs) derived from eastern Pacific geological records. The results from this analysis show the lagomorph populations of northern Baja California vary significantly in response to El Niño-based precipitation and SST, with substantial moisture-driven variability in the middle and late Holocene. A late Holocene moisture pulse and lagomorph population expansion is also coincident with previously documented changes in the population dynamics of other vertebrates across western North America, including humans. As the frequency and intensity of ENSO is anticipated to vary in the future, these results have important implications for change in future vertebrate populations.

Further analysis of the archaeological and faunal assemblage at Escorpiones is beyond the scope of this dissertation, but the analysis presented in Chapter 1 provides a climatic baseline for research relating to human subsistence and settlement patterns at the site. Future work will use the demonstrated link between ENSO and local vertebrate populations over time to generate, test and refine hypotheses regarding human use of the site and surrounding landscape through the Holocene.

The impacts of El Niño in northern Baja California for marine environments include higher tidal surf, elevated SST, reduced upwelling of nutrient-rich water, reduction in zooplanktonic biomass, reduction in the extent of seaweed beds, the decimation of kelp forests, and die-offs of related fish and molluscan faunas (e.g., Aguirre-Gomez *et al.*, 2003; Guzman *et al.*, 2003; López-Cortés *et al.*, 2003; Magaña *et al.*, 2003; Davis, 2006). Human foragers targeting marine prey might also see significant increases in the costs of extracting those prey items that remained as a result of higher tidal surfs and rougher seas associated with El Niño. El Niño should therefore have had a generally negative effect on human foraging in marine contexts in Baja California.

In terrestrial environments, however, foraging conditions generally improve for humans as a result of El Niño events. El Niño-based increases in precipitation drive aquifer recharge and reactivation of spring, marsh and riparian environments, and higher than normal terrestrial primary productivity. Increased vegetative biomass works its way up through the foodweb, resulting in higher biomass in nearly all terrestrial vertebrate communities (Holmgren *et al.*, 2006).

Models from behavioral ecology offer clear expectations for how these ENSO-based environmental changes should influence past human foraging behavior. The three most widely used models derived from behavioral ecology and commonly applied to archaeological materials are the Prey Model (PM), the Patch Choice Model (PCM) and the Ideal Free/Ideal Despotic Distribution models.

The prey model is the most widely applied foraging theory model in ethnographic and archaeological settings (Bird and O'Connell, 2006; Cannon and Broughton, 2010; Codding and Bird, 2015). The model defines the optimal suite of resources a forager should pursue upon encounter, assuming the forager's goal is to maximize the rate of caloric intake. Prey items are ranked by postencounter return rates (the amount of energy gained per unit time processing and eating the prey item), and the optimal diet is then defined by adding items in descending rank order starting with the highest return items. Prey items are added to the diet until adding the next prey item would reduce the total energetic return per unit time for foraging (Stephens and Krebs, 1986).

Overall foraging returns can be measured in a number of ways with archaeological materials. Indices of relative taxonomic abundance have proved especially fruitful. These indices provide estimates of foraging efficiency over time, by measuring the abundance of high-return prey types against low-return types (e.g., Bayham, 1979; Broughton, 1994, 1999, 2002; Butler, 2000; Lyman, 2003; Butler and Campbell, 2004; Nagaoka, 2005; Wolverton, 2005; Codding *et al.*, 2010). We predict that periods of more frequent El Niño events should result in lower foraging efficiency for marine prey types due to decreased marine prey abundance and higher pursuit costs, and in higher efficiency in terrestrial patches resulting from higher overall terrestrial productivity and prey abundance. Differential efficiency within these two broad prey categories could be tracked over time in the Escorpiones archaeofauna using marine and terrestrial foraging efficiency indices (e.g., Σ Pinniped NISP/Σ [Pinniped + Sea Otter] NISP, and Σ Artiodactyl NISP/Σ [Artiodactyl + Lagomorph] NISP).

Similar to the prey model, the patch choice model addresses the question of whether a forager should enter a patch and begin processing a resource, and also when the forager should be expected to leave to travel to another patch (MacArthur and Pianka, 1966). The model has algebraic and graphical solutions and has been fruitfully applied to archaeological materials in a variety of ethnographic (e.g., O'Connell and Hawkes, 1981; Winterhalder, 1981; Hawkes *et al.*, 1982; Smith, 1991; Sosis, 2002; Codding *et al.*, 2010) and archaeological contexts (e.g., Nagaoka, 2002; Jones, 2009; O'Connell and Allen, 2012; Wolverton *et al.*, 2015; see also Cannon and Meltzer, 2008). Patches are treated as discrete prey items in this model, and are ranked by in-patch total energetic return per unit time. The optimal set of patches is defined by adding patches in descending rank order to the diet until adding the next patch would reduce the forager's total energetic returns including travel time between patches.

An important prediction of both the patch choice model and the prey model is that the best patches and prey items within those patches will always be exploited. An index comparing the highest return marine prey against the highest return terrestrial prey could therefore track the relative importance of these patch types over time. Such an index could be calculated as (Σ Pinniped NISP/Σ Artiodactyl NISP). This index should be expected to vary negatively with the frequency of El Niño events given the negative impacts El Niño has on marine patches and its positive effects on terrestrial patches. This logic could also be applied to items of material culture such as tools. An index comparing marine-oriented foraging equipment such as fish hooks or harpoons to terrestrial-oriented hunting items such as dart points or rabbit nets over time might also be correlated with the frequency of El Niño events (e.g., Byers and Broughton, 2004).

The Ideal Free Distribution model (IFD; Fretwell and Lucas, 1970; Fretwell, 1972) offers useful expectations for Escorpiones and the landscape surrounding the site as well based on the frequency of El Niño events. The IFD is a distribution model wherein organisms are distributed across the landscape such that their density is directly proportional to the suitability of habitats (which is often defined as prey item abundance). While it would take additional archaeological survey in Baja California to properly apply this model, we should expect that during periods of more frequent El Niño events, terrestrial environments should have been more densely used by human foragers, and marine less so. Water is an important resource for many terrestrial vertebrates in this generally semi-arid environment and the increased availability of water across the landscape would increase the number of point sources for water as aquifers recharge and springs reactivate. Intersite distances in terrestrial settings might go down during such times, and spatial clustering could also go down as a result of more dispersed resources on the landscape. This model also predicts more intense use of marine habitats during low-frequency El Niño periods. We might therefore expect that during periods of frequent El Niño, site usage in coastal settings (including at Escorpiones) should decrease as more time was spent inland in terrestrial settings.

Billy Slope Bog

The second chapter of this dissertation discusses a multiproxy paleoecological record of the past 3000 years from the Range Creek Canyon (RCC), in the Tavaputs Plateau area of central Utah. Paleoecological proxy data discussed include a macroscopic charcoal-based fire history, pollen-based vegetation reconstruction, loss-on-ignition-based carbonate and organic carbon analysis, magnetic susceptibility-based sedimentation analysis and stable carbon isotope chemistry from a sediment core taken in a wet meadow in RCC. We compare the data to the limited existing literature on climate and paleoecology of the region. Results demonstrate broad agreement with regional climate syntheses documenting a warm, dry Medieval Climate Anomaly from AD 800-1300, a cool, dry Little Ice Age from AD 1300-1800 and a more equable historic period similar to modern after AD 1800 for the Tavaputs Plateau. The fire history suggests fires in RCC were driven largely by regional droughts through much of the record. Additionally, several lines of evidence demonstrate the core site itself served as an agricultural maize field during Fremont times at ca. AD 1050.

One of the more important climatic parameters identified for the Tavaputs record in Chapter 2 is precipitation seasonality, the difference between the amounts of winter and summer precipitation. Precipitation seasonality is important in this context because the time period this study spans includes the adoption and abandonment of maize agriculture by the human inhabitants of RCC during the Fremont period.

Using the framework of behavioral ecology, specifically the PCM outlined above, archaeologists have made significant progress in understanding the economics and ecological/demographic drivers and constraints of farming (Cannon, 2000; Barlow, 2002; Gremillon, 2004; Kennett and Winterhalder, 2006; Gremillon and Piperno, 2009; Gremillon *et al.*, 2014; Codding and Bird, 2015). One common thread among the behavioral ecological treatments of the rise of agriculture in North America is an apparent reduction in foraging efficiency at times agriculture rose in importance. Foraging efficiency can decline as a function of demographic expansion through harvest-pressure, or as a result of climate-driven reduction of high-ranking prey populations. In Utah and the four corners region, the rise of agriculture is generally coincident with an expansion of human populations during the Medieval Climate Anomaly (MCA) between AD 800 and AD 1300 (Massimino and Metcalfe, 1999; Benson *et al.*, 2006, 2007), suggesting demographic pressures may have driven declines in foraging efficiency during that period. But the florescence of farming populations during the Medieval Climate

Anomaly was also accompanied by dramatic climatic change, suggesting climate played an important role in agricultural productivity as well (Petersen, 1988, 1994; Coltrain and Leavitt, 2002; Benson *et al.*, 2006, 2007, 2009).

The most critical climatic factor for maize agriculture in RCC, and the arid West generally, is the availability of water during the growing season (Boomgarden, 2015). The productivity of maize is a function of watering regimes, and without sufficient growing season precipitation, extensive irrigation networks are required to produce significant maize crop yields. As Boomgarden (2015) demonstrates, precipitation and growing season length and temperature are inversely correlated with elevation in RCC. Where precipitation meets the minimum threshold at the north end of the canyon (above 9000' elevation), the growing season is much too short. Where the growing season is long enough to support a maize crop at the south end of the canyon (below 6000' elevation), direct precipitation alone is rarely (<5% of the time) enough to produce a significant maize harvest. Creek diversion and irrigation to some degree would always be necessary to rely on maize agriculture from year to year in RCC.

The nature of precipitation seasonality during the formative period in the Southwest has been neglected in the archaeological literature. Many scholars have assumed that an increase in precipitation during the growing season will always benefit maize agriculturalists (Petersen, 1988, 1994; Coltrain and Leavitt, 2002; Benson *et al.*, 2006, 2007, 2009). This may be true if precipitation falling directly on maize fields is sufficient to grow crops (rainfall farming). But it may be more complicated where direct precipitation is not sufficient and instead farmers need to divert water from drainage channels to irrigate fields. Whether the water being diverted comes in the form of massive single event floods (heavy summer precipitation) or a moderate, stable flow (winter precipitation and spring-fed streams) would significantly alter the complexity, and cost, of irrigation required to produce a harvest. The seasonal nature of precipitation during the transition from reliance on foraging to maize agriculture and back is therefore of critical importance for understanding the costs and benefits associated with each production strategy. The analysis presented in Chapter 2 suggests the maize farmers of RCC may actually have experienced decreased summer precipitation during periods of stable winter precipitation. In addition to reducing the amplitude of the daily variance in creek flows, reduced summer precipitation would likely have negatively impacted foraging return rates by reducing the abundance of wild food items. This can be seen in the BSB09B record as a reduction in the abundance of pinyon pine, one of the highest-ranked wild food items. Further experimental work dealing with the costs of building, maintaining and employing irrigation networks over several growing seasons will allow a better understanding of the effects of precipitation seasonality on the economics of maize farming and the tradeoffs between foraging for wild foods and agricultural production.

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CHAPTER 2

EL NIÑO CONTROLS HOLOCENE RABBIT AND HARE POPULATIONS IN BAJA CALIFORNIA

Introduction

The El Niño/Southern Oscillation (ENSO) is a major source of climatic variation worldwide, including in the eastern Pacific Ocean and the interior of western North America. The El Niño phase of ENSO brings warm sea surface temperatures (SSTs) to the eastern Pacific and drives especially heavy precipitation, while the La Niña phase is characterized by cooler SSTs and lower regional precipitation (Philander, 1985; Philander, 1990; Diaz and Markgraf, 1992). The variation in precipitation associated with ENSO has had a tremendous impact on a wide range of historic marine and terrestrial ecosystems as well as human populations over much of the world (Barber and Chavez, 1983; Meggers, 1994; Holmgren *et al.*, 2001; Stenseth *et al.*, 2002; Fagan, 2009). In recent years, increasing attention has focused on past patterns of ENSO variation, especially in relation to potential impacts on human cultures both in prehistoric and historic times (e.g., Sandweiss and Quilter, 2008; Caviedes, 2009). And while attempts have been made to evaluate the impacts of Holocene ENSO variation on certain marine fisheries and seabird populations (Broughton, 2004; Sandweiss and Quilter, 2008), little work has focused on its effects on past small mammal faunas. Modern studies of the latter suggest, however, that those impacts would have been substantial.

Irruptions of small mammal populations and associated increases in taxonomic diversity have been linked to enhanced precipitation associated with ENSO events in many areas of the world including South America, Africa, Australia and North America (Brown, 1973; Brown and Heske, 1990; Jaksic *et al.*, 1997; Ernest *et al.*, 2000; Ostfeld and Keesing, 2000; Holmgren *et al.*, 2001; Jaksic, 2001; Letnic *et al.*, 2005; Farias and Jaksic, 2007; Kelt *et al., 20*08; Previtali *et al.*, 2009a, 2009b; Thibault *et al.*, 2010; Lightfoot *et al.*, 2011; Meserve *et al.*, 2011). Various complexities in the response rates to enhanced precipitation have been linked to such issues as trophic level, generation time and specific feeding ecologies. Previtali *et al.* (2009a, 2009b), for instance, have shown that populations of degu (*Octodon degus*), a long-lived, slow reproducing rodent inhabiting semiarid areas of Chile, track ENSO variation with a lag response—exploding a year after wet El Niño events and crashing with a short delay after a dry La Niña. They also demonstrated an additive effect of consecutive wet years to degu populations. Populations of *Phyllotis darwini*, however, a shorter-lived, fast reproducing mouse reached population maxima immediately after the onset of wet El Niño conditions, without a noticeable lag. Response lags may also reflect the phenology of the specific plant structures utilized by small mammals. Granivorous rodents (e.g., *Dipodomys*) decline in activity levels and abundance during intense El Niño rains in southern California (Orland and Kelt, 2007; Kelt *et al.*, 2008), but increase dramatically several months later as an elevated abundance of seed resources materializes (e.g., Gutiérrez *et al.*, 2000).

Predatory vertebrates also show predictable lags based on the nature of the population response of their dominant prey species, and predation risk can interact with changes in primary productivity to produce significant differences in small mammal population dynamics under similar precipitation regimes (e.g., Jaksic *et al.*, 1997; Jaksic, 2001; Farias and Jaksic, 2007; Thibault *et al.*, 2010)

Despite our increased understanding of short-term ENSO effects on small mammal population dynamics–including an appreciation of the individualistic nature of species response–no detailed records of ENSO effects on small mammal populations have been provided on centennial or millennial time scales. Such information may be crucial to predicting long-term dynamics of mammalian communities in the context of future variation in ENSO.

The trans-Holocene mixed anthropogenic and raptor deposited vertebrate fauna from Abrigo de los Escorpiones (Figures 2-1 and 2-2; hereafter, Escorpiones) on the Pacific coast of northern Baja California, Mexico, provides a unique opportunity to provide such information. Although analyses are underway on many aspects of the rich vertebrate record from the site, lagomorphs (pikas, rabbits and hares) have proven to be especially sensitive to change in past moisture regimes in several other settings in western North America–especially the Great Basin (Grayson, 1977, 1983, 1985, 1987, 1998, 2000, 2005, 2006; Grayson *et al.*, 1988; Hockett, 2000, Schmitt *et al.*, 2002)–and we focus on that group here. In addition to providing a relatively high-resolution assessment of the impact of ENSO on Holocene small mammal populations, our analysis provides an unprecedented 10,000 year history of lagomorphs from a North American locality outside of the Great Basin.

Paleoclimates of Western North America and Baja California

Antevs' (Antevs, 1948, 1952, 1955) climate model for the Holocene Great Basin provides a starting point from which to explore the paleoclimate of northern Baja California and its influence on lagomorph populations. This extensively tested model proposes a relatively cool and moist early Holocene between 10,000 and 8000 years ago, a warmer and drier middle Holocene from about 8000 to 4000 years ago and a late Holocene after 4000 years ago with a mesic climate more or less similar to modern times. While over 60 years of paleoenvironmental research shows that many aspects of this characterization are overly simplistic, in broad outline, the trends he proposed have held up remarkably well for many areas of western North America (see review in Grayson, 2011). And while detailed Holocene paleoclimatic records are not abundant in Baja California, what data there are appear broadly consistent with the Antevs scheme.

Davis (2003) analyzed the lacustrine history from Lake Chapala of northern Baja California and found evidence supporting a cooler, wetter early Holocene, and a warmer, drier middle Holocene. Radiocarbon dating of Lake Chapala's high and low stands demonstrates the basin filled to a high stand around 9000 radiocarbon years before present (^{14}C yr BP), after which the lake persisted until at least 7600 ^{14}C yr BP. By 7450 ^{14}C yr BP, however, the lake had dried up and sand dunes formed in the basin as the climate transitioned to generally warmer, drier conditions in the region.

Recent syntheses of vegetation and pollen records from southern California and northern Baja California (e.g., Holmgren *et al.*, 2010, 2011; Barron *et al.*, 2012) suggest this wetter early Holocene was characterized by substantial summer precipitation associated with a more westward position of the North American Monsoon. After 7500

^{14}C yr BP, however, that system shifted eastward, leaving southern California and northern Baja with hot and dry summer conditions. These data are consistent with Rhode's (2002) analysis of plant remains from an early Holocene woodrat (*Neotoma* sp.) midden from the Sierra San Francisco in central Baja that suggests early Holocene climate was 5-6 degrees Celsius cooler than modern conditions, with at least twice the precipitation levels of the region today.

A generally cooler and wetter later Holocene is supported by the existing paleoenvironmental data from Baja California as well. Clark and Sankey (1999) and Sankey *et al.* (2001) report that insect and plant remains from a woodrat midden at Cataviña in northern Baja from 1700 ^{14}C yr BP demonstrate late Holocene climate in Baja California similar to, and perhaps slightly more mesic than modern.

Although the specific climatic forcing mechanisms underlying these trends are not fully resolved, Holocene patterns in precipitation in many areas of western North America and especially Baja California may be linked to variation in the ENSO. For example, the prevalence of more mesic conditions during the late Holocene may stem in part from an increased duration and incidence of wet El Niño events.

The timing of the onset of the modern periodicity of ENSO and the nature of its Holocene variation in general has been the subject of growing attention over the past 15 years (e.g., Moy *et al.*, 2002; Cane, 2005; Marchitto *et al.*, 2010; Cobb *et al.*, 2013). Most records show an onset of more or less modern ENSO variability at around 5000 calibrated radiocarbon years BP (cal yr BP; e.g., Sandweiss and Richardson, 1996; Rodbell *et al.*, 1999; Sandweiss *et al.*, 2001; Moy *et al.*, 2002), yet some records have been interpreted to show ENSO onset as late as 4000 cal yr BP (Shulmeister and Lees, 1995; Conroy *et al.*, 2008 Donders *et al.*, 2008).

Prior to the onset of the modern ENSO periodicity, conditions characteristic of either El Niño or La Niña may have dominated large blocks of time, up to several thousand years each. Antinao and McDonald (2013) show, for example, the terminal Pleistocene and early Holocene from 14,600-11,000 cal yr BP was dominated by semi-permanent El Niño-like conditions, while the period from 9000-6000 cal yr BP likely saw persistent La Niña-like conditions. La Niña in Baja California is generally associated with reduced SSTs and regional precipitation. This may account in part for the observed early Holocene mesic conditions and subsequent drying in the region after 8000 cal yr BP.

One of the best-resolved trans-Holocene records of ENSO is derived from the sedimentation record of Laguna Pallcacocha in the southern Ecuadorian Andes (Rodbell *et al.*, 1999; Moy *et al.*, 2002). Holocene variation in the thickness of clastic laminae deposited in this freshwater lake basin provides a record of the strength, frequency and duration of prehistoric El Niño high precipitation events. The record demonstrates that El Niño events increased in frequency through the Holocene, reaching its more or less modern periodicity around 5000 cal yr BP, with notable peaks centered at about 5000, 3000 and 1000 cal yr BP. We utilize this record as a proxy for precipitation variation and its influence on the Holocene history of lagomorphs in northern Baja California. Additionally, since ENSO phases are defined with respect to SST anomalies, we utilize an eastern Pacific SST proxy from the Soledad Basin off Baja's western coast (Figure 2-1; Marchitto *et al.*, 2010). This record records variation in Magnesium/Calcium ratios in planktonic Foraminifera over the Holocene and shows a strong link between local SSTs and ENSO.

Holocene Moisture History and Lagomorph Faunas in Western North America

The broad trends in Holocene climate change summarized above have provided a framework for understanding the history of lagomorph distributions and abundances in many settings across western North America, but the most detailed records are derived from dry cave faunas from the Great Basin. To provide a context for our analyses of the Escorpiones lagomorphs, we summarize key aspects of those patterns here.

In the first detailed assessment, Grayson (1977) evaluated the Holocene abundance of two species of *Lepus*: black-tailed jackrabbit (*L. californicus*) and white-tailed jackrabbit (*L. townsendii*), from Connley Caves in the northwestern Great Basin (Figure 2-1). These two species exhibit distributional and ecological differences: *L. townsendii* has a more northern distribution and tends to occupy higher elevation more grassy habitats with thicker sage. *L. californicus*, by contrast, has a more southerly distribution and prefers lower elevation and more open habitats. Grayson found that *L. californicus* replaced *L. townsendii* after the early Holocene and concluded the change was consistent with the Antevs model of Holocene climate change (but see also Purdue, 1980).

