Stories of the Sky Islands: Exhibit Development Resource Guide for Biology and Geology at Chiricahua National Monument and Coronado National Memorial

Prepared for the National Park Service under terms of

Cooperative Ecosystems Studies Unit Agreement H1200-05-0003

Task Agreement J8680090020

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In cooperation with the Arizona State Museum
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May 17, 2013

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Introduction

Beth Grindell, Ph.D.

In 2016, the National Park Service will turn 100 years old. In preparation for this centennial, Chiricahua National Monument and Coronado National Memorial are planning new visitor center exhibits. The Arizona State Museum (ASM) was engaged through the Cooperative Ecosystem Studies Unit (CESU) agreement between the University of Arizona and the National Park Service to provide planning support for developing those exhibits.

Chiricahua National Monument was established in 1924 by President Calvin Coolidge to preserve and protect this "wonderland of rocks" for the enjoyment and education of the American people. Coronado National Memorial was established in 1952 to commemorate Francisco Vásquez de Coronado's 16th century expedition into what is now the United States.

The unusual geological formations at Chiricahua and the unique Madrean Archipelago flora and fauna of the sky islands that make up the both Chiricahua and Coronado will be subjects for interpretive display in the Visitor Centers at both parks. To assist the selected exhibit design service in developing appropriate interpretive displays, the Arizona State Museum will provide an overview of current research and scientific understanding of the geology and biology of the two parks.

To accomplish this goal, ASM engaged graduate students Erin Elizabeth Posthumus from the School of Natural Resources and the Environment, Jesse Minor from the School of Geography and Development, and Adam M. Hudson from the Department of Geosciences as graduate research assistants to prepare background materials for use of NPS staff and exhibit designers. The topics to be developed were defined in discussion with NPS personnel from Chiricahua National Monument and Coronado National Memorial.

The goals include:

- Preparation of background research to summarize current thinking on major topics that will be interpretive subjects for the Chiricahua and Coronado visitor centers.
- An annotated bibliography for each of the topics.

The topics include:

- The geology and geologic processes that shaped the sky islands.
- The biological landscape—including flora and fauna and the forces that shape them, including the sky islands themselves, fire regimes and climatological history and potential climate change effects.

Adam Hudson's overview of geologic information includes a review of the geologic time scale and major time periods and turning points in geologic time, an overview of plate tectonics and the geologic history of southeast Arizona, as well as more detailed information related to the specific geologic history of Chiricahua and Coronado. After this overview, he provides some detail on the life history of the super volcano that created the unusual formations at Chiricahua and on cave formation processes that explicate the life history of Coronado Cave at Coronado.

Erin Posthumus's and Jesse Minor's stories of the sky islands review the ways in which "island" as metaphor for the local biology parallels and differs from oceanic islands, the fire history of the sky islands, patterns of plant and animal diversity in sky islands, the climatological history of the sky islands and potential effects of climate change on vegetation and wildlife. They also include stories of particular relevance to Coronado, including migration and the responses of wildlife to natural and artificial barriers and the effect of recent activities in the area, including forest fires and construction of an international boundary on the migration and, indeed, survival of the lesser long nosed bat.

For each topic an annotated list of key references, as well as a fuller bibliography of recent references is included. The materials should provide interpretive developers and NPS staff, with the most current information on each topic. This is not intended to serve as exhibit text but as information guides for exhibit developers to draw on for interpreting each topic.

Acknowledgements

I wish to thank the NPS personnel involved, including Julena Campbell, Chief of Interpretation, Southeast Arizona Group, Katy Hooper, Park Ranger for Coronado and Suzanne Moody, Park Ranger for Chiricahua.

Special thanks to Mitchel P. McClaran, Ph.D., Professor of Range Management, School of Natural Resources and the Environment, The University of Arizona, for advice and guidance to all participants.

Current Research and Information for Exhibit Development on the Geology of Chiricahua National Monument and Coronado National Memorial, Southeast Arizona, USA

Adam M. Hudson, M.S.

Section 1: Geologic Time and the Geologic Time Scale

Key Points:

- The history of the Earth is 4.6 billion years long.
- Geologists refer to time periods longer than 1000's of years as 'deep time,' because humans have difficulty comprehending the great lengths.
- The Geologic Time Scale is a timeline of Earth's history agreed upon by all geologists. It is divided, in decreasing order of length, into Eons, which contain multiple Eras, which contain multiple Periods, which contain multiple Epochs.

Key Words:

Deep time – the term used by geologists to describe very long periods of time that are difficult for people to comprehend.

Geologic Time Scale – The timeline created by, and used by geologists to document, investigate, and compare Earth's history between places and times.

Eon – The largest division of the Geologic Time Scale, which includes the Hadean, Archaean, Proterozoic, Phanerozoic.

Era - The second largest major division of the Geologic Time Scale, which includes, in order, the Paleoproterozoic, Mesoproterozoic, Neoproterozoic, Paleozoic, Mesozoic, and Cenozoic.

Period – The third largest major division of the Geologic Time Scale. Each *Era* is divided into multiple Periods.

Epoch – The fourth largest major division of the Geologic Time Scale. Each *Period* is divided into multiple Epochs.

Science Summary:

Generating the Geologic Time Scale

Geologists realized early on that they needed a consistent system for documenting the timing of geologic events in order to compare them between field areas, different mountain ranges, or even different continents. This necessitated the birth of the **Geologic Time Scale.**[1] In early geologic study, prior to the discovery of radioactive decay in the late 19th century, the Geologic Time Scale was only *relative*, meaning that absolute ages for each time interval were not known.[2] At that time, geologic ages could only be reported as younger or older relative to a known, widespread geologic marker within rocks.

Initially, the most important relative datum were *fossil organisms*. These organisms, mostly ocean-dwelling, were preserved in **sedimentary rocks** formed from slow deposition on the ocean floor. The bodies of the organisms, particularly their shells, were buried, compacted, and lithified (turned to rock), where they could be exposed later by tectonic uplift and erosion for geologists to find. Because of changing conditions on Earth and in the food chain, many species evolved and went extinct, to be replaced by new species during the past 540 Million years of the fossil record. Geologists used (and still do) the appearance and disappearance of certain fossil species as time markers to relate sedimentary rock sequences across large distances. This is called **biostratigraphy** because it uses the evolution and extinction of widespread biologic organisms to order rocks into relative time intervals.

The second major relative dating method was discovered with the exploration of the ocean floor during and following World War II.[1] Studying the magnetic properties of **volcanic rock** called **basalt** on the sea floor, geologists realized that the magnetic field of the Earth has not always been oriented the way it is today. In fact, it has flipped between the normal and reversed orientation hundreds of times over the past 250 Million years. Because this magnetic switch affects the *whole* Earth, any volcanic or sedimentary rocks containing enough iron will preserve the past orientation of the magnetic field and can then be used to create a record of magnetic field orientation through time. By matching up the sequence of magnetic field changes between different areas, geologists can determine relative age for rocks. This is called **magnetostratigraphy** because it uses the sequence of magnetic pole reversals to order rocks into time intervals.

Magnetostratigraphy is not limited by geography the way biostratigraphy is because the Earth's magnetic field changes are felt worldwide. However, the magnetic time scale is limited to 250 Million years ago and later because no ocean basalts exist that are older than this.[1] Older ocean basalts have been subducted back into the mantle through the continuous renewal and destruction of oceanic crust by seafloor spreading and subduction (see Section 2).

Since the mid-20th century geologists have been able to assign numerical ages (years ago) to the relative Geologic Time Scale. This is due to the discovery of radioactivity and radioactive decay. By observing the decay of unstable atoms, scientists discovered that the radioactive decay of the parent isotope to a stable daughter occurs at a fixed, measureable rate. After accurately measuring this rate, geologists can then measure the amount of parent and daughter in a rock and calculate how long it must have taken to result in the measured amount. Thus absolute radiometric dating was born.

The usefulness of a radioactive isotope for dating rock sequences depends upon its abundance and half-life. The most commonly used radioactive isotope decay chain is the uranium-238/lead-206 chain. This is because uranium is relatively abundant in the Earth's crust and the half-life (the time it takes for half of the initial amount of parent to decay to daughter) is very long (4.5 billion years), so this decay chain can be used to date very old rocks. Uranium/lead dating is the principal way that we know the age of the Earth and it is used to date the oldest rocks exposed at the Earth's surface (more than 4 billion years old). For dating volcanic rocks specifically, the decay chain of potassium-40 to argon-40 (half-life 1.3 billion years) is also very useful because many volcanic rocks are rich in potassium in their melts and mineral phases. The Turkey Creek Caldera in the Chiricahua National Monument was dated in this way to 26.9 Ma (Ma = million years ago).

For much younger geological circumstances, less than 1 million years old, other techniques must be used. For cave speleothems, like those in the cave in the Coronado National Memorial the decay of uranium-234 to thorium-230, daughter products in the decay chain of uranium-238, are used. This method is useful for caves because uranium is often incorporated into the same site as calcium in speleothem minerals. It can very accurately date speleothems as young as a few hundred years, but nothing older than about 600,000 years old. The carbon-14 or 'radiocarbon' decay to common nitrogen-14 is useful only for circumstances <50,000 years old. However, it is of great utility for dating organic material because it contains abundant carbon. That is why radiocarbon dating is used in a huge variety of young geologic and archaeological research.

The Geologic Time Scale: Important time periods and points

For the purpose of the geologic history of southern Arizona, we will mainly focus on the Phanerozoic Eon from 541 Ma to present, containing the Paleozoic, Mesozoic, and Cenozoic Eras (see Fig. 1).[2] Although plenty of Precambrian rocks are found in southern Arizona, their origin is often difficult to determine and there is a significant 1 billion year gap in Precambrian time called the **Great Unconformity** for which there are no rocks represented.[3] In any case, the modern landscape of southern Arizona is not significantly affected by the presence of Precambrian rocks. Note that most of the names of the periods of the Geologic Time Scale have historical significance. Many were coined for the places where they were first described in the geologic record. The majority of these are in the British Isles and western Europe, and so have little direct significance in the U.S. However, the Mississippian and Pennsylvanian periods are named for type sections in the U.S. In Europe those periods correspond to the Lower and Upper Carboniferous Period.[1]

The **Paleozoic Era** begins at 541 Ma, which is intentionally a non-round number. The beginning of the Paleozoic is marked by the beginning of the fossil record, following the **Cambrian Explosion**, named for the first **period** of the Paleozoic. The Paleozoic Era continues for nearly another 300 million years until 252 Ma. The thickness and portion of the Paleozoic record preserved in rocks in southern Arizona varies, but it is generally well represented.

The **Mesozoic Era** follows the Paleozoic, beginning at 252 Ma. The beginning of the Mesozoic at 252 Ma is coincident with the initial breakup of the global supercontinent **Pangaea.**[1] By the end of the Paleozoic, nearly all of the continental crust on Earth's surface was incorporated together into one huge continental mass spanning the South Pole and the equator in the Southern Hemisphere. During Mesozoic time, Pangaea began to separate, starting the slow march of the continents into the widely distributed configuration we see today. The Mesozoic is mostly widely known as the age dominated by the largest land reptiles in geologic history, the dinosaurs. It is divided into the Triassic, Jurassic, and Cretaceous periods. The Cretaceous ends with the extinction of the dinosaurs at 66 million years ago.[2]

The **Cenozoic Era**, which contains the **Paleogene, Neogene,** and **Quaternary** Periods marks the rise of land mammals and extends from 66 Ma to present time.[2] It is divided into seven **epochs**, three in the Paleogene, two in the Neogene, and two in the Quaternary (Fig. 1).[2] In southern Arizona many rocks of Cenozoic age are exposed, but they are mostly volcanic or land-derived sediments rather than marine rocks. The Cenozoic is marked by mountain-building in the western U.S. and therefore most of the continental landmass has been above sea level during Cenozoic time.[1,3]

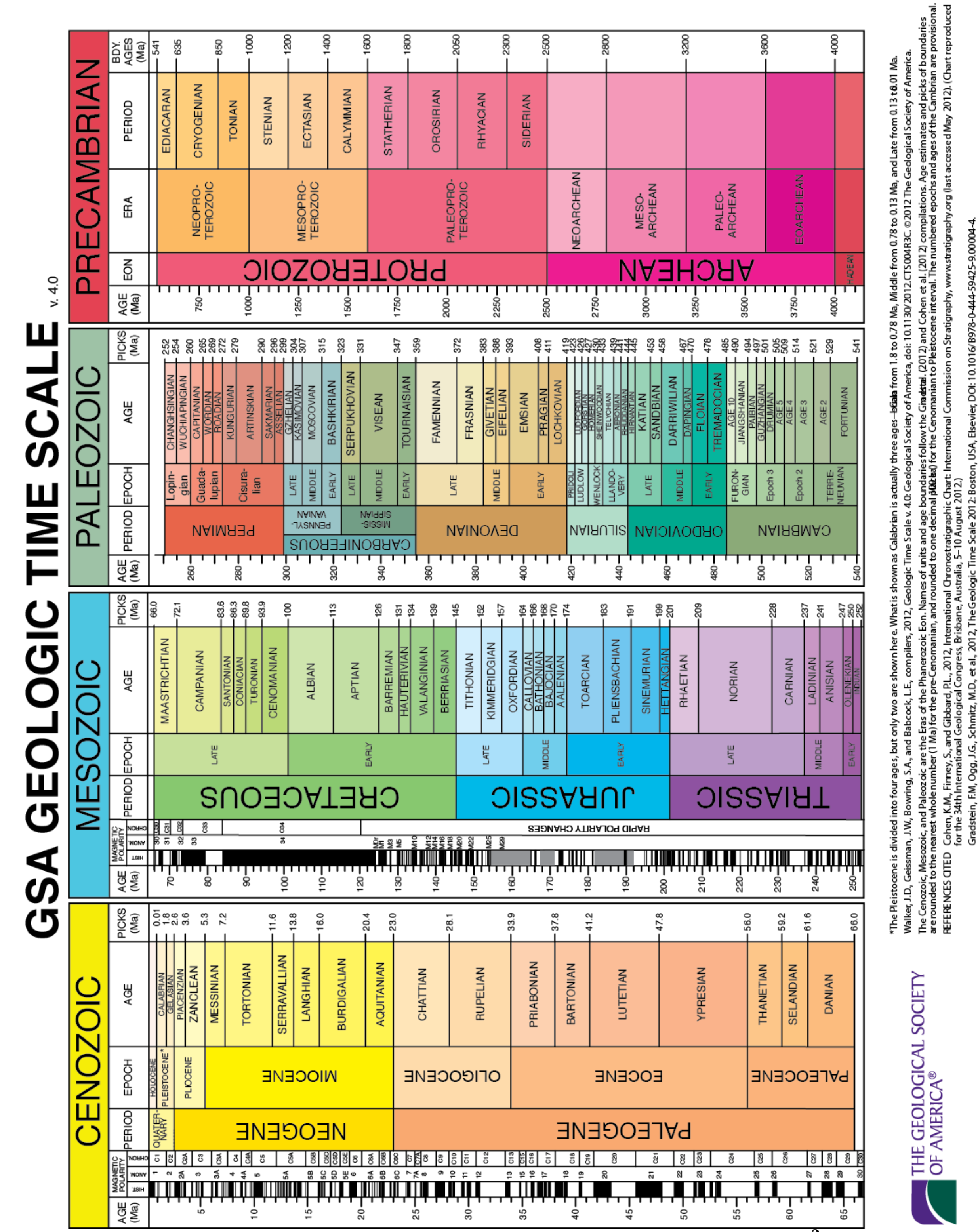

Figure 1. Geologic Time Scale for 2012. Adapted from Walker et al., 2012.[2]

Glossary of terms:

basalt – the dominant volcanic rock that makes up the ocean floor on Earth. It is derived directly from the molten mantle beneath Earth's crust.

biostratigraphy – a method of relative age dating for rocks that uses the appearance and extinction of certain fossil life or combinations of life to correlate the relative age of rock units between different places.

Cambrian Explosion – this term refers to the rapid appearance of a huge diversity of fossil life that occurred during the first period of the Paleozoic Era, starting 541 million years ago.

Cenozoic – the third Era of the Phanerozoic Eon, 66 million years ago to present.

Eon - the first major division of the Geologic Time Scale.

Epoch – the fourth major division of the Geologic Time Scale.

Era – the second major division of the Geologic Time Scale.

Geologic Time Scale – a timeline created and universally agreed upon by geologists that is used to order events in geologic history, give them ages, and correlate them to events across the globe.

Great Unconformity – a geologic unconformity refers to an interval of geologic time for which no rocks are preserved. The Great Unconformity is exposed across Arizona, but most famously in the Grand Canyon where it marked by an abrupt transition from basement rocks 1.6 billion years old to Paleozoic rocks 540 million years old with 1 billion years of time missing.

magnetostratigraphy – a method of relative age dating for geologic events based on using reversals in Earth's magnetic field to correlate the relative age of volcanic rocks' ages across the globe.

Mesozoic – the second major Era of the Phanerozoic Eon, 252-66 Ma.

Neogene – the second period of the Cenozoic Era, 23-2.6 Ma.

Paleogene – the first period of the Cenozoic Era, 66-23 Ma.

Pangaea – a global supercontinent that incorporated nearly all continental landmass on Earth assembled at the end of the Paleozoic Era 252 Ma.

Period – the third major division of the Geologic Time Scale.

Paleozoic – the first major Era of the Phanerozoic Eon, 541-252 Ma.

Quaternary – the third period of the Cenozoic Era, 2.6 Ma to present sedimentary rocks – one of the three major rock types, sedimentary rocks are formed sequentially by depositing sand, silt, or other small particles in layers, usually in a marine setting, but also in continental settings. Sedimentary rocks are deposited horizontally, get younger from bottom to top, and are the best preservers of fossils, and hence form the backbone of the geologic record.

unconformity – a contact between two rock types of very different age, usually indicating a period of erosion or simply no sediment deposition for long periods of time. Unconformities occur due to tectonic uplift, sea level change, volcanic eruptions or intrusions, or faulting, all of which place old rocks next to new rocks with a gap in time not represented by *any* rocks.

volcanic rock – one of the three major rock types, volcanic rocks are formed from the cooling of magma either at the surface as lava, or underground as crystalline rock like granite.

Select References (number corresponds to order of reference in this section of the text):

1.) Wicander, R., and Monroe, J.S., 2004, Historical Geology, Brooks/Cole – Thompson Learning, Belmont, California, 427 p.

2.) Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., compilers, 2012. Geologic Time Scale v. 4.0. Geological Society of America, doi: 10.1130/2012.

3.) Dickinson, W.R., 1989, Tectonic setting of Arizona through geologic time. *in* eds. Jenney, J.P., and Reynolds, S.J., Geological evolution of Arizona. Tucson, Arizona, Arizona Geological Society Digest 17, 1-16.

Section 2: Plate tectonic evolution and geologic history of southeast Arizona

Key Points:

- During most of the Paleozoic Era southern Arizona was situated on the passive western continental margin, similar to what we have on the east coast of the U.S. today. With no plate boundary nearby, not much mountain building or tectonic deformation occurred, just a lot of accumulation of marine sediments dependent on changing sea levels.
- During the late Paleozoic and Mesozoic Era southern Arizona was more tectonically active. The late Paleozoic is marked by the assembly of the supercontinent Pangaea, which juxtaposed continents Laurasia and Gondwana. By the Mesozoic, the subduction of the Farallon plate off the west coast of Laurentia resulted in extensive volcanism and mountain building, particularly during the Jurassic and Cretaceous periods. Much of the central and western U.S. was still below sea level, so there are a lot of marine sedimentary rocks accumulated during this time period, but also many **eolian** and **fluvial** rocks eroded and shed from the continental interior of Laurentia.

- During the Cenozoic Era southern Arizona continued to be tectonically active. Flattening of the subducting Farallon plate beneath North America resulted in uplift of the Rocky Mountains, which extended into Arizona. This is called the Laramide Orogeny. Most of the western U.S. was a high mountain range similar to the Andes during the early Cenozoic. By the late Cenozoic, the Farallon plate steepened again, letting hot mantle well up beneath North America causing rifting and volcanism. Basin and Range extension began coincident with this event, and continues under pressure of the San Andreas transform boundary. This continues to the present, and results in the topography of southern Arizona today with large flat basins and high 'Sky Island' mountain ranges.

Key Words:

Basin and Range Extension – the large extensional tectonic event that affected southern Arizona from around 30 Ma to present, caused by heating of the continental crust by mantle entering the space left by the steepened Farallon plate and tension along the San Andreas transform boundary.

fault – a geologic formation where rocks are bowed or pulled beyond their strength and a break occurs, often resulting in juxtaposition of rocks of very different ages.

fold – a geologic formation where previously flat sedimentary rocks are bowed and kinked like a rumpled carpet in response to compressional plate tectonics.

Gondwana – The southern of the two supercontinents, it contained South America, Africa, Australia, and Antarctica.

Laramide Orogeny – the large Cenozoic mountain-building event (orogeny means mountain-building) caused by the subduction of the Farallon Plate beneath the North American Plate (all of the western U.S.), which resulted in the uplift of the present day Rocky Mountains.

Laurasia – The northern of two supercontinents assembled during the Paleozoic Era, it contained North America and Eurasia.

Laurentia – The Mesozoic and later equivalent of the North American continent. Following the break-up of Pangaea, Laurentia refers to the continent west of the early Atlantic Ocean.

passive margin – a region of continental plate where no tectonic activity is occurring, usually resulting in slow accumulation of flat layers of marine rocks.

rifting – The process of separating tectonic plates by the upwelling of hot magma from the mantle forcing the plates apart and adding new crust to the separating plates.

subduction – The process by which an oceanic plate and a continental plate are smashed into each other, wherein the denser oceanic plate slides under the continental plate, leading to mountain-building, volcanism and deformation of the continental plate.

Science Summary:

A Note on Plate Tectonics: the dominant geologic theory that guides all geologic research is that of plate tectonics. The theory states that the surface of the Earth is divided into distinct semi-rigid 'plates' of crust, which move around in response to currents of convection within the underlying hot mantle. Plates come in two flavors: continental and oceanic. Continental plates form the continents, and are generally thicker, less dense, and 'float' higher on the mantle than oceanic crust. Oceanic crust is thinner, denser, and composed of basalt created at mid-ocean ridges. Depending upon their geographic and tectonic configuration at different points of geologic time, the plates may move towards or away from each other, resulting in extensional or compressional boundaries between plates. Tectonics, the movement of rocks due to plate influences, acts mostly at these plate boundaries, while the centers of plates are more quiescent places.[15] All of the discussion below about southern Arizona geologic history is placed in a plate tectonic framework.

Geologic conditions in southern Arizona have changed significantly over the course of Earth's history due the assembly and break up of two super continents, multiple mountain-building and collapse episodes and periodic rise and fall of global sea levels. During the Phanerozoic alone, southern Arizona has traversed over 60 degrees of latitude due to continental drift, from as far as 20° S to nearly 50° N, and back to the present position.[1] Much is still unknown about the specifics of these events, and the picture becomes more uncertain with increasing age. For that reason, I've chosen to focus here only on the Phanerozoic Eon of geologic history of southern Arizona beginning with the Paleozoic Era (Fig. 1). Before this point in time (around 541 Ma), there is no rock record, due to the Great Unconformity, and the Precambrian rocks of the Proterozoic and older are intensely deformed by multiple cycles of mountain-building and volcanism to the point where most information about the Earth's surface during those time periods is speculative and uncertain. Rocks of the Paleozoic, Mesozoic and Cenozoic Eras, on the other hand, are well represented in southern Arizona, and tell a coherent story about the region's history all the way up to the present.

