National Park Service
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Natural Resource Stewardship and Science

John Day Fossil Beds National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/846

ON THE COVER
Modern landscapes of the three units of John Day Fossil Beds National Monument.
Clockwise from upper left: Clarno Palisades, Sheep Rock, and Painted Hills.
Clarno and Painted Hills photographs by Jason Kenworthy (NPS Geologic Resources Division). Sheep Rock photograph by Robert J. Lillie (Oregon State University).

THIS PAGE
Murals representing paleoecosystems of the Clarno Nut Beds (Clarno Unit), Turtle Cove Member of the John Day Formation (Sheep Rock Unit), and Bridge Creek flora of the John Day Formation (Big Basin Member) (Painted Hills Unit). National Park Service murals by Larry Felder (Clarno and Bridge Creek) and Roger Witter (Turtle Cove), all photographed by Will Landon.

John Day Fossil Beds National Monument

Geologic Resources Inventory Report

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a conference call for John Day Fossil Beds National Monument (Oregon) on 30 January 2013, which was held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

In 1974, John Day Fossil Beds National Monument was established to preserve an outstanding collection of Paleogene and Neogene (Tertiary) fossils. The museum collections at John Day Fossil Beds National Monument include more than 60,000 specimens of plant and animal fossils that span more than 40 million years, a span of time encompassing most of the Cenozoic Era. Although other NPS units also protect Cenozoic fossils, the record preserved at John Day Fossil Beds National Monument far surpasses that of any other Cenozoic fossil park. The Clarno Nut Beds, for example, have yielded fossils of more than 145 genera and 173 species of fruits and seeds. The flora and fauna from the John Day Formation exquisitely capture the changing climatic conditions from the Late Eocene to Early Miocene. In 1948, University of California paleobotanist Ralph W. Chaney claimed, "no region in the world shows more complete sequences of Paleogene and Neogene land populations, both plant and animal, than the John Day formations."

The monument is divided into three administrative units: the Sheep Rock, Painted Hills, and Clarno units. The strata and fossils in these three units provide exceptionally precise and detailed accounts of global climate change, habitat transitions, and the adaptations of organisms to these and other changes.

About 45 million years ago, central Oregon had a subtropical climate. Global mean annual temperatures approached 25° C (77° F), warmer than the planet has known for the past 65 million years. The High Cascades did not exist, and thus did not block moisture from the Pacific Ocean. As a result, the region of present-day central Oregon received up to 135 cm (53 in) of rainfall annually.

Approximately 33 million years ago, the region's greenhouse climate changed from subtropical to temperate. Wooded areas became similar to today's eastern United States, with deciduous forests occupying the lowlands and coniferous forests growing at higher elevations.

Throughout the Paleogene and Neogene periods, volcanic ash, lava, and volcanic mudflows spread over the region from eruptions in the Blue Mountains (present-day northeastern Oregon) and other volcanic vents in today's central and eastern Oregon. Between 17 million and 6 million years ago, a colossal outpouring of basaltic lava flooded the region.

During the Pleistocene ice ages, which continued the cooling trend of the Late Neogene, alpine glaciers flowed down canyons in the developing High Cascades, and erosion began to carve the current landscape, exposing some of the fossilized remains that lay buried beneath present-day central Oregon.

The geologic features and processes in John Day Fossil Beds National Monument record the region's transformation from subtropical jungle to a high desert environment, as well as its volcanic history. The monument's paleontological resources are considered to be its most significant geologic feature, but its stratigraphic features, volcanic rocks, and paleosols are as intimately associated with the Paleogene and Neogene ecosystems as are the fossil remains. In addition, the tectonic regime along the western margin of North America established the foundation upon which these habitats emerged. The features and processes in John Day Fossil Beds National Monument include:

- Stratigraphic features and paleontological resources. Strata in John Day Fossil Beds National Monument document the depositional environments of the surrounding landscape through time. Lava flows, ash beds, and tuff layers provide evidence of volcanic activity in the region and radiometric age dates. Features in interbedded sedimentary layers in all three administrative units record deposition in alluvial fan, floodplain, stream, and lacustrine environments and provide a framework for understanding fossil fauna habitats. The past diversity of life in east-central Oregon is reflected in the myriad plant and animal fossils in John Day Fossil Beds National Monument. The fossils document evolutionary change and extinction through time, including an organism's response to changing climate, geologic events, and other factors.
- Paleosols. Features representing dozens of paleosol (ancient soil) types in John Day Fossil Beds National Monument, especially in the Clarno and John Day formations, document the transition from forested ecosystems to grassland habitats and are associated

with the fossil flora and changing climate documented in the monument.