Perhaps the most well-documented trends involve the dramatic terminal Pleistocene through middle Holocene range changes and declining abundances of the most mesic of the western lagomorphs: American pika (*Ochotona princeps*) and pygmy rabbit (*Brachylagus idahoensis*). American pikas are restricted today to higher elevation settings in habitats with talus slopes near mountain meadows with abundant herbaceous forbs. Pygmy rabbits require tall dense stands of big sagebrush (*Artemisia tridentata*) that occur in generally cooler and wetter lower and middle elevation environments. Both taxa decline in abundance relative to other small mammals from the late Pleistocene through the early Holocene in many western faunas (Butler, 1972; Grayson, 1977, 1983, 1985, 1988, 2000, 2006; Harris, 1985; Lyman, 1991; Hockett, 2000; Schmitt *et al.*, 2002). In addition, their overall geographic distributions have shifted upwards in both elevation (most clearly in pikas [Grayson, 2006]) and latitude as a result of increasing temperature and declining precipitation over this period of time, resulting in their disappearance within local faunal sequences.

Other climatically driven patterns have involved changing relative abundances of the two most widespread lagomorph genera in the west: *Sylvilagus* and Lepus. *Sylvilagus* is more abundant in habitats with thicker vegetative cover, whereas *Lepus* (especially *L. californicus*) is more abundant in more open, xeric habitats (e.g., Bayham, 1982; Bayham and Hatch, 1985; Schmitt *et al.*, 2002). Two Bonneville Basin dry cave deposits have provided the longest and most detailed Holocene records of the relative abundances of these taxa: Camels Back Cave and Homestead Cave.

From the trans-Holocene deposits of Camels Back Cave in western Utah, Schmitt *et al.* (2002) document a dramatic decline in the abundance of *Sylvilagus* (both *S. nuttallii* and *S. audubonii*) relative to *L. californicus* across the early Holocene sequence of deposits, with *Lepus* continuing to dominate both middle and late Holocene strata. The trend is interpreted to reflect the early and middle Holocene deterioration of more mesic sagebrush communities and the expansion of more open desert habitats.

Homestead Cave is located approximately 100 km to the north of Camels Back Cave, and has provided the best-dated, largest, and highest resolution late Quaternary record of small mammals, including lagomorphs, in North America (Figure 2-1; Grayson, 2000, 2006; Madsen *et al.*, 2001). Homestead Cave sits directly adjacent to Great Salt Lake and receives "lake-effect" enhancement of precipitation from Pacific storms and, as is the case today, the region has apparently always been wetter and cooler than Camels Back Cave located in Great Salt Lake Desert (Schmitt *et al.*, 2002). Accordingly, Holocene trends in lagomorphs are somewhat distinct between the two sites. Most notably, *Sylvilagus* dominates the terminal Pleistocene and early Holocene lagomorph fauna —as at Camels Back Cave—but declines relative to *Lepus* during the middle Holocene. However, unlike the Camels Back Cave record, *Sylvilagus* rebounds during the late Holocene. The abundance histories of several other mesic-oriented small mammals from Homestead Cave (e.g., western harvest mice [*Reithrodontomys megalotis*], Ord's kangaroo rat [*Dipodomys ordii*] and Great Basin pocket mouse [*Perognathus parvus*]) show these smooth middle Holocene "troughs," apparently reflecting hotter and drier climate at the time compared to both the early and late Holocene (Grayson, 2000, 2006; Madsen *et al.*, 2001). Given the broad climatic trends outlined above and the dramatic variation in ENSO based precipitation, we seek to answer the following question: Did the lagomorph population of northern Baja California follow the Great Basin trend of a shift toward more xeric taxa during the middle Holocene, or did ENSO play a more dominant role in shaping the lagomorph community?

Escorpiones and the Lagomorphs of Northern Baja California

Escorpiones is a large volcanic rockshelter located in northwestern Baja California, Mexico, near the town of Eréndira on the Pacific coast (Figures 2-1, 2-2). The site contains a large stratified shell midden mixed with raptor deposits and was excavated from 2000-2004 (Gruhn and Bryan, 2009). Excavation revealed a long history of human occupation and raptor deposition of faunal materials–31 radiocarbon assays, all on charcoal, span the entire Holocene. This work recovered a massive faunal assemblage representing a wide array of marine and terrestrial taxa, including a large collection of lagomorph specimens.

Three lagomorph species were identified in the Escorpiones fauna: brush rabbit (*S. bachmani*), desert cottontail (*S. audubonii*) and black-tailed jackrabbit (*L. californicus*). The historic ranges of no other lagomorph species approach this area of Baja (Huey, 1964; Hall, 1981). Of the three identified taxa, *S. bachmani* has the most mesic orientation due to diet and habitat and preferences. This rabbit feeds primarily on grasses and forbs within or near dense, brushy vegetative cover (Orr, 1940; Shields, 1960; Chapman, 1974). *S. audubonii* has a similar diet but prefers more open vegetation and can tolerate more xeric conditions than can *S. bachmani* (Chapman and Willner, 1978). *L. californicus* is the most xeric-oriented of the three taxa, and thrives in more sparsely vegetated environments (Orr, 1940; Davis, 1975; Best, 1996). Insofar as periods of high precipitation associated with El Niño dramatically increase primary productivity and vegetative cover in this part of the world (Polis *et al.*, 1997), we can anticipate four response patterns in these northern Baja lagomorphs to be reflected in the Escorpiones fauna:

1. Absolute lagomorph abundance should correlate positively with El Niño frequency and SST. During periods of elevated precipitation, we anticipate an overall increase in the density of lagomorphs on the landscape, regardless of changes in species relative abundance. Other things equal, we expect higher absolute deposition rates (total Number of Identified Specimens, NISP) of lagomorph materials at Escorpiones during such conditions.

2. The relative abundance of *Sylvilagus* should be positively correlated with El Niño frequency and SST. Higher regional precipitation should be associated with increases in the proportional abundance of the more mesic *Sylvilagus* relative to Lepus, as documented in several Great Basin faunas cited above. The *Sylvilagus* Index (SI = *Sylvilagus* NISP ÷ [*Sylvilagus* + *L. californicus*] NISP) should thus co-vary positively with El Niño frequency.

3. The relative abundance of *S. bachmani* should be positively correlated with El Niño frequency and SST. We expect the population of *S. bachmani*, the most mesic of the three species, to increase relative to the other two taxa during periods of higher precipitation. We use a Brush Rabbit Index (BRI = Σ *S. bachmani* NISP ÷ Σ [*S. bachmani* + *S. audubonii* + *L. californicus*] NISP) below to measure the relative abundance of this rabbit over time.

4. The proportion of un-fused elements in the assemblage should be positively correlated with El Niño frequency and SST. Small mammal populations tend to be skewed toward younger age classes during periods of population growth (e.g., Tkadlec and Zejda, 1998). More frequent bouts of increased precipitation and vegetation growth should have resulted in repeated (but relatively short-term) boom phases in lagomorph

population size at Escorpiones. The starvation phase of a boom-bust cycle is relatively short (Keith *et al.*, 1984), causing dramatic declines in population size, more rapid than the population growth during a boom. In other words, booms last longer than busts, and so the population age structure should be characteristic of a boom for a longer period of time. The absolute population size during booms will also be larger, such that more individuals will be deposited during boom phases than during busts. An increase in the frequency of boom-bust cycles caused by resource pulses such as temporary increases in precipitation and associated primary productivity should thus manifest itself in a faunal assemblage as a decrease in the average age at death of individuals deposited. We measure the average age at death in each excavation level as the proportion of un-fused skeletal elements using a Fusion Index (FI = Σ unfused NISP ÷ Σ [unfused + fused] NISP; lower values indicate more juveniles, higher values indicate more adults).

Dating, Stratigraphy and Temporal-Analytic Units

The materials analyzed in this study consist of the lagomorph remains recovered with 1/8 in (.32 cm) screens from two of the sixteen 2m x 2m excavation units–D3 and D4–from Escorpiones (Gruhn and Bryan, 2009). These units were chosen for analysis here because they are the best dated (dates from these two units make up 15 of the 31 radiocarbon dates from the site) and seem relatively undisturbed based on the radiocarbon chronology. Depth is significantly correlated with radiocarbon age in both units (for D3, $r = .91$, $P < .01$; for D4, $r = .93$, $P < .01$) and so depth, in general, is a good estimate of age in these deposits.

Unit D4 was excavated to 500 cm below the present ground surface (BPGS) and had associated radiocarbon dates ranging from 1350 ± 30 (Beta-311418) to 8870 ± 60 (Beta-173865) ^{14}C years BP. Unit D3 was excavated to 800 cm BPGS, with similar radiocarbon dates (Table 2-1). Both excavation units were excavated by 5 or 10 cm arbitrary vertical spits.

Four major stratigraphic units were encountered during the excavation (Figure 2-3; see Gruhn and Bryan [2009] for a more thorough discussion of the stratigraphy). The bulk of the shell midden material was contained in the upper three strata. The upper shell midden stratum consisted of a brown silty sediment matrix with multiple thick lenses of sediment and shell from rock mussel, abalone and small gastropods, and with abundant bird and small mammal bones. The middle shell midden zone consisted of a more compact brown ashy silt sediment matrix and shell midden material, with a lower number of faunal remains. The lower shell midden zone consisted of brown loamy silt sediment with abundant rock rubble and with abundant faunal remains. The three shell midden strata have abundant lithic artifacts indicating repeated intermittent human presence at the site after 9 ka, while the presence of faunal remains within and between the many shell midden lenses suggests raptor activity at the site was relatively constant over time, resulting in a steady input of faunal remains to the site. The lowest stratum consisted of a largely homogenized (based on the radiocarbon dates) rubble layer, largely sterile of human artifacts but with abundant faunal remains.

The stratigraphy at the site slopes down from an apex below the rim of the rockshelter both away from and into the rockshelter (Figure 2-3). This suggests materials in the three shell midden layers accumulated below the rim of the overhanging shelter and in the cave behind it gradually, as raptors eating their prey above the overhanging wall of the shelter and other predators including people occupying the shelter deposited materials. No cut marks were found on any lagomorph bones, and very few show burning or any other signs of a human hand in their deposition and so it is likely that the majority of them were deposited by raptors.

Despite the stratigraphy at the site being largely undisturbed as noted above, the radiocarbon chronology does show some problematic features. Dates below 470 cm BPGS in unit D3, and below 465 cm BPGS in unit D4 show several reversals, suggesting the lower midden zone and the rubble zone below may have undergone turbative homogenization. Because the radiocarbon chronology is problematic for these lower deposits in both units, only specimens recovered from above 470 cm BPGS in unit D3 and above 465 cm in unit D4 are analyzed and reported here. These depths correspond with dates (using the age-depth model described below) of 10,315 and 10,050 cal yr BP, respectively.

Several analytic steps were required in order to temporally align the Escorpiones lagomorph fauna with the El Niño and SST records. The El Niño record was presented as the frequency of wet El Niño events per 100 years (Moy *et al.*, 2002), and we chose to use the 100-year analytic unit to make our data and the SST data comparable. To provide chronological control for our lagomorph dataset, first, age-depth models based on the 15 radiocarbon dates for these units (Table 2-1) were used to assign date ranges to each 5- or 10-cm excavation level from the two units. Due to the sloping stratigraphy at the site, specimens from identical depths but in different horizontal excavation units may not have been deposited closely in age. Therefore two separate age models were created, one for each unit, so that specimens could be grouped for analysis by age. The two age models were created using smooth spline interpolation in the R software package Clam 2.2 (Blaauw, 2010; Figure 2-4). Calibration in the age models uses the IntCal13 calibration curve (Reimer *et al.*, 2013). Based on the date ranges for each 10 cm level, lagomorph specimens from each level were assigned to their closest 100-year time interval. This resulted in some 100-year intervals without associated bone data. For example, if level 20-30 cm had associated date ranges from 270 to 440 cal yr BP, the bones from that level would be assigned to the 200-299 interval rather than 400-499, even though some specimens would likely have been deposited within the latter period. To account for this imprecision, for that introduced from error terms included in our age-depth models themselves and for that introduced in the age-depth models used for the paleoenvironmental proxies against which we compare our lagomorph data, we used a 500-year moving average approach to calculate our lagomorph indices for each 100-year time interval. For example, the 500-year moving average for total lagomorph NISP for the 400-499 cal yr BP interval is calculated as the average of the 5 raw values for this measure between 200 and 699 cal yr BP. We stress here that our results are robust to a range of moving average window sizes–results are similar using 300- or 700-year windows.

While the chronological control established here is relatively fine-grained for trans-Holocene faunal assemblages in North America, some discussion is warranted with respect to El Niño event duration, lagomorph generation times and radiocarbon age error terms. Lagomorph generation times can be as short as several months, while the error terms for the radiocarbon dates used here average 50 years. There is therefore no way to assign any particular faunal remains to any particular ENSO event. We have overcome this weakness by using the moving average approach outlined above. We are not comparing lagomorph bones to ENSO events on a 1:1 basis; rather, we argue that the frequency of ENSO events on a centennial scale should be evident in lagomorph remains from Escorpiones over a similar time frame. That is to say, while we do expect that individual El Niño events would have resulted in impacts to the lagomorph population near Escorpiones on a time scale of one or two years, the nature of the records we use and the chronology employed here only afford a centennial-scale analysis. In any case, such issues, at worst, may inhibit our ability to detect relationships between past ENSO and lagomorph populations, should they have existed.

Taxonomic Identifications

The most accurate methods for taxonomic identification of lagomorph skeletal remains are based on cranial features or discrete traits of dental morphology such as crenulation patterns (Findley *et al.*, 1975; Dalquest, 1979; Dalquest *et al.*, 1989; Grayson, 2000). However, the lagomorph cranial materials from Escorpiones are largely edentulous–despite generally excellent bone preservation–thus precluding the use of such features for taxonomic identification. We therefore used a metric technique using cranial measurements, as this approach has proven successful with lagomorph materials in previous studies (Findley *et al.*, 1975; Grayson, 1977, 1983; Neusius and Flint, 1985).

The metric identification technique used in this study makes use of thirteen cranial measurements (Figure 2-5 and Table 2-2) derived from the premaxillae, maxillae and mandibles from 80 museum specimens of the three lagomorph species that occur in northern Baja California: *S. bachmani* (N = 30), *S. audubonii* (N = 30) and *L. californicus*

(N = 20). The means and ranges of the measurements for these three taxa are well-separated even though within each species, the samples included individuals collected across a broad geographic coverage (Table 2-3). This suggests that interspecific clinal variation will not likely affect the results of our identifications based on them (see Purdue, 1980). Several of the measurements are also partially redundant–for example, the length of the maxillary dental arcade and the length of the maxillary dental arcade minus PM1 and M3 (Figure 2-5, measurements A and B, respectively). These redundant measurements were recorded to increase the sample size of lagomorph specimens from the Escorpiones assemblage so as to include broken specimens from which the larger measurement could not be derived. ANOVA suggests each measurement should be useful to some degree in species identification for these three taxa, since all measurements are significantly correlated with taxon at the $\alpha < .001$ level. We used Discriminant Function Analysis (DFA) to predict species with our cranial measurements. Using the leave-one-out classification method and entering variables step-wise, the cross-validated success rates of DFA identification for museum specimens were 92.5% percent for maxillae, 96.3% for mandibles and 96.3% for premaxillae using all available measurements for each specimen. All postcranial elements not identified with the discriminant function method were identified to either the family or genus level using the reference collection from the Natural History Museum of Utah.

Small mammals in parts of North America have been shown to have undergone varying degrees of body size change in response to changing climate. Woodrats (*Neotoma* spp.) for example, tend toward decreasing body size in warming climates following Bergmann's Rule (Smith *et al.*, 1995, 1998; Smith and Betancourt, 1998, 2003). While this could influence our identifications using this metric approach, it would only affect indices derived from species-level identifications and only one of the four indices we use here is derived from such data (i.e., the Brush Rabbit Index).

Results

A total of 3463 specimens were identified from this sample and form the basis of the four independent indices above. As is typical for archaeological and paleontological lagomorph faunas, the collection is dominated by specimens identifiable to the genus level including *Sylvilagus* spp. (NISP = 2228), and *Lepus* spp. (NISP = 335), and an additional 294 specimens were identifiable to the order level. However, cranial measurements were used to identify 491, 79 and 36 specimens of *S. bachmani*, *S. audubonii* and *L. californicus*, respectively.

To evaluate the effect that El Niño and SST have had on lagomorph populations over the Holocene in this setting, data on the frequency of wet El Niño events per 100 years over the Holocene (Rodbell *et al.*, 1999; Moy *et al.*, 2002) and SST in the Soledad Basin (Marchitto *et al.*, 2010) were arrayed against our lagomorph NISP, *Sylvilagus* Index, Brush Rabbit Index and Fusion Index values in Figures 2-6 and 2-7. Table 2-4 presents the correlations between the frequency of El Niño events, SST and the Escorpiones lagomorph data over the Holocene. Although we emphasize that all but one of these relationships are statistically significant at the $\alpha = .01$ level (SST:Brush Rabbit Index, $r_s = .228$, $p = .025$), effect size is a further means of evaluating the strength of such relationships in zooarchaeological data (Wolverton *et al.*, 2014). In this context, we observe that 3 of the 4 comparisons with El Niño frequency produced effect sizes considered to be moderate to strong (Fusion Index : El Niño, $r_s = .688$; NISP : El Niño, $r_s = .601$; Brush Rabbit Index : El Niño, $r_s = .498$).

Discussion

As compared to the Holocene histories of lagomorphs in other parts of western North America–especially the Great Basin where the records are the most detailed–the Escorpiones lagomorph fauna exhibits both notable differences as well as interesting similarities. For example, local extirpations of mesic taxa did not occur in northern Baja with Holocene climate change as occurred in the case of American pika and pygmy rabbits in areas of the Great Basin. And although certain periods within the middle Holocene (e.g., 6500-5500 cal yr BP) were characterized by declines in overall lagomorph population densities and mesic-taxa relative abundances–reflecting arid conditions–these indices were generally high across much of this period. Indeed, a prominent peak in moisture is suggested by our indices between about 5500 and 4000 cal yr BP. This peak coincides with the onset of modern ENSO periodicity (Shulmeister and Lees, 1995; Sandweiss and Richardson, 1996; Rodbell *et al.*, 1999; Sandweiss *et al.*, 2001; Moy *et al.*, 2002; Conroy *et al.*, 2008; Donders *et al.*, 2008) and may mark the point at which the lagomorph population of northern Baja California became strongly controlled by ENSO. For example, the correlation between El Niño frequency and total lagomorph NISP for the past 5500 cal yr BP is much more strong ($r_s = .623$, $p < .001$) than for the period from 5500-10,300 cal yr BP ($r_s = .105$, $p = .476$). Certainly, the smooth middle Holocene troughs in the abundance of mesic taxa registered in many small mammal faunas including *Sylvilagus* populations in the eastern Great Basin

(Grayson, 1977, 1983, 1985, 1987, 1998, 2000, 2005, 2006; Grayson *et al.*, 1988; Hockett, 2000; Schmitt *et al.*, 2002) are not evident in the Escorpiones lagomorph fauna. This is not surprising, of course, given not only the distinct ecological context and taxonomic composition of this setting but the temperature ameliorating influence of the Pacific Ocean located currently just 100 m west of the site.

More similar to patterns deduced from Great Basin lagomorph faunas and many other regional vertebrate records is a dramatic increase in moisture during the late Holocene that is reflected in each of our lagomorph indices. More specifically, the lagomorph and El Niño records here suggest several spikes that occur between about 3200 and 700 cal yr BP. Moisture pulses within this period have been reflected in a wide range of other vertebrate records in several Great Basin faunas (Madsen *et al.*, 2001; Broughton, 2004; Schmitt and Lupo, 2005; Byers and Smith, 2007; Broughton *et al.*, 2008). Most notably, this trend has been linked to higher artiodactyl densities and corresponding increases in the human hunting of those animals. Holocene variation in artiodactyl population densities has been reconstructed from archaeological faunas but also from a unique fecal pellet record from Homestead Cave where the density of pellets per liter of sediment has been used as a proxy for regional artiodactyl populations (Byers and Broughton, 2004; Broughton *et al.*, 2008; but see also Grayson, 2011). We observe here that the Ecuadorian El Niño record shows a significant positive correlation (r_s = .563, P = .023) with the Homestead fecal pellet record.

It is also noteworthy that the most prominent late Holocene spike in El Niño frequency that is centered around 1000 cal yr BP (Figure 2-6) overlays temporally with the peak in site frequency of the agriculturally-based Fremont complex in the eastern

Great Basin–a time period also marked by a high stand of Great Salt Lake referred to as the Fremont Beach (Massimino and Metcalfe, 1999; Simms, 2008; Louderback *et al.*, 2011). Our analysis thus suggests a specific climatic mechanism to account for some of the more mesic late Holocene conditions–originally proposed in detail by Antevs–that appear to have influenced not only lagomorph populations, but those of other small mammals, artiodactyls and humans alike.

This record also reveals interesting relationships between the ranges of our lagomorph indices and ENSO frequency. For the Brush Rabbit Index, *Sylvilagus* Index and Fusion Index (Figure 2-7B, 2-7C, 2-7D), periods with low ENSO frequency tend to have the widest ranges, including many 100-year intervals with high values of these mesic indices. Periods with relatively more frequent El Niño events, however, tend to have only high Brush Rabbit Index and *Sylvilagus* Index values indicating mesic conditions. A slightly different relationship can be seen between El Niño frequency and NISP (Figure 2-7A). Low El Niño frequency tends to be associated with lower NISP while high El Niño frequency tends to be associated with high NISP. The widest range in NISP is found when El Niño is only moderately frequent, from 3-8 events per century.