Accordingly, the Cambrian **Bolsa Quartzite** represents the first period of the Paleozoic Era in southern Arizona.[2] This widespread unit, which appears in the sedimentary sequence of most Sky Islands was deposited in shallow sea water off the northwestern coast of the continent in the paleo-Pacific Ocean. This was connected to the east with the now closed **Iapetus Ocean,** which separated the continent of **Laurasia** (which eventually contained the core of the North American continent along with the Eurasian continent) from **Gondwana** (an amalgamation of the African, South American, Australian and Antarctic continents). The Bolsa Quartzite and subsequent Paleozoic marine rocks were deposited in a **passive margin** setting similar to that on the U.S. east coast today.[2] The nearest plate boundary was located in the Pacific Ocean, at a **mid-ocean ridge**, far away from southern Arizona. Therefore, the region was not tectonically active for most of the Paleozoic. Between the Cambrian (starting 541 Ma) and the Mississippian Periods (ending 323 Ma), sea level rose and fell many times in southern Arizona, likely due to growth and melting of ice sheets like modern Antarctica, which take water out of the global ocean and lower sea level.[3] Southern Arizona was almost continually below sea level, more than anywhere else in Arizona, but by the late Devonian Period, the coastline was more southwest-facing rather than northwest-facing, more towards the Iapetus Ocean.[3] The deepest marine waters occurred during the Mississippian, when southern Arizona was likely under several hundred feet of water.[1]

By the Pennsylvanian (starting 323 Ma), the regions of Laurasia to the northwest and east of Arizona (corresponding to Nevada and Utah to the west, and regions of Texas all the way through Arkansas and into the Appalachian states to the east) were undergoing severe mountain-building. The passive margins that were previously located along their coasts were replaced by **convergent plate boundaries** which uplifted the currently low relief Ouachita and Appalachian Mountains to heights rivaling the Himalayas. Southern Arizona was located in the interior of the continent and therefore escaped most of the **folding**, **faulting** and compression associated with these events. It was, however, warped down farther below sea level due to the weight of extra crust being added and deformed to the south and west.[1] At these low elevations, deep marine rocks continued to form until the late Permian Period (around 260 Ma) when the supercontinent Pangaea was assembled.[4] Southern Arizona was then above sea level and undergoing **erosion**, so no rocks are preserved for the end of the Permian or the Triassic Period.[5]

A major tectonic change, starting during the early Jurassic and continuing into the early Cretaceous, is manifested in southern Arizona by numerous volcanic rocks ranging about 190-150 Ma in age. These rocks include initial volcanic lava flows and magma bodies intruding the existing Precambrian and Paleozoic rocks, followed by many large **caldera**-type eruptions continuing into the Middle and Late Jurassic ~160-150 Ma.[6,7] These rocks are accompanied by **eolian** sedimentary rocks of Jurassic age, and finally capped by the sedimentary rocks of alluvial origin shed from eroded new mountain ranges. These Jurassic rocks outcrop in most mountain ranges in southern Arizona including the Tucson, Rincon, Sierrita, Santa Rita, Baboquivari, Dragoon and Huachuca Mountains. Together with many similar-aged rocks to the west, the earliest units tell the story of a Jurassic volcanic arc, which was located near the continental margin of the North American continent (Laurentia at the time). This arc would have consisted of volcanoes with slow-cooling magma chambers beneath them, similar to what is found in the Pacific Northwest or the Andes today.[8] The late Jurassic and Cretaceous volcanic rocks represent a change in tectonic stress from compressional to extensional, which manifested in huge **caldera** eruptions. The tectonic setting for the late Mesozoic calderas is characterized by **rifting** (extensional), associated with the injection of hot mantle material into the space left by a steepening subducting plate (Fig. 2).[8] This type of rift commonly leads to large caldera-type eruptions where hot magma from the mantle passes into the overlying continental crust (Precambrian through Paleozoic rocks, mostly), melting them and creating huge magma chambers (see Section 5). Extension in a direction perpendicular to the continent (southwest to northeast in this case) is driven by convective activity and bolstered by weakening of the crust through magma intrusion. This weakening and convective force stretches the crust like a taffy pull. Notably, the Jurassic Montezuma caldera exposed in the Coronado National Memorial in the Huachuca Mountains is one of the many caldera eruptions associated with intra-continental rifting.

As the subducting Farallon plate steepened, the focus of constructive arc magmatism moved southwest into northern Sonora and possibly the Baja Peninsula (Fig. 2 Step 3). By early Cretaceous time, terrestrial sedimentary rocks (preserved as the Bisbee Group in southern AZ) were shed into the extensional rift basins, similar to what occurs in the Basin and Range today.[6] Shallow marine rocks are preserved near the top of section, indicating that at least for the southern Bisbee formations, the region was under shallow ocean water during the Cretaceous period. This is associated with a deep rift connecting to the early Gulf of Mexico. Similar rocks are preserved in the Chiricahua Mountains.[9]

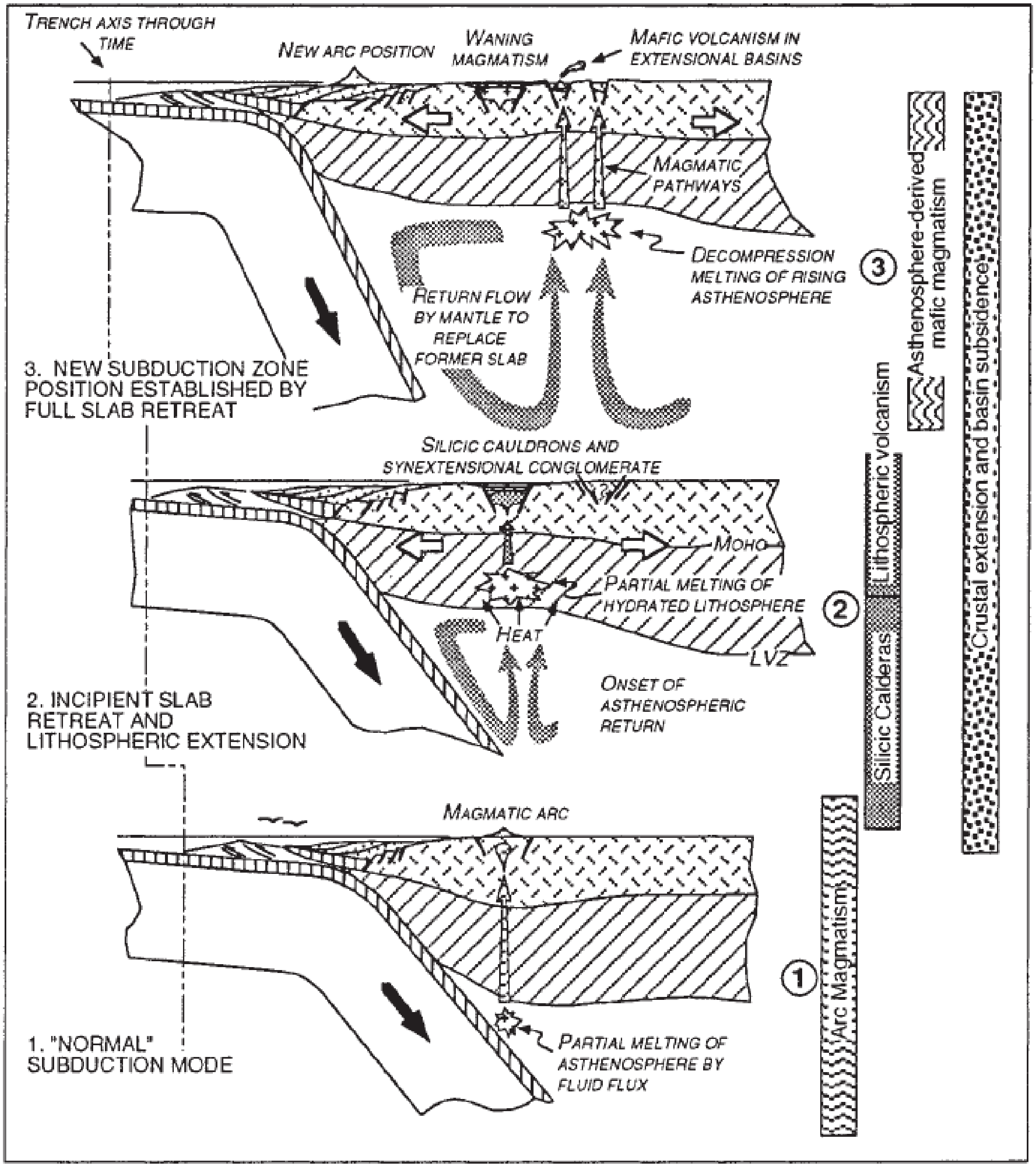

Figure 2. Plate tectonic mechanism for continental rifting above a steepening subducting plate. Adapted from Figure 4 of Lawton et al. (1999).[8]

By the end of the Cretaceous, southern Arizona was beginning to feel the effects of the **Laramide Orogeny** as the subducting plate shallowed again, causing a return to compressional tectonics.[8,9] This compression pushed southern Arizona above sea level, and upper Cretaceous rocks only appear as deposition in alluvial fans and riverbeds, similar to what is found in Arizona basins today. The Laramide Orogeny was a huge continental-scale mountain-building event that stretched from northern Canada to southern Mexico. It resulted from subduction of the Farallon plate under the North American plate and has many different manifestations throughout the Rocky Mountains. Laramide deformation is thought to begin as early as 80 Ma in the northern part of the continent (called the Sevier Orogeny), but does not occur until 70-40 Ma in most of the Rockies.[10] Most Sky Islands in southern Arizona, including the Huachucas and the Chiricahuas, preserve compressional structures of Laramide age.[11] These structures are large folds within existing Paleozoic and Mesozoic sedimentary rocks (the aforementioned marine rocks) and faults, which break through these rocks and place older rocks above and next to younger rocks in the stratigraphic sections. The compressional deformation was very extensive in Arizona, and it is further complicated later by Basin and Range faulting, contributing to the very complex geologic patterns found within the Sky Islands. In Arizona and New Mexico, Laramide deformation may have continued into the Oligocene Epoch, as late as 28 Ma.[12]

The transition to extension following the Laramide is signaled by continental rift calderas began erupting in southern Arizona as early as 28 Ma. This rifting event likely echoes the Jurassic rifting episode, as the Farallon plate steepened once again and hot mantle material began intruding and melting the thickened continental crust of the North American plate (Fig. 2).[8] Caldera eruptions associated with this rifting event are incredibly numerous in the San Juan Mountains of Colorado, and in the Sierra Madre Occidental of Mexico and Arizona. Within Arizona, fewer calderas erupted during this time period, two of which: the Portal caldera, and the Turkey Creek caldera, are both located in the Chiricahua Mountains,[13] but none of this age are located in the nearby Huachuca Mountains.

Extensive volcanism was also associated with widespread tectonic extension within the North American plate. Areas of southern Arizona, which were previously higher in elevation than those north of the Mogollon Rim, were brought to much lower elevation by this extension.[14] This is the beginning of **Basin and Range** tectonics in Arizona. Heating of the North American continent by mantle magma following the steepening of the subducting plate eventually softened rocks enough to begin extension by **ductile** processes. Under high enough temperatures, rocks behave like taffy and most of the early Basin and Range deformation was accomplished in this way along fault-like zones of detachment.[14] The rocks exposed in the western Catalina Mountains near Tucson are an excellent example, where deformed rocks are exposed at the surface. The adjacent Tucson Mountains, west of the city, were formerly above the Catalinas, but slid along the ductile detachment to their current position many miles to the west. As extension progressed, the hot, buoyant rocks below the **detachment zones** floated upward, and as they came up, their temperature cooled. By around 13 Ma, most detachment zones had cooled enough that extension now occurred in a brittle manner, where the solid rocks had to break in order to pull farther apart.[14] This type of brittle extension characterized the Basin and Range up to the present.

Clearly, the tectonic history of Arizona is long and complex, representing several episodes of compression and extension, which resulted in the final mosaic of rock units exposed in the Sky Islands of southern Arizona. Our understanding of the specifics of geological evolution in individual mountain ranges continues to improve, but much is still unknown, and because so much rock has been lost to erosion, faulting, and melting, there are things we will never know in detail. Southern Arizona, luckily has as complete a section of rocks, with the fewest unconformities of any location in the state, which allows geologists to provide the detailed reconstruction outlined above. The rocks exposed in both the Coronado National Memorial (Jurassic) and the Chiricahua National Monument (Neogene) are coincidentally very similar, resulting from two separate episodes of rifting and explosive caldera volcanism. Amazingly, in spite of the "recent" activity, the entire Phanerozoic geologic history of Arizona is preserved within the existing Sky Islands.

Exhibit Development Note: A similar overview description of the geologic history of southeast Arizona is given in the 2011 Geologic Resources Report for Coronado National Memorial,[5] which includes more detailed information. It also contains many useful illustrations including basic geologic concepts like faulting (p. 8), folding (p. 25) and plate tectonics (p. 34), along with several instructive 'geographic' maps showing what the continent looked like through different periods of geologic history (p. 33-36) that are likely to be useful for exhibit development. In addition, any introductory university-level Historical Geology textbook will have numerous illustrations of fundamental concepts of plate tectonics as well as paleogeographic maps for the world through geologic time. I recommend the textbook 'Historical Geology' by Wicander and Monroe, now in its seventh edition, but any edition will do (the fourth edition is cited here[15]).

Glossary of terms:

Basin and Range Extension – the most recent tectonic event in Arizona, named for the province in the western U.S. it created. It is characterized by extension of the continental crust of North America and results in the Sky Island topography of Arizona we have today.

Bolsa Quartzite – the oldest Paleozoic unit (Cambrian) deposited in southern Arizona in a near-shore marine environment.

caldera – a huge volcanic eruption feature, wherein a large amount of melted continental crust is evacuated explosively all at once from a subsurface magma chamber, causing the most devastating volcanic eruptions in the geologic record.

convergent plate boundary – a boundary between two plates of Earths' crust that are being pushed together, which generally results in folding, faulting and extensive mountain-building.

detachment zone – a wide planar zone of ductile deformation along which rocks deep (15-20 kilometers deep) under the Earth's surface can slide past each other for long distances to accommodate crustal extension.

ductile – rocks heated to high enough temperatures will deform like clay, flowing instead of fracturing and faulting, but without melting.

eolian – refers to sediments transported and deposited by wind; sand dunes are an eolian environment.

erosion – the geologic process by which existing rocks at the Earth's surface are destroyed and removed from the area by flowing water (rivers, ephemeral flow in washes) or wind, and deposited anywhere from nearby to the other side of a continent.

fault - a geologic formation where rocks are bowed or pulled beyond their strength and a break occurs, often resulting in juxtaposition of rocks of very different ages.

fluvial – refers to sediments transported and deposited by rivers.

fold – a geologic formation where previously flat sedimentary rocks are bowed and kinked like a rumpled carpet in response to compressional plate tectonics.

Gondwana - a supercontinent assembled in the Southern Hemisphere and extending to the South Pole during the Paleozoic Era, composed of parts of Africa, South America, Australia, and Antarctica.

Iapetus Ocean – an ocean that no longer exists, which was situated between the supercontinents of Laurasia and Gondwana during the Paleozoic Era.

Laramide Orogeny – the last major mountain-building event in the U.S. associated with shallow angle subduction of the Farallon plate beneath North America, and resulted in the Rocky Mountain uplift.

Laurasia – a supercontinent assembled near the equator extending to the Southern Hemisphere during the Paleozoic Era, composed of parts of North America, Greenland, and Eurasia.

mid-ocean ridge – a ribbon of extensive basalt volcanism that continually creates new oceanic crust in the middle of oceans, causing the crust on either side to spread apart. This is one of the driving forces of plate tectonics, as seafloor spreading pushes the oceanic plates into subduction zones at their opposite edges.

passive margin – a continental coast that has no plate boundary; as a consequence no deformation occurs and flat-lying layers of marine sedimentary rocks are deposited.

rifting – the plate tectonic process by which the upwelling of hot melted mantle rock heats and thins the continental or oceanic crust, resulting in lots of volcanic eruptions, magma chambers, and tectonic extension.

subduction – the plate tectonic process by which an oceanic plate and a continental plate collide at a convergent margin. The more dense oceanic plate always slides below the continental plate, resulting in a subduction zone. The area where the plates overlap is marked by violent volcanism and building of some of the highest mountains on Earth. The modern Andes is an excellent example.

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Section 3: Park-specific geologic history – Chiricahua National Monument

Key Points:

- Rocks of all ages from Precambrian to Holocene are exposed in the Chiricahua Mountains, generally depicting the regional geologic history outlined in Section 2, but the area within the Chiricahua National Monument is dominated by the volcanic rocks of the pre-caldera Faraway Ranch Formation and the tuffs erupted from the Turkey Creek Caldera.
- The Turkey Creek Caldera erupted at 26.9 Ma (Late Oligocene) as a one of two caldera eruptions (the Portal caldera is the first, but their ages are indistinguishable) associated with continental rifting during the transition from Laramide compression to the initial phase of Basin and Range extension in southern Arizona.
- The spectacular spires of the Monument were formed over millions of years through erosion by water and ice seeping into vertical joints formed by cooling contraction and bowing up from below in the ignimbrite of the three outflow layers of the 26.9 Ma Rhyolite Canyon Tuff.
- The deep erosion of the Chiricahua Mountains into steep canyons following its uplift as a Sky Island characterizes the modern state of the range today.

Key Words:

caldera – named for their 'cauldron' shape, this type of volcano is the most catastrophic type, resulting in huge eruptions of gas and water-charged tuff evacuating a subterranean magma chamber.

ignimbrite – a type of tuff erupted specifically during caldera-type eruptions, usually characterized by huge outpourings of ash, rock fragments, mineral crystals and molten lava carried in suspension by steam, and other dense volcanic gases with temperatures up to 900° Celsius (1800° Fahrenheit).

joint – a fracture or crack surface or system of cracks in rock usually developed in preferential directions due to internal stress or external movement of the area surrounding the rock.

resurgence – the process of the floor and area surrounding an erupted caldera bowing up in response to magma refilling the evacuated magma chamber below.

rhyolite – a type of volcanic rock erupted from caldera-type volcanoes as lava flows rather than ignimbrite eruptions.

tuff – a volcanic rock consisting of consolidated volcanic ash erupted into the air and then settled within and around the erupting volcano or vent. Can be erupted from any type of volcano.

Science Summary:

The most spectacular view that visitors see in the Chiricahua National Monument is the **geomorphic** features of the Rhyolite Canyon Tuff. To fully understand how the beautiful spires that characterize the landscape were formed, one has to understand the tectonic setting, geologic timeframe, and sequence of events especially over the last 30 Ma.

In Section 2, on the geologic history of southern Arizona, the general tectonic setting and geologic events for the whole Phanerozoic Eon were reviewed with an emphasis on the broad plate tectonic changes and the resulting rock types. Much of what was reviewed there is directly applicable to explaining the sequence and age of the rocks that are exposed in the Chiricahua Mountains. Like many mountain ranges in southern Arizona, the Chiricahuas host rocks of Precambrian age, overlain directly by Paleozoic marine rocks deposited on the passive continental margin of Laurasia (later Laurentia), separated by the Great Unconformity. The compressional tectonic environment of the early Mesozoic (Triassic and Jurassic) extensively folded and faulted the Paleozoic section in the Chiricahuas, which were then recycled by erosion into the Lower Cretaceous Bisbee Group rocks deposited unconformably on top of them. The mountain uplift of the early Mesozoic means no rocks are preserved of this age, another unconformity in the region. The Bisbee Group rocks, deposited in variable land and marine environments during the Cretaceous, have also been deformed by subsequent mountain-building and uplift during the Laramide Orogeny. Land-derived sediments, particularly river deposits and lake deposits unconformably overlay the Bisbee Group and were likely deposited in early Basin and Range-type valleys. These rocks are undated directly, but must be older than the 31-33 Ma mafic volcanic rocks that **intrude** them and overlay them.[1,2] The interpretation is that these sedimentary rocks represent a set of early basins and ranges present during and after the Laramide, but before the eruption of the Turkey Creek Caldera. Significant extension of the crust in an east-west direction was already occurring by 30 Ma in southern Arizona.[1,2]

As is commonly the case with extension within continental crust, the east-west stretching was accompanied by significant volcanic activity. Extension and volcanics go hand in hand: thinning of the crust via ductile deformation and faulting creates space and paths for mantle magma to intrude continental crust; all of the heating and magma intrusion melts continental crust, generating new magma with crustal composition and further weakens the crust, promoting further east-west extension. Because continental crust is **felsic**, and less dense than mantle magmas, large magma chambers of felsic **rhyolite** melt formed within the **country rock** over the basalts. These felsic melts are also very viscous, so they do not flow easily like basalts. They can build up a lot of pressure until a threshold point is reached and no more pressure can be accommodated by the magma or the roof of old country rock over the magma chamber. When this happens, huge amounts of magma can be mobilized and violently erupted onto the surface (see Section 5 for a more detailed description of caldera eruptions). This happened numerous times along the rift system from southern Colorado to central Mexico, but the two calderas, the Portal caldera and the Turkey Creek caldera, both found in the Chiricahuas, are the only post-Laramide eruptions in southern Arizona.

The Portal caldera erupted first, based on the fact that rhyolite from the Turkey Creek caldera partially fills the Portal caldera valley (in the Cave Creek valley near Portal, AZ), an impossible circumstance unless the Portal eruption occurred first.[2] It is speculated that the Jesse James Canyon ignimbrite in the Monument, which is known to have erupted from an earlier caldera, may have erupted from the Portal caldera, but that is unconfirmed.[1] The rhyolite **tuff** or **ignimbrite** that was erupted from the Portal caldera is also very thick on the eastern side of the Chiricahua Mountains. There are published potassium/argon ages for the Portal caldera, but they are not distinguishable from those from the Turkey Creek Caldera, indicating they likely occurred close to each other in time. The Turkey Creek Caldera, the actual crater of which is located south of the Monument, erupted catastrophically in three separate, but closely timed bursts of hot ash buoyed on water vapor and other gases escaping the over-pressurized magma chamber through the ring fracture (Fig. 3).[1] Each of these three 'members' of the **Rhyolite Canyon Tuff** were deposited in the crater left by the collapse of the caldera into the empty magma chamber and as **outflow** on the land surface surrounding the Turkey Creek volcano. The surrounding area was already somewhat mountainous, being built up by Laramide compression and more gentle and sequential eruption of lavas which form the Faraway Ranch Formation (30-33 Ma).[1] The flow of the eruption would have proceeded downhill, likely in a dominantly north direction, indicating the past topography of the Chiricahuas dipped northward prior to eruption[3]. The three members, Lower, Middle and Upper, are all exposed in the Monument today. The lower two members are the most **welded**, and they form most of the spires, particularly the Middle member. The Upper member is less welded and was more easily eroded. It is preserved best as a gentle slope beneath the capping dacite of Sugarloaf Hill.

The major caldera-forming eruption escaped through a ring-shaped fracture that was probably similar in size and shape to the underlying magma chamber, while the center of the caldera crater may have collapsed as one or several blocks into the evacuated space. This **caldera roof** is not exposed anywhere in the Turkey Creek caldera because it has been covered by tuff, and by subsequent eruptions of less explosive lava, also transported up through the **ring fracture** surrounding the crater margin (Fig. 3). This lava, a **dacite** with a slightly less felsic composition intruded beneath the caldera crater after eruption from a magma chamber farther below, bowing up the crater center into a **resurgent dome**. Some of the lava that escaped through the ring fault also flowed out of the crater, down a valley and over the Rhyolite Canyon Tuff within the Monument.[1] This dacite lava flow is preserved only as a tiny remnant, which armored the top of Sugarloaf Hill against erosion and causing it to stand higher than the surrounding area today.

Following the eruption of the Turkey Creek Caldera, southern Arizona continued to host volcanic eruptions and deformation associated with Laramide compression and incipient Basin and Range extension. For the Chiricahuas, it was most likely extensional tectonics at play, since many extensional faults cut through the Rhyolite Canyon tuff and earlier rocks of the Monument, specifically near the western range front and in the far eastern end of the Monument. These north-south trending faults are characteristic of the overall east-west stretching of the continental crust during Basin and Range extension. These faults drop portions of crust and unroof other portions, which rise because they are warm and less dense than the mantle, creating Sky Islands.