- Volcanic features in the John Day Formation. The variety and abundance of volcanic layers, including the impressive Picture Gorge Ignimbrite, Picture Gorge Basalt, and Rattlesnake Ash Flow Tuff, provide evidence of Oregon's evolving volcanic landscape. Remnants of three cataclysmic volcanic eruptions in the Blue Mountains are recorded in the volcanic tuffs of the Clarno and John Day formations in the monument.
- Folds and faults. Tectonic plate collisions during the Mesozoic and Early Paleogene produced folding and faulting in the John Day region. The Clarno Unit contains folding and an igneous intrusion. Faulting and two intrusive domes occur in the Painted Hills Unit, and the Sheep Rock Unit contains a dominant east–west-trending fault.
- Cave and karst features. Although not well defined, sinkholes and pseudokarst features occur in many areas of the monument, such as at Blue Basin and Carroll Rim. These features have not been inventoried or studied in detail.
- Fluvial geomorphic features. Point bars, cutbanks, natural levees, and other geomorphic features are associated with the John Day River, Pine Creek, Bridge Creek, and their tributaries that flow through John Day Fossil Beds National Monument. Recent river processes mimic those that have occurred in the past. Paleogene and Neogene carcasses, for example, accumulated on point bars, which form on today's John Day River under processes that are similar to those occurring in the past.
- Exceptional geologic landscape features. Each unit in John Day Fossil Beds National Monument contains a landscape that hosts exceptional geologic features, such as Sheep Rock, the Palisades, the Painted Hills, Picture Gorge, and the Clarno Nut Beds. Some of these landscapes, such as the badlands at Turtle Cove, the lahars of Hancock Canyon, and the Clarno Nut Beds, also have exceptional paleontological significance.

Geologic issues of particular and potential significance for resource management at John Day Fossil Beds National Monument were identified during a conference call on 30 January 2013. They include the following:

- Paleontological resource inventory, monitoring, and protection. In accordance with the 2009 Paleontological Resources Preservation Act (Public Law 111-11), John Day Fossil Beds National Monument implements a comprehensive, science-based paleontological resource management program that includes inventory, monitoring, research, and education, as well as the protection of resource and locality information. The monument has implemented a cyclic prospecting/management plan for over 25 years and is a Cooperative Area for the Management of Paleontology (CAMP). Sixteen parcels of land in the Bureau of Land Management Prineville District have been identified for inclusion in this unique CAMP system because of their abundant paleontological resources and/or unique strata.
- Flooding and subsequent erosion. The John Day River occasionally floods. Erosion may expose or destroy fossil sites.
- Slope movements. Landslides occur in the less resistant volcaniclastic rocks of the John Day Formation. Slope movements occasionally cover trails with debris.
- Potential seismic (earthquake) activity. Earthquakes are rare in central Oregon. Quaternary faults exist near the monument, but do not appear to intersect the monument's boundaries.
- Potential volcanic hazards. While past volcanic activity greatly impacted John Day Fossil Beds National Monument, volcanic hazards currently pose minimal risk to the park. Tephra fall from Cascades volcano eruptions may reach the park.
- Disturbed lands. No Abandoned Mineral Lands (AML) site is documented from the monument in the NPS AML database. However, past mining activities have left a very small coal mine in the Painted Hills and several abandoned exploratory hydrocarbon test wells at Clarno. The monument should consider documenting these features as part of the servicewide effort to inventory AML features.
- Cave and karst inventory and monitoring. Caves and karst features in the monument, including lava tubes in Picture Gorge, may contain paleontological and cultural remains. Monument staff may wish to conduct a cave inventory in the future.

In addition to detailed accounts of the Paleogene and Neogene, the rocks in the region of John Day Fossil Beds National Monument provide an account of the accretion of volcanic arcs to the margin of western North America during the Paleozoic and Mesozoic eras. Subduction of oceanic crust beneath the North American Plate resulted in deformation and volcanic activity throughout the Mesozoic and into the Cenozoic Era. As stratovolcanoes erupted, Pleistocene alpine glaciers flowed in the higher elevations of the Blue Mountains and Cascade Range.

John Day Fossil Beds National Monument is one of six NPS units established specifically to preserve and protect Cenozoic Era fossils. These six units, in addition to dozens of others that also preserve Cenozoic fossils, together offer a unique perspective on the responses of ecosystems to global climate change during the Paleogene and Neogene. This monument offers an exceptional opportunity to study more than 40 million years of past global climate change and its effects on terrestrial ecosystems, paleobiodiversity, and evolutionary change.

This Geologic Resources Inventory report was written for resource managers to support science-informed decision making, but it may also be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division did not conduct any new fieldwork in association with this report. Sections of the report discuss distinctive geologic features and processes within John Day Fossil Beds National Monument, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI geologic map data. A geologic map poster (in pocket) illustrates these data. The Map Unit Properties Table (in pocket) summarizes the report content for each geologic map unit.

Products and Acknowledgements

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop Geologic Resources Inventory products. This section describes those products and acknowledges contributors to this report.

Geologic Resources Inventory Products

The objective of the Geologic Resources Inventory (GRI) is to provide geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" section and Appendix B provide links to these and other resource management documents and information.

Additional information regarding the GRI, including contact information, is available at: http://www.nature.nps.gov/geology/inventory/. The current status and projected completion dates of products are at: http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx.

Acknowledgements

This report benefited greatly from the time, energy, and input of Joshua Samuels, the museum curator/chief of paleontology at John Day Fossil Beds National Monument. He provided a detailed summary of the geology and paleontology of the monument, as well as the history of paleontological research at the monument. That text formed the foundation for much of this report. He also provided the species lists (in pocket) and many photographs and figures. His subsequent reviews of the report are also greatly appreciated. Trista Thornberry-Ehrlich (Colorado State University) drafted a number of figures used in this report.

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Geologic Setting and Significance

This section describes the regional geologic setting of John Day Fossil Beds National Monument, and summarizes connections between geologic resources and other park resources and stories.