That the widest range of variation in the relative abundance of the more mesic rabbits at the site (Brush Rabbit Index and *Sylvilagus* Index) is found when ENSO is infrequent may suggest that during more marginal times, these taxa are more demographically unstable and subject to more frequent turnover in the species that is dominant in the community at any given point in time. Alternatively, the greater variation in the values of the proportional indices at low ENSO frequencies may be in part due to smaller sample sizes exacerbating the effect of stochastic variation in the relative abundances of different taxa. We are unaware of such a phenomenon being registered in modern analyses of small mammal faunas in relation to ENSO and, although its meaning is not fully clear, it underscores the potential insight that can be gained by examining these relationships on millennial timescales. Further work with other small mammals from the site, including the rich *Neotoma* and *Thomomys* fauna, may help clarify our understanding of this novel patterning.

We have argued above that changes in total lagomorph NISP over time were driven largely by the frequency of El Niño events, but changes in the guild of predators which deposited the remains over time may also have influenced the deposition of bones at the site. For example, if substantial temporal variation occurred in the frequency that raptors perched and fed on the rim of the rockshelter, we would expect variation in lagomorph deposition rates across the period of site occupation. However, this potential problem is alleviated by the weight of evidence approach we have taken here. If changes in NISP we observed over time were the result of changes in use of the site by raptors, they should be more or less independent from the taxonomic abundance indices and from patterns in the fusion index. That NISP, BRI, *Sylvilagus* Index and Fusion Index all vary in concert with one another suggests that it is not changes in the predator population or predator use of the site which is driving the trends but changes in the lagomorph population of this part of Baja California that we are detecting.

Today, Baja California is home to a menagerie of endemic small mammals and other vertebrates with many currently listed as sensitive or endangered. Indeed, the region is represented, collectively, by 11 endemic subspecies of *S. bachmani*, *S. audubonii* and *L. californicus* as well as black jackrabbit (*L. insularis*), the near threatened endemic hare species (IUCN, 2014). Although a series of reserves have been established to maintain regional biodiversity, the fragmented nature of many populations increases the possibility of stochastic extirpations or extinctions. Exacerbating these concerns, global climate change could substantially alter the current patterns of temperature and precipitation that influence the dynamics of small mammal populations. Although variation certainly exists in forecasted climate patterns, many models call for warmer temperatures, elevated winter precipitation, more extreme weather events, and more frequent ENSO events (Timmerman, 1999; IPCC, 2007; Latif and Keenlyside, 2008; Dominguez *et al.*, 2012; Wang *et al.*, 2013). Clearly, understanding the long-term effects of such climatic factors as ENSO will be critical to identifying taxa that will be most adversely affected. Our 10,000 year record of ENSO effects on Baja California lagomorphs may thus provide invaluable information to conservation biologists tasked with managing these taxa today and in the future.

In this vein, a key takeaway message from this study concerns the difference in the climatic responses of the taxa involved here in Baja California versus those in the Great Basin. While Holocene variation in ENSO appears to have had a strong effect on Baja lagomorphs, mesic oriented taxa persisted through the middle Holocene in this setting while they were depressed or extirpated altogether in the Great Basin. Most importantly, this geographic pattern in the impacts of Holocene climate change on western lagomorphs may have implications for targeting conservation efforts for a wide range of threatened taxa that are characterized by broad geographic ranges that extend from coastal settings into the interior. Namely, threatened mesic oriented taxa will be more vulnerable as distance increases from both the temperature ameliorating effect of the Pacific Ocean and the reach of ENSO based precipitation. Although the ecological and climatic variables differ, analogous conclusions have been reached in considerations of the fate of the American Pika that are thriving today in the Sierra Nevada but are struggling on many ranges of the central Great Basin (Beever *et al.*, 2010; Millar and Westfall, 2010; Erb *et al.*, 2011; Wilkening *et al.*, 2011). Our study may thus contribute to the growing understanding of the variables that enable threatened taxa to persist despite the myriad threats they may face in an uncertain climatic future.

Conclusion

The short time scales covered by our instrumental records of ENSO constrain our ability to model the variable effects of this phenomenon on marine and terrestrial ecosystems and the vertebrate faunas that comprise them. Indeed, the most detailed quantitative data on ENSO impacts on marine and terrestrial vertebrate faunas include only the last several major ENSO events (e.g., 1982-83, 1987-88, and 1997-98). A clearer understanding of the influence of ENSO on terrestrial and marine vertebrate faunas—that may be crucial to predicting the long-term future dynamics of vertebrate communities — would thus clearly benefit from fine-grained, millennial-scale ENSO-vertebrate response records extending back to the terminal Pleistocene. Our work with the lagomorph fauna from Escorpiones provides such a record and represents the first high-resolution trans-Holocene El Niño response record documented for any group of terrestrial vertebrates. Importantly, this record shows that aspects of the northern Baja California lagomorph fauna that are precipitation dependent–overall population size, age structure and relative abundance of mesic taxa–varied sensitively over the last 10,000 years in response to El

Niño-based precipitation. Further work with other aspects of the rich Escorpiones vertebrate fauna will allow us to gauge the variability of trans-Holocene ENSO impacts on a wide range of terrestrial and marine vertebrates.

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Table 2-1. Radiocarbon Dates from Units D3 and D4, Abrigo de los Escorpiones.

Unit	Depth	Stratum	^{14}C yr BP	Cal yr BP	Probability	Lab ID
D3	115	Upper Midden Zone	1680 ± 30	1527-1629 1653-1692	0.807 0.142	Beta-311419
D3	210	Upper Midden Zone	3130 ± 40	3262-3312 3316-3443	0.175 0.774	Beta-157354
D3	301	Upper Midden Zone	4460 ± 90	4864-5311	0.95	Beta-157355
D3	410	Lower Midden Zone	8470 ± 40	9441-9533	0.95	Beta-311421
D3	470	Lower Midden Zone	8560 ± 100	9318-9355 9400-9822 9846-9868 9873-9887	0.017 0.917 0.01 0.006	Beta-157356
D3	670	Rubble Stratum	8650 ± 40	9745-9751 9765-10158	0.007 0.942	Beta-311422
D4	50	Upper Midden Zone	1610 ± 90	1334-1707	0.95	Beta-144831
D4	70	Upper Midden Zone	1350 ± 30	1184-1204 1239-1312	0.074 0.875	Beta-311418
D4	200	Middle Midden Zone	6340 ± 100	7007-7132 7141-7432	0.124 0.825	Beta-146369
D4	270	Middle Midden Zone	6960 ± 30	7697-7855 7904-7917	0.921 0.028	Beta-311420
D4	340	Lower Midden Zone	8040 ± 70	8648-8675 8683-8689 8691-9093 9101-9122	0.024 0.005 0.904 0.017	Beta-144833
D4	430	Lower Midden Zone	8790 ± 40	9269-9684 9653-9938 9994-10005 10030-10035 10064-10119	0.011 0.876 0.006 0.03 0.054	Beta-144834
D4	460	Lower Midden Zone	8240 ± 160	8773-9531	0.95	Beta-146370
D4	465	Lower Midden Zone	8870 ± 60	9741-10181	0.95	Beta-173865
D4	510	Rubble Stratum	8540 ± 110	9291-9799 9802-9819 9846-9867 9874-9886	0.93 0.007 0.009 0.005	Beta-146372

Table 2-2. Measurements Used for Taxonomic Identification.

Maxilla	
A	Dental arcade length (P^1-M^3)
B	Dental arcade length (P^2-M^2)
C	Distance between mesial central alveolar spines of P^3 and M^1
D	P^3 alveolus width
E	Maxillary breadth
Premaxilla	
F	I^1 alveoli (pair) width
G	I^2 alveoli (pair) width
Mandible	
H	Dental arcade length (P_1-M_2)
I	Width of P_2 alveolus
J	Mandible height at P_1/P_2 margin (mesial)
K	Mandible height at M_1/M_2 margin (mesial)
L	Mandible height at mental foramen
M	Diastema

Table 2-3. Descriptive Statistics of Measurements (in mm) Used in Taxonomic Identification from Museum Specimens.

	*Sylvilagus bachmani**				*Sylvilagus audubonii***				*Lepus californicus***			
Maxilla	Mean	SD	Range	N	Mean	SD	Range	N	Mean	SD	Range	N
A	10.85	0.65	8.83 - 11.71	30	12.15	0.46	11.34 - 13.21	30	15.49	1.09	12.53 - 17.77	20
B	7.68	0.51	6.08 - 8.44	30	8.22	0.35	7.54 - 8.97	30	10.75	0.65	8.8 - 11.79	20
C	1.81	0.14	1.43 - 1.99	30	1.95	0.14	1.65 - 2.24	30	2.59	0.22	2.0 - 2.92	20
D	3.40	0.27	2.73 - 3.81	30	4.21	0.31	3.48 - 4.63	30	5.30	0.33	4.36 - 5.69	20
E	15.28	0.76	12.96 - 16.3	30	17.13	0.59	16.02 - 18.19	30	22.38	1.32	18.62 - 24.91	20
Premaxilla												
F	4.96	0.29	4.34 - 5.52	30	5.89	0.24	5.43 - 6.37	30	8.00	0.58	6.29 - 8.77	20
G	2.76	0.30	1.7 - 3.17	30	3.21	0.23	2.6 - 3.57	30	4.18	0.34	3.4 - 4.75	20
Mandible												
H	9.17	0.65	7.35 - 10.53	30	10.12	0.42	8.97 - 10.8	30	12.93	0.91	10.57 - 14.82	20
I	2.44	0.18	1.9 - 2.83	30	2.80	0.15	2.48 - 3.02	30	3.60	0.17	3.3 - 3.86	20
J	8.48	0.97	5.57 - 10.95	30	10.78	0.51	9.76 - 11.82	30	14.01	1.09	11.86 - 16.29	20
K	8.88	0.91	6.47 - 11.29	30	10.86	0.52	10.02 - 11.94	30	13.35	1.13	11.14 - 15.87	20
L	5.42	0.46	4.33 - 6.81	30	6.41	0.32	5.78 - 7.01	30	8.63	0.75	7.49 - 10.13	20
M	11.92	1.07	8.84 - 14.0	30	13.84	0.75	12.09 - 15.07	30	19.60	1.52	16.0 - 22.66	20

* *S. bachmani* specimens are from the Museum of Vertebrate Zoology, University of California, Berkeley.

** *S. audubonii* and *L. californicus* specimens are from the Natural History Museum of Utah, University of Utah.

Table 2-4. Spearman's Rank Correlation Coefficients (r_s) Between El Niño Frequency, Soledad Basin SST and Abrigo de los Escorpiones Lagomorph Data.

		A	B	C	D	E	F
A. El Niño Frequency	r_s	1.00	.390**	.735**	.514**	.241*	.672**
B. Soledad Basin SST	r_s	.390**	1.00	.456**	.234*	.356**	.352**
C. Lagomorph NISP	r_s	.735**	.456**	1.00	.554**	.450**	.616**
D. Brush Rabbit Index	r_s	.514**	.234*	.554**	1.00	.370**	.538**
E. *Sylvilagus* Index	r_s	.241*	.356**	.450**	.370**	1.00	.359**
F. Fusion Index	r_s	.672**	.352**	.616**	.538**	.359**	1.00

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

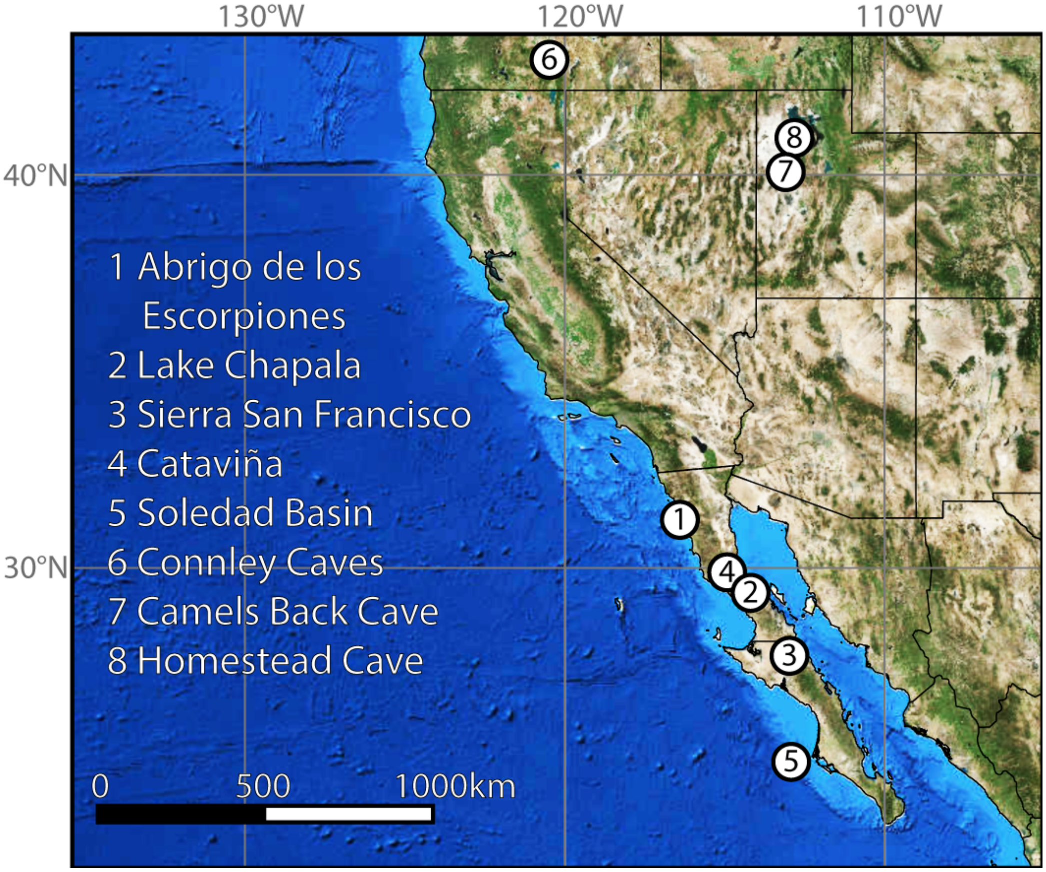

Figure 2-1. Map of Southwestern North America Showing Abrigo de los Escorpiones and Archaeological and Paleoenvironmental Research Sites Mentioned in Text.

Figure 2-2. Interior View of Abrigo de los Escorpiones and Surrounding Landscape. Excavated Portion Is at Center.

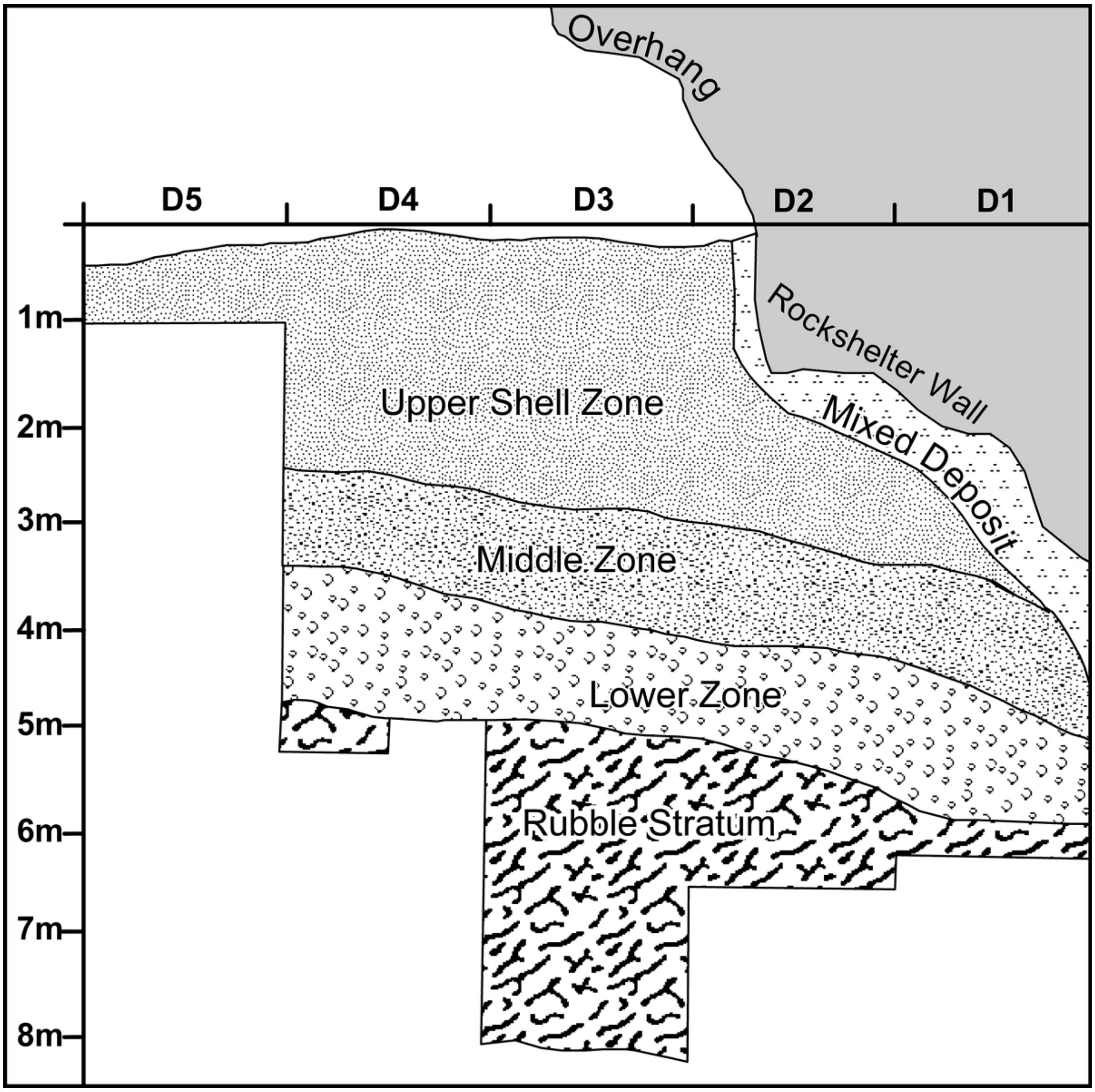

Figure 2-3. Stratigraphy at Abrigo de los Escorpiones, Re-drawn from Gruhn and Bryan (2009).

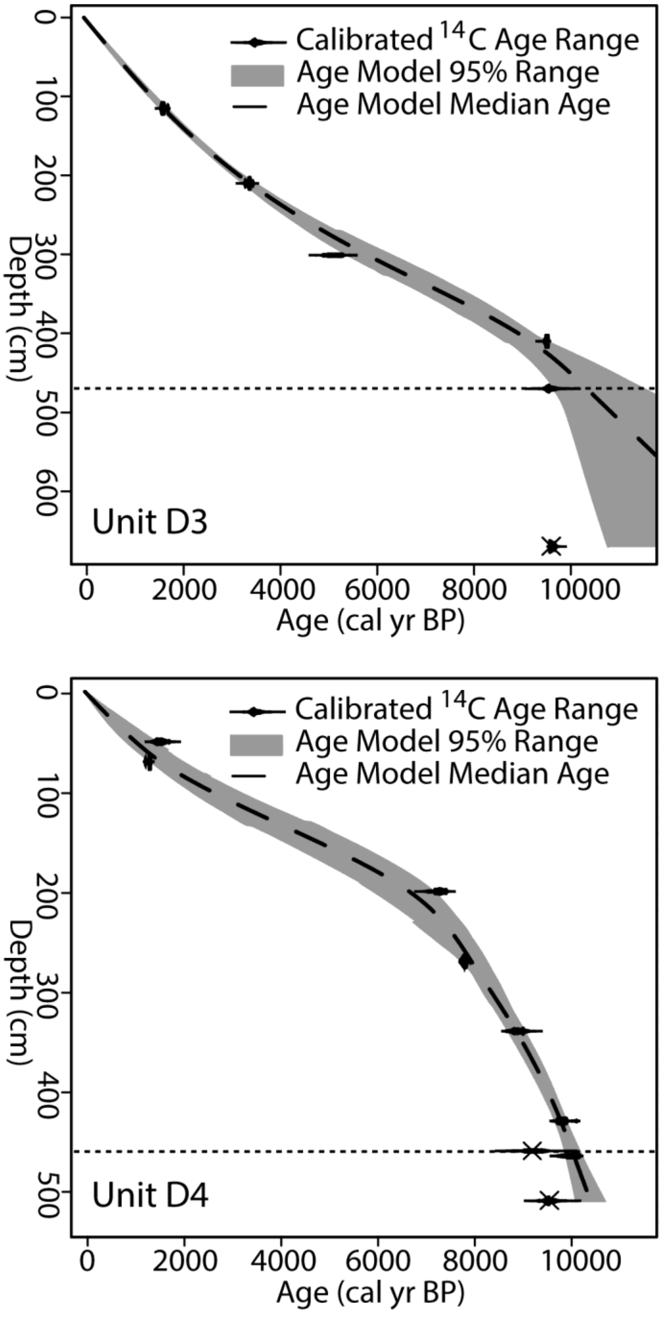

Figure 2-4. Age–depth Models Used for Chronological Control. Specimens Recovered from Depths Below Dashed Lines Were Not Included in This Study.

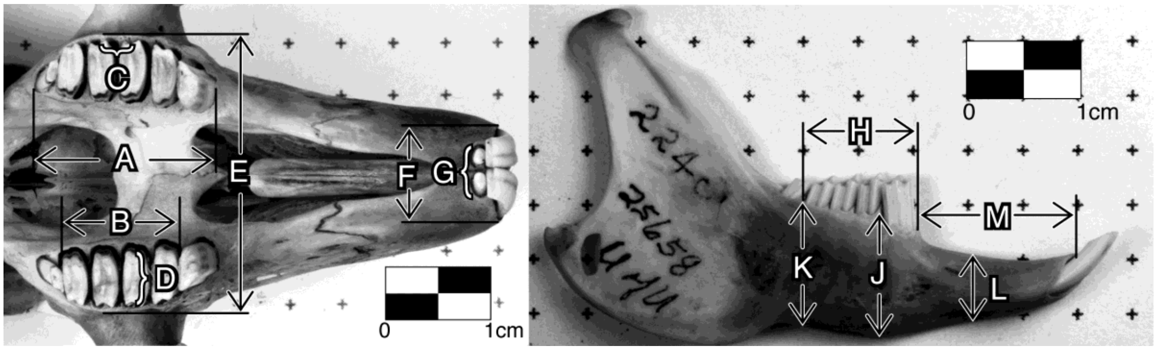

Figure 2-5. Cranial Measurements Used for Taxonomic Identification. Letters Refer to Measurements Described in Table 2-2.