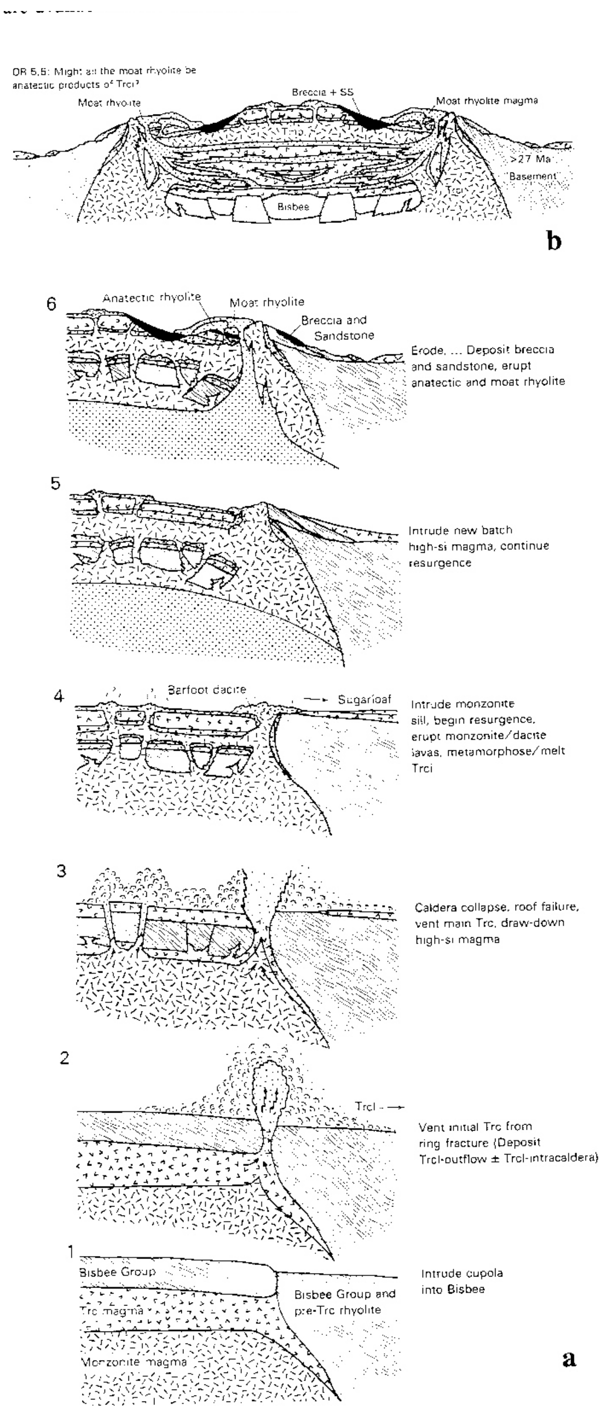

Figure 3. Eruption, collapse and resurgence sequence for the Turkey Creek Caldera of the Chiricahua Mountains. Adapted from Pallister et al., 1990[3] Figure 10.

Because the Sky Islands are high mountain ranges, they receive a lot of storm activity and are very susceptible to erosion. Erosive processes have been occurring in the Chiricahuas since well before the eruption of the caldera, but the spires exposed today are relatively young. Based on the rate of erosion through the full thickness of the Rhyolite Canyon Tuff, it is estimated that even the tallest spires (120 feet or higher) in the Monument are unlikely to be more than 3 million years old, and most are likely younger than this.[1,3] Even though the many of the spires are large and tall, their size is small compared to the amount of material that must have been removed to form the canyons of the Monument. Over the last 27 million years, as much as 36 billion cubic meters of tuff has been eroded from within the Monument, mostly by the creation and falling of generation after generation of columns slowly eroded and carried down the valley into the basin to the west.[3] The columns seen today are only the latest generation being slowly eroded by wind, water and ice.

Formation of the Spires of the Monument

In his PhD dissertation at the University of Arizona, D.B. Hall[4] conducted the only comprehensive study of the **geomorphology** of the spectacular spires formed in the lower and middle members of the Rhyolite Canyon Tuff. Using a combination of aerial photography and field observations, he carefully measured the size and shape of hundreds of the blocks making up the spires in the Rhyolite Canyon and Heart of Rocks areas of the Monument. He found that most blocks are rectangular to cubic, generally 10-15 feet on each horizontal face, and usually 10-15 feet high, although many spires are taller, consisting of several stacked blocks with joints in between.[4] The edges of each block are defined by **joints** in the tuff located roughly perpendicular to one another in two vertical planes and one horizontal plane, forming cube-like shapes. Based on the orientation of the joints, it is likely that they formed when zones of weakness created by cooling of the tuff were stressed by resurgence of the caldera. As the magma chamber below the caldera refilled over 1 million years after the eruption, the Earth's surface was pushed up like a bubble (Fig. 4). The Rhyolite Canyon Tuff of the Monument, although not over the caldera itself, was bowed up as well, and it cracked along zones of weakness in the rock to form the rectangular blocks of the incipient columns.

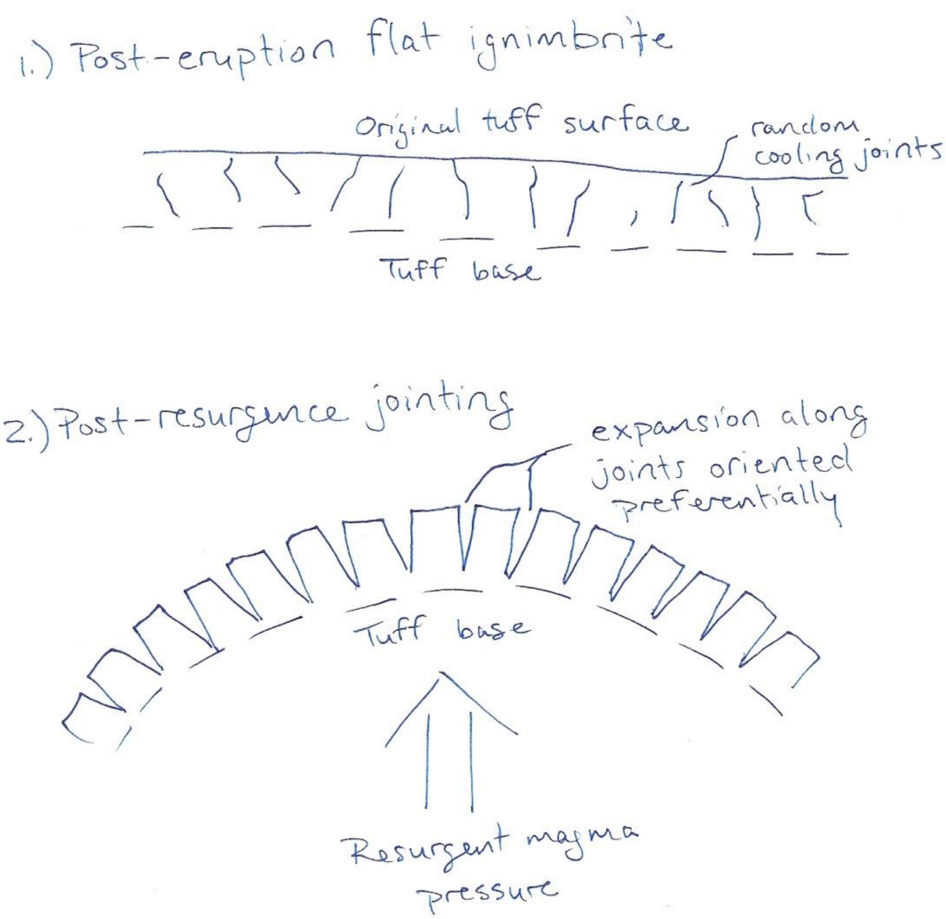

Figure 4. Schematic illustration of preferential jointing in the Rhyolite Canyon Formation caused by resurgence of the Turkey Creek Caldera.

The spaces between columns, initially very small, are widened by water movement along the joints, usually near the ground or in the soil. Very little water erosion occurs above the ground. Below ground level, water can dissolve the minerals of the rock, widen cracks by the expansion of ice and carry material out during storms. This was presumably more effective during wetter, colder, glacial periods during the last 2 million years, with less erosion occurring during the intervening warm periods like we are experiencing currently (See Section 6). Hall concluded that the columns of the Monument are actually very stable, and do not fall often, despite their precarious appearance. There is little evidence of toppled blocks near to the spires or in the canyons today, supporting this conclusion. They instead are slowly degraded by surface weathering, possibly punctuated by infrequent very strong earthquake activity that causes many columns to fall all at once. However, the most recent earthquake of sufficient magnitude must have been several million years in the past, allowing time for all of the toppled blocks left behind to be weathered to sand and carried out of the canyons.

Exhibit Development Note: Credit is due to John Pallister and Edward du Bray of the U.S. Geological Survey, who put years of work into mapping and interpreting the geology of the Monument and surrounding mountains and whose publications[1,2,3] should be the first resource for accurate text and illustrations to be adapted for exhibits. Their publications, especially the interpretive map and pamphlet,[1] have several illustrations that can be easily drawn from. The state of their understanding remains the closest to the geologic 'truth' for the area, despite it being nearly 20 years old. For the geomorphology of the spires of the monument, D.B. Hall's PhD dissertation[4] remains the most in depth study, although there are few figures useful for exhibit development.

Glossary of terms:

caldera roof – the preexisting rocks above the magma chamber prior to eruption of the caldera, which sink into the crater of the caldera as one or many pieces after the eruption.

dacite – a type of volcanic rock with 60-70% SiO_2 content, less felsic than rhyolite.

felsic – a descriptor for volcanic rocks with high SiO_2 content, the more SiO_2, the more felsic. Felsic rocks are generally derived from melting of continental crust and left over melt after less felsic minerals (stable at higher temperatures) have been removed. Common in caldera magma chambers.

geomorphology– the study of the land forms at the Earth's surface and the processes that shape them.

outflow – the portion of tuff from a caldera eruption that flows out of the caldera crater onto the surrounding land surface.

resurgent (dome) – the doming upward of the center of a collapsed caldera floor and surrounding land surface caused by new magma refilling the evacuated magma chamber after caldera eruption.

ring fracture – the ring-shaped break in the caldera roof that develops near to the edge of the magma chamber and allows the ignimbrite flows to escape. It is often then filled with lava flows from below, which cools to form a distinct ring of rock defining the caldera margin.

rhyolite – a type of volcanic rock with >70% SiO_2 content, usually erupted in pre- and post-caldera eruptions.

welded (tuff) – welded tuffs are formed by compaction of eruptive flows under high heat, which makes them harder and more resistant to weathering, and also results in bubbles and circular glass regions to become flattened and elongated.

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Section 4: Park-specific geologic history – Coronado National Memorial

Key Points:

- Almost all of the Coronado National Memorial is within the boundary of the Jurassic Montezuma caldera, which erupted during a period of continental rifting in southeastern Arizona, similar to the geologic context of the Turkey Creek caldera of Chiricahua National Monument.
- The northern part of the Memorial hosts the Jurassic (168 Ma) Huachuca Granite, which is the remnant of a cooled magma chamber that likely caused resurgence of the Montezuma caldera. Within it, large blocks of Paleozoic marine limestone are preserved, one of which hosts the Coronado Cave.
- Subsequent Laramide age compression and Basin and Range extension have created several large faults within the caldera rocks and the Huachuca granite, that put land-

derived sedimentary rocks of Cretaceous age in the middle of Montezuma Canyon, and Paleozoic marine rocks next to the Jurassic caldera rocks to the east of the Memorial.

- Basin and Range extension in the late Cenozoic resulted in the uplift of the Huachuca Mountains as a Sky Island, featuring the complex mosaic of rock types that characterizes most ranges in southern Arizona.

Key Words:

granite – a rock formed as a felsic remnant of a magma chamber that cooled underground without erupting to the surface.

limestone – a sedimentary rock formed in the ocean by accumulation of the shells of tiny organisms all the way up to seashells and the skeletons of corals, all of which get buried and preserved as layers of rock.

Science Summary:

An interesting connection between Chiricahua National Monument and Coronado National Memorial, geologically, is that they both sit on former caldera supervolcanoes. In the case of Coronado, the Montezuma Caldera, located at the far southern extent of the Huachuca Mountains, was the first in a series of caldera-type eruptions during the late Jurassic (~150-170 Ma). The regional tectonic setting for the caldera eruption is related to subduction beneath the North American continent from the southwest beginning in the early Jurassic, with rifting within the continent by the late Jurassic (see Section 2).[1] Since calderas are usually associated with extensional rift tectonics, it is no surprise that they occurred during this time. The Montezuma eruption is undated directly, but it was likely followed closely by the resurgent filling of the magma chamber by the Huachuca Granite.[2] The Huachuca Granite is dated to 168 Ma, or late Jurassic.[3] The Huachuca Granite is a prominent feature within the Memorial, and forms the pink cliffs of Montezuma Peak overlooking Montezuma Canyon.

The Montezuma caldera is ~140 million years older, and therefore it is very poorly preserved and the caldera margins are not delineated by a ring fracture like those in the younger calderas of the Chiricahua Mountains. The outflow tuff from the Montezuma caldera is preserved to the north in the Mustang Mountains, where it has been separated from the eruption crater by Basin and Range extension.[2] Just east of the Memorial, the intra-caldera ignimbrite that would have filled the crater during eruption is preserved, but within the Memorial, only a small band of it is located on the southern side of Montezuma Canyon, due to faulting. The small band is overlain by the outflow tuffs of the nearby Late Jurassic Turkey Canyon caldera (not to be confused with the Oligocene Turkey Creek caldera of Chiricahua; apparently there are many turkeys in Arizona), that erupted from the Canelo Hills just west of the Huachuca Mountains.[2] This kind of overlapping of flows from multiple calderas is common, and can be very difficult to decipher, especially when additional faults have moved things around.

A minor compressional **thrust fault** is located just east of the Memorial, which thrusts a sheet of rocks containing older Paleozoic marine sediments, Montezuma caldera tuff, and Cretaceous marine sediments, over the Huachuca Granite (Fig. 5). The fault is marked by a transition from the blocky pink granite to the eastward-sloping linear bands of sedimentary rocks visible from the Montezuma Canyon Road on the north side of the valley just outside the

Memorial. This fault is post-Cretaceous in age, since it offsets Cretaceous rocks, and is likely related to Laramide compressional tectonics. Two extensional faults run almost parallel to the bottom of Montezuma Canyon within the park. These features are related to Basin and Range extension and place a band of Cretaceous marine sediments sandwiched between Huachuca Granite to the northeast and the Jurassic ignimbrites of the calderas to the southwest.

No rocks younger than Cretaceous are preserved in the Memorial, but the existing geology preserves evidence of most of the geologic history of Arizona. The current location of the park is within Montezuma Canyon, which was likely carved over the last 10-15 million years by erosion and sediment transport from the mountains into the valley that opened during Basin and Range extension.

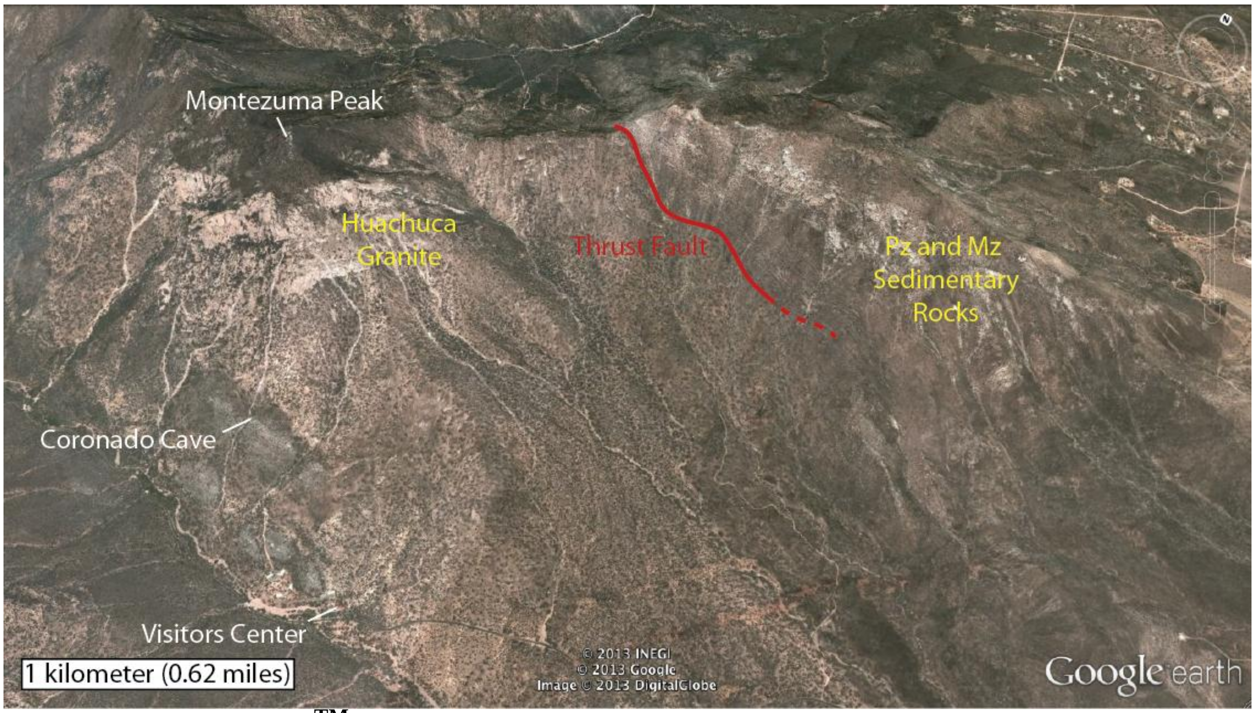

Figure 5. Google Earth™ image showing a northeast-facing oblique view of the southern Huachuca Mountains. Approximate surface expression of thrust fault shown in red. Huachuca Granite and Paleozoic and Mesozoic sedimentary rock packages located on either side of the fault are labeled. Locations of Montezuma Peak, Coronado Cave, and the park visitor center are shown for reference. 1 km scale shown by length of white box.

Coronado Cave Formation:

The Coronado Cave is a unique geological feature within the Memorial. Details on cave formation processes will be given in Section 6, but the setting of the Coronado Cave specifically, is treated here. All natural caves form within a rock type called **limestone** that forms in the ocean by the buildup of layers of the tiny shells of organisms that live near the ocean's surface. The limestone that hosts the Coronado Cave is in the Naco Group of Pennsylvanian to Permian age (251-299 Ma).[4] Narrowing it down more closely than this is not possible due to the deformation of the limestone blocks by the caldera eruption and resurgence. In fact, the block of limestone that hosts the cave is an island of country rock floating within the Huachuca Granite.

It was probably incorporated from the caldera roof remnant during intrusion of the molten granite, but was too large to be melted before the magma chamber cooled.[1]

Today the cave is exposed within a small steep canyon within the Memorial (Fig. 5). The cave chamber may have existed without any connection to the surface for a long period of time, but this is unknown. Hundreds of thousands of years of groundwater traveling up through the limestone widened the cavity that became the cave. As the cavity widened, parts of the roof fell in, breaking from the unstable ceiling. Many blocks of limestone of all sizes litter the cave floor today. In places within the cave where water continued to drip and flow in from the surface, **cave formations** have developed by the progressive precipitation of new calcite in layers on the cave walls, ceiling and floor. Today only a few areas have dripping water. More drips were likely present during the many glacial periods of the last 2 million years, but during warm periods like the present, southern Arizona is much drier. Today most water is taken up by plants at the surface or evaporates before flowing to the cave.

The timing of the Coronado Cave opening at the surface is unknown, but human and animal presence is easily seen in the cave. A mantle of dust, brought in by people and blown by the wind, covers most surfaces. Caves that are open are often near the end of their lives because a connection to the outside atmosphere promotes drying of the cave. Under current climate change conditions, increased drought is likely for southern Arizona, meaning that conditions for calcite formation are not likely to improve in the future. The state of the formations in the cave today are likely the best that will occur, so preserving them for future visitors is important.

Exhibit Development Note: The 2011 NPS Geological Resources Inventory Report for the park[1] *provides a very specific, and more comprehensive review of the geologic history within the park and a good overview of the regional geologic history. However, it is written at the level of an undergraduate geosciences student, and so may be difficult to interpret for non-geologists.*

Glossary of terms:

calcite – a very common mineral with the formula $CaCO_3$ used by marine invertebrates to create their shells, corals to create their skeletons, and precipitated inorganically to form cave formations.

cave formations – any of a myriad of types of calcite formations created by progressive drip and flow of water causing precipitation of calcite in layers on the walls, floor and ceiling of caves. These include stalactites (from the ceiling) stalagmites (from the floor) and many others.

granite - a rock formed as a felsic remnant of a magma chamber that cooled underground without erupting to the surface.

limestone - a sedimentary rock formed in the ocean by accumulation of the calcite shells of tiny organisms all the way up to seashells and the skeletons of corals, all of which get buried and preserved as layers of rock.

thrust fault – a type of compressional fault formed by thrusting rocks of older age up and over the younger rocks overlaying them. These faults can be small or very large spanning entire mountain ranges and thrusting rocks horizontally for hundreds of miles over the layers beneath.

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Section 5: Life History of a Supervolcano – Caldera Eruptions

Key Points:

- The term *caldera* is quite broad in terms of volcano type because it only implies collapse of the roof over a magma chamber or volcanic vent, which leaves a circular or elliptical crater on the Earth's surface following eruption. This type of structure can be almost any size, and result from any type of volcanic eruption.
- Supervolcano calderas, which erupt >1000 km^3 of material, enough ignimbrite to cover the entire area of Chiricahua National Monument in a sheet 12 miles thick, occur under special tectonic circumstances, and none have occurred during the period of human record.
- Supervolcano calderas require unusually intense heating from the mantle beneath felsic continental crust to generate large viscous magma chambers from which huge eruptions occur. This occurs either by extensional tectonics or by a mantle hot spot.
- Caldera eruptions have 4 phases: 1) minor pre-collapse eruptions from the magma chamber below, 2) heating at the base of the magma chamber mobilizing the slushy magma, 3) major eruption and roof collapse, 4) post-collapse resurgence and additional minor eruptions.

Key Words:

airfall tuff – the initial eruptive phase in a caldera eruption, consisting of small ash particles borne high into the atmosphere by hot pressurized gases rushing out of the magma chamber through the ring fracture.

flare up - an informal term applied to periods of geologic history marked by an unusually large number of caldera-forming eruptions, often associated with increased injection of mantle magma into the crust and extension due to a steepening of the subducting oceanic plate.

surge deposit – the second eruptive phase in a caldera eruption, consisting of larger ash particles and small magma droplets, carried downhill in a water-like flow of superheated gases. It is often found directly beneath the major ignimbrite sheets.

viscous/viscosity – a measurement of the resistance of a material to flow, typically used to describe liquids. Materials like water that flow easily are called low viscosity, while gels that flow slowly are viscous.

Science Summary:

The term *caldera* is a Spanish word derived originally from the Latin term 'caldaria' meaning 'cooking pot.' It was introduced into the geological lexicon by German geologist Leopold von Buch in publication following his 1815 visit to two caldera volcanoes in the Canary Islands,[1] referring to the bowl-like shape of the volcanic depressions. In the most general terms, it refers to any volcanic eruption resulting in a crater, which in some form applies to most eruptions.[2] It is a particular subset of volcanic eruptions, however, for which the term caldera has particular meaning: **rhyolitic** supervolcanoes. From here onward, any reference to calderas should be interpreted as this type.

Environment of Formation

As with all volcanism, calderas form due to the interaction of hot magma from the Earth's mantle with the cool, solid crust of Earth's surface, generated by particular tectonic circumstances. Caldera supervolcanoes rarely occur without high heat input from the mantle beneath continental crust, because large volumes of felsic material must be melted and felsic material is only available in abundance in the continents. In addition to felsic material, an *unusually* high amount of heat and magma from the mantle must penetrate into the continental crust to create large felsic magma chambers. This occurs in two ways: by regional or local rifting, or less commonly due to a mantle 'hot spot.' Both the Montezuma Caldera and the Turkey Creek Caldera formed by the first mechanism. The Yellowstone Caldera currently located under Yellowstone National Park is a mantle hot spot.