Park Setting

Located in semi-arid eastern Oregon, John Day Fossil Beds National Monument includes more than 5,700 ha (14,000 ac) in three widely separated administrative units: the Sheep Rock, Painted Hills, and Clarno units (fig. 1). Established in 1974, the monument preserves outstanding Cenozoic fossil localities and strata that contain a great variety of fossils from hundreds of species. The fossils and strata document an incredible global climate change and subsequent evolution of habitats from about 51 million to 7 million years ago, from the Eocene to the Late Miocene epochs (fig. 2). Fossil plants and animals in the monument record the transition from an exceptionally warm global "greenhouse" climate to a global "icehouse" climate that led to the Pleistocene ice ages. The fossil assemblages also reflect a variety of factors that contributed to evolutionary changes and paleobiodiversity throughout these epochs, such as biogeographic isolation, interspecific and intraspecific competition, and geologic events.

The thousands of fossil specimens collected from John Day Fossil Beds National Monument, combined with fossils discovered at Fossil Butte National Monument (Wyoming), Badlands National Park (South Dakota), Florissant Fossil Beds National Monument (Colorado), Agate Fossil Beds National Monument (Nebraska), and Hagerman Fossil Beds National Monument (Idaho) capture the diverse habitats of jungles, woodlands, and savannas that sequentially characterized western North America prior to the onset of the Pleistocene ice ages. Geologic Resources Inventory reports have been completed for all of these parks, see KellerLynn (2006) and Graham (2008, 2009a, 2009b, 2012a).

Oregon's current landscape is a product of recent fluvial processes and tectonic events that have affected the western margin of North America since the Paleozoic (fig. 3). During the Mesozoic, subduction along the western margin of North America accreted several regionally extensive, fault-bounded blocks of similar rocks (terranes) to the continent. These terranes traveled unknown distances from their places of origin before docking to the North American continent. In the Neogene, basalts erupted and covered much of the Columbia River Basin. Farther south, extension pulled apart the crust, resulting in Basin-and-Range topography. Most recently, fluvial systems have incised steep ravines in the relatively soft strata.

Significance of John Day Fossil Beds

John Day Fossil Beds National Monument was established by Congress to preserve a portion of the significant paleontological resources in the John Day Basin. The monument contains a nearly continuous fossil record spanning 44 million years of the Paleogene and Neogene. The fossil diversity recorded at John Day Fossil Beds National Monument is unsurpassed by any other North American Tertiary paleontological site. Worldwide, few other fossil localities, if any, provide such access to a nearly continuous 44 million years of Paleogene and Neogene history (Joshua Samuels, John Day Fossil Beds NM, museum curator/chief of paleontology, written communication, 11 April 2013).

Radiometric age dates from volcanic ash and lava flows, which are interlayered with fossiliferous sedimentary strata, provide time constraints on distinct fossil assemblages that are rarely found in the geologic record. According to Joshua Samuels (written communication, 11 April 2013), some fossils can be constrained to a period of less than 100,000 years. Such precision allows comparison of the fossil assemblages from John Day Fossil Beds National Monument with other Paleogene and Neogene fossil assemblages from sites throughout the world. Global comparisons further an understanding of how organisms and their environments changed through time.

The relatively complete paleontological and geological record of this region continues to provide research and educational opportunities. Increased understanding of the original depositional environments, represented by geologic features within individual rock layers, as well as new fossil discoveries, enhance the geologic story of how species and their ecosystems evolved through time. The integration of rock and fossil data enables researchers to better understand how climate change and geologic events impacted species diversity, evolution, and extinction.

Overview of the Geologic Setting

The units of John Day Fossil Beds National Monument cover portions of two physiographic provinces in eastern Oregon: the Blue Mountains (Sheep Rock Unit) and the Deschutes-Columbia Plateau (Clarno and Painted Hills units) provinces (fig. 4). The triangular Blue Mountains Province contains approximately 140,000 km^2 (55,000 mi^2) of rugged, mountainous topography. The Baker, Wallowa, Olds Ferry, and Izee terranes, which were once volcanic island arcs and marine basins, form the foundation of the Blue Mountains Province (Orr and Orr 2012). These terranes accreted to the western margin of