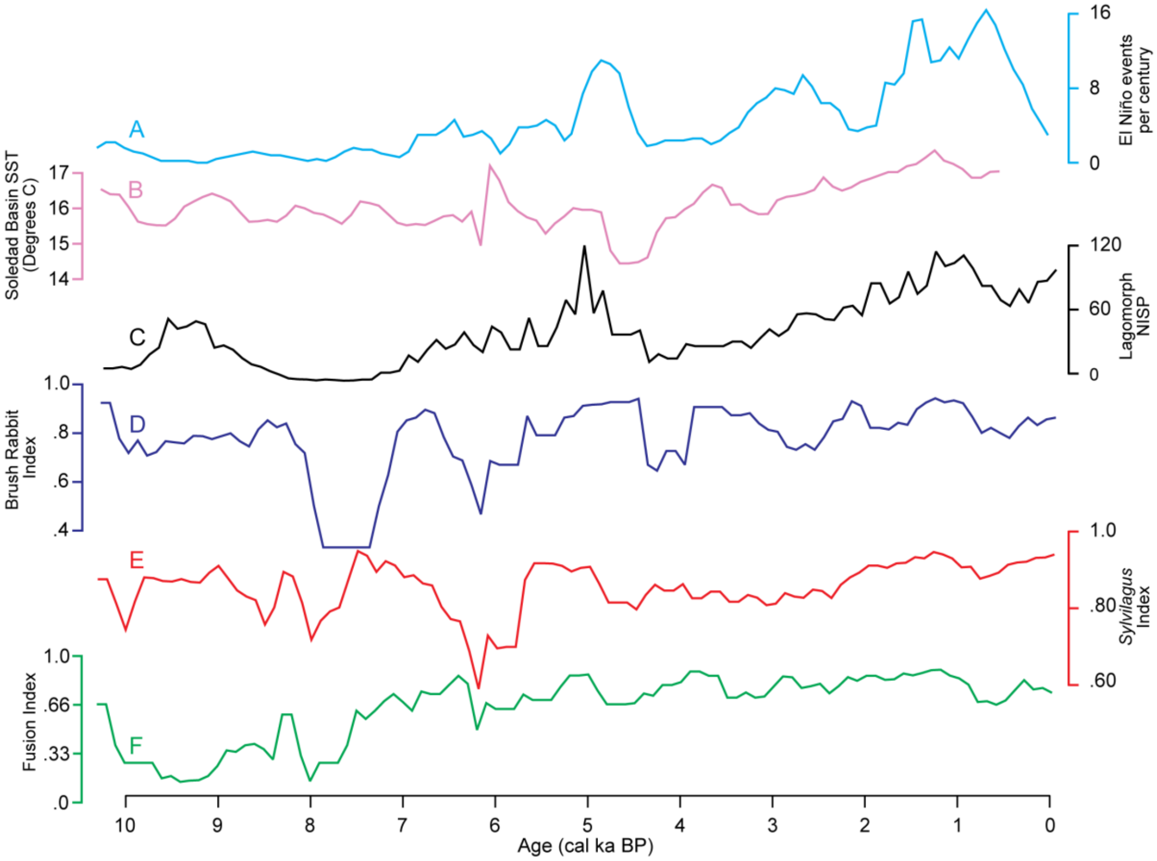

Figure 2-6. Smoothed (500-year Running Mean) Holocene El Niño Frequency (Moy *et al.,* 2002), Soledad Basin SST (Marchitto *et al.,* 2010), and Abrigo de los Escorpiones Lagomorph Taxonomic Abundance and Age Data.

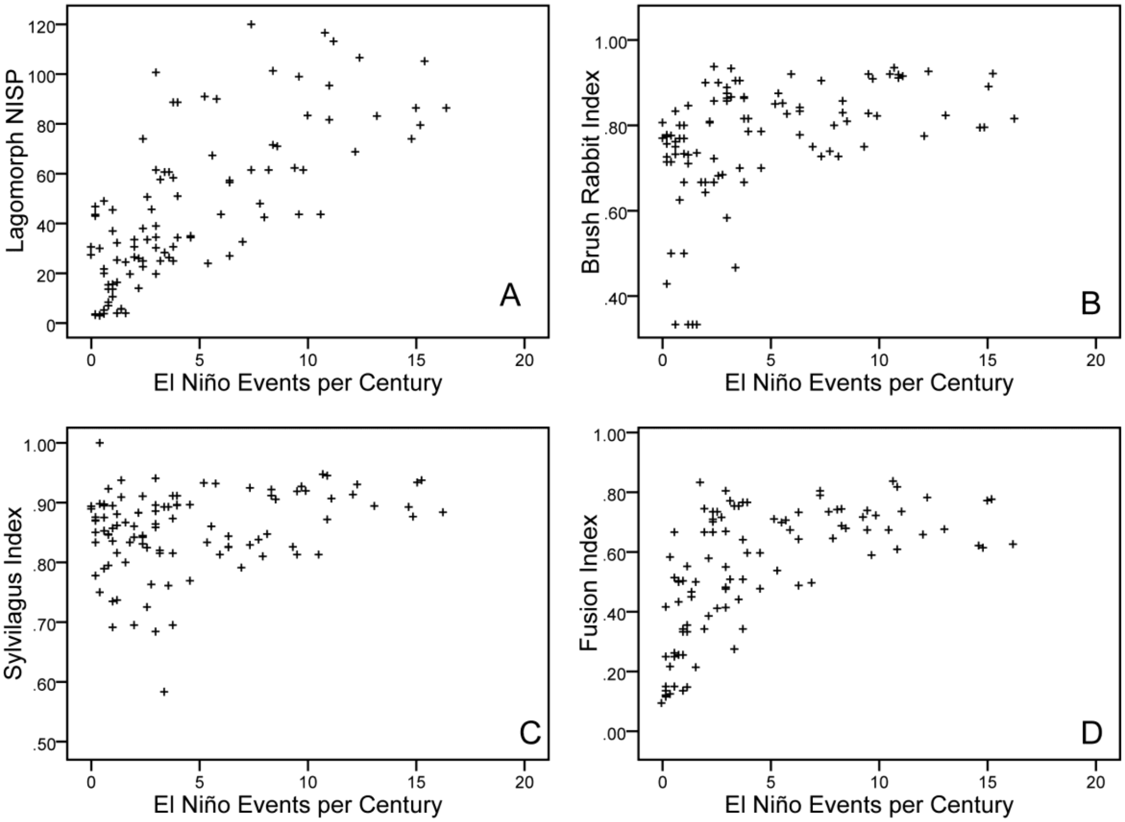

Figure 2-7. Scatterplots of the Relationships Between Holocene El Niño Frequency and A. Lagomorph NISP, B. Brush Rabbit Index Values, C. *Sylvilagus* Index Values and D. Fusion Index Values at Abrigo de los Escorpiones.

CHAPTER 3

PALEOENVIRONMENTAL INVESTIGATIONS AT
BILLY SLOPE BOG, A FREMONT MAIZE FIELD
IN RANGE CREEK CANYON, UTAH

Introduction and Site Description

This chapter reports the results of a multiproxy paleoenvironmental analysis of a sediment core (BSB09B) recovered from Range Creek Canyon (RCC) in Utah's Tavaputs Plateau during the 2009 field season. The core was taken from Billy Slope Bog (BSB; 39.428° N, 110.215° W; Figure 3-1), which lies just north of the confluence of RCC and Billy Slope Canyon, approximately 8 km south of the north gate to the Range Creek Field Station. Paleoenvironmental investigation in RCC began in 2005. The primary goal of this project and the present study is to provide ecological and climatic context to archaeological investigations in the canyon. Additionally, the Tavaputs Plateau is generally in a "dead zone" regarding paleoenvironmental research. With the exception of a tree ring sequence described below, no published paleoenvironmental records exist for the area extending back into the Fremont period (before ca. AD 1200).

Several cores have been taken and analyzed in the canyon from sites at varying locations in the canyon to date for the Range Creek Research Project. Morris (2010) analyzed charcoal and pollen from a core taken from Cherry Meadows, a site 5 miles north of the Range Creek Field Station headquarters (Figure 3-1). The Cherry Meadows record she analyzed only extends back to the period just after the Fremont abandonment of Range Creek, and was therefore unsuitable for use in interpreting the paleoclimatic context of Fremont habitation of the canyon. Morris' results did, however, demonstrate the utility of pollen and charcoal analysis in RCC. She showed that the pollen record accurately reflected the timing of historic occupation of the canyon by cattle ranchers, specifically using the appearance of the pollen of white mulberry (*Morus alba*) at ca. AD 1850 to mark the historic period. Due to the length and quality of the BSB09B sediment core analyzed and reported in this chapter, BSB has been the focus of the most intensive paleoenvironmental investigation in RCC to date.

BSB is a spring-fed wet meadow located about halfway up RCC (Figure 3-1). The site is not a bog in the proper sense. A spring feeds the meadow on the upslope end, and it filters through the meadow and drains down canyon such that while it is perennially wet, it is not an anoxic bog. At an elevation of 6100 feet above sea level, the coring site was chosen due to its proximity to the spring and the perpetually saturated sediments. This wet environment has sediments that offer the best preservation of pollen and other organic materials. Additionally, 23 prehistoric archaeological sites have been recorded within 1 km of the meadow. The nearby sites include all the prehistoric site types found in the canyon: multidwelling villages, single dwelling residences, storage and rock art sites. Virtually all of the sites with diagnostic artifacts in RCC or rock art are associated with the Fremont archaeological complex, which in RCC predominately dates to between AD 900 and AD 1100 (Boomgarden *et al.*, 2014). The Fremont farmed corn, beans and squash, but continued to rely on hunting and gathering more than their neighbors to the south (Morss, 1931; Simms, 1986; Coltrain and Leavitt, 2002). The presence of the full range of prehistoric sites nearby suggests prehistoric agricultural activities likely occurred in and around BSB, taking advantage of the perennial spring as a water source for irrigation. The BSB site therefore has considerable potential to yield paleoenvironmental data relevant to archaeological investigations in the canyon.

Dominant vegetation communities near the site today consist of stands of Douglas fir (*Pseudotsuga menziesii*), two-needle pinyon pine (*Pinus edulis*) and juniper (*Juniperus osteosperma* and *J. scopulorum*) on the canyon walls. The gallery forest surrounding Range Creek and BSB consists primarily of box elder (*Acer negundo*) and narrow-leaf cottonwood (*Populus angustifolia*). The well-drained sediments near the BSB support big sage (*Artemisia tridentata*) and rubber rabbitbrush (*Ericameria nauseosa*), while the meadow itself is covered in alfalfa (*Medicago sativa*), introduced by cattle ranchers in the late 19th century, grasses and various shrub and wildflower species.

The study described below is strictly a paleoenvironmental reconstruction, although the broader goal is to provide insight into the past environmental contexts within which humans lived. Of special interest are the climatic parameters which influence agricultural productivity, specifically with respect to maize agriculture. Boomgarden (2015) has shown the most important climatic factors for maize agriculture productivity in RCC today are temperature and precipitation. We have therefore chosen paleoenvironmental proxies which will contribute to our understanding of these climate parameters before, during and after the Fremont occupation of RCC.

Paleoenvironmental Context

Climate in western North America during the past 2000 years is marked by two major global climatic epochs, the Medieval Climate Anomaly (MCA) from approximately AD 1000-1300, and the Little Ice Age (LIA), from approximately AD 1550-1850 (Mann, 2001; Mann *et al.*, 2009). The MCA saw an increase in global annual average temperature of around 0.5°C, although terrestrial records indicate the Northern Hemisphere was more affected. The LIA saw a subsequent cooling, and as with the MCA, effects were more pronounced in the Northern Hemisphere. Although most records do show some degree of warming and subsequent cooling during the MCA and LIA, the effects on precipitation appear spatially and seasonally heterogeneous.

The Medieval Climate Anomaly and Little Ice Age in the Southwest

In the Southwest United States, the MCA also saw an increase in the frequency and intensity of monsoon rains, and increased temperatures over North America may have driven a northwestern expansion of the North American Monsoon system (NAM; Adams and Comrie, 1997), which today doesn’t extend north beyond the Colorado river (Mitchell, 1976). At Beef Pasture in the La Plata Mountains of southwestern Colorado for example, Petersen (1988, 1994) saw an increase in the percentage of pinyon pine pollen coincident with a reduction in spruce (*Picea* spp.) pollen between AD 800 and AD 1100. The reduction in spruce indicates an upward migration of tree-line at this high-elevation site and warmer summer temperatures while the increase in pinyon pollen indicates an increase in summer precipitation at the site during this interval (see discussion of pinyon in P:DF section below). This increase in precipitation is consistent with recent syntheses of NAM precipitation over the Holocene (Metcalfe *et al.*, 2015), and is hypothesized to have contributed to the rise of maize agriculture in the four corners region during this period (Benson *et al.*, 2006, 2007; Benson and Berry, 2009). Pinyon declines after AD 1200 in the Beef Pasture record, and remains low until the historic period suggesting the monsoon never strengthened again to MCA levels. Petersen (1988, 1994) also shows that nearby tree ring records provide further evidence for a cool, dry LIA. Tree ring width at high-elevation sites in southern Colorado is controlled by summer temperatures; warm summers provide longer growing seasons and water availability is generally not limiting due to decreased evapo-transpiration at higher elevations. At lower elevation sites where growing season is longer, precipitation has a stronger controlling effect on tree ring width. Through the LIA period, tree ring records show narrower widths at both high- and low-elevation sites, indicating a generally cool, dry LIA in southwestern Colorado.

Some have argued the rise and fall of agriculture in the Fremont area was also driven by periods of increased summer precipitation during the MCA and persistent droughts at its termination similar to the pattern identified by Petersen (1994) and Benson *et al.* (2007). This hypothesis is supported by some tree ring records from the western margin of the Great Basin. Leavitt (1994), for example, analyzed stable carbon isotope and ring-width values from the Methuselah walk bristlecone pine tree ring sequence taken from the White Mountains in eastern California. He found evidence for an extreme wet period between AD 1080 and AD 1129. Leavitt and Coltrain (2002:456) hypothesize that this wet interval may have been region-wide, increasing available summer moisture for maize farming across the Fremont area.

Tree ring data can be used to test this hypothesis locally for the Fremont of RCC.

The best available precipitation record for the Tavaputs plateau during the past 2000 years comes from the Harmon Canyon Douglas fir tree ring chronology (Knight *et al.*, 2010). Harmon Canyon drains north into Nine Mile Canyon from near Bruin Point (Figure 3-1). Its proximity to RCC means the precipitation record for Harmon Canyon likely reflects that at RCC as well. The chronology shows a great deal of variation in precipitation during the past 2000 years with several prominent wet and dry periods lasting tens to hundreds of years. But the record shows no consistent Fremont-aged increases in precipitation. Instead, it shows a relatively stable Fremont period with very few extreme wet or dry periods from AD 850-1130. The end of the Fremont occupation of RCC is coincident with a dramatic drought identified in the Harmon Canyon record between AD 1125 and AD 1161.

The AD 1100s drought was region-wide, affecting sites from Oregon to New Mexico (Knight *et al.*, 2010: Figure 8). An analysis of upper Colorado River flows for the past 1300 years based on tree rings from sites across the upper Colorado River basin (Meko *et al*., 2007; this multichronology record includes the Harmon Canyon sequence) shows this period was extremely dry. The upper Colorado River Basin record shows a 62-year period of generally dry conditions from AD 1118-1179, with an exceptionally dry 13-year period from AD 1143-1155. During this 13-year period, Colorado River flow was consistently lower than the lowest single year flow recorded during the historic period from AD 1906-2004.

The AD 1100s dry period is believed to be responsible for the Ancestral Puebloan abandonment of the San Juan basin including a cessation of building of Chaco Canyon great houses and construction at Aztec West at AD 1130 (Benson *et al.*, 2006). The period after the AD 1100s drought in Harmon Canyon is followed by "high amplitude, low frequency fluctuation" marked by multidecade extreme droughts for the remainder of the MCA (Knight *et al.*, 2010:114). Thus while the tree ring data support the hypothesis that the termination of maize farming in RCC does appear associated with the same drought which caused the decline of maize farming in the San Juan Basin, the florescence of maize farming in RCC does not appear to be associated with an increase in summer precipitation.

The Medieval Climate Anomaly and Little Ice Age in Central Utah

Morris and colleagues reported Holocene pollen and charcoal abundances from Blue and Emerald lakes (Morris *et al.*, 2010, 2013) on the Wasatch Plateau, approximately 100 miles west-southwest of RCC. The pollen records are largely in agreement with the Colorado Plateau with respect to temperature and moisture history during the MCA. At Emerald Lake (Morris *et al.*, 2013), several pollen taxa indicate increased moisture during the period. *Pediastrum* (green algae), an indicator of permanent standing water, increases, *Artemisia* (sage) decreases and *Abies* (firs), which require significant winter precipitation, appears relatively stable during the MCA. During the subsequent LIA portion of the record, *Abies* declines dramatically, indicating decreased annual snowpack, and *Artemisia* increases to a maximum, indicating drier conditions on average. *Pediastrum* declines and *Salix* (willows) and Cyperaceae (sedges) increase as lake level dropped, decreasing standing water and allowing shallow-water marsh plants to colonize the basin margin. These changes during the LIA indicate generally cool and dry conditions at Emerald Lake.

The record at nearby Blue Lake (Morris *et al.*, 2010) spans only the past 750 years but is largely in agreement with that of Emerald Lake. Poaceae (grasses) are most abundant and *Artemisia* is rare during the terminal MCA portion of the record, indicating warm, wet conditions. But after 500 calibrated radiocarbon years before present (cal yr BP), grass declines precipitously relative to *Artemisia* and reductions in *Picea* and *Abies*, and the charcoal record shows reduced wildfire frequency and intensity after AD 1450. The changes in pollen percentages and charcoal frequency were likely driven by a reduction in summer high temperatures and a resulting decrease in convective summer precipitation events during the LIA. Together these proxies indicate a cool, dry LIA period on the Wasatch Plateau. The historic period in both these Wasatch Plateau record also appears relatively stable and similar to modern after 150 cal yr BP.

Approximately 100 miles to the Southwest of the Wasatch Plateau, Clear Creek Canyon separates the Pavant and Tushar range and drains the north slope of the Tushars. A large-scale archaeological salvage excavation project was undertaken in Clear Creek Canyon at Five Finger Ridge in the 1980s in support of a freeway expansion project. The salvage project revealed a large Fremont settlement dating between AD 1100 and AD 1300 (Talbot *et al.*, 2000). In order to generate a paleoecological context for interpretation of the archaeological record at the site, Newman (2000) analyzed pollen from sediment profiles in two nearby caves, Sheep Shelter and The Cave of 100 Hands. Newman's results show both agreement and disagreement with the Wasatch Plateau and southwestern Colorado records. The MCA portion of the records shows that the MCA in Clear Creek Canyon was "warm, with sufficient precipitation to allow the expansion of woodland environments," and with possibly "more winter precipitation" (Newman, 2000:307). In other words, the period was warm and wet, but the increased moisture may have come in the form of increased snowpack, not an invigorated or expanded monsoon activity.

Similar to patterns observed on the Wasatch Plateau and southwestern Colorado, the LIA portions of the Clear Creek record shows general cooling with increasing ratios of pine to juniper (decreasing temperature), decreasing ratios of Cyperaceae to Amaranthaceae (decreasing moisture) and high ratios of arboreal to non-arboreal pollen types (overall dryness) at Sheep Shelter. However, the ratio of Poaceae to *Artemisia* counterintuitively increases after ca. 500 radiocarbon years before present (^{14}C yr BP) in the Sheep Shelter records. This ratio is usually interpreted as a proxy for overall mesic conditions (high Poaceae indicates mesic conditions, high *Artemisia* indicates xeric conditions). High values in the Sheep Shelter record for the LIA thus indicate relatively wet conditions. At the Cave of 100 Hands, the ratio of grasses to sagebrush declines precipitously at 500 ^{14}C yr BP, and then abruptly returns to high values and remains high though the rest of the LIA, indicating relatively wet conditions during the LIA. So while certain taxa in the pollen of the Clear Creek record do seem to indicate a cold, dry LIA, others indicate wet conditions. Additional paleoenvironmental work in the vicinity of the Tushar and Pavant ranges seems warranted but the general pattern of MCA warming and LIA cooling holds for this location.

The previous brief discussion should show that broad regional patterns in climate should be evident in the record for the past 2000 years in RCC. We anticipate seeing evidence for a warm MCA interval and a cool LIA. Regional precipitation responses to these epochs appear spatially heterogeneous, but the nearest record to RCC, the Douglas fir chronology from Harmon Canyon, suggests a relatively dry, stable MCA period with moderate annual snowpack and a generally dry but variable LIA.

Chronological Control

Chronological control is provided by three radiocarbon dates on aggregated pollen samples recovered from the core. Pollen was aggregated by chemical digestion following Brown *et al.* (1992). Dates are provided in Table 3-1.