The rifting resulting in the calderas of southeast Arizona was the product of two separate episodes of steepening of the subducting oceanic plate beneath the western margin of North American. Under normal circumstances, significant volcanism occurs in a distinct band or **volcanic arc** parallel to the convergent plate boundary where the subducting plate is deep enough so that water carried down from the surface ocean lowers the melting temperature of the solid upper mantle and sends mantle basalt magma up into the overlying continental plate. This only happens in a discrete band because at shallower depths, temperature is not high enough to melt, and below this all of the water is consumed. The distance from the coast of this 'arc' of volcanism is controlled by how steeply the subducting oceanic plate dips (Fig. 2). If it is very steep, the arc will be near the coast, if it is relatively flat, it will be further inland. The exact control on the steepness of the subducting plate is not clearly known, but it is probably related to the speed of convergence (faster subduction results in a flatter plate angle), along with some other considerations.[3] This steepness can vary along the length of a subduction zone during a particular period, and varies in a single location through geologic time. Multiple caldera eruptions and the extensional tectonics associated with them occur during '**flare ups**' when the subducting plate goes from flat to steep over the course of several million years. In southeast Arizona, this occurred both during the Jurassic, and during the Oligocene, resulting in two ignimbrite flare ups that included the Montezuma and Turkey Creek calderas, respectively.[3]

As the subducting plate 'rolls back' to a steeper angle, areas of the upper mantle and overriding continental crust that were formerly insulated from the intense heat in the mantle below by the lower oceanic plate are once again exposed and a huge amount of convecting heat is funneled into this band causing melting and magma injection into the continental crust (Fig. 2). The magma injected into the crust is mostly basalt, but it melts felsic continental crust on contact, creating large magma chambers of felsic melt. The melting and heating weakens the crust and promotes extension and thinning (rifting). The large felsic magma chambers are the source for caldera eruptions.

There have been no major caldera eruptions in recorded human history, which is surprising because the geologic conditions for calderas still exist in the U.S. and many places in the world. In the last 2 million years in the U.S. alone, three major caldera eruptions have occurred (Long Valley caldera, eastern California, Jemez caldera, New Mexico, and Yellowstone caldera, Wyoming). Smaller eruptions are much more common, and often can relieve the overpressure required for a caldera eruption without catastrophic collapse.

Caldera Eruptions

The process of caldera eruption proceeds in four basic steps detailed separately below:[2]

1) Minor eruptions onto the surface from mantle basalts and rhyolites from the felsic magma chamber and possible bowing up of the surface as magma is injected from below.
2) Heating of the felsic magma chamber by basalts from below remobilizes the felsic magma chamber, creating overpressure and effectively priming the chamber for eruption.
3) Sufficient overpressure is achieved to overcome the strength of the country rock roof so that a ring fracture develops, releasing the pressure catastrophically and erupting airfall and surge deposits of ash through the ring fracture. Then, part or all of the magma in the magma chamber is erupted through the ring fracture, being squeezed out by the weight of the collapsing magma chamber roof.
4) Resurgence of the caldera floor and surrounding area occurs as magma refills the chamber from below, often resulting in additional small eruptions. After sufficient refill has occurred, additional large eruptions may occur along with the development of adjacent or overlapping collapse calderas.

Step 1: Prior eruptions

The regions of extension where calderas form have many active volcanoes before caldera formation, due to the large volumes of felsic magma pooled in the crust and basaltic magma being injected from the mantle. For this reason, volcanic rock assemblages near calderas often have many small lava flows of many compositions that surround or are found under the outflow ignimbrites of the caldera eruption. Often, the caldera magma chambers themselves have one or many small volcanoes sitting on top of them. These eruptions often produce small hills of lava that create local topographic relief at the Earth's surface. In the Chiricahua National Monument, the volcanics of the Faraway Ranch Formation represent this phase of prior eruption in the life history of the Turkey Creek caldera.[4] For the Montezuma caldera, pre-existing lava flows have not been noted explicitly, but likely occurred.

Step 2: Magma chamber heating from below

Felsic magma chambers begin life when liquid basalt magma intrudes into fractures and faults already existing in the continental crust. This mantle magma heats the surrounding country rock as well, causing it to melt. Since hot magma is less dense than solid rock, the magma rises through crust until it reaches a depth where heat input from below cannot keep up with the cooling of the magma nearer the surface. When this occurs, magma pools, unable to melt the country rock above it any further. Often times, there is enough heat and pressure from gases dissolved in the magma to continue to the surface, and small eruptions occur. Otherwise the magma sits within the magma chamber slowly cooling.

In volcanic arc settings, these magma chambers can be huge. The Sierra Nevada Mountains of California, for example, are almost entirely composed of granite that cooled in a series of overlapping Jurassic and Cretaceous magma chambers several hundred miles long and the width of the entire mountain range, extending more than 20 miles deep. Caldera magma chambers are typically smaller, but can be 10-30 miles in diameter. These chambers slowly cool, and mineral crystals grow within the magma chamber. Early on, heat currents within the magma chamber freely **convect**, keeping the chamber a homogenous temperature and composition. However, in felsic chambers, once enough mineral crystals form (>50% of the volume), convection is impeded by the solid crystals, and ceases. Most large magma chambers spend the majority of their existence in this state. The magma chamber sits in the crust as a mush with liquid filling the spaces in a tightly packed mass of crystals.[5] In this state, large eruptions are not likely to occur because the magma is sludgy and hard to move.

Periodically, the magma chamber is remixed and mobilized out of the mushy state by increased heating from below. When a new flow of basalt magma makes its way up beneath the base of the mushy magma chamber, it locally heats the felsic magma at the base of the chamber like a burner under a pot of water. The localized heating melts the crystals at the base of the chamber and reinvigorates convection in a basal layer as thin as 3 feet. The hotter basal layer increases in thickness and buoyancy due to the heating until it is hot enough to overcome the weight of the overlying mush and it 'bubbles' up through, mixing it and remelting crystals along the way. Continued heating from below will eventually reinvigorate convection within the entire chamber, similar to a pot transitioning to a rolling boil.[6] This process can mobilize an entire magma chamber in less than one year, very fast in geologic terms, leaving it primed for a large eruption.[6] More often than not, no eruption occurs however, and the magma chamber cools back to its mush state.

Step 3: Roof failure and eruption

With a mobilized magma chamber, the conditions are right for a violent caldera eruption. The magma composition and the strength of the country rock roof over the magma chamber determines whether eruption occurs.[7] Volcanic eruptions of all kinds occur due to the pressure in the buoyant hot magma overcoming the strength of the rock above and escaping to the surface. This often occurs via pre-existing faults or fractures where the rock is weakest. Magma composition controls how much pressure is required before the magma itself moves. Magmas with low SiO_2 content like basalts are very fluid and so they flow easily as soon they overcome the strength of the country rock. Felsic magmas, on the other hand, are highly **viscous** and they are less likely to flow, especially when they have a high percentage of crystals, so they can build up significant internal pressure without exerting huge force on the chamber roof. This provides a volatile situation for eruption.

Magma pressure often causes the overlying rock to bulge up, stressing it. The stress is maximized in magma chamber roofs that are wide horizontally and thin in depth.[7] When significant pressure is exerted by the magma, the roof breaks, generally along a circular fracture near to the magma chamber margin, called the *ring fracture*. Most eruptive energy and volcanic material escapes the chamber around the sides in this way. The energy release in a caldera eruption is like stretching a rubber band to its absolute limit: when it breaks the elastic snap rapidly releases all the energy built up during stretching. When the ring fracture opens, all of the pent up energy in the viscous magma is released.

Like opening a shaken soda bottle, all of the dissolved gases in the magma rush to the surface carrying with them the smallest ash and magma particles and erupting them high into the air. This **airfall tuff** then mantles the surrounding landscape in ash, and can travel for hundreds of miles. Airfall tuffs from the Yellowstone Caldera, for example, can be found as far south as northern Arizona. The ash that is too densely packed or too large in particle size to escape high into the air instead flows downhill along the ground like water, suspended by superheated gases. This forms the **surge deposit** found at the base of most ignimbrites, including those of the Rhyolite Canyon Formation in Chiricahua National Monument.[8] The surge deposit can often have ripples and waves within it similar to what is found in water-laid sand deposits elsewhere.

The majority of the pressure is relieved during the initial ashy eruptive phases. With the pressure relieved, the bowed up caldera roof then collapses inward under its own weight. This generally occurs as single or multiple large blocks of country rock dropped down along the ring fracture.[2] The collapse may occur around the entire circumference of the ring fracture or it may drop asymmetrically on one side, causing a trapdoor-like hinging of the caldera roof.[2] The force of the collapse is part of what provides the pressure to push large volumes of ignimbrite magma out of the magma chamber. Widening of the ring fracture and opening of new fractures in the roof during roof collapse provide more space for magma to escape. The ignimbrite flow, called a **pyroclastic flow,** is much thicker and more solid than the surge deposit, smashing its way up through the ring fracture and out of the caldera depression where it flows radially downhill onto the surface, filling valleys first, then topping ridges[4]. The topography of the pre-eruption land surface can often be estimated by tracing the elevation of the base of the ignimbrite flows. As it barrels downhill, the pyroclastic flow, composed of ash, magma droplets, and crystals buoyed on hot gases, picks up rock fragments from the surface as it flows over and incorporates them as well. The flow continues until cooling and loss of gas makes it too viscous to move further. The flow continues cooling and off-gassing in place, slowly compacting under its own weight, forming progressively welded layers with greater depth.

This eruptive sequence may be repeated several times before the caldera roof collapses into a stable position where no more magma is squeezed out. At Turkey Creek caldera in Chiricahua National Monument, this happened three times in rapid succession, erupting an estimated 500-1500 km^3 of ignimbrite. At Coronado National Memorial, only one ignimbrite is tied to the collapse of the Montezuma caldera, and significant time elapsed before the eruption of calderas to the north covered it. It likely had similar size to the Turkey Creek caldera.

Step 4: Resurgence and post-collapse eruptions

Following the collapse of the caldera roof, the formerly convex volcano is replaced by a concave, circular or elliptical crater. The Turkey Creek Caldera of the Chiricahuas is mostly circular, and due to tectonic deformation, the shape of the Montezuma Caldera is impossible to determine. The crater may be hundreds to a thousand feet deep at the surface, but the actual caldera floor is far below this, since the crater is filled with hundreds to thousands of feet of ignimbrite during eruption.[2] During and following collapse, the walls surrounding the crater are often unstable and large blocks and landslides of country rock will fall down onto and into the ignimbrite.

When the major eruptive phase ceases, the magma chamber may begin to refill from below, causing the surface to bulge up resurgently. During this period, additional small eruptions often issue out of underground fractures in the caldera roof and along the ring fracture. These form small lava domes on the floor of the caldera (Fig. 6). In the Turkey Creek Caldera, one primary eruption proceeded through the ring fault and cooled there, preserved as solid rock today (Fig. 3). This dacite also erupted out of the crater and remains preserved on Sugarloaf Hill in the Monument. An additional rhyolite eruption is also known within the caldera margin.[4]

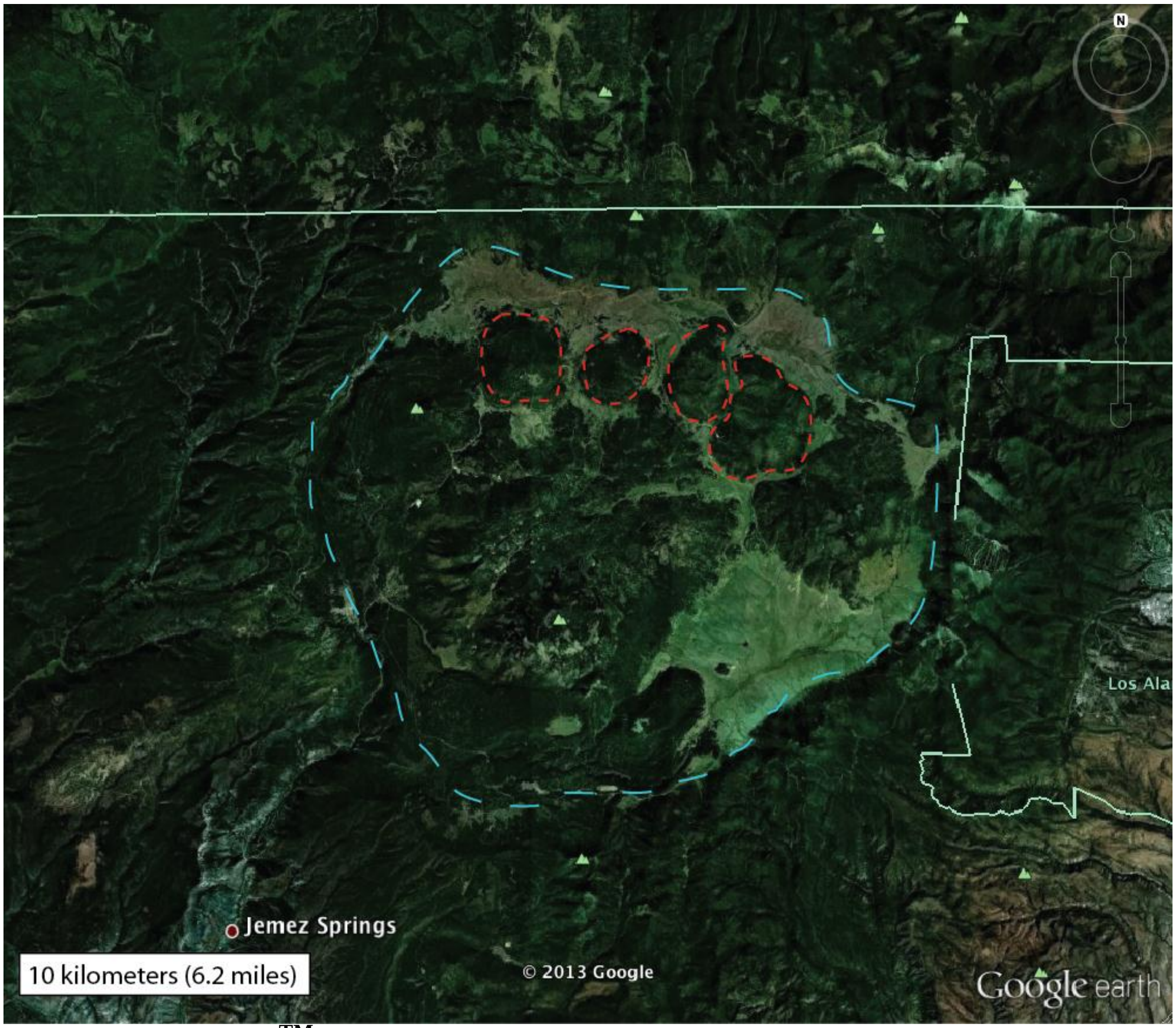

Figure 6. Google Earth™ image of surface expression of the Jemez Caldera, central New Mexico. The last major caldera eruption was 1.5 Ma. Approximate caldera margin shown in blue dashed line. Lava domes from post-collapse eruptions shown by red dashed lines. 10 kilometer scale shown by length of white box.

Caldera preservation and interpretation:

In the period directly following caldera eruption, the surface surrounding the caldera is a barren semi-flat expanse of cooled ignimbrite with a crater near the center. The ignimbrite often mantles existing high topography, and itself forms an area higher than the surrounding valleys. This makes it susceptible to erosion by water and wind. Over the course of millions of years, the ignimbrite surface is cut by erosion into canyons and ridges like that found in the Sky Islands today. Most of what geologists know about the process of caldera eruption and collapse is gained from investigating calderas and ignimbrites in this dissected state. The removal of material by erosion exposes the layers within the outflow and in the caldera, showing the sequence of eruptive events, collapse of the caldera walls, and intrusions along the ring fracture. If the landscape is deeply eroded, the granite remnant of the underlying magma chamber may be exposed. This is the case with Huachuca Granite of the Montezuma National Memorial. The horizontal and vertical sequence of rock types lets geologists determine the history of eruption.

Erosion also exposes previously buried rock surfaces, allowing geologists to correlate units to each other and relate outflow units to their respective calderas. Without study of old, eroded calderas, we would have a very limited understanding of the inner workings of caldera magma chambers beneath the surface today. By studying them, we gain insight into the size, frequency, and potential danger these supervolcano eruptions pose to humans.

Glossary of terms:

airfall tuff – the initial eruptive phase in a caldera eruption, consisting of small ash particles borne high into the atmosphere by hot pressurized gases rushing out of the magma chamber through the ring fracture.

convection – the process where heat currents in a liquid or gas medium cause hotter material to rise to the top where it cools and sinks again in a continuous cycle. This process occurs because the object is heated from below.

ignimbrite flare up – an informal term applied to periods of geologic history marked by an unusually large number of caldera-forming eruptions, often associated with increased injection of mantle magma into the crust and extension due to a steepening of the subducting oceanic plate.

pyroclastic flow – the third and major eruptive phase in a caldera eruption, consisting of a thick avalanche-like flow of ash, magma droplets and rock fragments carried downhill suspended by superheated gases. This phase deposits the main thickness of ignimbrite flows associated with calderas.

rhyolitic – a classification for an eruptive volcanic rock with >60% SiO_2 content, or a felsic volcanic rock, often created by partial melting of continental crust.

surge deposit – the second eruptive phase in a caldera eruption, consisting of larger ash particles and small magma droplets, carried downhill in a water-like flow of superheated gases. It is often found directly beneath the major ignimbrite sheets.

viscous/viscosity – a measurement of the resistance of a material to flow, typically used to describe liquids. Materials like water that flow easily are called low viscosity, while gels that flow slowly are viscous.

volcanic arc – a discrete band of volcanism that develops on the continental plate parallel to a convergent margin where the subducting oceanic plate is at a depth where ocean water lowers the melting point of the basalt enough for significant magma to be generated. This magma then ascends buoyantly into the overlying continental crust, creating magma chambers and surface eruptions.

Exhibit Development Note: Logically, most exhibit development that incorporates the information in this section will be useful for Chiricahua National Monument. For this purpose I would, again, suggest the work of du Bray and Pallister (see Section 3). Additional illustrations of the process of caldera formation that might be useful can be found in the work[8] of Peter Lipman of the U.S. Geological Survey, who has focused specifically on calderas in the western U.S. throughout his career. A similar set of diagrams can also be found here.[9] For more in depth and basic information, an introductory textbook on volcanology will certainly contain information and illustrations on caldera eruptions, also, though I have no specific suggestions.

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Section 6: Life History of a Cave – Cave formation processes and history

Key Points:

- Cave formation requires two basic ingredients: limestone bedrock and aggressive (acidic) water to dissolve it. This process can take thousands to millions of years.
- There are two types of caves: epigenic caves, formed by water entering from above, and hypogenic caves, formed by aggressive groundwater coming up from below. Coronado Cave has aspects of both, but was probably dominantly hypogenic with respect to the formation of the main chamber.
- Formations within the cave are created by the precipitation of calcite from water seeping in through cracks above the cave. Calcite is precipitated from the water in response to CO_2 gas being released into the cave atmosphere. Cave formations develop slowly, taking thousands or hundreds of thousands of years.
- Caves that have entrances exposed at the surface by erosion eventually dry out and fill with sediment from outside over hundreds of thousands of years.

Key Words:

aggressive water – water with sufficient acid content to dissolve limestone, forming caves.

Paleoclimate science – the study of past climate, including temperature, precipitation and weather patterns, and the mechanisms that cause climate change, over geologic history.

speleothem – a general term for a cave formation (such as a stalagmite or stalactite) that forms by dissolving calcium carbonate or calcite, the mineral that makes up limestone, and redepositing it under a drip that builds up over thousands of years into many different shapes.

Science Summary:

Caves of all kinds have been explored and used by humans for thousands of years. Whether a few feet deep, offering only shelter from the wind and rain, or containing miles of passages, caves have played an important role for humans throughout geologic time. The word 'cave' is a loose term that can mean any opening or chamber within any rock type. The most extensive and beautiful caves form in limestone, and the remaining text will be limited to limestone caves. Limestone **karst** regions containing caves are found worldwide, occupying 10-20% of the Earth's land area.[1] Karst is most often located in areas near coastlines with large amounts of marine limestone, and in regions receiving high rainfall needed to dissolve calcite beneath the ground surface. However, even dry desert areas like southern Arizona can have caves preserved in the Sky Islands where Paleozoic and Mesozoic marine limestone have been lifted by tectonics up to higher, wetter locations. This is certainly the case for the Coronado Cave of Coronado National Memorial. To gain a better understanding and appreciation for the slow development and delicate nature of limestone caves and cave formations, we must learn about the process that initiates cave passageways, the process that develops cave formations, and the process by which caves become open to surface, and dry out. Lastly, we review an exciting frontier in cave science that allows geologists to learn about climate change through caves stretching back hundreds of thousands of years.

Cave forming conditions and cave inception:

All caves require two ingredients: 1) a significant thickness of limestone to be dissolved in direct contact with 2) **aggressive** water with sufficient acid content to dissolve said limestone. Limestone is found in abundance in most geologic settings so water is generally the limiting factor on the speed at which a cave develops and how large it will eventually become. The path water takes in order to contact the limestone also determines how the cave develops. There are two major types of caves.

Epigenic caves, making up around 80-90% of all known caves, are formed from *above* by rainwater infiltrating into the soil and being collected in streams and rivers.[1,2] This will dissolve limestone, creating depressions that progressively pool and funnel water into the widening opening. **Hypogenic** caves are formed from *below* by inundation of limestone bedrock in the subsurface by rising aggressive groundwater. Coronado Cave is most likely of this hypogenic type, although it certainly has epigenic aspects as well. The groundwater becomes aggressive by incorporating sulfuric (H_2SO_4) or carbonic (H_2CO_3) acids from sulfur-rich rock and sediment layers or dissolving CO_2 from underground volcanic activity, respectively. Both cave types form most often with no connection to the surface. Even though they make up only 10-20% of *known* caves, the majority of hypogenic caves have not been discovered, and will remain unknown unless erosion exposes them at the surface. Because Coronado Cave is mostly hypogenic, epigenic caves are not covered further in detail.

Hypogenic caves can form some the largest and most spectacular passages and rooms known.[3] Carlsbad Caverns National Park is a well-known example. Because they are formed near the **water table** by water percolating up from below, the passages are often wide with a high ceiling, and sometimes consist of large single rooms.[1,3]

In the case of the Coronado Cave, aggressive groundwater is created when the **hydrothermal** mineral **pyrite** (chemical formula FeS_2) is dissolved to form sulfuric acid. Pyrite is commonly found where hot magma interacts with limestone country rock. Hot hydrothermal water dissolves primary volcanic minerals and those in the overlying limestone, which are later precipitated as pyrite near the contact between the magma and the limestone. The contact between the limestone block containing the cave and the Huachuca Granite is nearby, providing a likely region for the generation of sulfuric acid in the groundwater millions of years later. Though the magma chamber cooled to granite by 168 Ma, the pyrite remained unreactive along the contact for millions of years until it was dissolved later by groundwater. The timing of this process is not known for the Coronado Cave but it is most likely to be in the last few million years during the period of Basin and Range extension.

When aggressive water comes in contact with limestone bedrock, dissolution occurs. The amount of dissolution is controlled by the concentration of acid in the water and the amount of time it spends in contact with a particular location on the limestone surface. In hypogenic caves, this dissolution occurs at many locations, but always near depth of the water table. This causes widespread dissolution within small openings called **pores** that eventually join together as the limestone between them is dissolved. As more cavities are opened and joined, the groundwater, which is being pushed *upward* by hydraulic pressure from uphill in the valley, can be forced through widened rising shafts.[3] Rising groundwater fills the cave chamber, widening and raising the ceiling, producing large chambers.

Cave formation stops with the retreat of the groundwater table. This may have been in response to erosion lowering the stream channel of Montezuma Canyon below the level of the cave. If this is the case, the cave may have been abandoned for millions of years considering the valley bottom is currently ~350 ft below the cave entrance. The cave entrance was probably more recently exposed by erosion along the steep alluvial channel draining from the face of Montezuma Peak.