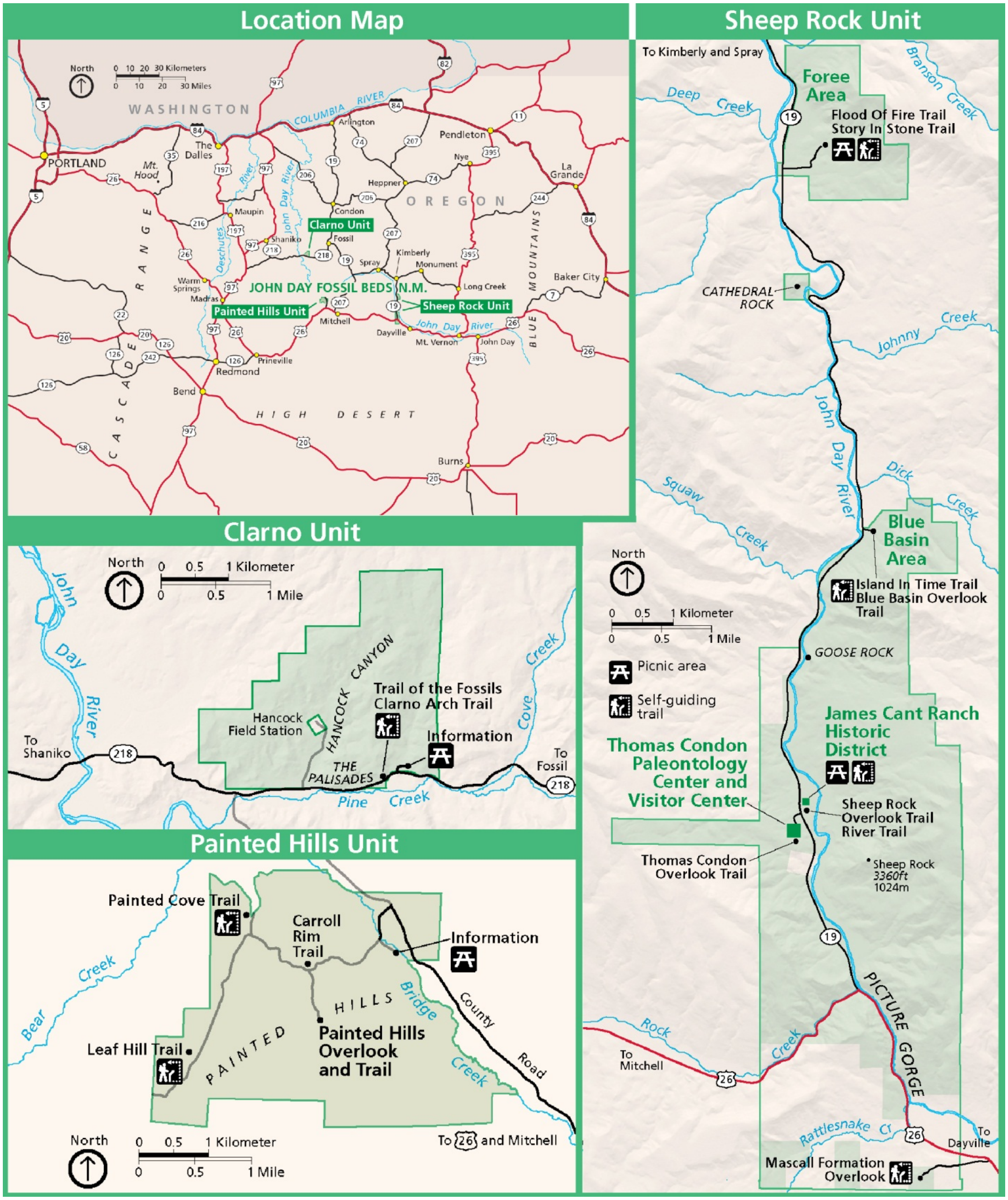

Figure 1. Maps of John Day Fossil Beds National Monument's three units: Painted Hills, Clarno, and Sheep Rock. National Park Service maps, available online: http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=JODA (accessed 12 February 2014).

North America during the Cretaceous (fig. 3) when the North American Plate collided with the Farallon Plate (see the "Geologic History" chapter). During the Pleistocene ice ages, alpine glaciers carved peaks, scoured bedrock, and eroded U-shaped valleys in the Blue and Wallowa mountains (Bishop 2003; Orr and Orr 2012).

The Clarno and Painted Hills units are located in the Deschutes-Columbia Plateau Province, an area that extends from the Blue Mountains to the Cascade Range and north to the Columbia River (fig. 4). Columbia River flood basalts are the centerpiece of the province. More than 300 separate basalt flows created the broad, relatively level plateau in the Mid–Late Miocene (17–6 million years ago) and generated approximately 230,000