An age-depth model was created with the three pollen radiocarbon dates using smooth-spline interpolation in the R age-depth modeling package CLAM using its default settings (Blaauw, 2010). We assigned the top of the core (0-1 cm) the age of -59 ± 10 cal yr BP, equivalent to the calendar year 2009, the year the core was collected. Calibration was performed using the IntCal13 calibration curve (Reimer *et al.*, 2013). The model used shows a nearly linear age-depth relationship, and indicates the 5 m record spans the past 8000 years, with a mean resolution of 15 years per centimeter (Figure 3-2). This record is one of the highest resolution and longest paleoenvironmental archives from the Colorado Plateau recovered to date. The study presented here focuses on the top 150 cm of the core which spans the past 3000 years.

To supplement this study, an additional core was collected from BSB in 2014 for the purpose of X-ray fluorescence-based (XRF) elemental analysis. Preliminary results from XRF on the core indicate the presence of a volcanic tephra with a geochemical signature consistent with Mount Mazama ash in sediments dating to 7400-7800 cal yr BP using the radiocarbon chronology from our 2009 core (Ward, 2016). The Mount Mazama eruption has been dated to 7627 ± 150 cal yr BP (Zdanowicz *et al.*, 1999). To show that the Mount Mazama ash is found in the stratigraphically correct position at BSB, Figure 3-2 shows two separate age-depth models. On the left is an age-depth model created using only the three available radiocarbon dates for the core, and assuming a modern date for the surface. The model on the right uses the same three radiocarbon dates, and two additional stratigraphic index dates, a date of 7267 cal yr BP for the depth of Mazama ash, and a hypothetical Fremont-aged date of 1000 ± 50 ^{14}C yr BP for the depth of 56-57 cm below present ground surface, the depth from which a grain of maize pollen was identified during pollen analysis of the BSB09B core (see Zone 3 discussion below). As Figure 3-2 shows, these two age-depth models are nearly identical, supporting the validity of the radiocarbon-only model, which is the model we used for the analysis presented here.

Core Collection, Storage, and Lab Analysis Protocol

The BSB09B core was collected in 7 nonoverlapping drives with a 5 cm Livingstone Piston corer. Core sections were extruded in the field and wrapped in 0.5 mil (12.5 µm) plastic wrap and aluminum foil, and transported to the Records of Environment and Disturbance (RED) lab, Department of Geography, University of Utah, for analysis. Upon arrival at the RED lab facility, the core sections were opened, described and cut into 1 cm thick (15.7 cc) sections of sediment. These sections were individually bagged and stored at 1°C in the cold storage facility at the RED lab awaiting analysis. For each analysis, samples of the required volume were removed as needed and the remaining material was immediately returned to cold storage.

Non-Pollen Paleoecological Proxies

Stable Carbon and Nitrogen Isotope Analysis of Sediments

Carbon exists in as two stable (nonradioactive) isotope forms: ^{13}C and ^{12}C. The difference between the two isotopes is a single neutron present in the heavier and rarer ^{13}C, which causes it to move differently through natural systems. The ratio of ^{13}C:^{12}C is reported as parts per thousand (per mil, ‰) in delta notation ($\delta^{13}C$), and is calculated as $\delta^{13}C = (R_{sample}-R_{standard})/R_{standard} \times 1000$ ‰ where $R = {}^{13}C/{}^{12}C$ following Fry (2007).

During photosynthetic processes, plants using the C3 photosynthetic pathway fix less ^{13}C during photosynthesis, resulting in relatively depleted $\delta^{13}C$ values. Plants using the C4 photosynthetic pathway fix relatively more of the heavier isotope and have enriched $\delta^{13}C$ values. The CAM photosynthetic pathway used by native cactuses produces similarly enriched $\delta^{13}C$ values (O'Leary, 1981; Farquhar *et al.*, 1989).

Under natural conditions, the range of $\delta^{13}C$ values associated with C3 and C4 pathways do not overlap. Relatively few plants native to Utah use the C4 photosynthetic pathway, mostly those in the goosefoot family (Amaranthaceae) such as *Atriplex* spp.

Nitrogen also exists in two stable isotope forms, ^{14}N and ^{15}N. Again the difference is the mass of a single neutron present in the heavier isotope of nitrogen resulting in an approximate 3‰ increase in $\delta^{15}N$ with each increase in trophic level, associated in part with discrimination against isotopically heavy urea at renal membrane boundaries. Most plants obtain nitrogen from soil ammonium (NH4+) or nitrate (NO3-) and those in temperate ecosystems have mean $\delta^{15}N$ values of 3-6‰ with a 0-9‰ range, contingent upon temperature and water stress (Pate, 1994; Bocherens and Drucker, 2003). Conversely, plants that fix atmospheric nitrogen such as legumes have mean $\delta^{15}N$ values of ~ 1‰, with a –2-2‰ range (Evans and Ehleringer, 1994; Pate, 1994).

RCC is virtually devoid of wild C4 plants. At sites dating to the Fremont occupation of the canyon, the common presence of maize cobs and associated storage features indicates that people who lived there during this time were farming maize. Both archaeological and modern maize exhibit highly enriched $\delta^{13}C$ values, the latter expressing a mean of ~-12.5‰ and the former, grown before fossil fuel depletion of atmospheric CO2, enriched 1-2‰ relative to this average (Marino and McElroy, 1991; Tieszen and Fagre, 1993). We would therefore expect BSB09B sediments to show uniformly low values of $\delta^{13}C$ through the entire record, and any positive deviations should demonstrate the presence of the remains of maize plants at the site (Webb *et al.*, 2007).

We analyzed the stable carbon and nitrogen isotope composition of bulk sediment samples from the core for evidence of maize agriculture during the Fremont occupation of RCC. Variation in the contribution to the sediment organic matter of BSB09B by plants using a C4 photosynthetic pathway should be detectable in sediments as variation in $\delta^{13}C$ values. We initially analyzed 1 sample per 8 cm over the entire length of the core. After identifying a peak in $\delta^{13}C$ at 56-57 cm, we analyzed 1 sample per cm between 50-68cm in depth.

Macroscopic Charcoal Analysis

Macroscopic charcoal analysis is a method for reconstructing long-term changes in local fire regimes. Experimental work suggests charcoal particles larger than 125 μm are the most representative of local fire histories (Whiltlock and Millspaugh, 1996;

Gardner and Whitlock, 2001; Whitlock and Larsen, 2002). Charcoal analysis was carried out on samples of 1 to 5 cc for each 1 cm core increment. Sediment samples were washed through 125 μm screens, to remove the smaller particles. The remaining >125 μm charcoal particles were counted under a dissecting microscope at 10-40x. Variation in the resulting particle concentrations (particles per cc) and influx (particles per cm^2 per year) of charcoal is an indicator of fire frequency, severity or extent near the site over time (Higuera *et al.*, 2010; Kelly *et al.*, 2011). Charcoal frequency for the samples analyzed ranges from zero to 17,955 particles per cc (zero to 892.84 particles per cm2 per year), with a mean value of 697.31 ± 1826.67 particles per cc (34.71 ± 90.82 particles per cm^2 per year).

Charcoal influx data were analyzed with CHAR analysis (Higuera *et al.*, 2009). Background charcoal influx was calculated using a 500-year moving average. Fire events are defined in the record as events where charcoal influx exceeds the 500-year mean (background) value by two standard deviations.

Magnetic Susceptibility

Magnetic susceptibility (MagSus) provides an estimate of the amount of iron-bearing allochthonous inorganic sediment being deposited over time in a closed-basin depositional setting (Thompson *et al.*, 1975). While BSB is not a closed basin, its topographic setting and the nature of deposition approximate a closed-basin for the purposes of interpreting MagSus. Peaks in MagSus may result from increases in the amount of clastic sediment (high MagSus) relative to organic matter (low MagSus) deposited at a site. Peaks can occur as a result of the loss of upslope vegetative cover resulting from drought or fire, or from increases in precipitation resulting in the acceleration of alluvial and colluvial processes.

We measured MagSus at 1 cm increments with 8 cc sediment samples. Samples were removed from the cold storage facility, allowed to sit in measurement cups for 24 hr to reach room temperature, and analyzed with a Bartington MS2 cup Magnetic Susceptibility System. MagSus values for the samples analyzed range from 3.3 to 16.4 SI, with a mean of 7.6 ± 2.2 SI.

Loss on Ignition

Loss on Ignition (LOI) involves the combustion of sediment samples in order to determine the percentage weight of carbonates, organic material and inorganic sediment, which combust at different temperatures (Bengtsson *et al.*, 1986; Dean, 1974). Samples of 1 cc were isolated, weighed and allowed to dry at 100°C for 24 hr. Samples were then combusted for 2 hr at 550°C and reweighed, providing a measurement of total organic carbon (TOC) in the samples. Samples are then combusted for an additional 2 hr at 900°C and weighed again, providing an estimate of the inorganic carbonates lost in each sample and inorganic sediment remaining.

In a closed-basin lacustrine setting, the carbonate content of sediments provided by LOI allows a relatively robust estimate of water temperature, depth and internal productivity over time (Bischoff *et al.*, 1997; Oviatt, 1997; Wetzel, 2001; Patrickson *et al.*, 2010). BSB, however, is not a closed-basin setting; water from the upslope spring perpetually saturates the meadow, but ultimately exits the system on the downslope side. In open-system deposits such as these, LOI is most useful as a measure of sedimentation rates and vegetative productivity.

LOI for this study was performed for each 1 cm sample from the top 150 cm of the core. Carbonate values for the sediments analyzed here ranged from 0 to 8.84% with a mean value of 2.65 ± 1.4%. The non-carbonate organic component of samples ranged from 1.0 to 22.15% with a mean value of 5.02 ± 4.41%. The inorganic sedimentary component of samples ranged from 37.95 to 96.31% with a mean value of 75.06 ± 11.30%.

For many of the samples analyzed, organic carbon and charcoal concentrations are tightly correlated. This is to be expected since charcoal is itself organic carbon. At some points in the core, however, organic carbon and charcoal concentrations differ. These points in the core indicate particularly wet intervals, or intervals with few dry periods. Vegetative productivity is high enough to cause an increase in the organic component of sediments, and dry periods are infrequent enough to preclude wildfires.

Pollen-Based Environmental Proxies

A total of 24 pollen samples were examined from the core from its upper 144 cm. Pollen was analyzed at 1 cm increments for the top 6 cm, and at 8 cm increments from 16 to 120 cm. Samples from 128, 136 and 144 cm were also analyzed, but pollen preservation in these samples was insufficient for analysis.

Pollen was processed using standard chemical digestion following Faegri (1989). We used spores of the exotic Lycopodium as a tracer for influx calculation. After processing, samples were suspended in Silicon oil, mounted on microscope slides and analyzed at 500x magnification. Samples were counted to 300 terrestrial pollen grains or

300 Lycopodium spores, whichever was reached first. Pollen was identified using a dichotomous key (Kapp *et al.*, 2000) and by comparison with the western North American pollen collection housed at the RED lab. We use the term 'pollen taxon' to refer to the lowest taxonomic level of identification for any particular pollen grain. Undifferentiated Asteraceae (sunflower family) as a pollen taxon, for example, includes many of the genera within the family Asteraceae, but not *Artemisia* or *Ambrosia*, whose unique exine morphology makes them identifiable at the genus level. *Artemisia* and *Ambrosia* are therefore separate pollen taxa.

Table 3-2 presents all pollen taxa identified in the upper 144 cm of the core, along with examples of each pollen taxon which have been found in RCC. Some pollen taxa include only one or a few species, while others like Asteraceae include many genera and dozens of species not mentioned in the table. Table 3-2 also includes a plant category designation which indicates the kind of plant each pollen taxon represents. Categories are trees and shrubs (TRSH), upland herbs (UPHE) and aquatic vascular plants (AQVP) that thrive in marshes and bogs. Pollen influx and percentage data were calculated using the Tilia software package (Grimm, 1990).

Pollen Sums and Ratios

We use several pollen ratios and sums to evaluate the relative abundance of certain ecological indicator plant taxa over time in the core. Ratios were used as proxies for temperature, effective precipitation and precipitation seasonality. All ratios and sums were calculated using pollen influx for each taxon. Sums were normalized to a zero to one scale by dividing all sums by the maximum value. Ratios were calculated using the formula (*a*-*b*)/(*a*+*b*), resulting in values from -1 to +1. Positive values indicate higher relative abundance of taxon *a*, and negative values indicate dominance of taxon *b*. Changes over time in the ratio of one taxon to another should indicate climatic changes favoring one taxon over the other. A brief description of each sum or ratio is provided for reference in Table 3-3.

TPI (Terrestrial Productivity)

Total pollen influx (TPI) was used as a measure of total vegetative productivity over time. TPI is a measure of the number of terrestrial pollen grains per year per unit area falling at a site. It is calculated here as (total pollen grains per cm^2 per year). For the samples analyzed here, its value ranges from 99.73 to 4398.94, with a mean of 1312.63 ± 1263.28 grains per cm2 per year.

APA (Summer Precipitation)

Following Brunelle *et al.* (in review) we use the sum of *Ambrosia*, Poaceae and Amaranthaceae (APA) as a proxy for summer precipitation based on the climate space for these taxa (Williams, 2006). Pollen percentages for these taxa are higher in sites where most of the annual precipitation falls in summer. In the samples analyzed from BSB09B, APA values range from 7 to 75 grains per sample, with a mean value of 37.29 ± 20.05 grains per sample.

P:J (Overall Moisture)

The ratio of *Pinus* to *Juniperus* pollen (P:J) has been used as a proxy for mesic/xeric conditions in Great Basin settings (Louderback and Rhode, 2009; Brunelle *et al.*, in review). Pines generally require cooler and/or wetter conditions than junipers, especially with respect to summer precipitation (see discussion of pinyon and Douglas fir below). Two-needle pinyon and the three species of juniper occurring in RCC today are consistent with this generalization, and we use the ratio as a mesic/xeric index. Higher P:J values indicate more pinyon and relatively mesic conditions, while lower values indicate more juniper and more xeric conditions.

Nearly all pine pollen grains in core were identified as two-needle pinyon pine using the key provided by Jacobs (1985). This key identifies pollen grains of haploxylon type less than 70 µm in total length as *P. edulis*/*P. monophylla* and haploxylon grains larger than 70 µm as *P. flexilis*/*P. strobiformis*. Only one diploxylon pine grain was identified, a grain of ponderosa pine (*P. ponderosa*) in the 6-7 cm sample.

Cupressaceae pollen is only identifiable to the family level. Three species of Cupressaceae occur in RCC, Utah juniper (*J. osteosperma*), Rocky Mountain juniper (*J. scopulorum*) and common juniper (*J. communis*). All three of these taxa thrive in relatively xeric conditions compared to two-needle pinyon pine, so the family-level identification is sufficient for goal of the P:J ratio. The ratio was calculated as (*Pinus* – *Juniperus*) / (*Pinus* + *Juniperus*). P:J values for the samples analyzed here range from -0.33 to 0.60 with a mean of 0.14 ± 0.26.

A:P (Annual Average Temperature)

We use A:P, the ratio of box elder to cottonwood (*Populus* spp.), as a proxy for summer temperature based on the climate zones these trees occupy today. The gallery forest surrounding BSB today consists of a mix of box elder and narrowleaf cottonwood trees. Pollen percentages in the BSB09B core show, however, that the composition of the gallery forest has changed through time from dominance by one or the other taxon for periods of several hundred years.

Using PRISM climate data (PRISM Climate Group, 2004), we compared the annual minimum, maximum and mean temperatures within the geographic ranges of these two species (as defined by Little, 1971). Our analysis used the 800 m resolution 30-year climate averages for the period 1981-2010. Analysis was restricted to the subset of each tree species range within the continental US, the area for which PRISM climate data are available.

Table 3-4 presents the temperature ranges both tree species occupies today, along with quaking aspen (*P. tremuloides*, see discussion next paragraph). While narrowleaf cottonwood and box elder do have considerable overlap in the temperature variables we analyzed, box elder occurs in areas with higher minimum, maximum and mean annual temperatures. The average annual minimum, maximum and mean temperatures over the geographic range of narrowleaf cottonwood are -1.84, 12.81 and 5.48 degrees Celsius. The corresponding values for the geographic range of box elder are 1.64, 16.85 and 9.25 degrees Celsius, several degrees warmer for each value. Changes in the abundance of box elder relative to narrowleaf cottonwood pollen in the BSB09B core should therefore indicate changes in annual average temperature over time, dominance by box elder indicating warm periods, and dominance by *Populus* indicating cooler intervals.

Pollen of box elder is identifiable at the species level, whereas *Populus* is only identifiable at the genus level. The only species of *Populus* within several miles of BSB today is narrowleaf cottonwood. Fremont cottonwood (*P. fremontii*) occurs several miles to the south at lower elevations in RCC. Quaking aspen occurs in RCC at elevations above 8000’ and is a notoriously short-travelling and poorly preserving pollen grain (Sangster and Dale, 1964). Quaking aspen therefore likely never migrated close enough to BSB to contribute pollen to the core. However, quaking aspen occupies a slightly cooler temperature range than does narrowleaf cottonwood (Table 3-4). Its inclusion in the ratio of box elder to *Populus* pollen therefore would only strengthen our interpretation of that ratio with respect to temperature.

A:P is calculated as (*A. negundo – Populus*) / (*A. negundo* + *Populus*). Values closer to +1 indicate warmer periods and values closer to -1 indicate cooler. In this study, the A:P values range from -1 (samples with only *Populus*) to +1 (samples with only box elder), indicating periods during which the gallery forest surrounding BSB was composed entirely of one taxon or the other. The mean A:P value for the samples analyzed here is -0.12 ± 0.63.

P:DF (Precipitation Seasonality)

The ratio of pinyon to Douglas fir is used here as an index of precipitation seasonality. Two-needle pinyon pine is adapted to areas receiving abundant summer precipitation. Compared to the single-needle species found in the Great Basin (*P. monophylla*), the two-needle pine has several adaptations requiring summer precipitation.

The two-needle per fascicle configuration increases the surface area of needles which allows for a greater amount of transpiration during the day, but requires higher soil moisture, especially in summer. Two-needle pinyon also produces smaller seeds than its single-needle counterpart, also necessitating higher soil moisture throughout the critical first summer growing season (Petersen, 1988, 1994).

Douglas fir, however, is an excellent indicator of winter snowpack. Knight *et al.* (2010: Figure 3), for example, show that winter snowpack on the Tavaputs Plateau is the most important factor in Douglas fir annual ring widths. The relative abundance of Douglas fir pollen in sediments from RCC should therefore be a good indicator of the amount of winter precipitation over time.

To demonstrate the precipitation mode preference of these two species of trees, Figure 3-3 compares the distribution of Douglas fir to two-needle pinyon as a function of a Precipitation Seasonality Index (PSI). The PSI shown in Figure 3-3 is calculated as (MJJASO-NDJFMA) ÷ (MJJASO + NDJFMA), where MJJASO is the sum of May, June, July, August, September and October precipitation, and NDJFMA is the sum of precipitation falling in the months of November, December, January, February, March and April. A value of +1 indicates all annual precipitation at a location falls during the summer, while a value of -1 indicates all precipitation falls during winter. Precipitation data in Figure 3-3 are from the PRISM Climate Group (2004). Monthly precipitation data are 4 km resolution 30 year normals for the period 1981-2010. Precipitation seasonality index statistics provided in Table 3-5 represent mean, standard deviation and the range of index values within the geographic distribution of each tree species as defined by Little (1971). The figure shows that these two tree species are distributed consistent with their precipitation preferences described above. Two-needle pinyon occurs at medium elevations in the Southwest, where the summer monsoon dominates the annual precipitation signal. Douglas fir favors both higher elevations in the Southwest (areas with greater snowpack), and a generally more northwestern distribution where the winter storm track dominates annual precipitation.

Given the distinct precipitation preferences for two-needle pinyon and Douglas fir, the ratio of pinyon to Douglas fir pollen should provide a measure of precipitation seasonality over time in the BSB09B sediments. We calculated P:DF as (*Pinus* – *Pseudotsuga*) / (*Pinus* + *Pseudotsuga*). Positive values indicate periods with more summer than winter precipitation, while negative values indicate periods with greater winter precipitation. The analyzed samples from BSB09B produced P:DF values from 0 (no pinyon present) to 1 (no Douglas fir present), with a mean value of 0.60 ± 0.24.

Results and Discussion

Stable Carbon and Nitrogen Analysis of BSB09B Sediments

Figure 3-4 shows δ^{15}N and δ^{13}C values for a variety of native Utah plants and maize from experimental, ethnographic and archaeological settings, and sediment organic remains from the BSB09B core. As the figure demonstrates, C3 plants (most of the native plants of Utah) have δ^{13}C values between -29 and -22‰. Most C4 plants produce δ^{13}C values of between -16 and -11‰. Maize analyzed by Coltrain and Leavitt (2002) produced δ^{13}C values of between -12 and -10‰, slightly enriched over native Utah C4 plants. Maize grown at the Range Creek Field Station in 2014 as part of Boomgarden's (2015) research produced values of between -12.7 and -11.0‰ with a mean value of 11.7

± 0.4‰. The positive $\delta^{13}C$ values of BSB09B sediments at 56 and 62 cm in depth (dating to 1050 and 1170 cal yr BP, respectively) indicate the presence of the remains of maize plants in these sediments. The fields surrounding BSB were therefore likely used as agricultural fields during the Fremont occupation of RCC.

Pollen Percentages

Pollen percentages for taxa that compose more than 1% of the identified pollen in any sample are presented in Figure 3-5. Taxa which do not compose more than 1% are not included in Figure 3-5 but were used to calculate the total pollen influx discussed below. We used Tilia's stratigraphically constrained cluster analysis function (CONISS) to identify major pollen zones (Grimm, 1987, 1990). Results show five stratigraphic zones which correspond well to documented climatic epochs in the western hemisphere (the Medieval Climate Anomaly, Little Ice Age and historic period). These temporal zones are used to organize the discussion below, and to organize Figures 3-5, 3-6, 3-7 and 3-8.