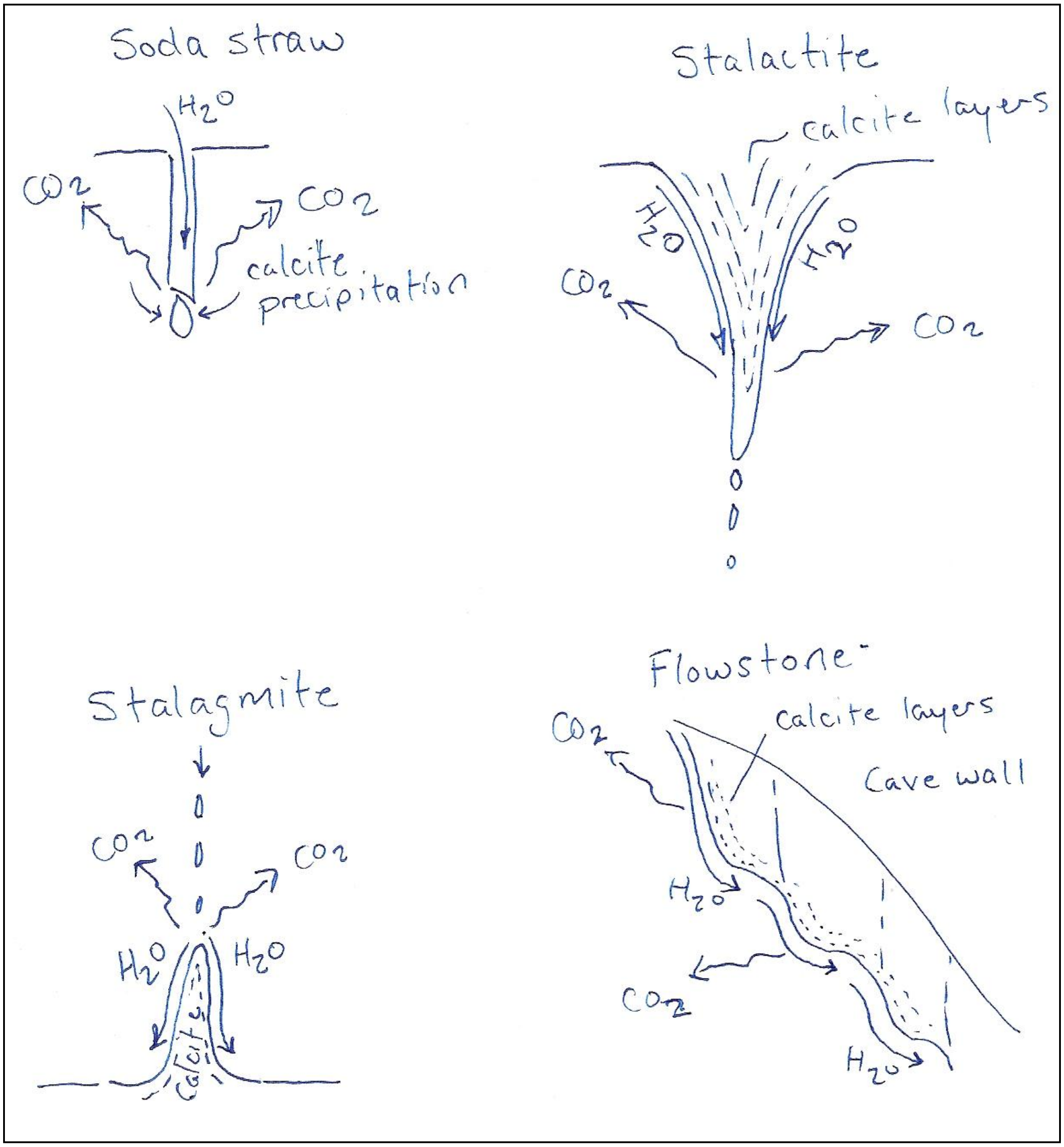

Figure 6. Schematic illustrations of common cave formations and their formation processes.

Cave formations:

Although Coronado Cave has a hypogenic origin, the formations within it, called **speleothems,** were created by the same top-down process that produces epigenic caves. Rainwater falling on the soil surface above the cave does not all run off into Montezuma Canyon. Most of it evaporates or infiltrates into the soil surface where it is used by plants. A small amount of this water continues downward through the soil, and as it does, it dissolves CO_2 gas produced by the decomposition of soil organic material and respiration by plant roots, creating carbonic acid (H_2CO_3). At the base of the soil, where it meets the **bedrock**, the acidic water dissolves the calcite making up the limestone. The water continues flowing through joints, fractures, or faults in the limestone, dissolving all the way. Eventually, many of the flows intersect the cave chamber, forming a drip or a flow along the ceiling or walls. When the water, full of dissolved calcite, enters the cave it releases CO_2 gas. Generally, the cave atmosphere has much lower CO_2 concentration than the soil where it was initially acquired, and the concentration of CO_2 in the water will re-equilibrate to the new pressure, kind of like popping your ears when you change elevation. With the CO_2 gone, the water is no longer very acidic and it will precipitate some or all of the calcite it dissolved on its journey into the cave. This sequential precipitation of calcite creates the cave formations (Fig. 6).

The type of drip coming into the cave controls the shape of the cave formations. A single, slow drip from the ceiling will often form a **soda straw,** which grows downward as calcite precipitates around the drip at the end. A stronger or older drip from the ceiling will produce a **stalactite**, an icicle-like formation formed as water flows over the outside and down to the tip, precipitating calcite all the way. On the floor below, the water dripping from stalactites form pointed mounds called **stalagmites** directly below the water drip. As more time goes by, the mounds of calcite grow large and many formations may converge together. If a stalactite-stalagmite pair grow long enough, they eventually join into a **column**. If water flows into the cave through the wall or on a sloping part of the ceiling, the drop may run along it precipitating calcite in a line along its path. Sequential drips continue to follow the same path, creating curtain-like draperies of **flowstone**.

Formations continue to build up indefinitely unless the water supply is removed. Summer drought conditions may reduce rainfall, stopping drips periodically. Minor tectonic movements may close fractures, or open new ones, changing the location of drips. Throughout the life of a cave, which may span millions of years, the locations and intensity of drips are likely to change many times. It is important to remember that speleothems are fragile, and even the fastest-growing of them take thousands of years to reach large size. The slowest take hundreds of thousands or even millions of years. If they are broken, they cannot be replaced, so cave visitors and cave scientists must be careful to preserve the caves.

Opening at the surface and cave drying:

Many epigenic caves spend their entire existence with openings to the surface because it is through these openings that aggressive water is delivered to widen the passages. For hypogenic caves, entrances to the surface are caused by erosion through the limestone containing them. Mixing with outside air over time equalizes the temperature and gas content of the cave atmosphere with the surface, often changing the dynamics of calcite precipitation. For long caves, this effect is muted far from the entrance, but for short caves like the Coronado Cave, the cave air almost certainly reaches equilibrium with the outside atmosphere within days or weeks. Usually this results in increased precipitation of calcite because atmospheric CO_2 is much lower than that in most caves.

Once a cave is open, the relative humidity, or water content in the air, is almost always lowered, causing increased evaporation of drip water. If the opening is large enough, dust may be blown into the cave mouth and be brought in by animals and people. This dust absorbs moisture and mantles cave surfaces, inhibiting calcite growth. With progressively more erosion of the land surface, the cave opening will eventually widen. If aggressive groundwater is still working at lower levels in the limestone, the cave floor may collapse over time into lower chambers.[5] Otherwise, the cave will progressively fill with sediment and dry out. At that point, the cave formations cease, and the cave becomes a **dry cave.** Eventually, the roof may collapse, or be eroded, exposing the former cave at the surface. Thus ends thousands or millions of years of formation, lost to the inexorable march of erosion through geologic time.

Paleoclimate Science: reconstructing past climate change with speleothems

Using speleothems to study climate and climate change has become a productive field in paleoclimate science over the past 20 years. Using uranium-thorium dating (see Section 1), layers of calcite formed sequentially over thousands of years can be accurately dated to within 5 year accuracy. This establishes a firm, precise timeline for the growth of the speleothem that geologists can use to relate to other climate records worldwide. This technique can date materials younger than ~500,000 years (0.5 Ma), which is more than enough to study significant climate changes spanning several ice ages.

It is the chemical composition of these speleothems that provide the most valuable information. Calcite, with the chemical formula $CaCO_3$, contains a lot of oxygen in its crystal structure. Most of this oxygen (99.8%) is an **isotope** called ^{16}O (pronounced oxygen sixteen), the most common form on Earth. The remaining 0.2% is ^{18}O (oxygen eighteen), a slightly heavier isotope. The relationship between the abundance of these two isotopes is dependent upon many things, but they are mostly related to changes in climate.[6]

In caves, both oxygen isotopes are brought in as water (H_2O) and incorporated into the calcite of forming speleothems. The relative concentrations of the two isotopes is determined by the outside temperature, the season of precipitation, and the source of moisture, allowing geologists to distinguish changes in any of those three climate aspects through time according to changes in the relative proportion of the isotopes in the speleothems. This approach has been particularly successful for creating records of the strength of summer monsoons worldwide.[7] It has also been applied to caves in southern Arizona, allowing climate scientists to interpret changes in winter precipitation in Arizona across the global transition from **glacial climate** to **interglacial climate.**[8]

Over the last 2 million years Earth has gone through a series of cyclical changes in global temperature termed 'Ice Ages.' Ice Ages are characterized by glacial climate conditions, with large continental ice sheets covering Canada and the northern U.S., and much lower average temperature in southern Arizona. The coldest part of an Ice Age occurs around once every 100,000 years, followed by an abrupt switch to warm interglacial climate like that of today. During this transition, the ice sheets melt, and ocean circulation and storm patterns are affected by many abrupt changes, which are recorded by speleothems. The transition from the latest glacial to the current interglacial occurred roughly during the interval 12-17 thousand years ago.

During this interval, the oxygen data from the Cave of the Bells in the Santa Rita Mountains, show that southern Arizona abruptly got drier around 15 thousand years ago, probably similar to the climate today, but switched abruptly back to colder, wetter glacial conditions around 13 thousand years ago (Fig. 7). A third abrupt change to warmer conditions occurs just before 11 thousand years ago. This type of abrupt switching is known in climate records around the globe, and is caused by collapsing of the major ice sheets in response to warming climate. Thanks to the speleothems from the Cave of the Bells, we now know how rainfall in southern Arizona is affected by climate changes like this in the past, which gives us insight into how it may change under similar circumstances in the future.

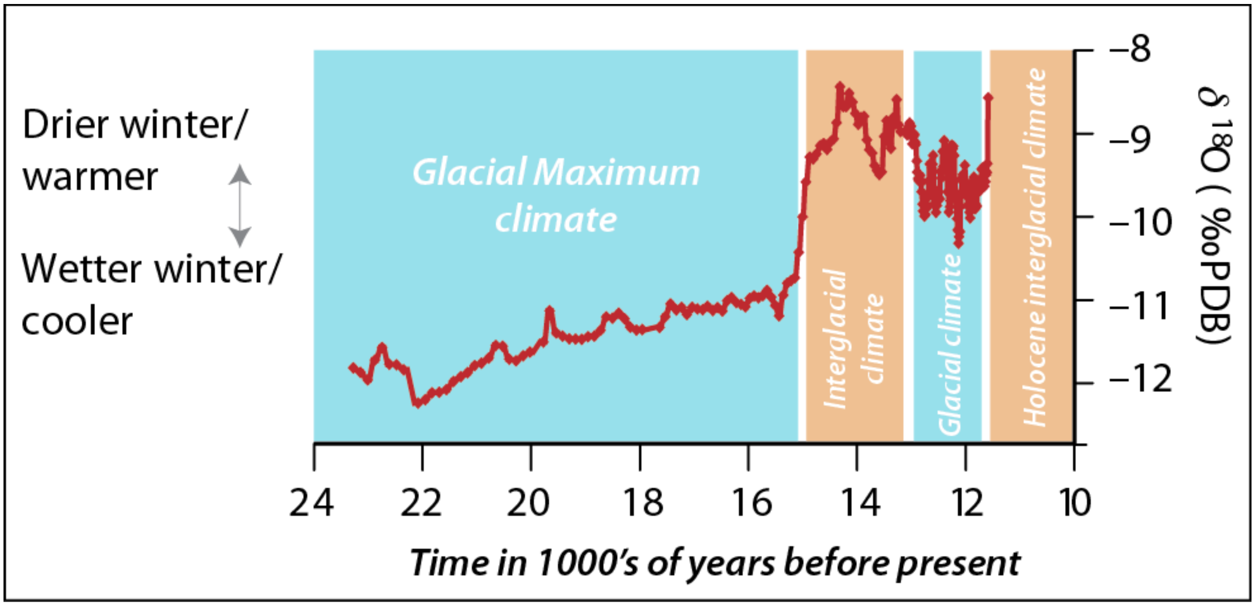

Figure 7. Cave of the Bells (Santa Rita Mountains, Arizona) oxygen isotope climate record. Modified from Wagner et al. (2010).[8] Isotope variations shown by the red line. Periods of glacial and interglacial climate are shown by blue and tan vertical bars, respectively. Higher oxygen isotope values (up on this graph) correspond to warmer, drier winter conditions in southern Arizona similar to today, while lower values (down on this graph) indicate the opposite.

Exhibit Development Note: the Coronado Cave is a hypogenic cave, similar to Carlsbad Caverns, so internal NPS reports (for example the Geological Resources Report[9]) pertaining to the general formation setting and processes for cave passages and formations can provide additional info and graphics for exhibit development. The book by John Barnett[10] also provides a description of cave and cave formation development processes and good illustrations of both, including a diagram showing how groundwater intrudes into hypogenic caves from below.

Glossary of terms:

aggressive water– a term describing water with sufficient acidity to dissolve limestone, forming caves.

bedrock – a geological term for a solid rock material often deeply rooted, as opposed to soil, alluvium or loose sediments.

column – a speleothem formed by joining one or more stalactites from the ceiling with stalagmites from the floor to create a single pillar-like formation.

dry cave – a cave with insufficient water to create speleothems, often due to climate changes or drying by evaporation through surface opening.

epigenic cave – a type of cave formed by rainwater infiltrating into the limestone from above.

flowstone – a general term for a speleothem formed by water running down cave walls or sloped ceiling and floors rather than dripping. Generally forms ribbons, draperies or amorphous masses of calcite.

Glacial climate – periods in Earth's history where global temperatures were much lower than present, occurring frequently in the last 2 million years, characterized by large continent scale ice sheets covering much of Canada and northern Europe.

hydrothermal – a descriptor for volcanically heated waters circulating through rocks near to magma bodies, often carrying dissolved minerals that are deposited when conditions cool.

hypogenic cave – a type of cave formed by aggressive groundwater is pushed up into limestone from below.

Interglacial climate – periods in Earth's history where global temperatures were similar or higher than today, characterized by stronger monsoons and much smaller global ice sheets.

isotope – variants of atomic weight within a particular chemical element, having a set atomic weight. For example oxygen sixteen (^{16}O) has 8 protons and 8 neutrons. Oxygen eighteen (^{18}O) has eight protons and *ten* neutrons, but it is still oxygen because the element is determined only by the number of protons.

karst **–** a type of terrain characterized by deep canyons and sinkholes formed by the dissolution of thick limestones. Florida has a lot of karst area.

pyrite – a gold colored cube-shaped sulfide mineral (FeS_2) found commonly in association with rocks affected by hot volcanic fluids. Also called 'fools gold'.

soda straw – an informal term for a straw-shaped speleothem found on cave ceilings formed by precipitation of calcite around the outside of single water drip over a long period of time.

speleothem – a general term for a cave formation (such as a stalagmite or stalactite) that forms by dissolving calcium carbonate or calcite, the mineral that makes up limestone, and redepositing it under a drip that builds up over thousands of years into many different shapes.

stalactite – an icicle-like speleothem found on cave ceilings formed by flow of water down the outside of the formation and pooling at the tip, precipitating calcite the whole way.

stalagmite – the partner speleothem to a stalactite found on cave floors, formed below the drip of a stalactite where calcite precipitates in sequential layers forming a tall thin cone. The most commonly used speleothem for climate research.

water table – a schematic term used to describe the semi-planar surface within the soil below which is saturated with groundwater and above which has significant air space.

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Stories of the Sky Islands: Effects of Climate Change and Ecological Disturbance on Wildlife, Vegetation, and Fire in Chiricahua National Monument and Coronado National Memorial, Southeast Arizona, USA

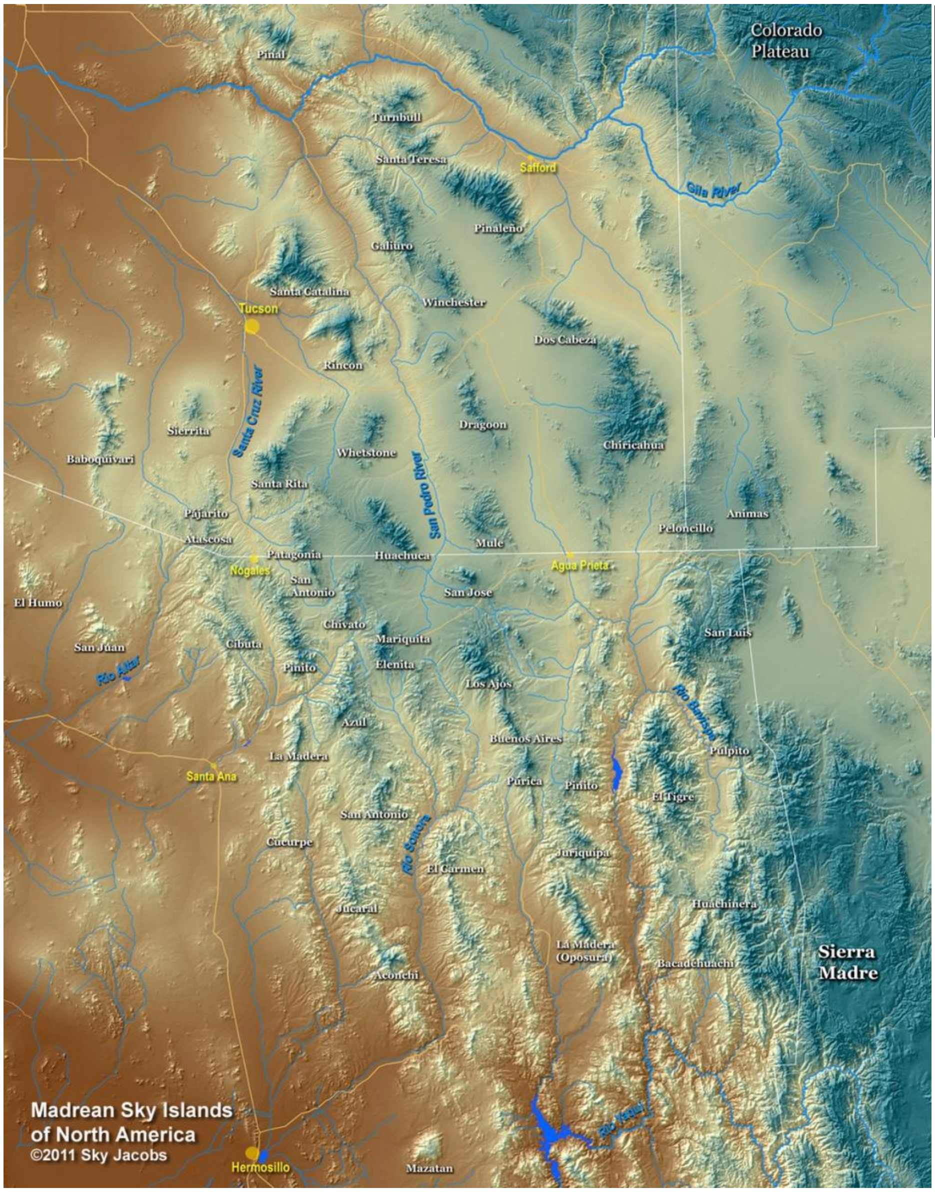
Erin E. Posthumus and J. Jesse Minor

Stories of the Sky Islands in General

How Sky Islands are like Aquatic Islands

- **Forested habitat surrounded by a 'sea' of desert grasslands**

The Madrean Archipelago represents 40 'sky island' mountain ranges spread across Arizona, New Mexico, Sonora and Chihuahua between the Mogollon Rim and the Sierra Madre Occidental.[1,2] Topographic variability in the Madrean province is very high, and ranges between 1250 ft to as much as 6750 feet (380m-2060m) between valley bottoms and ridge tops,[1] which provides a strong influence on local climate factors (temperature and precipitation, and hence vegetation) on the sky island ranges. Strong vertical zonation in vegetation types results in 'stacking' of biotic communities[1,3] which creates barriers to migration and transport for forest obligates or organisms with limited dispersal capabilities. As with literal islands, certain organisms can propagate or travel between various sky islands, but the desert and grassland 'seas' provide a substantial barrier to many organisms due to disconnected or fragmented habitats, or physiological stresses such as water limitation or heat intolerance experienced at lower, hotter elevations.



Map of the Sky Islands of the Madrean Archipelago. Higher elevations are shown in blue, with lowlands in brown.

Map Source: Madrean Archipelago Biodiversity Assessment. http://www.madrean.org/maba/symbfauna/images/sky-

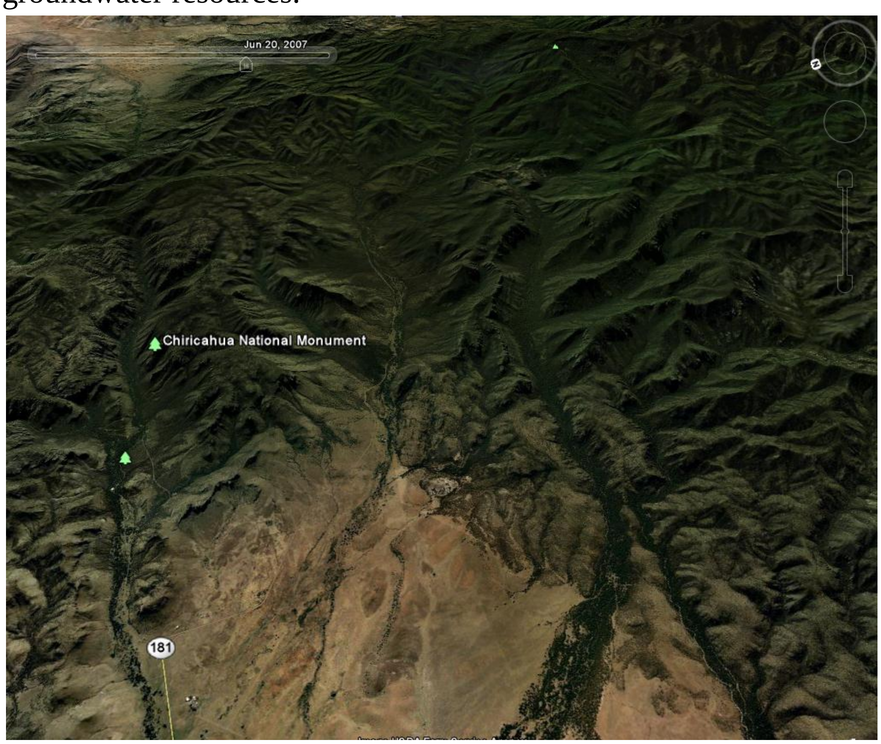
How Sky Islands are unlike Aquatic Islands

- **Sky Islands have fuzzy ecotones and diffuse boundaries**

Islands and sky islands are ideal places to study biodiversity because of their isolation and the sharp differences between islands and their surroundings. Sky islands differ from aquatic islands in some important ways. Analysis of sky islands at large geographic extents suggests relatively discrete divisions between vegetation types, while analysis at smaller geographic extents shows much more complicated pattern across elevational gradients. Unlike the distinct boundary between land and water for aquatic islands, the boundary between sky island and "desert sea" is less distinct. For example, grasslands grade into oak savannah with little distinction between the two types. Despite numerous descriptions of 'biotic stacking[2]' and 'life zones,' there is considerable variation in terms of what vegetation type is found at various elevations. The typical Sky Island pattern of diffuse boundaries between vegetation types is further enhanced by strong aspect influence on insolation and soil moisture, hydrological factors such as streams and cold air sinks, and the effects of past ecological disturbances, which can include factors such as canopy gaps opened up by crown fires, legacies of grazing such as reduced fine fuels and increases in unpalatable species, and alterations to forest structure and composition promoted by storms, drought, insects, and logging.