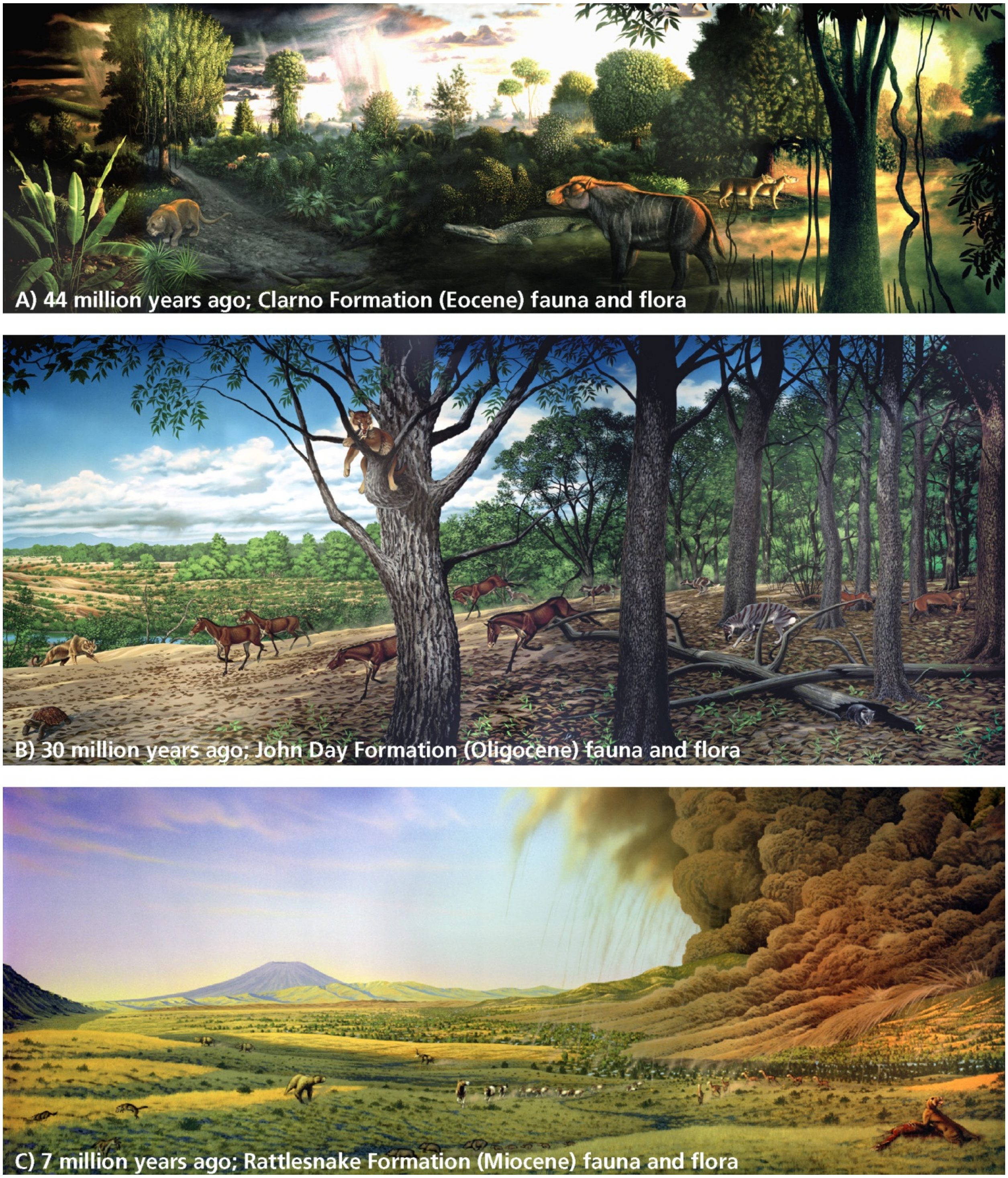

Figure 2. Murals from John Day Fossil Beds National Monument depicting Paleogene and Neogene global and regional climate change. A) Plant and animal species from the Clarno Nut Beds document the subtropical climate in the region of present-day central Oregon during the the Eocene (44 million years ago). B) Plant and animal species from Turtle Cove document the transition to cooler and drier conditions and the opening of woodland habitats in the Oligocene (30 million years ago). C) Plant and animal species from the much younger Rattlesnake Formation indicate the presence of steppe environments with shrubland and tall grasslands in the cooler, drier Late Miocene (7 million years ago). The explosive volcanic eruption depicted in this mural deposited the Rattlesnake Ash Flow Tuff. National Park Service murals by Larry Felder (Clarno) and Roger Witter (Rattlesnake), photographed by Will Landon. Keys to the organisms depicted in these murals may be found in Fremd (2010).