The pollen spectrum of the historic period (Zone 1, see temporal zone definitions below) provides a convenient baseline from which to compare change in pollen spectra over time at BSB. Differences between prehistoric and modern pollen spectra should indicate the ways in which the climate of each zone differed from today. In order to track the environmental change indicated by each Pollen-based environmental proxy over time, we compare the mean for each proxy by pollen zone relative to the mean for the historic zone below. The means for each zone and differences between each zone and the historic zone are listed in Table 3-6.

Temporal Zones

Results for each proxy are described by temporal zones below. Charcoal influx data, MagSus, LOI and stable carbon and nitrogen isotope ratios are presented in Figure 3-6. Pollen-based environmental proxies are presented in Figure 3-7. We discuss results in chronological order from oldest to youngest, beginning with the Pre-Zone 5 zone.

Pre-Zone 5 – 3000-2350 cal yr BP

While the pollen record from BSB09B was only described and analyzed back to 2350 cal yr BP, analyzed charcoal counts, MagSus and LOI records extend to 3000 cal yr BP. We call the period from 3000-2350 cal yr BP Pre-Zone 5.

Fire frequency (fires per 500 yr) was highest during Pre-Zone 5, although peak magnitudes were relatively low, especially against the record of Zone 4. Fires were therefore frequent but of relatively low severity. MagSus values were relatively low, suggesting the frequent fires did not denude the hills of vegetation above BSB severely enough to cause an increase in erosion. TOC was relatively low and carbonates were highest during this period. These values suggest the spring feeding BSB was active during this period, resulting in an increase in carbonate precipitation in the waters of BSB.

Zone 5 – 2350-1950 cal yr BP

Fire frequency continues to decline throughout this zone, a pattern that began in Pre-Zone 5. MagSus remains low and relatively constant throughout the zone. TOC co-varies with charcoal influx, indicating some of the variability in TOC is likely a direct result of the amount of charcoal present in each sample. The most salient feature of the pollen record during Zone 5 (Figure 3-5) is relatively high percentages of herbaceous flowering plants, especially those of *Ambrosia* (ragweed), undifferentiated Asteraceae and *Thalictrum* sp. (meadowrue).

The mean TPI, a measure to terrestrial productivity, is low over Zone 5, especially in relation to Zone 4, while APA (summer precipitation) and P:J (overall moisture) are higher than average, although the trend in APA through this zone is generally positive (wetter) and P:J is generally negative (dryer). A:P (summer temperature) is quite low, suggesting relatively cool conditions, although it demonstrates considerable variance with a positive peak in about the middle of the zone. P:DF (precipitation seasonality) during this period is close to the sequence average, suggesting precipitation seasonality more or less like modern.

Two fire events are recorded in the first half of Zone 5 and none thereafter (Figure 3-6). Fire frequency may have declined as a result of generally low productivity (low TPI), caused by cool (lower A:P), wet (higher APA and P:J) summers during this period. A spike occurs in A:P (higher summer temp) around 2200 cal yr BP, suggesting a warm period around that time. The charcoal record indicates the warm period is associated with the two fire events. After the fires, A:P returns to low values, indicating cooler temperatures by 2000 cal yr BP. MagSus remains stable over Zone 5, indicating the fires did not cause widespread vegetation loss on the hills upslope from BSB, and may have been limited to the gallery forest surrounding the creek.

Zone 4 – 1950-1300 cal yr BP

Fire frequency is low in Zone 4, but two fire events are identified in Zone 4, at 1842 and 1442 cal yr BP (AD 108 and 508, respectively). These two fires have peak magnitude of ~17,000 and ~6000 particles/cm2/year, the highest values in the entire sequence. MagSus increases during or after the latter fire, indicating the 1442 cal yr BP fire cleared vegetation upslope from the bog and subsequently allowed increased erosion and sedimentation at BSB. TPI is relatively high near the 1442 cal yr BP event, and the high TPI indicates higher annual precipitation which may also have contributed to increased erosion after the fire event. TOC is relatively high through Zone 4, but the most prominent peaks are associated with the two large fire events.

The aquatic pollen types Equisetaceae (horsetail) *Typha latifolia* (cattail) and Cyperaceae all increase during this period, indicating marshy conditions were present at BSB and that the spring feeding the bog was active. Grasses are abundant and pinyon and Douglas fir are both higher during Zone 4 than during any other, suggesting moderately high precipitation during both summer and winter.

TPI (productivity), APA (summer precipitation) and P:J (moisture) increase to maxima in Zone 4. A:P (summer temperature) increases during the first half of Zone 4 and declines during the second, indicating a gradual infiltration of a cottonwood dominated gallery forest during the first half of Zone 4, and a subsequent return to cottonwood dominance by the end of Zone 4. P:DF (precipitation seasonality) remains close to the sequence average through Zone 4. Overall, Zone 4 appears to have been moderately wet, with reduced precipitation seasonality (relatively wet summers and winters).

The high severity (inferred from the high amount of charcoal produced) of the two recorded fires and the long interval between them likely resulted from generally mesic conditions driving large increases in biomass, punctuated by severe droughts. Knight *et al.* (2010) identify the years from 1840 to 1770 cal yr BP (AD 110-180) and 1448 to 1406 cal yr BP (AD 502-544) as the most extreme droughts in the Harmon Canyon chronology based on duration and magnitude of the deviation from long-term mean precipitation. Local expressions of these droughts are likely important contributing factors to these two fires in RCC. The more recent drought is evident in the tree ring records from SE Oregon, central Nevada and New Mexico (Knight *et al.*, 2010: Figure 8). This fire is also associated with an increase in MagSus values, indicating the fire may have been local severe enough to remove vegetation and temporarily increase erosion and sedimentation into the bog.

Zone 3 – 1300-850 cal yr BP

A single fire event occurred in Zone 3, dating to 1222 cal yr BP. It is tempting to speculate that the single fire event and the absence of fire events thereafter in Zone 3 are the result of human activity, since the human occupation of RCC occurred during this pollen zone. The fire event may have, for example, been set by humans intending to clear the land around BSB for maize agriculture. Absence of fires for the rest of Zone 3 may then have resulted from continued use of the site by agriculturalists, who kept weedy species at bay by weeding and tending maize fields. This would have resulted in decreased fuel loads near the site and less frequent fires until after agricultural activities at the site halted. An interesting coincidence in this regard is an enrichment in stable carbon isotope ratios at approximately the same depth as the fire event (Figure 3-6; see discussion below), and the presence of maize pollen very close in depth, indicating the site was used for maize agriculture near the time of the fire. As is discussed below, however, pollen abundance and ratios indicate generally warm and dry conditions at the site at this time. Reduced fire frequency could simply be the result of reduced fuel loads near the site due to decreased overall productivity.

We have no way to rule out human activity as contributing to the fire history of Zone 3. The lack of fire during Zone 3 could simply have resulted from generally low precipitation on average, preventing fuel accumulation. But the relatively stable Douglas fir pollen during this period does suggest relatively stable snowpack from year to year. And the decrease in pinyon pollen relative to Douglas fir and Juniper suggests drier, hotter summers. Increased seasonality generally leads to *increased* wildfires as fuels dry out more frequently during hot, dry summers, and so the absence of fire during Zone 3 is noteworthy. We can therefore rule out neither human intervention nor climate-driven explanation for charcoal in Zone 3. But climatic evidence from pollen and evidence from stable carbon isotopes indicating field management by human agriculturalists make it appear likely that human activity contributed to the charcoal record of Zone 3.

MagSus is slightly elevated and stable through Zone 3, consistent with generally low productivity and increased mineralogic input (decreased organics) during this period. TOC and carbonates are low and relatively stable through Zone 3, again consistent with low terrestrial productivity.

Zone 3 is marked by a reduction in most pollen taxa, and an increase only in more xeric oriented taxa such as Amaranthaceae (goosefoot) and Cupressaceae. Aquatics disappear completely and most upland herbs decline. Within the tree taxa, mesic species decline (pinyon, Douglas fir and *Populus*), while xeric/heat tolerant taxa (box elder and Cupressaceae) increase through the zone. A relatively high P:DF (precipitation seasonality) ratio indicates moderately dry summers and wet winters. TPI (terrestrial productivity), APA (summer moisture) and P:J (overall moisture) are very low for this period, consistent with warm, dry summers. A:P (summer temp) starts the zone relatively low and transitions to very high toward the end of Zone 3, consistent with warming summers throughout the zone. These proxies together indicate generally warm and dry conditions during the MCA in the Tavaputs Plateau area.

A dominant climate driving mechanism during this period may have been the presence of persistent La Niña-like conditions in the northern hemisphere (Mann *et al.*, 2009; Cohen *et al.*, 2012; Metcalfe *et al.*, 2015). La Niña conditions are associated with generally dry winters in the Southwest and wet winters in the Northwest. The Tavaputs Plateau, however, lies in the dipole zone between the northwestern and the southwestern United States, and the effects of the El Niño/Southern Oscillation (ENSO) are less pronounced than to the north or south (Wise, 2010). But ENSO does affect Tavaputs region precipitation. Knight *et al.* (2010) found a significant negative correlation between ENSO and Douglas fir ring widths, indicating El Niño years on average bring more winter precipitation to the region. Table 3-7 presents the average summer and winter precipitation values for Bruin Point at the north end of RCC, for El Niño, La Niña and ENSO neutral years, since 1950 (based on historic southern oscillation index values from the NOAA climate prediction center, found at http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

Precipitation data for Table 3-7 are from the PRISM Climate Group (2004). The table shows that while El Niño years do result on average in slightly heavier winter precipitation at Bruin Point (consistent with the findings of Knight *et al.*, 2010), La Niña years do not differ significantly from ENSO neutral years with respect to winter precipitation. Both El Niño and La Niña years have reduced summer precipitation on average at Bruin Point. All other things being equal, a persistent La Niña like climate state would therefore result in slightly less-than-average snowpack and reduced summer precipitation from year to year. This is consistent with the pollen record from BSB09B Zone 3, which shows reduced *Pinus* and *Pseudotsuga* pollen, but higher than average P:DF (precipitation seasonality), and lower P:J (moisture), low TPI (productivity) and APA (summer precipitation).

Despite the generally warm, dry climate indicated by the paleoenvironmental proxies reported here, Zone 3 also records two lines of evidence for maize agriculture occurring at BSB during the Fremont occupation of RCC. The 56-57 cm sample from BSB09B contained a single grain of maize pollen. Figure 3-8 shows this grain of pollen compared to a reference grain from the RED lab pollen collection. Using the pollen-based radiocarbon chronology, this sample dates to between 930 and 1190 cal yr BP, with a median date (CLAM's 'best') of 1060 cal yr BP. Additionally, the samples 62-63 and 66-67 cm (calibrated 2σ age ranges of 1059-1305 and 1142-1380 cal yr BP, respectively) show enriched values of $\delta^{13}C$, indicating the presence of maize plant material just below the level with maize pollen in the sediment of BSB09B. These two lines of evidence suggest the field surrounding BSB was used as a maize field at some point between 1380 and 930 cal yr BP (AD 570 and 1020). Eleven maize cobs from RCC have been dated using radiocarbon (Boomgarden, 2015). These 11 cobs have calibrated radiocarbon median ages ranging from 1020-850 cal yr BP (AD 930-1100), consistent with the age of evidence of maize agriculture from BSB09B.

Zone 2 – 850-150 cal yr BP

Charcoal influx remains relatively low throughout Zone 2, but fire frequency increased after the termination of Zone 3. Three fire events are indicated at 782, 442 and 262 cal yr BP (AD 1168, 1508 and 1688, respectively). All three of these fire events are associated with extreme multidecadal droughts evident in the Douglas fir tree ring record from the Tavaputs Plateau (Knight *et al.*, 2010).

MagSus increases over the first half of Zone 2 to a maximum just after the 442 cal yr BP (AD 1508) fire event. Based on the amount of charcoal recovered, the 442 cal yr BP fire was likely a severe event that caused a brief increase in mineralogic sediment input to the bog. The severity of the fire may be related to increased overall moisture and productivity after AD 1300 (650 cal yr BP). Knight *et al.* (2010) identify a prolonged overall wet period in the Tavaputs Plateau Douglas fir chronology between AD ~1300 and AD ~1600, punctuated by several dry periods, notably one from AD 1491-1510 (459-440 cal yr BP). This drought was the most severe in the chronology by two measurements, average deviation from mean annual precipitation (-36 cm) and percentage of period below the drought threshold (58%; Knight *et al.*, 2010: Table 2). High MagSus values during this period may thus be the result of a severe fire event, or drought-induced de-vegetation, or both. An increase in TOC at the same depth as the MagSus maximum, likely due to the increase charcoal influx, implies fire is at least partly responsible for the increased MagSus values. Carbonate values are relatively low and stable over Zone 2.

A transition to wetter conditions after AD 1300 is indicated by an increase in the aquatic taxa Cyperaceae and Equisetaceae. Upland herbs also increase in general during Zone 2. Amaranthaceae, Brassicaceae (mustards), Cichoroideae (dandelions and chicory), Poaecae (grasses) and *Thalictrum* all increase in Zone 2.

The beginning of Zone 2 saw a transition to overall wetter conditions as evidenced by a slight increase in TPI (productivity), and by increases in APA (summer precipitation) and P:J (moisture) values, with warm summers indicated by a high A:P (summer temp) ratio. A transition occurred beginning around 600 cal yr BP and extending over the next few hundred years from relatively warm and wet to cool and dry conditions. By the end of Zone 2, low TPI, low APA, low P:J, low A:P and low P:DF are all consistent with a cool, dry Little Ice Age in the Tavaputs plateau region.

Zone 1 – 150 cal yr BP - Present

This zone consists of the essentially “modern” pollen signal in RCC. TPI increases slightly, and APA and P:J both increase, indicating generally wetter conditions than during the LIA. The A:P value indicates a transition from a gallery forest dominated by narrowleaf cottonwood during the LIA to one dominated by box elder for the historic period, indicating warmer conditions after the LIA. The dominance of box elder has continued to present, and the gallery forest surrounding the site today is composed of almost exclusively by box elder. P:DF increases, indicating a return to a bi-modal precipitation regime with moderate amounts of both winter and summer precipitation. In the Tavaputs region today, annual precipitation is generally bi-modal, with peaks in late spring and early fall. The P:DF ratio suggests this pattern has been in place for approximately 100 years, before which either snowpack was greater on average or summer precipitation less frequent, or both.

Fire frequency remained relatively high during Zone 1, with one fire indicated some time during the past 100 years. Low MagSus indicates the fire was not severe enough to de-vegetate the slope above BSB and cause an erosional event.

Billy Slope Bog and Regional Paleoenvironments

To summarize the above sequence, the period from 2350-1300 cal yr BP was relatively wet and cool, with infrequent, high severity fires. The MCA portion of the BSB09B record from 1300-600 cal yr BP appears to have been warmer and drier overall, with very infrequent of wildfire. The LIA portion of the record from 600-150 cal yr BP shows cool and dry conditions during that period, and increased fire frequency. More or less modern vegetation after 150 cal yr BP demonstrates a relatively stable historic period to present, with generally warmer and wetter conditions than during the LIA. Comparing this record with other regional paleoenvironmental records reveals some interesting similarities and differences.

Petersen (1988, 1994) sees an increase in the abundance of pinyon pollen as evidence for a warm, wet MCA in southwestern Colorado. A subsequent decline in pinyon pine after AD 1200, and regional tree ring records showing narrow rings at high elevation sites (cold conditions) and narrow rings at low elevation sites (dry conditions) provide evidence for a cool, dry LIA in the southern Rocky Mountains. The Wasatch

Plateau records from Morris *et al.* (2010, 2013) also show evidence for a warm, wet MCA with subsequent cooling and drying during the LIA. These records are in general agreement with the BSB09B record presented here. Low precipitation is indicated by TPI, APA and P:J, and warm temperatures are indicated by high A:P. A cold, dry LIA is indicated by low TPI, APA, P:J and A:P. During the LIA in RCC, Amaranthaceae reaches its zenith, while Cyperaceae are also relatively high (Figure 3-5). This likely indicates generally dry conditions in terrestrial settings, with cold enough temperatures and moderate snowpack such that the spring at BSB remained active through this period.

The pollen record from Clear Creek (Newman, 2000) shows interesting agreements and disagreements with the BSB09B record. Newman (2000:307) points out that the period from 2700 BP (ca. 2800 cal yr BP) to 1500 BP (ca. 1400 cal yr BP) shows "particularly high ratios of sedges and cattails." This corresponds to BSB09B pollen Zones 4 and 5, both of which have high sedge percentages. TPI, the measure of total vegetative productivity, is highest during Zone 4, and APA, the proxy for summer precipitation, is high during both Zones 4 and 5. These data together suggest the Tavaputs Plateau and Clear Creek Canyon both saw a cool and wet, relatively productive period between 2800-1400 cal yr BP.

The trend in the ratio of pinyon to juniper in Clear Creek is exactly opposite that reported here for BSB09B (Figure 3-9). It is interesting to note that the human occupation of Five Finger Ridge was non-synchronous with that of RCC (Figure 3-10). The distribution of calibrated radiocarbon median dates spans 830-1170 (median ages; Boomgarden *et al.*, 2014), while the occupation of Five Finger Ridge has been dated to between AD 1100 and AD 1300 (Talbot *et al.*, 2000: Table 4.7). This pattern may indicate ecological factors these two sites shared which made irrigation-based maize agriculture attractive.

Implications for Maize Agriculture in RCC

As noted in the introduction to this section, while this study is primarily a paleoenvironmental reconstruction, the ultimate goal of paleoenvironmental research in RCC is to provide information which can aid in the interpretation of human behavior before, during and after the Fremont period. For this reason, we now focus our discussion on the climate parameters which influence maize agriculture and human foraging productivity.

One of the most interesting aspects of Southwestern archaeology is the history of maize cultivation in the region. Maize first appeared in the Four Corners region of the American Southwest at some point around 4100 cal yr BP (Merrill *et al.*, 2009). By 1000 cal yr BP, maize cultivation had expanded to form the basis of many archaeological economies and was a dietary staple across the four corners region and Fremont area (Coltrain and Leavitt, 2002; Coltrain *et al.*, 2007). By 650 cal yr BP (AD 1300), maize cultivation ended in many areas likely due to severe long-term droughts and widespread crop failure over periods of several decades. Abandonment of settlements and aggregation to still tenable refugia occurred as people like the ancestral Puebloans and the Fremont concentrated in the few remaining areas suitable for agriculture (Benson and Berry, 2009).

As noted above, several scholars have argued that the rise of agriculture in the Southwest occurred as a result of an increase in summer temperature and precipitation during the MCA, making farming an attractive economic strategy (Matson *et al.*, 1988; Petersen, 1994; Leavitt and Coltrain, 2002; Benson *et al.*, 2007). The hypothesis has support from southwestern paleoenvironmental records, but does suffer from one weakness. It relies on the assumption that farming is a superior economic strategy, and will always be pursued when and where possible. Others have suggested, however, that agriculture arose in the Southwest not due to increases in summer rains, but as a response to deteriorating environmental conditions. Cannon (2000; see also Broughton *et al.*, 2010) analyzed the relative abundance of artiodactyls (deer, sheep and pronghorn) to leporids (rabbits and hares) in the Mimbres-Mogollon area of southern New Mexico during the Pithouse and Pueblo time periods. His analysis shows a steady decline in foraging efficiency during periods of increased reliance on maize agriculture at sites in the Mimbres-Mogollon culture area over the period from AD 200-1450. The analysis demonstrates that reliance on maize farming became more important to Mimbres people as encounter rates with high value prey items such as large mammals declined.

Barlow (1997, 2002) expands upon the idea of declining foraging efficiency contributing to the rise of agriculture, with an ethnographic analysis of the energetic economics of aboriginal maize farming. Her novel and empirically-based approach uses the framework of optimal foraging theory, using caloric return rates (measured in calories generated per hour of labor) obtained from ethnographic cases as the currency. She makes the observation that agricultural strategies can be placed on a continuum of low- to high-investment, based on the number of hours required. Low-investment agriculture consists of simple plant-and-leave strategies while high-investment agriculture includes time-consuming activities such as field preparation, weeding and building and maintaining irrigation infrastructure. Her analysis demonstrates two key findings: (1) practitioners of the lowest investment forms of agriculture generally see the highest returns per unit time invested, while more intensive strategies generate lower rates of return, and (2) caloric returns for all strategies of maize agriculture are generally lower than many of the upon encounter return rates documented for many wild food resources in the Great Basin and Colorado Plateau (Simms). This economic analysis shows that investment should be made in agriculture only when average rate of return for hunting and gathering declines below that for the most profitable agricultural strategies, and intensification should only occur with further declines in hunting and gathering.

Boomgarden (2015) explored the possibility that the lowest investment form of maize cultivation, rainfall farming, could have been practiced in RCC. Her analysis shows that in RCC under modern climate conditions, which lack a vigorous, predictable monsoon season, summer precipitation is insufficient to rely on direct rainfall alone to grow maize. Boomgarden observes that generally, while effective moisture rises with elevation, temperature and growing season length drop with elevation. This relationship has likely influenced settlement patterns throughout southwestern prehistory, especially for maize horticulturalists. Matson *et al.* (1988), for example, compare growing season length and precipitation to the Basketmaker and Pueblo period settlement patterns on Cedar Mesa in southeastern Utah. In most years on the uplands of Cedar Mesa, which usually experience an influx of monsoon rain, growing season precipitation is sufficient to meet the bare minimum requirements for a marginal maize crop. But during the Basketmaker period from ca. AD 200-720, colder annual temperatures meant the growing season was too short in the uplands and agricultural activities were restricted to elevations below 2000 m. The subsequent Pueblo occupation from ca. AD 1060-1270 occurred during the warmer MCA interval, during which time growing season at the higher sites would have been long enough to support maize horticulture. Matson *et al.* see a shift in settlement patterns at this time, to a preference for higher elevation sites.