- **Hydraulic connectivity and habitat corridors extend deep into adjacent ecotypes**

Sky islands are hydrologically connected with surrounding desert and grassland 'seas' and their associated riparian ecosystems and aquifers. This hydraulic connectivity differs from aquatic islands, which have hard ecotones between land and water characterized by very distinct boundaries between terrestrial and aquatic ecosystems. The differences are even starker in the case of oceanic islands surrounded by salt water. Precipitation falling on high-elevation portions of the sky island systems makes its way into riparian systems that tie sky islands to their grassland and desert surroundings.[4] Because of their capacity to carry water, their increased evapotranspiration potential, and their tendency to carry cooler, denser air originating in higher elevations, lower-canyon riparian areas typically contain biodiverse and important pine-oak gallery forests that can extend deep into grassland and desert areas,[4,5] much like a 'river of trees' extending from higher mountain elevations. Viewed as a sometimes distant source for precipitation and surface runoff, sky islands provide critical flows of water and nutrients to lower-productivity desert and grassland riparian systems. Groundwater originating in the sky islands is critical for deeply rooted phreatophytic species, whose roots can take advantage of groundwater resources.



Google Earth imagery of Bonita Canyon and Pine Canyon draining westward out of the Chiricahua Mountains. The imagery is from June 2007, before the 2011 Horseshoe 2 Fire, and dramatically illustrates the effect of riparian areas and canyon drainages on the elevational pattern and distribution of tree species.

- **Habitat Connectivity**

One of the principal effects of sky islands differing from aquatic islands is that non-volant (non-flying or gliding) animals have the capacity to travel between sky island peaks. The differences between desert grassland and montane forest are substantially less than the difference between island forest and open ocean. Animals that can make use of the habitat and resources that connect sky islands are able to travel among and between sky islands and are not limited to elevationally-bounded forests.[6] In this sense, the desert and grassland biomes should be viewed as a filter,[7] which permits certain organisms to pass through, and not as an indiscriminant barrier to inter-mountain travel.

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Authors from Sky Island Alliance, the University of Arizona and Washington State University discuss the wealth of diversity in the Sky Island region, and how migration of wildlife contributes to this diversity. Barriers to this diversity include urbanization, rural development, astronomical development on mountaintops, mining and grazing. The authors call for international and interagency cooperation to develop a system of core preserves surrounded by buffer areas and linked by corridors to facilitate movement of wildlife.

2. Warshall, P. 1995. The Madrean sky-island archipelago: A Planetary Overview. 6-18p. *In*: DeBano, L. F., P. F. Ffolliott , A. Ortega-Rubio, G. J. Gottfried, R. H. Hamre, and C. B. Edminster, tech. cords. 1995. Biodiversity and Management of the Madrean Archipelago: the Sky Islands of Southwestern United States and Northwestern Mexico. 1994 Sept. 19-23; Tucson, AZ. Gen. Tech. Rep. RM-GTR -264. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 669pp.

3. Skroch, M. 2009. The Sky Islands of North America: a globally unique and threatened inland archipelago. International Journal of Wilderness 15:9-14.

Skroch cites Marshall (1957) to explain the concept of ‘biotic stacking,’ which occurs because of the strong elevational gradients and associated zonations of temperature and precipitation. This zonation creates “tight associations” of plants and animals, which differ across the biogeographic template of the 40 Sky Islands. Skroch notes that half of all American bird species can be found in the Sky Islands, and 104 species of mammals. In addition, there is rich herpatofaunal diversity: 6 species of snake, 29 frogs and toads, 37 lizards, and 11 turtles. These diversity numbers mask high rates of endemism (species found nowhere else). Geographic isolation of Sky Island systems has led to divergent evolution of a variety of species since the Pleistocene. Threats to Sky Island communities come from climate change, development and land use change, and border activities, especially the construction of border walls and fences.

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6. Whetstone, J. 1995. Riparian Zones: Neither Mountain nor Desert. 338-343p. *In*: Biodiversity and management of the Madrean Archipelago: the Sky Islands of Southwestern United States and Northwestern Mexico. Gen. Tech. Rep. GTR-RM-264. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 669 p..
Whetstone makes the important point that, despite numerous analogies drawn between sky islands and literal islands, riparian corridors provide critical habitat that profoundly ties montane and valley systems together. These low-elevation riparian corridors contain most plant species found in surrounding montane and grassland/shrubland areas, and "nearly all the wildlife found in the surrounding habitats." Viewed in this way, riparian areas are narrow, biodiversity ribbons that should be a focus of conservation and restoration effort.

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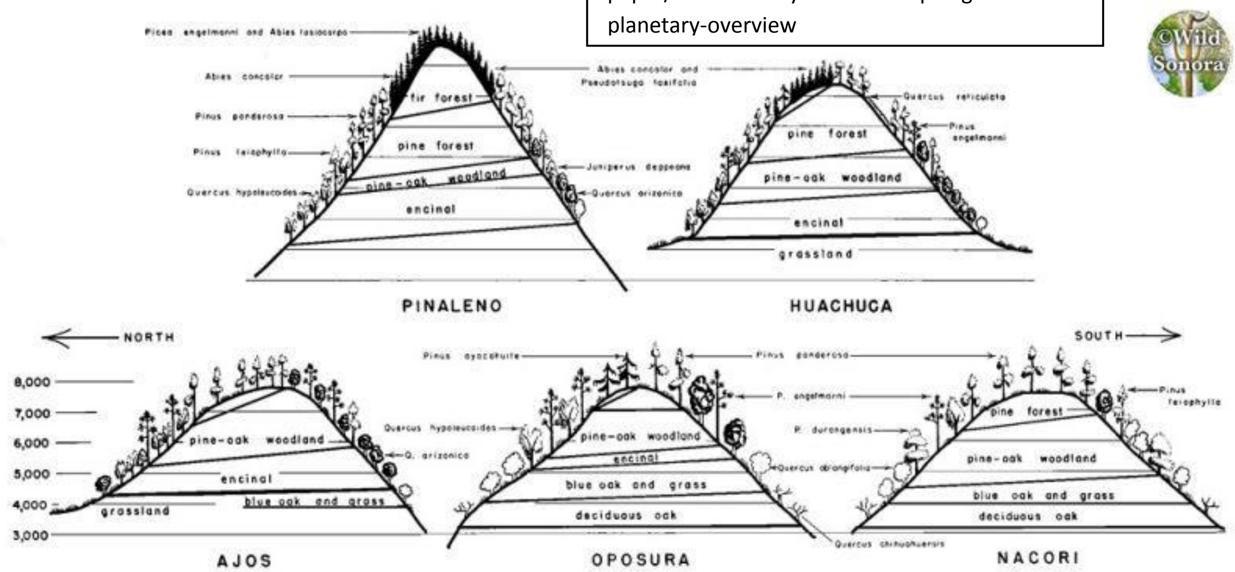
Patterns of Diversity in the Sky Islands:

- **Convergence of ecozones, orientation of mountains, and elevational range lead to high diversity in the sky islands**

The Madrean Archipelago, with its more than 40 montane sky islands, has one of the highest levels of species richness in North America.[1] In particular, the area is host to high number of mammal,[1] reptile and amphibian,[2] and hummingbird[3] species. This diversity has been attributed to the location of the sky islands at the convergence of the Chihuahuan and Sonoran Deserts, the Rocky Mountains and the Sierra Madre.[4] Each of the mountains of this region has a strong Northwest-Southeast orientation, which encourages floral and faunal movement up from the neotropic into the temperate biotic zone.[5] The steep mountains, which reach their maximum height in the Pinaleño Mountains at 10,719 ft (3267 m) compress the biota into relatively constricted vertical spaces and produce rapid species turnover with elevational change.[5] Despite the fact that many Sky Island species thrive in northerly latitudes, there is reason to believe that the Madrean populations of these species are well-adapted to subtropical variations in photoperiod and to the dryer, hotter conditions experienced even at high elevations in the Southwestern United States.

Influence of aspect on the elevational distribution of forest types in the Sky Islands

http://www.wildsonora.com/research-paper/madrean-sky-island-archipelago-planetary-overview



- **Patterns of diversity are influenced by post-Pleistocene colonization of the sky islands, vicariance events, and subsequent extinctions and colonizations**

Distribution and abundance of species in the sky islands may be attributed to the colonization of the sky islands during drier and warmer conditions after the Pleistocene epoch, vicariance events that isolated species, and subsequent extinctions and colonizations. Vicariance, or causes of geographic isolation, may include processes such as continental drift, mountain building, or sea level rises[6]. In New Mexico and Arizona, there is support that some species were isolated on mountaintops by climatic and vegetation change, and then biotic communities were changed by extinctions of some species and colonizations by others.[78]. This isolation of species on mountaintops has led to local evolution in species, creating sub-species endemic to particular sky islands. This has created an overall high rate of endemism in the Madrean sky islands.[9]

- **Threats to biodiversity in the sky islands include isolation of populations and limited area of certain vegetation types on mountaintops.**

The Madrean Sky Islands represent the southernmost extent of a number of species, which occur from northern Mexico to Canada. Examples include the Mount Graham red squirrel (*Tamiasciurus hudsonicus grahamensis*) and the long-tailed vole (*Microtus longicaudus*), as well as Ponderosa Pine (*Pinus ponderosa*), limber pine (*Pinus flexilus*), and other dry mixed conifer species. The Chiricahua Mountains are home to the southernmost population of Engelmann Spruce (*Picea engelmanii*). These species are limited by bioclimatic factors such as drought intolerance or habitat needs that are not met at lower elevations. This leads to small population sizes and reduced genetic variability as a result of the relatively small area available for these species at sufficiently high elevations. Due to the island like nature of the mountains, some species are characterized by subpopulations connected by riparian corridors between mountains.[10,11] These subpopulations, which already face low genetic diversity and reduced habitat area, are also threatened with man-made boundaries resulting from development and land use changes, climate change, and border fence construction.[10,11,12,13,14]

- **Recent changes to the sky island biota include extinctions, re-introductions, and new occurrences of species.**

Locally extinct species include some of the largest carnivores, grassland associated birds, and species of fish and amphibians with small, isolated populations.[10,15,16,17,18] Attempted reintroductions of species to the greater Sky Island ecosystems include native fish, Tarahumara frog (*Lithoboates tarahumarae*), Chiricahua leopard frog (*L. chiricahuensis*), northern leopard frog (*L. pipiens*), California condor (*Gymnogyps californianus*), Aplomado falcon (*Falco femoralis*), prairie dog (*Cynomys* spp.), elk (*Cervus canadensis*), and bison (*Bison bison*).[19] Newly documented species include the Brazilian free-tailed bat,[20] and some species, such as the cliff chipmunk (*Tamias dorsalis*), Mexican vole (*Microtus mexicanus*), yellow-nosed cotton rat (*Sigmodon ochrognathus*), white-nosed coati (*Nasua narica*) and collared peccary (*Pecari tajacu*) have expanded their ranges in the Sky Island region.[15,19,21] Other species whose ranges reach their northern limit in Arizona have had more frequent detections in recent years, including the jaguar (*Panthera onca*) and ocelot (*Leopardus pardalis*).[19]

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Authors from Los Alamos National Laboratory and the Forest Service's Forest Health Monitoring Division discuss the link between topography and biodiversity, and discuss the topographic diversity of the Madrean Archipelago. The Madrean Archipelago is characterized by the mixing of Neotropic and Holarctic flora and Neotropic and Nearctic fauna, three major climatic zones (tropical, subtropical, and temperate) and high topographic relief with each mountain range in a northwest/southeast orientation. The authors create a map of predicted biodiversity based on a topographic analysis algorithm, and find a good fit in areas of particular topographic characteristics. The authors note that certain other factors may play a role in biodiversity of the region, including a bimodal rainfall pattern, diverse bedrock geology, hydrologic distribution, and other features of topography such as slope aspect.

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Authors from the Ecology and Evolutionary Biology department at the University of Arizona analyze forest-dwelling small mammal species on mountains in New Mexico and Arizona. They investigate whether assemblages follow a pattern of vicariance as has been found in the Great Basin, where species with former ranges that spread across the Great Basin have likely been completely isolated by subsequent vegetation change and have not experienced colonization between mountaintops. In these authors' analysis of New Mexico and Arizona, both isolation and area were significant contributors to variation in numbers of species, showing support for both vicariance and post-Pleistocene colonization and extinctions. The "sea" of woodlands and grasslands surrounding the sky islands may provide less of a barrier to dispersal than the desert scrub of the Great Basin. See Lomolino et al. 1989 for further analysis.

8. Lomolino, M. V., J. H. Brown, and R. Davis. 1989. Island biogeography of montane forest mammals in the American Southwest. Ecology 70:180-194.

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Authors from Arizona State University and the University of Arizona compare early naturalists' inventories from the Southwest and compare species lists to current state summaries and peer-reviewed articles. Nine species were extirpated prior to 1900, including the 3 large carnivores (grizzly bear, *Ursus arctos*, gray wolf, *Canis lupus*, and jaguar, *Panthera onca*), the black-footed ferret (*Mustela nigripes*), 2 ungulates (elk, *Cervus elaphus*, and bison, *Bison bison*), and grassland-associated birds (Aplomado falcon, *Falco femoralis*, sage grouse, *Centrocercus urophasianus*, and sharp-tailed grouse, *Pediocetes phasianellus*). Thirty-four species have experienced large range reductions and 55 show increased distributions since 1890. The majority of species with decreased ranges are grassland affiliated, while species with increased distributions are mostly species with range centers in Mexico, suggesting a shift in species northward.

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Weldon Heald coined the term 'Sky Island' in his 1967 book about the unique ecology of the Chiricahua Mountains. Written primarily from his ranch, which is now the American Museum of Natural History's Southwestern Research Station. Heald provides a first-person account of the unique natural features that drew him to the Chiricahuas in the first place. One of the more valuable features of this book is his chronicling of important species and events in the canyons surrounding his ranch, and also his account of changing conditions in the mountains: frequent floods and changing land management.

Fire History in the Sky Islands

Fire is a natural and reoccurring ecological disturbance in the sky island systems and is fundamentally important in shaping southwestern grasslands, savannahs, forests and shrublands. Over time, wildfires have a tendency to burn with characteristic patterns that together create what is known as a fire regime. Fire regime characteristics include the type of fire (surface fire or crown fire), its timing (seasonality, synchrony with drought or other climatic features), and its intensity (ranging from low to high, and which influences ecological effects). Fire regimes can change over time as a result of changing climatic conditions, altered vegetation and fuel loads and patterns, and altered ignition sources (typically a human factor). As a result, the landscape patterns of fire, and the ecological effects of fire, can be stable over long periods of time (centuries or longer) or can rapidly shift into new fire regime characteristics. The legacy effects of past fires can even limit or direct fire spread, in the case of landscape mosaics of burned and unburned fuels.[1] In the Madrean Archipelago, fire frequency was historically highest in the dry grasslands and ponderosa pine forests, and had lower frequency of occurrence in pine-oak gallery forests and in mesic mixed conifer forests.[2,3] In ponderosa pine forests with grass understory, fires could recur as often as every 1-2 years, with fire frequencies of 4-20 years common across the Madrean Sky Islands.[4] Humans have influenced fire frequency, seasonality, and possibly fire size through time[5,6] by reducing ignitions and controlling the spread of fires. The resulting increase in fuels has led to an increase in fire intensity and fire size, after an ignition occurs.[7] Increases in burned area and in fire severity have a tendency to create larger landscape mosaics consisting of larger patch sizes, which will have an influence on future trajectories of vegetation recovery and associated habitat value for wildlife and corridors for migration and dispersal.

References and Annotated Sources:

1. McKenzie, D., and M. C. Kennedy. 2011. Scaling laws and complexity in fire regimes. Chapter 2. In: The Landscape Ecology of Fire. ed. D. McKenzie, C. Miller and D. A. Falk, 27-49. Springer, Netherlands. 312pp.

2. Margolis, E., T. Swetnam, and C. Allen. 2011. Historical stand-replacing fire in upper montane forests of the Madrean Sky Islands and Mogollon Plateau, southwestern USA. Fire Ecology 7:88-107.
Margolis et al. use aspen stands, conifer scars, and age structure data in high elevation forest stands to reconstruct the size and age of stand-replacing fires. Across a network of sites in the Southwest, evidence of stand-replacing fire patches as large as 200-500 ha suggest that aspen-dominated areas of high-severity fire are within the historical range of variability for these forest types. At lower elevations and on dryer aspects, frequent and low-severity fire regimes (fires every 5-11 years) are more typical.

3. Morino, K. A., C. H. Baisan, and T. W. Swetnam. 2000. Historical fire regimes in the Chiricahua Mountains, Arizona: an examination of fire along an elevation gradient and in mixed-conifer forests: final report. Tucson, Ariz.: Laboratory of Tree-Ring Research, The University of Arizona.
This report examines fire frequencies along a gradient in elevation, in the process testing the idea that fire frequencies follow something like a normal distribution, with low fire frequencies at the lowest and highest elevations, and higher frequencies at middle elevations. The primary objective of this study was to examine fire frequencies in mixed-conifer forests across the variable of elevation. This report returns mean fire intervals of 6.5-15.4 years, with fires occurring as frequently as 1 year apart, and as long as 49 years between fires. This study reflects general trends in fire-climate and fire-history studies: a high degree of spatial and temporal variability is common in forested areas with complex topography and flammable fuels. One important thing to note is that because of fire exclusion, even the longest intervals without fire have been exceeded, and as such, these areas are now probably well outside their historical range of variability.

4. Swetnam T.W., Baisan C.H., P. M. Brown, and A. C. Caprio. 1989. Fire History of Rhyolite Canyon, Chiricahua National Monument. University of Arizona, Tucson, Arizona: Laboratory of Tree-Ring Research, Report Number, USDI National Park Service, Cooperative Park Service Studies Unit Technical Report No. 32.

5. Kaib, J.M. 1997. Fire History in Apacheria: the anthropogenic influence on fire regimes in the Southwest borderlands. Unpublished Thesis, University of Arizona. 23pp.
Kaib's thesis finds that in fire scarred material recovered from Rhyolite and Pine Canyons in the Chiricahua Mountains, fire frequencies during times of Spanish and US aggression and military incursion into Apache homelands decreased from peacetime frequencies of 2.60 and 2.63 years (1710-1748; 1786-1831) to wartime frequencies of 1.85 years (1680-1710); 1.52 years (1748-1786); and 2.18 years (1831-1872). This fire frequency evidence, coupled with documentary sources, suggests that human ignitions can overwhelm background climate and vegetation-driven fire dynamics at a landscape scale. Nevertheless, Kaib argues that fire frequencies are generally climatically driven, and respond to vegetation cycles rather than ignition source.

6. Seklecki, M. T., H. D. Grissino-Mayer, and T. W. Swetnam. 1996.
Fire history and the possible role of Apache-set fires in the Chiricahua Mountains of Southeastern Arizona. United States Department of Agriculture Forest Service General Technical Report RM-GTR-289:238-246.
Seklecki et al's paper examines changes in fire frequency during times of US and Spanish hostility towards Apache groups. The paper makes cautious claims that a slight but noticeable increase in fire frequency during times of active military engagement reflects fire use by Chiricahua Apache groups. Typical fire-climate signals break down slightly during the analysis period of this paper. The change in fire frequency is augmented by an unusually high number of dormant-season (late fall-early spring) wildfires. Ultimately, though, this paper abandons the claim of a significant and detectable anthropogenic influence on fire frequencies in the Chiricahuas, falling back on climate as a proximal driver of fire frequency. It should be noted that recent, large fires have been ignited, under extreme conditions, but the Seklecki et al. paper basically argues that human influence on fire frequencies, through the mechanism of multiple ignitions, could potentially drive fire regimes. The dendrochronology methods used by this paper are not well suited for analysis of large, single events.

7. Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313:940-943.

Historical Climatology of the Arizona Sky Islands

- **Temperature and precipitation means and extremes**

Much of the Madrean Archipelago, and certainly most of the Arizona sky islands, fall within the broader Sonoran Desert climate and biome region. The major climatic factors that influence vegetation patterns in the Sonoran Desert and its surrounding biomes is the timing and amount of precipitation, and the frequency and duration of cold events. Chihuahuan Desert and desert grasslands tend to bound the Sonoran Desert to the north and east, and are characterized by cooler temperatures, particularly colder winter temperatures that inhibit growth of Sonoran Desert vegetation such as the saguaro cactus (*Carnegiea gigantea*). The dominant climate pattern of the Sonoran Desert and nearby grasslands is one of high temporal variability of summer and of year-to-year precipitation, and a gradient from summer monsoon-dominated precipitation regime in the southeast (Chiricahua Mountains, Coronado National Memorial) to a nearly 50:50 distribution of winter and spring precipitation regime in the northwest Sonoran Desert.[1] Frost events tend to last less than 24 hours,[1] with longer durations of freezing temperatures found at higher elevations and in the northeastern Sonoran Desert. Freezing temperatures probably both limit the distribution of cold-intolerant plants, and provide a competitive advantage for species that are less adapted for heat and drought stresses. Prior to the early 1900s, extreme frost events occurred every 2-3 years, and now appears to occur on the order of every 20 years.[2] In this region, climate variability is still high, with significant frost events occurring in the winters of 2011 and 2013. Even under climate change scenarios, a warmer Southwest will still likely experience extreme events such as frost years.

Precipitation in the Sonoran Desert region of the sky islands is typically bimodal, with the bulk of precipitation falling in the warm season (North American Monsoon), and a lesser peak in the cold season.[3] Warm-season precipitation is highly variable and is not correlated with winter precipitation in any meaningful, time-stable way,[3] which means that the strength of the summer monsoon is independent of the amount of antecedent winter rains: a strong monsoon can follow a wet or dry winter, and a wet or dry winter might be followed by a weak monsoon season. The sky island region is subject to long-term droughts, which are linked to monsoon failure and periodically to winter-season droughts[3] and are most severe when droughts occur in consecutive seasons. Average precipitation for this area is 336mm,[3] but is spatially highly variable and ranges from <100mm (4 in) in low-elevation desert scrub to >800mm (32 in) on high mountain peaks[4]. Snow rarely falls on lower elevation sites but can provide a substantial portion of the precipitation at high elevations. To be available for plant growth, rainfall events of 6-8mm are required to wet the top 8cm of soil.[4] Climate change projections of warmer temperatures and decreases in summer precipitation may predict decreased plant growth, more wilting, and possibly mortality.