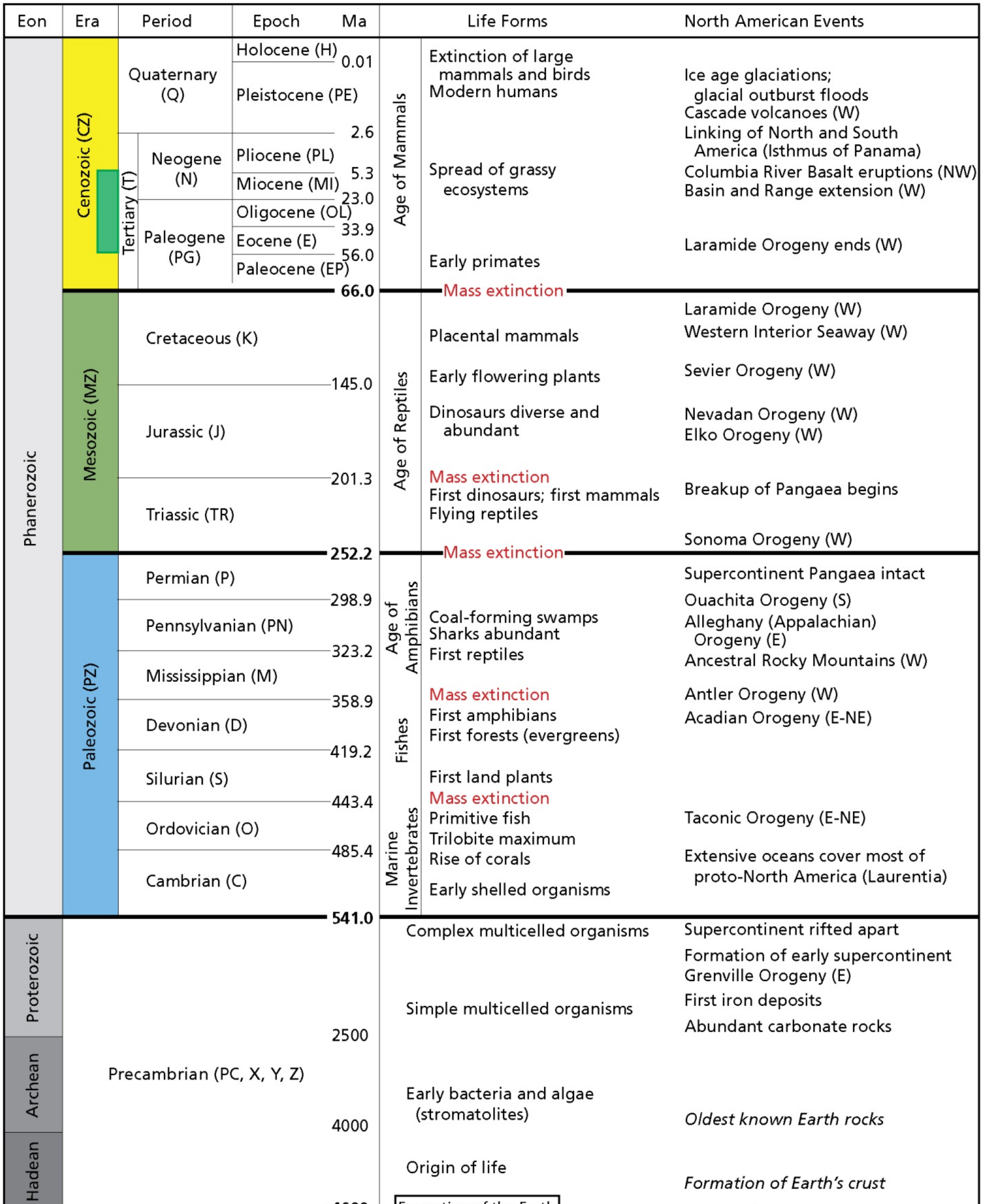

Figure 3. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (Ma). The green bar in the "Era" column indicates the expanse of time encompassed by rocks in John Day Fossil Beds National Monument. National Park Service graphic with dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 10 January 2014).