For the Fremont maize farmers of RCC, there is no elevation with the adequate temperatures and precipitation of growing corn without some form of irrigation (Boomgarden, 2015). Since caloric returns for intensive, irrigation-based maize agriculture are particularly low, following the logic of Barlow (2002) above, maize agriculture should only have been practiced in RCC in times of pronounced wild resource scarcity. The paleoenvironmental data presented above demonstrate that in RCC, the Fremont period was likely a time of wild resources scarcity. Pinyon pine, for example, is ethnographically one of the most important food items wherever it occurs. At BSB, the pollen of pinyon sees a sharp decline between 1300 and 850 cal yr BP, indicating this important ethnographic food source became scarce during the Fremont occupation of RCC. The proxies for summer and total annual precipitation also indicate a relatively dry period, and many of the wild animal and plant food resources upon which Fremont foragers would have relied also decreased in abundance at this time. These data are consistent with Barlow's (1997, 2002) results, and not consistent with the hypothesis that increased summer precipitation drove the rise of agriculture in this part of the Fremont area.

Conclusions

We have presented a multiproxy paleoenvironmental reconstruction for the past 3000 years at BSB in RCC. Enriched $\delta^{13}C$ values and maize pollen show that the site was used as a maize field at some point between 930 and 1190 cal yr BP (AD760-1020). The presence of maize pollen together with the enriched $\delta^{13}C$ values at BSB is supporting evidence that the stable carbon signature identified in these sediments is indeed evidence of local maize agriculture. A similar enrichment in $\delta^{13}C$ was found in sediments from Cherry Meadows (core RCCM07B). The results presented here indicate the isotopic enrichment at Cherry Meadows is evidence that site too was utilized by the Fremont inhabitants of RCC for maize agriculture. These results indicate stable carbon isotope analysis of sediment organics may be a useful tool in identifying prehistoric maize fields in areas where pollen and organic carbon are likely to be preserved. Our pollen-based radiocarbon chronology is supported by our paleoenvironmental data, which are in agreement with local, regional and hemispheric climate records. The BSB09B record shows a cool, wet period preceding the Fremont occupation of RCC, a warm, dry MCA interval, a cool dry LIA and a historic period since AD 1850 largely similar to modern conditions.

Finally, it appears likely that maize farming in RCC was at least partly driven by deteriorating environmental conditions. Reductions in the abundance of ethnographically important pollen taxa like pinyon pine mark the beginning of the Fremont period in RCC. The reduction of pollen from plants favoring summer precipitation also indicates a period of generally lower summer precipitation. This indicates that the Fremont maize farmers of RCC would have needed to irrigate fields in order to produce maize.

The need for irrigation to grow maize in RCC produces a number of interesting implications and avenues for further research in the canyon. During the Fremont period, maize productivity on a canyon-wide scale would have been a function of several variables, including annual snowpack and groundwater holding potential of the Tavaputs plateau above. On a local scale in the canyon, it would have been a function of groundwater holding potential at varying sites throughout the canyon, amount of irrigable land at varying elevations, and the costs of building and maintaining irrigation networks. The costs of irrigating may further be broken down into building dams and maintaining ditches, both of which may also be influenced by empirical variables relating to available water. The frequency and intensity of precipitation events during the growing season may create a tradeoff between building dams and maintaining ditches. More frequent monsoons would cause frequent dam failure of weak dams while building more robust dams would cause ditches to fill with sediments from flood events. A better understanding of the costs of building and maintaining dams and ditches would thus contribute significantly to our interpretation of the Fremont occupation of RCC and of prehistoric maize cultivation more broadly.

Analysis of oxygen isotopes of archaeological maize cobs in RCC may also contribute in this regard. Williams *et al.* (2005), for example, show that maize grown in the Southwest can be identified as having been grown from predominantly winter (snowmelt and perennial creeks) or monsoon-based precipitation based on the relative abundance of the two isotopes of Oxygen, ^{18}O and ^{16}O. Identifying the nature of the water used to grow maize in RCC would contribute to an understanding of the tradeoffs maize farmers in RCC faced.

Interpretations of pollen data presented in this paper would be strengthened by more thorough analysis of available tree ring datasets. For example, the Douglas fir chronology from Harmon Canyon (Knight *et al.*, 2010) has not been analyzed for early wood/late wood thicknesses. Such an analysis would provide a better understanding of precipitation seasonality on the Tavaputs Plateau for the past two millennia. Analysis of oxygen isotopes of tree rings in that chronology would also provide a better understanding of climatic mechanisms driving precipitation seasonality and abundance there. A chronology of pinyon pine from the Tavaputs Plateau could also improve interpretation of the pollen data presented here, with special attention paid to stand age to identify periods of high and low seedling recruitment. Since trends in the ratio of pinyon to juniper at Clear Creek Canyon are exactly opposite those found at BSB, the comparison of pinyon pine ring widths to historic climate data in these two locations over time, and a more intensive paleoenvironmental investigation of Clear Creek Canyon and the Tushar range generally may also be illuminating.

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Table 3-1. Radiocarbon Dates from BSB09B Pollen Samples.

Depth	^{14}C Age	Calibrated Age	Probability	Lab ID
147-148	2780 ± 35	2789-2956	95%	UGAMS-6410
299-300	4480 ± 35	4978-5010	6%	UGAMS-6411
		5035-5290	89%	
473-474	6900 ± 40	7666-7827	95%	UGAMS-17701

Table 3-2. Scientific and Common Names, and Plant Types for BSB09B Pollen Taxa. Plant Types Are Trees and Shrubs (TRSH), Upland Herbs (UPHE) and Aquatic Vascular Plants (AQVP).

Pollen Taxon	Scientific Name	Common Names	Type
Aceraceae *Acer negundo*	*Acer negundo*	Box elder	TRSH
Apiaceae	*Cymopterus petraeus*	Turpentine spring parsley	UPHE
	Ozmorhiza depauperata	blunt-seed sweet root	
Asteraceae *Ambrosia*	*Ambrosia* spp.	Ragweed	UPHE
Asteraceae *Artemisia*	*Artemisia tridentata*	Big sagebrush	UPHE
	A. ludoviciana	white sagebrush	
Asteraceae Cichoroideae	*Agoseris glauca*	Pale agoseris	UPHE
	Cichorium intybus	Chicory	
	Taraxacum oficinale	common dandelion	
	Tragopopon dubius	western salsify	
Asteraceae Sunflower (High Spine)	*Cirsium* spp.	Thistle	UPHE
	Ericameria nauseosus	Rubber rabbitbrush	
	Erigeron spp.	Daisy	
	Helianthus spp.	Sunflower	
Betulaceae	*Alnus incana*	Gray alder	TRSH
Brassicaceae	*Lepidium* spp.	Pepperweed	UPHE
	Descurainia spp.	Tansymustard	
	Nasturtium officinale	Watercress	
	Sisymbrium	Tumblemustard	
	Stanleya pinnata	Prince's plume	
Amaranthaceae	*Atriplex canescens*	Four-wing saltbush	UPHE
	A. confertifolia	Shadscale	
	Chenopodium spp.	Goosefoot, lambsquarter	
	Suadea spp.	Seepweed	
Cupressaceae	*Juniperus osteosperma*	Utah Juniper	TRSH
	J. scopulorum	Rocky Mountain Juniper	
Cyperaceae	*Carex* spp.	Sedges	AQVP
Ephedracae	*Ephedra viridis*	Mormon Tea	UPHE
Equisetaceae	*Equisetus* spp.	Horsetail	AQVP

Table 3-2 Continued.

Pollen Taxon	Scientific Name	Common Names	Type
Fabaceae	*Astragalus* spp.	Milkvetch	UPHE
	Hedysarum spp.	Sweetvetch	
	Medicago sativa	Alfalfa	
	Melilotus officinalis	Sweet clover	
	Trifolium pratense	Red clover	
Fagaceae *Quercus*	*Quercus gambelii*	Scrub oak	TRSH
Liliaceae	*Allium* spp.	Wild onion	UPHE
	Calochortus nuttallii	Sego lily	
Malvaceae	*Spharalcea* spp.	Globemallow	UPHE
Onograceae *Epilobium*	*Epilobium* spp.	Willowherb	UPHE
Poaceae	*Elymus* spp.	Wildrye squirreltail	UPHE
	Festuca spp.	Fescue	
	Hordeum spp.	Barley	
	Poa spp.	Meadow Grass Bluegrass	
	Sporobolus cryptandrus	Sand dropseed	
	Stipa hymenoides	Ricegrass	
Poaceae *Zea mays*	*Zea mayz*	Maize	
Polygonaceae *Eriogonum*	*Erigonum* spp.	Buckwheat	UPHE
	Rumex crispus	Curly Dock	
Pinaceae *Abies*	*Abies lasiocarpa*	Subalpine Fir	TRSH
Pinaceae *Pseudotsuga*	*Pseudotsuga menziesii*	Douglas Fir	TRSH
Pinaceae *Picea*	*Picea engelmani*	Engelman Spruce	TRSH
Pinaceae *Pinus* (haploxylon)	*Pinus edulis*	Two-Needle Pinyon Pine	TRSH
	P. flexilis	Limber Pine	
Pinaceae *Pinus* (diploxylon)	*Pinus ponderosa*	Ponderosa Pine	TRSH
Primulaceae	*Dodocatheon alpinum*	Alpine Shooting Star	UPHE
Rhamnaceae	*Ceanothus martinii*		UPHE

Table 3-2 Continued.

Pollen Taxon	Scientific Name	Common Names	Type
Rosaceae	*Purshia* spp. *Amelanchier utahensis* *Prunus virginiana*	Cliffrose Utah Serviceberry Chokecherry	TRSH
Rosaceae *Cercocarpus*	*Cercocarpus ledifolia*	Mountain Mahogany	TRSH
Salicaceae *Populus* type	*Populus tremuloides* *P. fremontii* *P. angustifolia*	Quaking Aspen Fremont Cottonwood Narrowleaf Cottonwood	TRSH
Salicaceae *Salix*	*Salix exigua*	Coyote Willow	AQVP
Sarcobataceae	*Sarcobatus vermiculatus*	Greasewood	TRSH
Saxifragaceae	*Philadephus microphyllus*	Littleleaf Mock-Orange	UPHE
Scrophulareaceae *Mimulus*	*Mimulus guttatus*	Seepspring Monkey Flower	UPHE
Solanaceae	*Physalis virginiana*	Virginia Groundcherry	UPHE
Ranunculaceae *Thalictrum*	*Thalictrum fenderli*	Fendler's Meadowrue	UPHE
Typhaceae	*Typha latifolia*	Broadleaf Cattail	AQVP
Urticaceae	*Urtica diocia*	Stinging Nettle	UPHE

Table 3-3. Pollen Sums and Ratios Used in This Study.

Name	Abbrevation	Proxy target
Total Pollen Influx	TPI	Total Vegetative Productivity
Amaranthaceae + Poaceae + *Artemisia*	APA	Total Annual Precipitation
Pinus : *Juniperus*	P:J	Precipitation and Temperature
Acer negundo : *Populus*	A:P	Temperature
Pinus : Douglas fir	P:DF	Precipitation Seasonality

Table 3-4. Annual Average Minimum, Maximum and Mean Temperatures for the Geographic Ranges of Narrowleaf Cottonwood, Quaking Aspen and Box Elder.

	Annual Average Minimum Temperature (degrees C)		
	Narrowleaf Cottonwood	Quaking Aspen	Box Elder
Minimum	-12.14	-12.59	-11.84
Maximum	12.81	12.27	18.73
Mean	-1.84 ± 3.09	-1.63 ± 3.0	1.64 ± 4.48

	Annual Average Minimum Temperature (degrees C)		
	Narrowleaf Cottonwood	Quaking Aspen	Box Elder
Minimum	0.06	0.65	1.81
Maximum	28.92	27.75	30.64
Mean	12.81 ± 4.16	12.43 ± 3.57	16.85 ± 4.49

	Annual Average Minimum Temperature (degrees C)		
	Narrowleaf Cottonwood	Quaking Aspen	Box Elder
Minimum	-5.76	-5.60	-4.98
Maximum	20.84	19.87	22.69
Mean	5.48 ± 3.52	5.4 ± 3.15	9.25 ± 4.39

Table 3-5. Precipitation Seasonality Index Values for Two-Needle Pinyon and Douglas Fir Geographic Ranges.

Species	Range (km^2)	Mean PSI	PSI Range
Two-needle Pinyon	246,417	0.17 ± 0.20	0.3 - 0.92
Douglas Fir	719,328	0.27 ± 0.30	0.0 - 0.91

Table 3-6. Mean Pollen Sum and Ratio Values, by Pollen Zone for BSB09B.

		TPI		APA		P:J		A:P		P:DF	
Pollen Zone	Age (Cal yr BP)	X_z	X_z-X_1	X_z	X_z-X_1	X_z	X_z-X_1	X_z	X_z-X_1	X_z	X_z-X_1
1	-59 - 150	0.37	-	0.58	-	0.10	-	0.30	-	0.71	-
2	150 - 850	0.10	-0.27	0.48	-0.10	-0.04	-0.14	-0.37	-0.67	0.62	-0.09
3	850 - 1300	0.04	-0.33	0.12	-0.46	-0.18	-0.28	0.11	-0.19	0.38	-0.33
4	1300 - 1950	0.83	0.46	0.51	-0.07	0.43	0.33	-0.44	-0.74	0.50	-0.21
5	1950 - 2350	0.16	-0.21	0.64	0.06	0.38	0.28	-0.56	-0.86	0.60	-0.11

X_z = Zonal Mean for Each Pollen Zone

X_z-X_1 = Difference Between Zone Mean (X_z) and Historic Mean (X_1).

Table 3-7. Average Seasonal Precipitation (mm) at Bruin Point for ENSO Phases Since 1950.

	E Niño Avg	La Niña Avg	ENSO Neutral
DJFMAM	238.82	221.48	229.96
JJASON	302.98	314.41	341.2

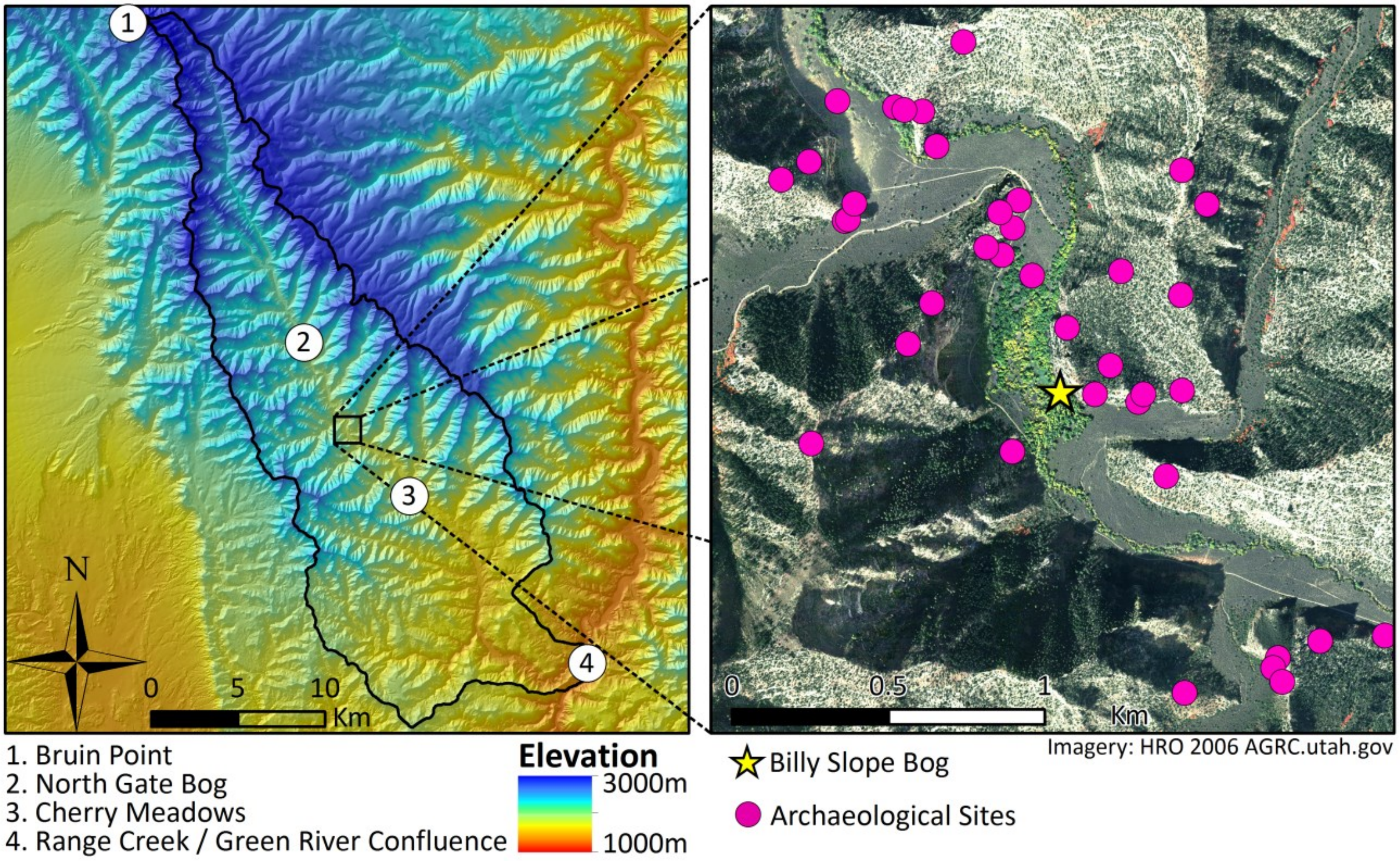

Figure 3-1. Map of Range Creek Canyon Showing Location of Billy Slope Bog and Sites Mentioned in Text, and Recorded Archaeological Sites Within 1 km of Billy Slope Bog.

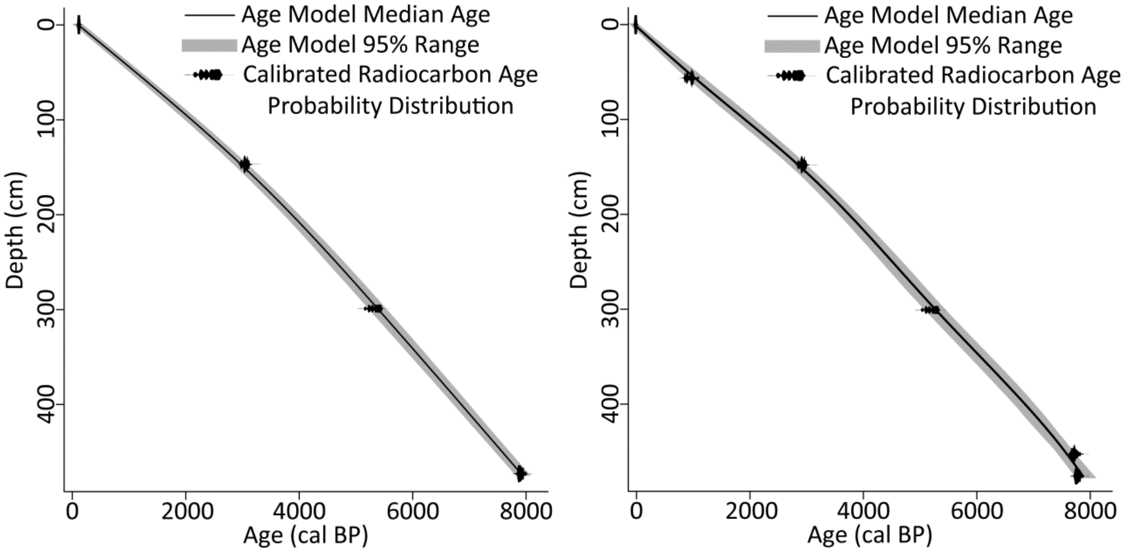

Figure 3-2. Age-depth Model Used for Chronological Control. Model at Left Was Used in This Study and Is Based on Three Radiocarbon Dates from Pollen in BSB09B Sediments, and Assuming a Calibrated Radiocarbon Age of -59 cal yr BP (AD 2009) for Depth 0. Model at Right Includes Those Four Dates in Addition to a Hypothetical Date of 1000 ± 50 ^{14}C yr BP for Depth 56-57cm (the Depth at which a Grain of Maize Pollen Was Identified), and a Date of 6845 ^{14}C yr BP for Depth 450-451 cm (the Depth at which an XRF Signature of Mazama Ash Was Found).