Potential effect of climate change on wildlife:

- **Climate change is likely to bring expanded desert scrub and decrease in montane forest types to the Sky Islands.**

Over the next century, climate change will likely result in temperature increases of 2-5^{o} C and increased variability of extreme events.[5,6] In the Madrean Archipelago, these climatic changes will likely result in expansion of desert scrub and decrease in montane forest types, resulting in substantial decrease in vertebrate populations that will especially affect mammals and reptiles that are restricted in their dispersal abilities.[7,8,9]

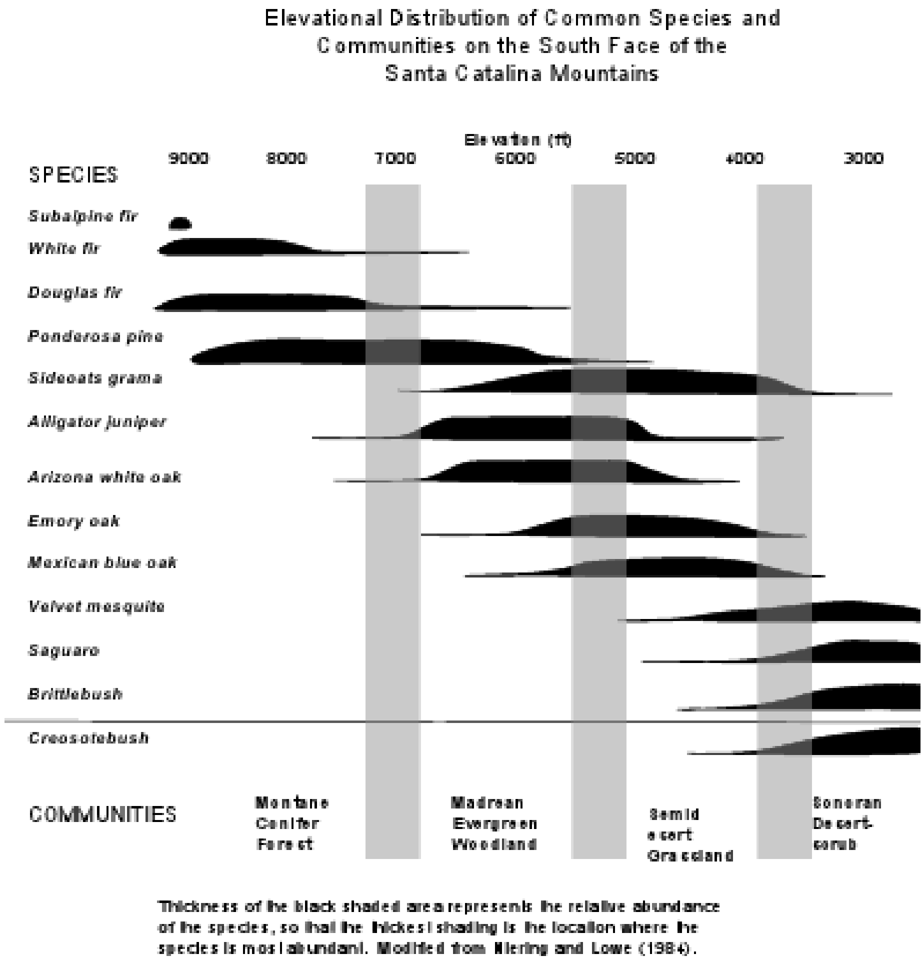
- **Climate change is likely to change fire regimes and together will alter vegetation patterns in the Sky Islands.**

Warmer conditions are projected to increase fire season length because of a reduction in snowpack and earlier spring melt, which leads to earlier dry conditions than in the past.[10,11] Longer fire seasons are correlated with increases in fire frequency, fire intensity, and fire size.

Larger, more intense wildfires have the capacity to reshape southwestern montane ecosystems, causing type conversions from forest to shrubland, and from savannah to grassland types.[12] Larger wildfires have the potential to create landscape mosaics composed of larger patches, with implications for post-fire ecological recovery and future trajectories of ecological disturbance,[13,14] which depend upon preexisting landscape mosaics and legacies of previous disturbances. Powerful monsoon storms falling after intense fires have the capacity to erode thousands of years of accumulated sediment in a single rainfall event. In the Chiricahua Mountains, it is possible that pine-oak gallery forests, ponderosa pine forests, and dry mixed conifer forest will burn and be replaced by chaparral or shrubland vegetation types. In addition, remnant patches of Engelmann spruce found at higher elevations in the Chiricahua Mountains are at risk from crown fire, the likelihood of which increases with warming conditions and longer fire seasons.

- **Climate change is likely to shift the distribution of plant species in the Sky Islands**

Climate change predictions of warmer and dryer conditions have prompted speculation that the elevational distribution of individual species and of vegetation types will shift in response to changing conditions. Simple models predict that species and vegetation types will "march upslope" to keep pace with their optimal climatic conditions. Other models suggest that species will still occur at the lower and upper boundaries of their current ranges, but that their distributions will shift upslope so that the bulk of their individuals will occur at higher, more mesic sites than at present.[15] In the Madrean Sky Island system, certain vegetation types, such as desert grasslands and savannahs, can move upslope with little trouble. Vegetation types found at high-elevations, such as the spruce-fir forests in the Pinaleño Mountains, or the relict and isolated population of Engelmann spruce (*Picea engelmanii*) in the Chiricahua Mountains, already exist at the highest elevations and cannot move to higher, more mesic sites as the climate warms and dries. High-elevation vegetation types such as spruce-fir forests, mixed-conifer forests, and ponderosa pine (*Pinus ponderosa*) forests have a limited extent. Because of the tapering nature of mountain peaks, there is progressively less space at higher elevations, which means that as climate warms and vegetation types adjust to changing climatic conditions, certain vegetation types could potentially run out of space and be replaced by adjacent vegetation types. Climate change-induced vegetation shifts will likely occur as a result of gradual shifts in species distributions and abundance within species ranges, punctuated by ecological disturbances such as wildfire, storms, drought, or insect outbreaks. These punctuated events are likely to cause dramatic shifts in vegetation types, including conversion of forests to shrubland or grassland, with attendant changes to habitat and community structure and function. It is also likely that climatic changes will reduce regeneration of certain species such as ponderosa pine at the lower elevation of their ranges, as climatic conditions become too harsh for either seed production, seedling establishment, or competitive conditions become too intense for juvenile trees. Warmer, drier conditions will favor oaks, juniper, and various chaparral and grass species over tree species.



Distribution of species by elevation. The pattern of species abundance along the elevation gradient has a characteristic 2-tailed shape, with the lowest abundance at the highest and lowest elevational ranges of a given species. The exception to this pattern is species that run into topographic limitations, such as mountaintops, above which they cannot grow, and valley floors. In these cases (Subalpine fir and White fir, for example), any physiological capability to grow higher in elevation is not captured in realized species ranges.

Image courtesy of Dr. Mitchel McClaran

- **Small, terrestrial vertebrates at the upper elevations in the sky islands are most at risk from climate change.**

Species with small, isolated populations are at risk from adverse effects of low genetic variation. Montane species in particular are at risk from climate change effects, due to their existence at the temperature limit of their range.[7,16] Species especially at risk from climate change in the Sky Islands include the elegant trogon (*Trogon elegans*) and the Tarahumara frog (*Rana tarahumarae*), due to their habitat requirements, physiology, and phenology,[17] as well as many small, non-volant mammals, and reptiles due to their geographic and elevational restrictions.[9]

- **Climate change will likely result in reduced genetic variability and phenological mismatch.**

Many isolated populations of species will likely experience reduction in genetic variability that could lead to population extinction.[18] This is mainly due to the climate-induced shift upslope of vegetation types on which certain species depend, which results in a smaller sized area of habitat. Smaller habitat leads to a reduction in population size which can reduce genetic variability. The timing in many life cycle events in plants and animals (phenology) is directly linked to climate. With warmer temperatures as a result of climate change, many species may experience mismatches between plants and their pollinators or predators and their prey.[16,19,20]

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1. Weiss, J. L., J. T. Overpeck. 2005. Is the Sonoran Desert losing its cool? Global Change Biology 11: 2065–2077.

2. Turner, D. S., S. Brandes, M. Fishbein, P. W. Hirt. 1995. Preserve design for maintaining biodiversity in the Sky Island Region. 531-533p. *In*: DeBano, L. F., P. F. Ffolliott , A. Ortega-Rubio, G. J. Gottfried, R. H. Hamre, and C. B. Edminster, tech. cords. 1995. Biodiversity and Management of the Madrean Archipelago: the Sky Islands of Southwestern United States and Northwestern Mexico. 1994 Sept. 19-23; Tucson, AZ. Gen. Tech. Rep. RM-GTR -264. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 669pp.

3. Griffin, D., C. A. Woodhouse, D. M. Meko, D. W. Stahle, H. L. Faulstich, C. Carrillo, R. Touchan, C. L. Castro, and S. W. Leavitt. 2013. North American monsoon precipitation reconstructed from tree-ring latewood. Geophysical Research. Letters 40:1-5.

4. Baker, M.B., Jr., L. F. DeBano, and P.F. Ffolliott. 1995. Hydrology and Watershed Management in the Madrean Archipelago. p: 329-337. *In*: DeBano, L.F., P.F. Ffolliott , A. Ortega-Rubio, G. J. Gottfried, R. H. Hamre, and C. B. Edminster, tech. cords. 1995. Biodiversity and Management of the Madrean Archipelago: the Sky Islands of Southwestern United States and Northwestern Mexico. 1994 Sept. 19-23; Tucson, AZ. Gen. Tech. Rep. RM-GTR -264. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 669pp.

5. Easterling, D. R., G. A. Meehl, C. Parmesan, S. A. Changon, T. R. Karl, L.O. Mearns. 2008. Climate extremes: observations, modeling, and impacts. Science 289:2068–2074.

6. IPCC. 2007. Climate Change 2007: Synthesis report: contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, United Kingdom.

7. McDonald, Kelly A., J. H. Brown. 1992. Using montane mammals to model extinctions due to climate change. Conservation Biology 6:409-415.

Authors from University of New Mexico use a scenario of temperature increase in 3° C and the resulting loss in vegetation types caused by this increase to predict extinctions of montane small mammals. The authors then compare this resulting habitat for each of 19 mountaintops in the Great Basin, and determine, using the species-area relationship, the decrease in species richness of 14 species of small mammals. The authors find a decrease in persistence on mountaintops ranging from 9 - 62% for each species, and the likely extinction of 3 of the 14 species throughout the region.

8. Schloss, C. A., T. A. Nuňez, and J. J. Lawler. 2012. Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. Proceedings of the National Academy of Sciences 109:8606-8611.

The authors model the ability of 493 mammals to track climate changes by looking at the velocities species need to move and dispersal distances and frequencies. On average, over 9% of mammals will not be able to keep pace with climate change, in some places up to 39% of mammals. Eighty-seven percent of species will experience reductions in range size, and 20% of those will be due to limited dispersal abilities. Effect of climate change will depend on the response capacity of mammals. The authors do not take into account landscape permeability, which will likely reduce dispersal ability of most species.

9. Koprowski, J. L., S. L. Doumas, M. J. Merrick, B.Oleson, E. E. Posthumus, T. G. Jessen, R. N. Gwinn. It's lonely at the top: endemic biodiversity at risk to loss from climate change. USDA Forest Service RMRS Madrean Conference Proceedings. *In press*.

The authors, from University of Arizona, look at current climate change predictions and patterns of elevational distribution of reptiles and mammals in the Madrean Archipelago. Based on temperatures in current elevational ranges and geographic distributions, the authors predict range shifts and determine species that would lose at least 80% of their ranges to be ‘at risk.’ The author’s assessments suggest that 15-25% of reptile and mammal species are at risk due to habitat loss alone, even without considering other factors such as effects of temperature increase on thermoregulation and food sources.

10. Williams, A. P., J. Michaelsen, S. W. Leavitt, and C. J. Still. 2010. Using tree rings to predict the response of tree growth to climate change in the Continental United States during the twenty-first century. Earth Interactions 14:1-20.

11. Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313:940-943.

12. Archer, S. R., and K. I. Predick. 2008. Climate change and ecosystems of the southwestern United States. Rangelands 30:23-28.

13. McKenzie, D., and M. C. Kennedy. 2011. Scaling laws and complexity in fire regimes. Chapter 2. In: The Landscape Ecology of Fire. ed. D. McKenzie, C. Miller and D. A. Falk, 27-49. Springer, Netherlands. 312pp.

14. McKenzie, D., Z. Gedalof, D. L. Peterson, and P. Mote. 2004. Climatic change, wildfire, and conservation. Conservation Biology 18:890-902.

15. Breshears, D.D., T. E. Huxman, H.D. Adams, C. B. Zou, and J. E. Davison. 2008. Vegetation synchronously leans upslope as climate warms. Proceedings of the National Academy of Sciences 105:11591-11592.
A number of climate change predictions suggest that the elevational distributions of species will shift higher in elevation with increasing temperatures. Breshears et al. provide evidence that as temperatures warm, the frequency distribution of individuals of a species will shift upslope in response to higher temperatures, but that the species range still holds roughly stable at the current upper and lower limits of its distribution. This finding has important implications for management, and also suggests that the phenotypic plasticity inherent to a population might provide additional adaptive capacity in the face of climate change. Other authors, in response to Breshears et al., argue that the shift in frequency distribution observed in this paper represents a mechanism by which species ranges do in fact shift over elevational gradients, and that Breshears et al. are describing an ephemeral process.

16. Parmesan, C. 2006. Ecology and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution and Systematics 37:637-639.
The author, from the University of Texas, presents a large scope review of ecological changes in phenology and distribution of plants and animals in response to climate change. Montane species with restricted ranges are likely to experience the most severe range contractions, and whole species isolated on mountains have already gone extinct.

17. Coe, S. J., D. M. Finch, and M. M. Friggens. 2012. An assessment of climate change and the vulnerability of wildlife in the Sky Islands of the Southwest. Gen.Tech.Rep.RMRS-GTR-273. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 217 pp.
General technical report from the USFS’s Rocky Mountain Research Station discusses likelihood of key environmental changes to the Coronado National Forest (CNF): increased average annual temperature and temperature extremes, reduced average annual precipitation, including a reduction in snowfall and snowpack, changes to the timing of peak stream flow (particularly those fed directly by snowmelt), increased wildfire activity, and a reduction in riparian forest and woodlands. The authors assess the vulnerability of 30 vertebrate species (determined to be high priority by CNF biologists) in CNF, reflecting measures of habitat, physiology, phenology, and biotic interactions. Species assessed include birds, mammals, reptiles and amphibians. Most vulnerable species in ranking include the elegant trogon (*Trogon elegans*) and the Tarahumara frog (*Rana tarahumarae)*, and habitat

was the area of highest vulnerability. For each species assessed, background information (with an extensive bilbiography) and an explanation of the score is given.

18. Ditto, A. M. and J. K. Frey. 2007. Effects of ecogeographic variables on genetic variation in montane mammals: implications for conservation in a global warming scenario. Journal of Biogeography 34:1136-1149.

Authors from University of New Mexico predict reduced genetic variability in isolated populations of montane small mammals in response to global warming. This study compares genetic variation (allozyme variation) with island area to predict changes in genetic variation following reduction in habitat area from global warming. The authors look at two species in particular that are found in the Sky Islands, the red squirrel (*Tamiasciurus hudsonicus*) and the Mexican woodrat (*Neotoma mexicana*). Island area and isolation of populations both have effects on genetic variation, thus reductions in area due to temperature shift upslope and resulting vegetation change as well as further isolation of populations may result in population decline.

19. Visser, M. E.and C. Both. 2005. Shifts in phenology due to global climate change: the need for a yardstick. Proceedings of the Royal Society B: Biological Sciences 272: 2561-2569.

Authors from Europe discuss the need for a yardstick that will predict how much will a species will be able to shift their phenology given the changes in its environment. Different types of shifts are proposed as potential yardsticks of climate change effects, including avian breeding phenology, avian migration phenology, insect phenology and phenology in aquatic systems. the authors assuming that food source (rather than, for example, predator risk) is the agent influencing the phenology of species, and that only a single activity (for example, breeding) per year is important. Review shows that most species react to climate change differently than the species on which they depend.

20. Crimmins, T. M., M. A. Crimmins, and C. D. Bertelsen. 2011. Onset of summer flowering in a ‘Sky Island’ is driven by monsoon moisture. New Phytologist 191:468-479.

The following were not cited above but provide useful information:

Kupfer, J. A., J. Balmat, and J. L. Smith. 2005. Shifts in the potential distribution of Sky Island plant communities in response to climate change. *Connecting mountain islands and desert seas: biodiversity and management of the Madrean Archipelago II*485-490.

Kupfer et al. published the results of a modeling exercise in the Rincon Mountains that examines the ecological changes associated with climate-change induced alterations to temperature and precipitation. Their model predicts that with an average increase of 3°C (5.4°F) and 10% precipitation over time, conifer forests (mixed conifer, ponderosa pine) will be reduced by more than 50% of their current coverage in the Rincon Mountains of Arizona

Munson, S. M., and M. H. Reiser. Jan 2013. Chihuahuan Desert Plant Responses to Climate Change. *Chihuahuan Desert Network Resource Brief: Chihuahuan Desert Inventory & Monitoring Network, National Park Service.* 1-4.

This paper explores drought-related climatic tipping points that favor certain species and vegetation types over others in Chihuahuan Desert grasslands. Certain grasses, such as Black Grama, are more sensitive to drought than they are to abundant moisture- their abundance on the landscape is disproportionately affected by dry periods. Shrub forms are sensitive to winter and summer precipitation amounts. Community indices such as species richness are strongly influenced by drought: as seasonal or annual precipitation amounts decline, overall species richness in a variety of elevational settings also declines. The authors make little note of the effects of temperature on these plants, but it can be assumed that warmer temperatures, even with historically normal precipitation, will mimic and enhance drought conditions.

Stories for Coronado National Memorial

Migration and Flow

- **Natural barriers such as mountain ranges contributed to species diversity, but man-made barriers may decrease diversity.**

The Sky Island region is characterized by high mountains and desert seas, with subpopulations of animals that migrate among the montane islands.[1,2] Mountain uplift, climate and vegetation change have created natural barriers that have caused speciation. The recent construction of a fence along the US-Mexico border has created a man-made barrier that has decreased connectivity of habitats for wildlife, especially those with small geographic ranges split by or in proximity to the border.[3] Natural barriers have persisted for geologic time, and the patterns of diversity observed in Sky Islands reflect the influence of natural barriers. More recent human barriers have the potential to promote extinction and reduced gene flow between vulnerable populations.

- **The border fence likely affects large terrestrial animals, migrating species, and even some species that fly.**

Effects of the fence are not limited to the physical barrier, but also include a 4 m wide road with a high volume of traffic, large numbers of stadium lights, and low level aircraft flights.[2] Populations of large terrestrial species, such as the bighorn sheep, and even some that migrate by flight but fly low to the ground, such as the pygmy owl, will likely experience loss in connectivity and restricted movement.[4] Species with small populations whose ranges overlap the border or with ranges in close proximity to the border will be at risk.[3] Both wildlife habitat and wildlife movements are affected by border fence construction, patrol and lighting.[2.3.4.5]

- **Crossing structures and limits to vegetation disturbance may decrease effects of the border fence on wildlife.**

For wide ranging mammals, recommended mitigation measures include crossing structures or fence gaps. For small migratory species, tall trees, limited disturbance of vegetation, and fence structures that allow passage of small animals may reduce negative effects. Remote sensing and remote surveillance of the border as a substitute for fences may decrease the human activity near the border that disturbs wildlife and also improve understanding of wildlife movements while also reducing barriers to gene flow and wildlife migration, and reducing habitat fragmentation. Translocations may be used as a last resort.[3,4]

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2. Vacariu, K. 2005. Threats to cross-border wildlife linkages in the Sky Island Wildlands Network. 353-356p. *In*: Gottfried, G. J., B. S. Gebow, L. G. Eskew, C. B. Edminster, compilers. 2005. Connecting mountain islands and desert seas: biodiversity and management of the Madrean Archipelago II. 2004, May 11-15; Tucson, AZ. Proceedings RMRS-P-36. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 631pp.

Author from the Wildlands Project discusses species with trans-border movement or connected subpopulations that are affected by border security measures, including jaguar, Mexican gray wolf, cougar, black footed ferret, ocelot, Mexican spotted owl, aplomado falcon, and southwestern willow flycatcher. In addition to the physical fence structure, other border activities affecting wildlife include a 4 m wide road running along the majority of the borderline that has high traffic volume, 1000 watt stadium lights, and low level aircraft flights. The author calls for more research on effects of these different activities, and gives socio-political recommendations for protecting wildlife linkage areas.

3. Lasky, J. R., W. Jetz, and T. H. Keitt. 2011. Conservation biogeography of the US-Mexico border: a transcontinental risk assessment of barriers to animal dispersal. Diversity Distributions 17:673-687.

Authors from University of Texas, Yale University and UC San Diego discuss three aspects of the border fence that affect animal dispersal: human altered landscapes, fences and walls, and areas of high human activity. The authors identify a threat to connectivity of populations and population levels due to decreased connectivity for species already listed as threatened under IUCN, and those with small geographic ranges split by or in proximity to the border. Species found to be most at risk included 4 species listed by IUCN, 23 species with ranges less than 10^5 km, and 29 species with marginal overlap with the border. The Madrean Archipelago was one of three regions of particular concern in this study that spanned the length of the US-Mexico border.

4. Flesch, A. D., C. W. Epps, J. W. Cain, M. Clark, P. R. Krausman, and J. R. Morgart. 2009. Potential effects of the United States-Mexico border fence on wildlife. Conservation Biology 24:171-181.

The authors, from 4 universities and the US Fish and Wildlife Service, discuss the potential effects of the border fence on wildlife and their movements. Two species with different life histories were selected as case studies: the ferruginous pygmy owl (*Glaucidium brasilianum*) and the desert bighorn sheep (*Ovis canadensis mexicana*). Pygmy owls averaged flight heights of only 1.4 m, and flights mostly less than 4 m, suggesting high fences and gaps in vegetation coverage may limit dispersal ability in this species. Bighorn sheep made large movements that crossed 11 km valleys, and 9 populations in Sonora are linked by dispersal to populations in Arizona. These results have implications for other terrestrial species that are too large to pass through fence infrastructure and avoid areas near the fence due to lack of vegetation cover, , or that fly at heights less than 4 m. Recommended mitigation measures include crossing structures or fence gaps for wide ranging mammals and tall trees, limited disturbance of vegetation, and fence structures for small animals. Remote surveillance technology may improve understanding of wildlife movements, and translocations may be used as a last resort.

5. Atwood, T. C., J. K. Young, J. P. Beckmann, S. W. Breck, J. Fike, O. E. Rhodes, and K. D. Bristow. 2011. Modeling connectivity of black bears in a desert sky island archipelago. Biological Conservation 144:2851-2862.

Conservation of the Lesser Long-nosed Bat

- **Low number of roosting locations and a dependence on a special food source makes the lesser long nosed bat susceptible to extinction.**

The migratory lesser long-nosed bat, *Leptonycteris yerbabuenae,* lives in Arizona from early April to mid to late September.[1] The bat feeds primarily on nectar of Cactaceae and Agavaceae families, but also cactus fruits, and is an important pollinator and seed disperser for these plants.[1] During migration, the bat follows a "nectar corridor" of flowering cactus and agave.[2] The species was listed as endangered in 1988, due to a population decline that seemed to be mirrored by a decline in seed set in multiple species of agave.[3,4] Recent construction of the fence along the US-Mexico border, followed by large wildfires in 2011, removed many plants of agave on which this bat depends. Restoration projects by Coronado National Memorial have so far planted 3000 agaves.[5]

- **Bats depend on agaves more than agaves depend on bats.**

Lesser long-nosed bats consume nectar and pollen from agave flowers and nectar, pollen and fruit from columnar cacti such as saguaro.[1] Bats are major pollinators of Cactaceae, Agavaceae, and principal pollinator of *Ceiba grandiflora* and disperser of cactus seeds.[1] However, because lesser long-nosed bats are found in low desnities at the northern limits of their range in southern Arizona, they may be unreliable pollinators for agave and cactus in this area, and bird and insect pollinators may be equally effective as pollinators of these plant species.[2] Therefore, while the bats depend on agave and cactus as their primary food source, the plant species may be less reliant on the bats for pollination.

- **Lesser long-nosed bat performs important ecosystem services.**

In Mexico, the lesser long-nosed bat is one of 2 species that are the principal pollinators of blue agave *(Agave tequilana*), the main ingredient in tequila. While many agave farmers rely on vegetative propagation of plants, this results in a low genetic diversity of these plants, making them more susceptible to disease and increasing potential economic loss to farmers. If bats were permitted to pollinate agave flowers on farms, plants would develop higher genetic diversity and resistance to pathogens.[6]

References and Annotated Sources:

1. Cole, F. R. and D. E. Wilson. 2006. *Leptonycteris yerbabuenae*. Mammalian species 797:1-7.
Species account for lesser long-nosed bat including information on distribution, ecology and conservation. This species is a seasonal migrant to Arizona, arriving in early April and departing in mid to late September, with occasional sightings in winter, and following a “nectar corridor” of CAM plants on route. *L. yerbabuanae* is a major pollinator of Cactaceae and Agavaceae and disperser of cactus seeds. Listed as endangered in 1988, threats to this species include harvesting of plants used for food, loss of cave-roosting sites and killing for pest control.