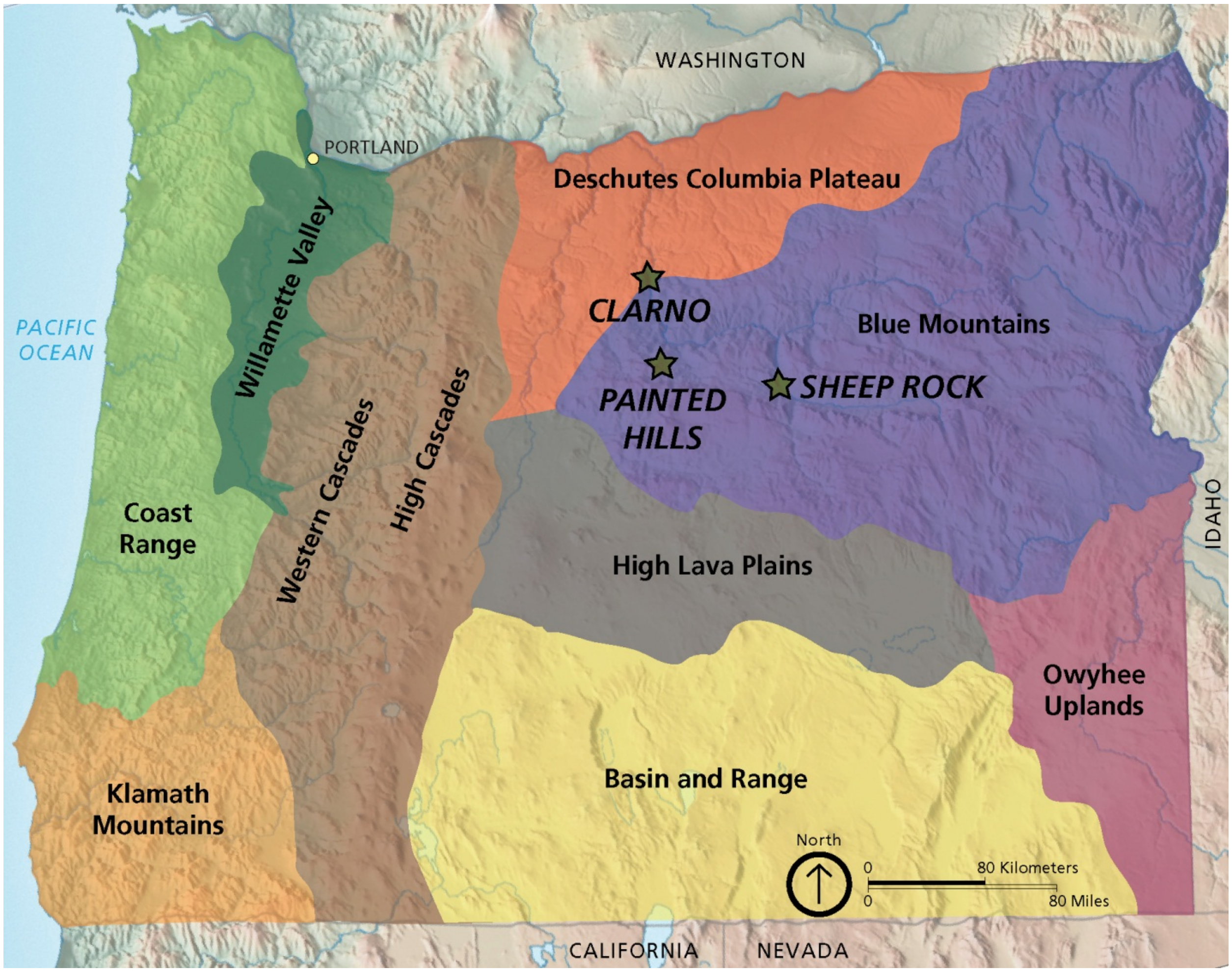

Figure 4. Physiographic provinces of Oregon. The units of John Day Fossil Beds National Monument (green stars) lie within the Blue Mountains and Deschutes-Columbia Plateau provinces. Map by Trista Thornberry-Ehrlich (Colorado State University) with information from Orr and Orr (2012). Basemap by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 10 June 2014).

km^3 (56,000 mi^3) of basalt, which is about 20 times the current volume of Lake Superior (Hooper et al. 2007).

The High Lava Plains Province (fig. 4), which borders the Blue Mountains Province to the south, is noted for containing bimodal magma consisting of: (1) dark basalt that originated deep within the mantle and (2) contrasting, light-colored rhyolite that flowed from shallow, explosive eruptions (Orr and Orr 2012). The Rattlesnake Ash Flow Tuff (commonly known as the RAFT), a signature unit in the Rattlesnake Formation (geologic map unit QTr), erupted in the High Lava Plains Province 7.05 million years ago and flowed into the Sheep Rock Unit (Streck and Grunder 1997; Streck et al. 1999). The tuff is one of the farthest-traveled ignimbrites in Oregon and contains the greatest volume of rhyolite on the High Lava Plains.

Rock units in the region range from Paleozoic to Pleistocene in age (fig. 3), but strata within the monument consists primarily of Paleogene and Neogene units (fig. 5). The Clarno Formation (Tcl) and John Day Formation (Tjd) contain the greatest diversity and abundance of fossils, but fossils are also present in the Mascall Formation (Tm) and Rattlesnake Formation (QTr). Within these formations, sedimentary rocks are interlayered with extrusive igneous volcanic tuff, basalt, and ash-flow (ignimbrite) deposits. The John Day and Clarno formations are found in all three units of the monument, whereas the Rattlesnake and Mascall formations are present only in the Sheep Rock Unit (fig. 5).

Because the Clarno Formation does not contain regional stratigraphic markers and is represented by limited exposures in the Sheep Rock and Painted Hills units, the members and beds cannot be confidently traced from one monument unit to another. As a result, no regional stratigraphy for the Clarno Formation has been established. Rather, the Clarno Formation has been mapped and described separately in the three units of John Day Fossil Beds National Monument (see GRI GIS data). The Clarno Formation is overlain by the 39-million-year-old Member A welded tuff (Tja), which marks the base of the John Day Formation in the Painted Hills and Clarno units (Peck 1964; Robinson 1975; Bestland and Retallack 1994a; Retallack et al. 1999; McClaughry et al. 2009b).

Period	Epoch	Formation (map symbol)	Park Unit SR	Park Unit CL	Park Unit PH	Paleoenvironment
Neogene	Miocene	Rattlesnake Formation (QTr)				Steppe environment. Shift from riparian woodlands to tall grassland and semiarid wooded shrubland.
Neogene	Miocene	Mascall Formation (Tm)				Wooded environments similar to modern temperate forests in the eastern United States. Swamp cypress along bodies of water, deciduous forests in lowlands, and coniferous forests in upland habitats.
Neogene	Miocene	Picture Gorge Basalt (Tcrbp)				Part of the Columbia River Basalt Group. Basalt flows that erupted about 16 million years ago.
Neogene	Miocene	John Day Formation: Rose Creek Member; Johnson Canyon Member; Balm Creek Member				Transition to cooler, drier conditions. Bunch grasslands become more common at the expense of forests, woodlands, and swamps.
Paleogene	Oligocene	John Day Formation: Haystack Valley Member (Tjh)				Hardwood forests; developing open areas.
Paleogene	Oligocene	John Day Formation: Kimberly Member (Tjk)				Open forest. Overall faunal assemblage (including herbivores adapted for running and burrowing) suggests more open habitats.
Paleogene	Oligocene	John Day Formation: Turtle Cove Member: Upper (Tjut); Picture Gorge Ignimbrite (Tji); Lower (Tjl)				Forests begin to open up as global climate becomes cooler and drier. Grassy woodlands and wooded grasslands increase. Span of about 5 million years documents significant faunal and evolutionary changes as regional environment changes.
Paleogene	Oligocene / Eocene	John Day Formation: Big Basin Member: Upper (Tjub); Middle (Tjmb); Lower (Tjlb)				Warm temperate climate with a transition to a cooler, more seasonal climate in the early Oligocene.
Paleogene	Eocene	Clarno Formation (Tcg, Tcan, Tcsr, Tcr, Tca, Tcla, Tcau, Tcrh, Tcch, Tcab, Tccp, Tcap, Tcd, Tclc)				Broad-leaved evergreen subtropical forests. Both waterlogged and well-drained forest landscapes.
Paleogene	Paleocene	Regional Unconformity: strata of this time were eroded prior to the Eocene or were never deposited.				
Cretaceous		Mitchell Group (Kc)				Submarine density flow deposits associated with a submarine fan system.