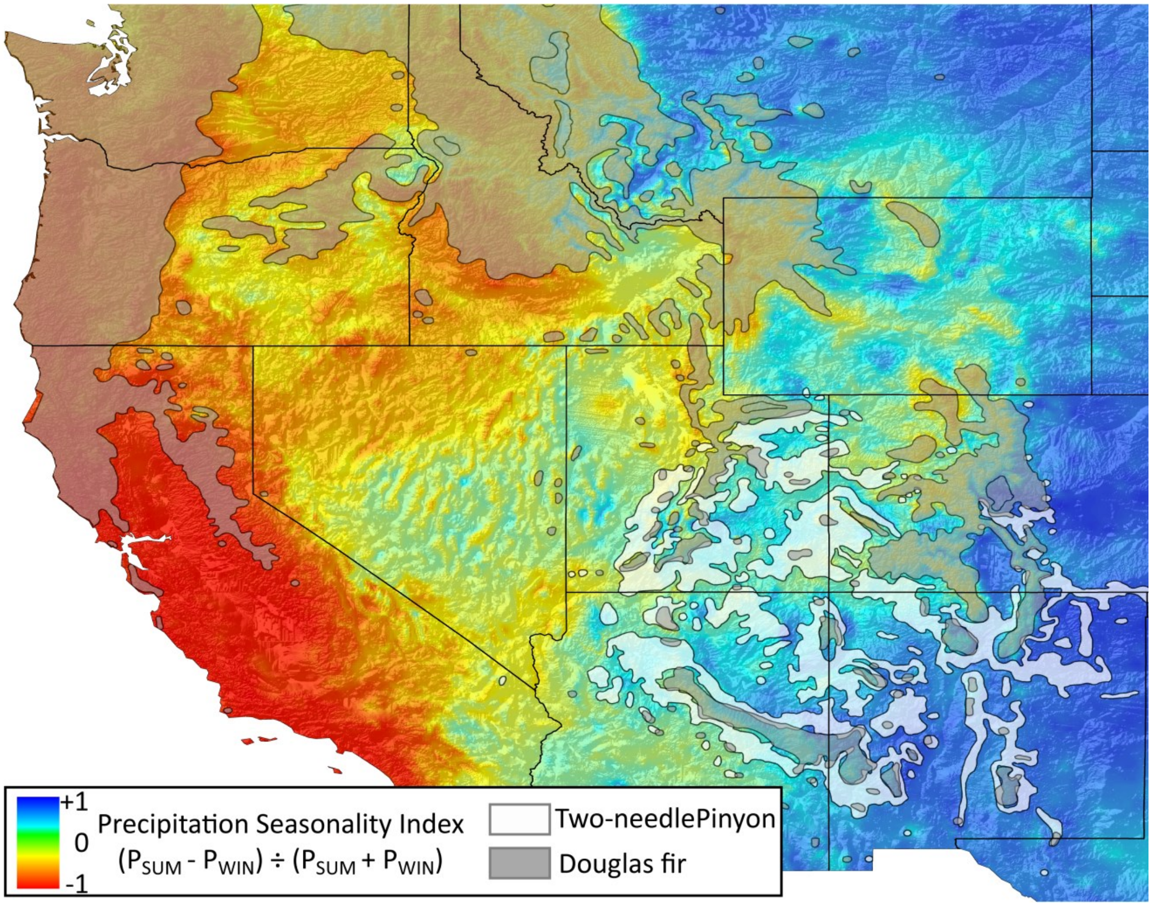

Figure 3-3. Map of the Western United States Showing the Distribution of Two-needle Pinyon and Douglas Fir, Compared to a Precipitation Seasonality Index (PSI). PSI Is Calculated as $(P_{summer} – P_{winter}) \div (P_{summer} + P_{winter})$ where P_{summer} is the Sum of Precipitation Falling During the Months of May-October, and P_{winter} is the Sum of Precipitation Falling During the Months of November-April. This Equation Results in Values from -1 (All Annual Precipitation Falling Between Nov.-Apr.) to +1 (All Annual Precipitation Falling Between May-Oct.).

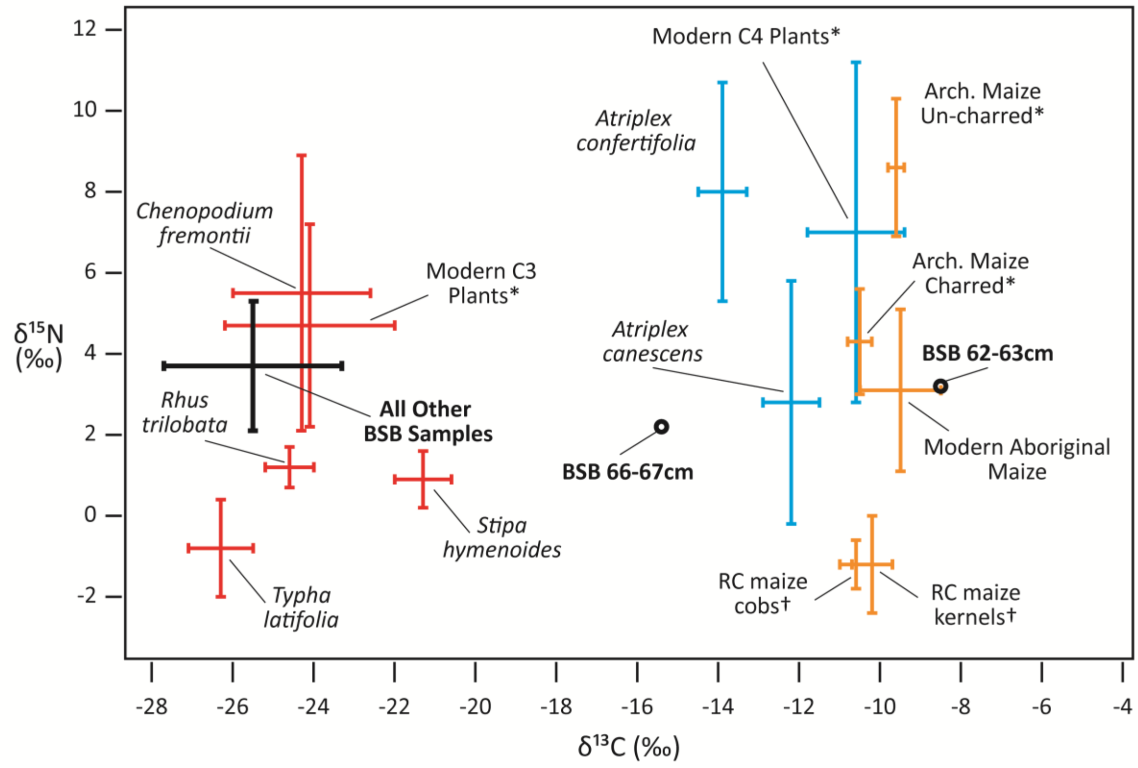

Figure 3-4. Stable Nitrogen and Carbon Isotope Ratio Values for Native Utah C3 Plants (Red) and C4 Plants (Blue), Archaeological and Experimentally Grown Maize (Orange) and Sediment Samples from BSB09B (Black). Values for Individual Plant Species Come from Plants Collected in RCC.

*Modern C3 Plant, Modern C4 Plant, Archaeological Charred Maize and Archaeological Un-charred Maize Sample Data Are from Coltrain and Leavitt (2002).

†Range Creek Maize Data Came from Maize Grown During the Course of Shannon Boogmgarden's (2015) Ph.D. Dissertation Research.

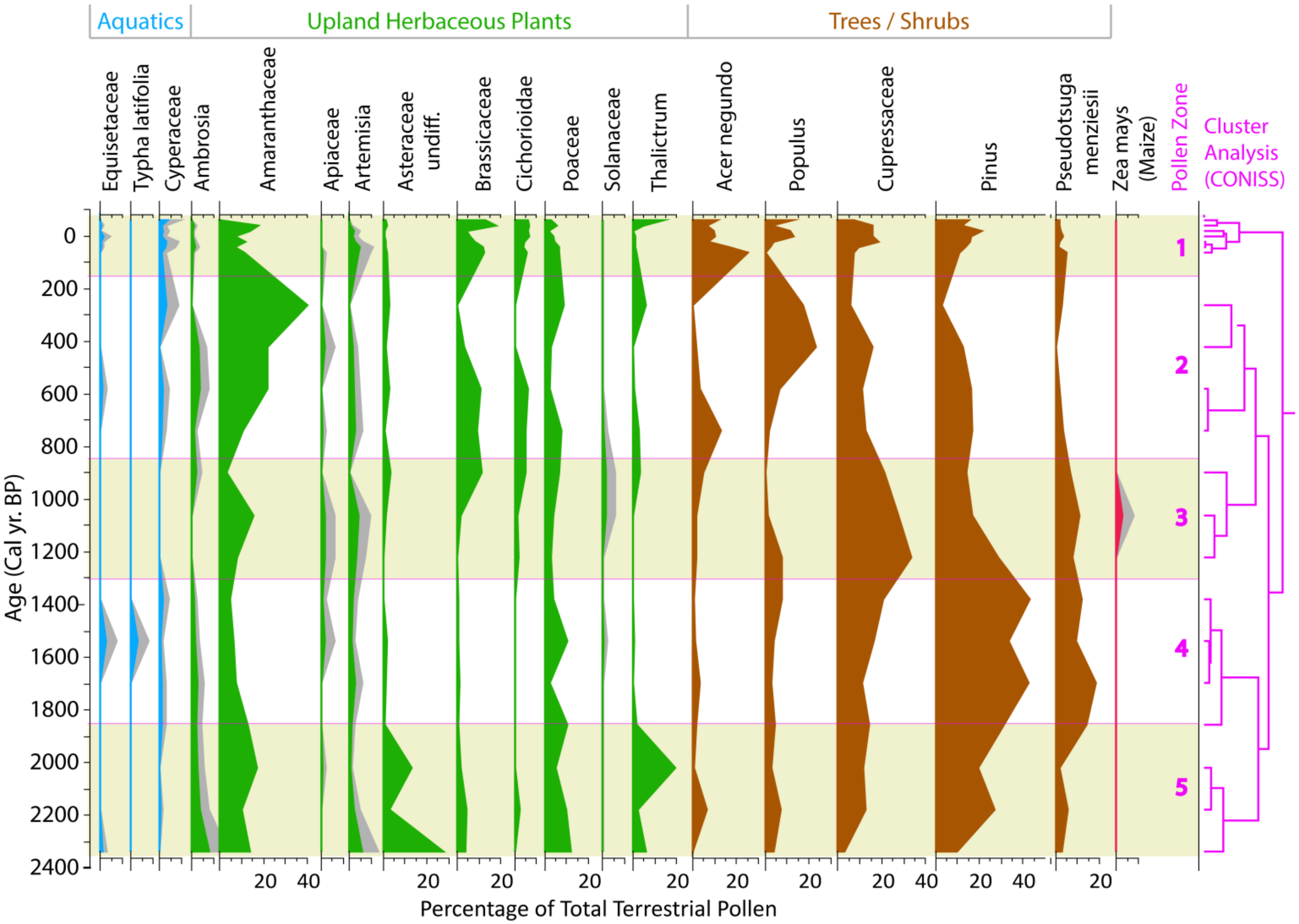

Figure 3-5. Pollen Percentages for Pollen Taxa which Make up More Than 1% for Any Sample.

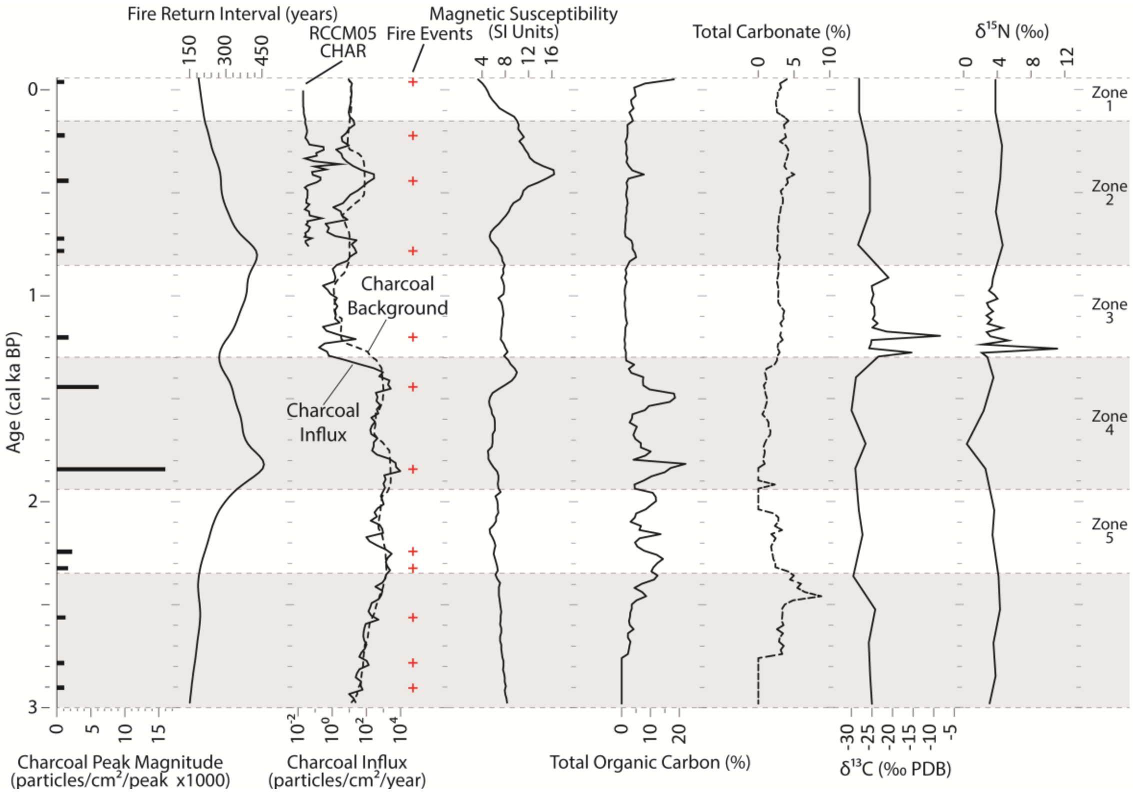

Figure 3-6. Fire History and Magnetic Susceptibility, Total Organic Carbon, Total Carbonate, Stable Carbon and Stable Nitrogen Values for BSB09B Sediments.

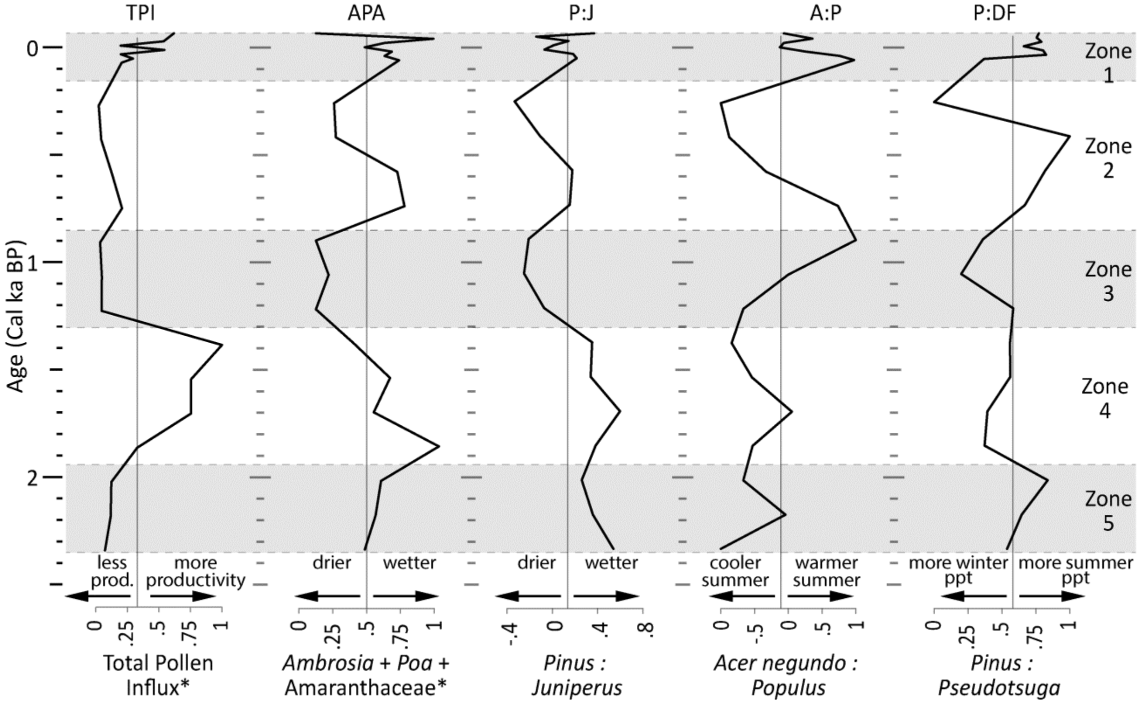

Figure 3-7. Pollen Sums and Ratios for the Past 2350 Calibrated Radiocarbon Years. TPI - Total Pollen Influx (Terrestrial Productivity Proxy); APA – The Sum of Amaranthaceae + Poaceae + *Artemisia* (Summer Precipitation Proxy); P:J – Pinyon:Juniper (Overall Moisture Proxy); A:P – *Acer*:*Populus* (Summer Temperature Proxy); P:DF – Pinyon:Douglas Fir (Precipitation Seasonality Proxy).

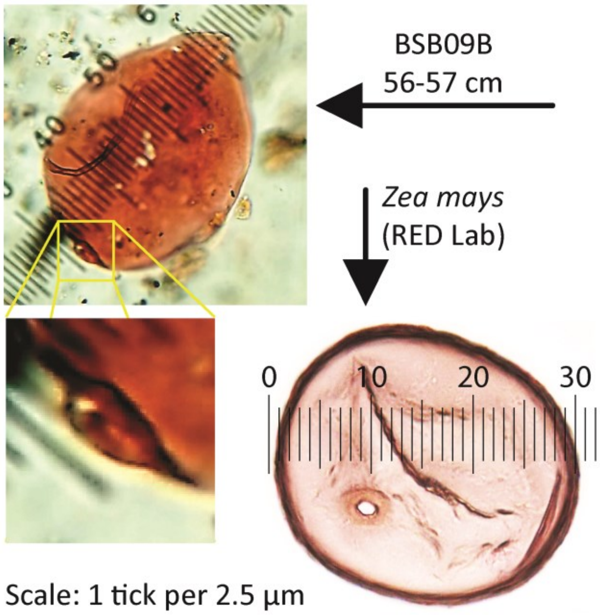

Figure 3-8. Maize Pollen Identified in BSB09B Sample 56-57 cm (left) and a Modern Sample from the RED Lab Reference Library. Both Grains Are More or Less Psilate, 75 Microns in their Maximum Dimension, and Have a Single Annulated Pore.

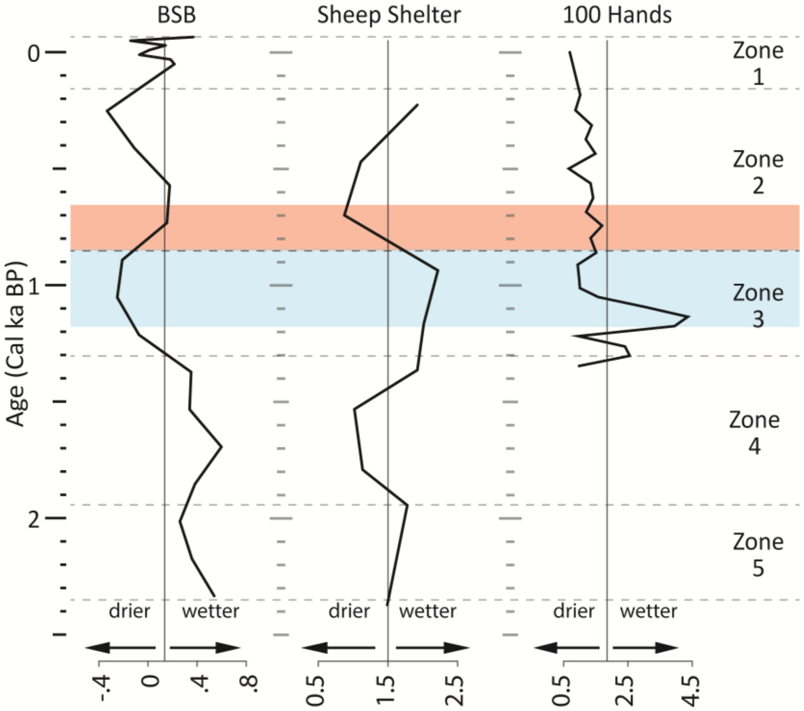

Figure 3-9. *Pinus*:*Juniperus* Ratio Values for BSB09B and Clear Creek Canyon Sites from Newman (2000). Blue Shading Represents Fremont Occupation of Range Creek Canyon, while Red Shading Represents the Fremont Occupation of Five Finger Ridge (Talbot *et al.,* 2000).

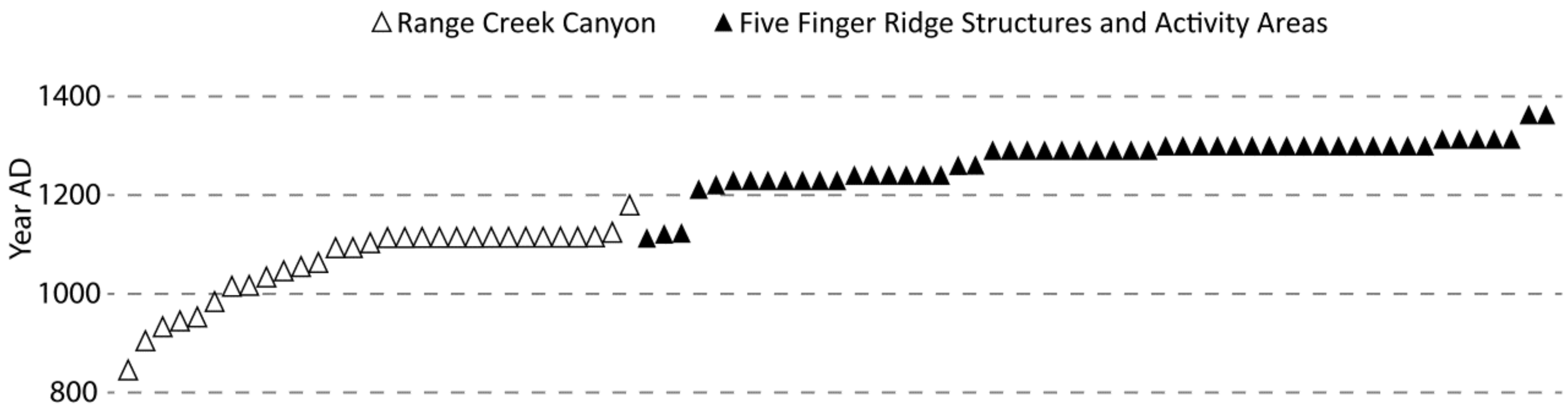

Figure 3-10. The Distribution of Calibrated Radiocarbon Median Ages for Range Creek Canyon Fremont Aged Sites and Five Finger Ridge Index Dates from Talbot *et al.* (2000) Table 4.7.