2. Fleming, T. H., C. T. Sahley, N. Holland, J. D. Nason, and J. L. Hamrick. 2001. Sonoran desert columnar cacti and the evolution of generalized pollination systems. Ecological Monographs 71:511-530.
Researchers at University of Miami’s Department of Biology used carbon isotopes from bats captured from Guatemala to Arizona to investigate diet of migrating bats. Columnar cacti and Ditepalae agaves provide a nectar corridor for bats during migration between Mexico and Arizona, and create seasonal dietary specialization in migrating bats. Spring diet is composed of 4 species of columnar cacti and *Agave colorata*. Fall diet is composed of species of *Agave* in the Ditepelae group. Authors suggest that elimination of these dietary components along the migration corridor will negatively affect bats and the reproductive success of their nectar sources.

3. U.S. Fish and Wildlife Service. 1995. Lesser Long-nosed Bat Recovery Plan. U.S. Fish and Wildlife Service, Albuquerque, New Mexico. 45 pp.
This document is the recovery plan from the US Fish and Wildlife Service for the lesser long-nosed bat, *Leptonycteris yerbabuenae.* This species was listed endangered throughout its range in the US (1988) and Mexico (1991). No critical habitat was designated for this species. During the time of the recovery plan, an estimated 60,000 individuals resided or fed in the southwest. This species is a seasonal resident in Arizona from early April to late September, but has been seen at hummingbird feeders in the region in January and February. The recovery criteria for this species included a stable population or increase in population as detected in roost monitoring, protection of roosts and forage plants, and a lack of new threats to species or habitat.

4. U.S. Fish and Wildlife Service. 2007. 5-year review of the lesser long-nosed bat. U.S. Fish and Wildlife Service, Albuquerque, New Mexico. 43 pp.
This five year review of the recovery plan for the lesser long-nosed bat, *Leptonycteris yerbabuenae*, found an increasing population trend since the listing of this species in 1988, though the number of maternity roosts (3) in the US remained the same. The limited number of roost sites shows the vulnerability of this bat to impacts to the roost sites. Other potential threats include border activities such as new surveillance roads and use of mines and caves by border crossers. The review does not discuss habitat lost during construction of border infrastructure. The final recommendation for this species is reduction of its status to threatened, although the authors acknowledge that it would not take much to threaten the species with extinction due to its few roosting sites and specialist diet.

5. McHugh, K. 2013. Agave Restoration Project. National Park Service Resource Brief: Experience Your America. April 2013. Unpublished report.

6. López-Hoffman, L., R. G. Varady, K. W. Flessa, and P. Balvanera. 2009. Ecosystem services across borders: a framework for transboundary conservation policy. Frontiers in Ecology and the Environment 8:84-91.

Bird Residents and Migrants in Coronado National Memorial

We compiled a species list from a comprehensive bird survey conducted at Coronado National Memorial between 2002 and 2004[1] and a study of riparian habitats in Huachucas from the 1980's[2] with eBird (eBird.org, Cornell University) checklists and three field guides, Birds of Arizona[3], Birds of Southeastern Arizona[4] and the Sibley Guide to Birds of Western North America to develop a master of list of 209 potential species that may be observed in and around Coronado National Memorial (Appendix A). Each species has been classified as either a resident or non-resident, and the status for each resident is given as rare, uncommon, fairly common, common, or accidental, as well as the status for each non-resident for summer and/or winter for Arizona.

References and Annotated sources:

1. Schmidt, C.A., Powell, B.F., Swann, D.E. and Halvorson, W.L., 2007, Vascular plant and vertebrate inventory of Coronado National Memorial: U.S. Geological Survey Open-File Report 2007-1393. 114 pp.
Comprehensive survey of birds at Coronado National Memorial between 2002 and 2004. Used four field methods: variable circular plot counts for diurnal breeding birds, nocturnal surveys for owls and nightjars, line transects for winter (non-breeding season) birds, and incidental observations. Recorded 129 species, including 5 new species for CORO: wild turkey, rock pigeon, yellow-billed cuckoo, Botteri's sparrow, and northern cardinal. The most widespread species during breeding season were ash-throated flycatcher, Beweck's wren, and also mourning dove, rufous-crowned sparrow, Scott's oriole, and house finch.

2. Strong, T. R. and C. E. Bock. 1990. Bird species distribution patterns in riparian habitats in southeastern Arizona. The Condor 92:866-885.
The authors, from University of Colorado at Boulder, used a circular plot method to conduct point counts for birds in riparian areas in the Huachuca Mountains. The authors compare avian richness and density in vegetation types with different dominant tree species, in winter and in summer. Two species lists are given in the appendix listing all birds encountered in summer and in winter, and a list of the dominant tree vegetation types in which these birds were detected.

3. Tekiela, S. 2003. Birds of Arizona field guide. Adventure Publications, Inc. Cambridge, Minnesota. 345pp.

4. Taylor, R.C. 2010. Birds of southeastern Arizona. R. W. Morse Company, Olympia, WA. 430 pp.

Glossary of Terms Used in this Document

- **Archipelago**: A large group or chain of islands. In the case of the Madrean Archipelago, the term is used metaphorically to describe the chain of mountaintop Sky Islands extending from northern Mexico to the Mogollon Rim.

- **Biome**: A major regional or global biotic community, typically defined by grouping of terrestrial plants, and by characteristic climatic features. The Sonoran Desert is defined by the presence of saguaro cacti and other plants, and by a particular precipitation and temperature regime. The Chihuahuan Desert is defined by the dominance of grasses, agave and *Opuntia* species, and by winter rainfall and colder temperatures than the Sonoran Desert.

- **Diversity** (biodiversity): The variety of living organisms considered at all levels, from genetics through species, to higher taxonomic levels, and including the variety of habitats and ecosystems.

- **Ecotone**: The transition zone between two distinct ecosystems. Ecotones can be a sharp boundary between two very different ecosystems, or they can represent a much more gentle transition. Often, the mix of vegetation in provides benefits to habitat specialists from both sides of the ecotone, as well as generalist species. Ecotones can also be unique habitats in their own right. Prominent examples of ecotones include the intertidal zone and forest-meadow boundaries. Ecotones tend to have high species richness and diversity.

- **Endemic**: Any localized process or pattern, but usually applied to a highly localized or restrictive geographic distribution of a species.

- **Gallery forest**: Forests that occur as corridors along rivers, canyons, or other drainages and that project into landscapes that otherwise do not support forests. In Sky Island canyons, gallery forests typically contain Douglas-Fir and southwestern white pine at the upper reaches, ponderosa pine and Chihuahua Pine in the middle to lower reaches, and Chihuahua pine and various Madrean oaks in the lower reaches. As the gallery forests extend deep into desert grasslands, the gallery forest will be dominated by mesquite. In all these cases, the gallery forests contain species at lower elevations than they are typically found.

- **Madrean**: Used as an adjective to describe and place biotic elements of the greater Sierra Madre Occidental biomes.

- **Mesic**: Of, characterized by, or adapted to a moderately moist environment. In the Madrean Sky Islands, this generally means that the sites maintain some moisture year round, and are not subject to prolonged annual dry periods. Mesic sites in the Sky Islands tend to be located on north-facing slopes, in drainages, near perennial water sources such as seeps and springs, or at high elevation, where temperatures are cooler, evaporation is less, and precipitation is higher than at lower elevations.

- **Phenology**: Study of the timing of biological activity over the course of a year, particularly in relation to climate. Examples include the emergence of leaves and flowers, timing of migration in birds, and timing of developmental cycles in insects. Phenology is a useful way in which to document the effect of variations in climate on plants and animals.

- **Phreatophyte**: A deeply rooted plant that obtains water from a permanent water source (such as a seep or spring) or from the water table (aquifer). Phreatophytes are critical to dryland water cycling, as they make water available to other plants in the upper soil levels. The most critical phreatophyte in the Madrean system is the mesquite (*Prosopis* species).

- **Vicariance**: The process of a continuously distributed taxon becoming separated by an intervening geographic event (such as mountain uplift or river flow) or extinction of intervening populations, resulting in subsequent independent histories of the fragmented taxon, and possible speciation events. In the case of the Madrean archipelago, the division of previously-connected forests by grasslands and deserts effectively created a barrier between now separated mountain peaks. In a longer geographic sense, the formation of the Basin and Range province mountains themselves can be considered a vicariant event that separated previously-connected terrestrial and aquatic biomes. The creation of man-made barriers that halt gene flow between populations can be considered a small-scale vicariant event.

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Appendix A: Coronado National Memorial Bird List

Table of birds that may be found in or in proximity to Coronado National Memorial. List compiled from a comprehensive bird survey conducted at Coronado National Memorial between 2002 and 2004(Schmidt et el. 2007), a study of riparian habitats in Huachucas from the 1980's (Strong and Bock 1990) with eBird (eBird.org, Cornell University) checklists and three field guides, Tekiela's Birds of Arizona, Taylor's Birds of Southeastern Arizona and the Sibley Guide to Birds of Western North America to develop a master of list of 209 potential species. Each species has been classified as either a resident or non-resident, and status for each resident is given as rare, uncommon, fairly common, common, or accidental, as well as the status for each non-resident for summer or winter for Arizona.

Common name	Scientific Name	Res-ident	Status	Non-res-ident	Summer Status	Winter Status
Anseriformes						
mallard	*Anas platyrhynchos*			✓	rare	common
Galliformes						
Gambel's quail	*Callipepla gambelii*	✓	common			
scaled quail	*Callipepla squamata*	✓	common			
Montezuma quail	*Cyrtonyx montezumae*	✓	fairly common			
wild turkey	*Meleagris gallapavo*	✓	fairly common			
Ciconiformes						
turkey vulture	*Cathartes aura*			✓	common	uncommon
black vulture	*Coragyps atratus*	✓	uncommon			
Falconiformes						
Cooper's hawk	*Accipiter cooperii*	✓	fairly common			
northern goshawk	*Accipiter gentilis*	✓	rare			
sharp-shinned hawk	*Accipiter striatus*			✓	rare	uncommon
golden eagle	*Aquila chrysaetos*	✓	uncommon			
zone-tailed hawk	*Beteo albonotatus*			✓	uncommon	rare
red-tailed hawk	*Buteo jamaicensis*	✓	common			
Swainson's hawk	*Buteo swainsoni*			✓	fairly common	
common black-hawk	*Buteogallus anthracinus*			✓	uncommon	
northern harrier	*Circus cyaneus*			✓	casual	common
white-tailed kite	*Elanus leucurus*			✓	uncommon	rare
bald eagle	*Haliaeetus leucocephalus*			✓	rare	uncommon
Harris' hawk	*Parabuteo unicinctus*	✓	fairly common			
merlin	*Falco columbarius*			✓		uncommon
prairie falcon	*Falco mexicanus*	✓	uncommon			
peregrine falcon	*Falco peregrinus*	✓	uncommon			
American kestrel	*Falco sparverius*	✓	fairly common			
Charadriformes						
killdeer	*Charadrius vociferous*	✓	common			
Columbiformes						
band-tailed pigeon	*Columba fasciata*			✓	common but irregular	casual
rock pigeon	*Columba livia*	✓	common			

Common name	Scientific Name	Res-ident	Status	Non-res-ident	Summer Status	Winter Status
Inca dove	*Columbina inca*	✓	fairly common			
common ground-dove	*Columbina passerine*	✓	uncommon			
white-winged dove	*Zenaida asiatica*			✓	common	rare
mourning dove	*Zenaida macroura*	✓	common			
Cuculiformes						
yellow-billed cuckoo	*Coccyzus americanus*			✓	fairly common	
greater roadrunner	*Geococcyx californianus*	✓	fairly common			
Strigiformes						
barn owl	*Tyto alba*	✓	fairly common			
great-horned owl	*Bubo virginianus*	✓	common			
northern pygmy owl	*Glaucidium gnoma*	✓	uncommon			
western screech-owl	*Megascops kennicottii*	✓	fairly common			
whiskered screech-owl	*Megascops trichopsis*	✓	fairly common			
elf owl	*Micrathene whitneyi*			✓	common	
flammulated owl	*Otus flammeolus*			✓	fairly common	
Mexican spotted owl	*Strix occidentalis lucida*	✓	uncommon			
Caprimulgiformes						
Mexican whip-poor-will	*Caprimulgus arizonae*			✓	fairly common	
common nighthawk	*Chordeiles minor*			✓	uncommon	
common poorwill	*Phalaenoptilus nuttallii*			✓	fairly common	rare
Trogoniformes						
elegant trogon	*Trogon elegans*			✓	fairly common	rare
Apodiformes						
white-throated swift	*Aeronautes saxatalis*	✓	fairly common			
violet-crowned hummingbird	*Amazilia violiceps*			✓	uncommon	rare
black-chinned hummingbird	*Archilochus alexandri*			✓	common	
Lucifer hummingbird	*Calothorax lucifer*			✓	rare	
Anna's hummingbird	*Calypte anna*	✓	common			
Costa's hummingbird	*Calypte costae*			✓	uncommon	fairly common

Common name	Scientific Name	Res-ident	Status	Non-res-ident	Summer Status	Winter Status
broad-billed hummingbird	*Cynanthus latirostris*			✓	common	rare
magnificent hummingbird	*Eugenes fulgens*			✓	common	rare
plain-capped starthroat	*Heliomaster constanii*			✓	rare	
white-eared hummingbird	*Hylocharis leucotis*			✓	rare	
blue-throated hummingbird	*Lampomis clemenciae*			✓	fairly common	rare
broad-tailed hummingbird	*Selasphorus platycercus*			✓	common	uncommon
rufous hummingbird	*Selasphorus rufus*			✓	common	
Allen's hummingbird	*Selasphorus sasin*			✓	uncommon	
Calliope hummingbird	*Stellula calliope*			✓	uncommon	
northern flicker	*Colaptes auratus*	✓	common			
gilded flicker	*Colaptes chrysoides*	✓	fairly common			
acorn woodpecker	*Melanerpes formicivorus*	✓	common			
Lewis's woodpecker	*Melanerpes lewis*			✓		irregular
Gila woodpecker	*Melanerpes uropygialis*	✓	common			
Arizona woodpecker	*Picoides arizonae*	✓	fairly common			
ladder-backed woodpecker	*Picoides scalaris*	✓	common			
hairy woodpecker	*Picoides vilosus*	✓	fairly common			
red-naped sapsucker	*Sphyrapicus nuchalis*			✓	fairly common	uncommon
red-breasted sapsucker	*Sphyrapicus ruber*			✓		casual
Williamson's sapsucker	*Sphyrapicus thyroideus*			✓	casual	rare
yellow-bellied sapsucker	*Sphyrapicus varius*			✓		casual
Passeriformes						
greater pewee	*Contopus pertinax*			✓	uncommon	rare
western wood-pewee	*Contopus sordidulus*			✓	common	
Pacific-slope flycatcher	*Empidonax difficilis*			✓	fairly common	casual
buff-breasted flycatcher	*Empidonax fulvifrons*			✓	fairly common	
Hammond's flycatcher	*Empidonax hammondii*			✓	common	uncommon

Common name	Scientific Name	Res-ident	Status	Non-res-ident	Summer Status	Winter Status
dusky flycatcher	*Empidonax oberholseri*			✓	fairly common	rare
cordilleran flycatcher	*Empidonax occidentalis*			✓	fairly common	
willow flycatcher	*Empidonax traillii*			✓	rare	
gray flycatcher	*Empidonax wrightii*			✓	rare	fairly common
ash-throated flycatcher	*Myiarchus cinerascens*			✓	common	rare
dusky-capped flycatcher	*Myiarchus tuberculifer*			✓	common	
brown-crested flycatcher	*Myiarchus tyrannulus*			✓	common	
sulphur-bellied flycatcher	*Myiodynastes luteiventris*			✓	fairly common	
vermilion flycatcher	*Pyrocephalus rubinus*			✓	common	uncommon
black phoebe	*Sayornis nigricans*	✓	common			
Say's phoebe	*Sayornis saya*	✓	common			
western kingbird	*Tyrannus verticalis*			✓	common	casual
Cassin's kingbird	*Tyrannus vociferans*			✓	common	casual
loggerhead shrike	*Lanius ludovicanus*	✓	fairly common			
Bell's vireo	*Vireo bellii*			✓	common	
Cassin's vireo	*Vireo cassinii*			✓		rare
warbling vireo	*Vireo gilvus*			✓	fairly common	
Hutton's vireo	*Vireo huttoni*			✓	fairly common	uncommon
plumbeous vireo	*Vireo plumbeus*			✓	common	rare
western scrub-jay	*Aphelocoma californica*	✓	fairly			
Mexican jay	*Aphelocoma ultramarina*	✓	common			
Stellar's jay	*Cyanocitta stelleri*	✓	common			
pinyon jay	*Gymnorthinus cyanocephalus*	✓	uncommon			
common raven	*Corvus corax*	✓	common			
Chihuahuan raven	*Corvus cryptoleucus*	✓	common			
horned lark	*Eremophila alpestris*	✓	fairly common			
barn swallow	*Hirundo rustica*			✓	common	casual
violet-green swallow	*Tachycineta thalassina*			✓	common	casual
bridled titmouse	*Baeolo wollweberi*	✓	common			
verdin	*Auriparus flaviceps*	✓	common			
juniper titmouse	*Baeolo ridgwayi*	✓	uncommon			

Common name	Scientific Name	Res-ident	Status	Non-res-ident	Summer Status	Winter Status
brown creeper	*Certhia americana*	✓	fairly common			
bushtit	*Psaltriparus minimus*	✓	fairly common			
white-breasted nuthatch	*Sitta carolinensis*	✓	common			
cactus wren	*Campylorhynchus brunneicapillus*	✓	common			
canyon wren	*Catherpes mexicanus*	✓	common			
rock wren	*Salpinctes obsoletus*	✓	fairly common			
Bewick's wren	*Thryomanes bewickii*	✓	fairly common			
house wren	*Troglodytes aedon*			✓	fairly common	fairly common
ruby-crowned kinglet	*Regulus calendula*			✓	rare	common
blue-gray gnatcatcher	*Polioptila caerulea*			✓	uncommon	uncommon
black-tailed gnatcatcher	*Polioptila melanura*	✓	common			
mountain bluebird	*Sialia currucoides*			✓		fairly common
western bluebird	*Sialia mexicana*	✓	fairly common			
eastern bluebird	*Sialia sialis*	✓	uncommon			
hermit thrush	*Catharus guttatus*	✓	fairly common			
Swainson's thrush	*Catharus ustulatus*			✓	uncommon	
varied thrush	*Ixoreus naevius*			✓		rare
Townsend's solitaire	*Myadestes townsendi*			✓	casual	uncommon
American robin	*Turdus migratorius*	✓	fairly common			
gray catbird	*Durnetella carolinensis*			✓	casual	casual
northern mockingbird	*Mimus polyglottos*	✓	common			
Bendire's thrasher	*Toxostoma bendirei*	✓	fairly common			
crissal thrasher	*Toxostoma crissale*	✓	fairly common			
curve-billed thrasher	*Toxostoma curvirostre*	✓	common			
cedar waxwing	*Bombycilla cedrorum*			✓	casual	fairly common
phainopepla	*Phainopepla nitens*	✓	common			
red-faced warbler	*Cardellina rubrifrons*			✓	common	
yellow-rumped warbler	*Dendroica coronata*			✓	fairly common	common
black-throated gray warbler	*Dendroica nigrescens*			✓	common	rare
hermit warbler	*Dendroica occidentalis*			✓	common	accidental
yellow warbler	*Dendroica petechia*			✓	common	

Common name	Scientific Name	Res-ident	Status	Non-res-ident	Summer Status	Winter Status
Townsend's warbler	*Dendroica townsendi*			✓	common	rare
black-throated green warbler	*Dendroica virens*			✓	casual	accidental
Grace's warbler	*Denroica graciae*			✓	common	
common yellowthroat	*Geothypis trichas*			✓	common	fairly common
yellow-breasted chat	*Icteria virens*			✓	common	casual
painted redstart	*Myioborus pictus*			✓	common	rare
MacGillivray's warbler	*Oporomis tolmiei*			✓	rare	
orange-crowned warbler	*Oreothlypi celata*			✓	rare	uncommon
Nashville warbler	*Oreothlypis ruficapilla*			✓	fairly common	
ovenbird	*Seiurus aurocapilla*			✓	casual	casual
Lucy's warbler	*Vermicora luciae*			✓	fairly common	
Virginia's warbler	*Vermicora virginiae*			✓	fairly common	
Wilson's warbler	*Wilsonia pusilla*			✓	common	casual
hepatic tanager	*Piranga flava*			✓	fairly common	casual
western tanager	*Piranga ludoviciana*			✓	fairly common	casual
summer tanager	*Piranga rubra*			✓	common	casual
Abert's towhee	*Pipilo aberti*	✓	fairly common			
green-tailed towhee	*Pipilo chlorurus*			✓	common	uncommon
canyon towhee	*Pipilo fuscus*	✓	common			
spotted towhee	*Pipilo maculatus*	✓	fairly common			
Botteri's sparrow	*Aimophila botterii*			✓	fairly common	
rufous-winged sparrow	*Aimophila carpalis*	✓	fairly common			
Cassin's sparrow	*Aimophila cassinii*	✓	fairly common			
rufous-crowned sparrow	*Aimophila ruficeps*	✓	fairly common			
grasshopper sparrow	*Ammodramus savannarum*	✓	fairly common			
black-throated sparrow	*Amphispiza bilineata*	✓	common			
lark bunting	*Calamospiza melanocorys*			✓		irregular but common
chestnut-collared longspur	*Calcarius ornatus*			✓		
lark sparrow	*Chondestes grammacus*	✓	fairly common			

Common name	Scientific Name	Res-ident	Status	Non-res-ident	Summer Status	Winter Status
dark-eyed junco	*Junco hyemalis*			✓		common
yellow-eyed junco	*Junco phaeonotus*	✓	common			
Lincoln's sparrow	*Melospiza lincolnii*			✓		irregular but common
song sparrow	*Melospiza melodia fallax*	✓	common	✓		
swamp sparrow	*Melozpiza georgiana*			✓		rare
savannah sparrow	*Passerculus sandwichensis*			✓		common
fox sparrow	*Passerella ilaca*			✓		rare
vesper sparrow	*Pooecetes gramineus*			✓		common
black-chinned sparrow	*Spizella atrogularis*	✓	uncommon			
Brewer's sparrow	*Spizella breweri*			✓		common
chipping sparrow	*Spizella passerina*	✓	uncommon			
white-throated sparrow	*Zonotrichia albicollis*			✓		uncommon
white-crowned sparrow	*Zonotrichia leucophrys*			✓		common
northern cardinal	*Cardinalis cardinalis*	✓	common			
pyrrhuloxia	*Cardinalis sinautus*	✓	common			
blue grosbeak	*Guiraca caerulea*			✓	common	casual
lazuli bunting	*Passerina amoena*			✓	rare	rare
indigo bunting	*Passerina cyanea*			✓	uncommon	casual
rose-breasted grosbeak	*Pheucticus ludovicianus*			✓	rare	casual
black-headed grosbeak	*Pheucticus melanocephalus*			✓	common	
eastern meadowlark	*Sturnella magna*	✓	common			
western meadowlark	*Sturnella neglecta*			✓	rare but irregular	fairly common
red-winged blackbird	*Agelaius phoeniceus*	✓	common			
bronzed cowbird	*Molothrus aeneus*			✓	fairly common	rare
brown-headed cowbird	*Molothrus ater*	✓	fairly common			
Bullock's oriole	*Icterus bullockii*			✓	fairly common	casual
hooded oriole	*Icterus cucullatus*			✓	fairly common	casual
northern (Baltimore) oriole	*Icterus galbula*			✓	casual	
Scott's oriole	*Icterus parisorum*			✓	fairly common	casual

Common name	Scientific Name	Res-ident	Status	Non-res-ident	Summer Status	Winter Status
streak-backed oriole	*Icterus pustulatus*			✓	casual	rare
pine siskin	*Carduelis pinus*			✓	uncommon	fairly common
lesser goldfinch	*Carduelis psaltria*	✓	common			
American goldfinch	*Carduelis tristis*			✓	casual	irregularly rare to uncommon
Cassin's finch	*Carpodacus cassinii*			✓	accidental	irregular and uncommon
house finch	*Carpodacus mexicanus*	✓	common			
purple finch	*Carpodacus purpureus*			✓		casual
house sparrow	*Passer domesticus*	✓	common			