Figure 5. General stratigraphic column for pre-Quaternary formations mapped within and adjacent to the three units of John Day Fossil Beds National Monument. Yellow indicates units present in the respective monument units; dashed yellow for the Clarno Formation in the Sheep Rock Unit signifies that the formation is present, but of very limited extent. SR = Sheep Rock Unit; CL = Clarno Unit; PH = Painted Hills Unit. Paleoenvironmental interpretations were taken from several sources, including Bestland and Retallack (1994a, 1994b), Bestland et al. (1999), Retallack et al. (2000), Retallack (2004b, 2007), Sheldon (2006), and Bestland et al. (2008). See the Map Unit Properties Table for more detail.

The John Day Formation (Tjd) is a complex series of strata exposed throughout central and eastern Oregon. The formation ranges in age from Late Eocene to Early Miocene (about 39–18 million years ago) and includes seven members, four of which are mapped in the monument (fig. 5; Albright et al. 2008; Hunt and Stepleton 2004). The sedimentary and igneous rocks of the John Day Formation lie unconformably above the Clarno Formation and Goose Rock Conglomerate and below the Columbia River Basalts (Peck 1964; Fisher and

Rensberger 1972; Robinson and Brem 1981; Robinson et al. 1984; McClaughry et al. 2009b).

The John Day Formation is exposed in three distinct regions (facies), which have distinct nomenclatures for individual units (table 1; Robinson et al. 1984). The Blue Mountains separate the western and eastern regions and restrict much of the coarser-grained pyroclastic material to the western region. The southern region occurs south of the Ochoco Mountains and is similar to the Turtle Cove Member, except that it lacks the Picture Gorge Ignimbrite (Tji). Within each region, distinctive lithological characgteristics and marker beds allow the tracing of discontinuous exposures over considerable distances (Albright et al. 2008).

Western region members A–I are defined primarily by the presence of ash-flow tuff at their bases (Peck 1964). In the monument, these include the ash-flow tuffs of Member A (Tja) and Member B basalts (Tjb), both of which are the same as the lower Big Basin Member (Tjlb) of the eastern region. The eastern region's Picture Gorge Ignimbrite (Tji) is the same as Member H of the western region (fig. 5; Fisher and Rensberger 1972).

Table 1. John Day Formation regions and members.

Region	Designated Members	Monument Unit
Western	Members A–I	Clarno
Eastern	Rose Creek Johnson Canyon Balm Creek Haystack Valley Kimberly Turtle Cove Big Basin	Painted Hills Sheep Rock
Southern	Kimberly Turtle Cove Big Basin	None (occurs south of the monument)

The stratigraphy of the John Day Formation has been studied for more than 100 years (Merriam 1901; Hay 1963; Peck 1964; Fisher and Rensberger 1972; Robinson and Brem 1981; Robinson et al. 1984, 1990). In 1972, the formation in the eastern region was subdivided into four members (in ascending order): Big Basin, Turtle Cove, Kimberly, and Haystack Valley members (Fisher and Rensberger 1972). The Haystack Valley Member has subsequently been subdivided into the Haystack Valley, Balm Creek, Johnson Canyon, and Rose Creek members (fig. 5; Hunt and Stepleton 2004). Starting in the 1990s and culminating in a 2008 paper, radioisotopic and paleomagnetic data were used to age-date strata representing the entire John Day Formation (Swisher 1992; Fremd et al. 1994; Albright et al. 2008).

The Miocene-aged Picture Gorge Basalt Subgroup (Tcrbp) forms part of the widespread Columbia River Basalt Group, which overlies the John Day Formation (fig. 5). The subgroup has been subdivided into three formations (Twickenham, Monument Mountain, and Dayville basalts) and 17 members (Bailey 1989). Sixty-one basalt flows have been identified in the region. Although the thickness of the Picture Gorge Basalt Subgroup at its type section at Picture Gorge may reach 412 m (1,353 ft), with individual basalt flows as much as 16 m (52 ft) thick, the thickest sequence of basalts occurs on Monument Mountain where the total thickness is 570 m (1,900 ft; Bailey 1989; Niewendorp et al. 2006). The Picture Gorge Basalt caps the 340-m- (1,100-ft)- tall Sheep Rock, which provided the name for the Sheep Rock Unit (fig. 6).

The basalts are typically overlain by the Mascall Formation (Tm), but they are unconformably overlain by the Rattlesnake Formation (QTr) where the Mascall Formation is absent. Near Sheep Rock and Blue Basin, the basalts may unconformably overlie the Kimberly and Turtle Cove members of the John Day Formation. At the south end of Foree and north of the Sheep Rock Unit, the basalts overly the Rose Creek Member.

Sheep Rock Unit

More than 30 million years are represented by the Paleogene and Neogene strata in the Sheep Rock Unit. It is the only unit in which the Miocene Rattlesnake and Mascall formations are exposed (fig. 5). The Rattlesnake Formation (QTr), the youngest unit in the monument, continues to be the subject of stratigraphic revision, with some investigators proposing to subdivide the Rattlesnake Formation into three separate formations and others suggesting elevating the formation to group status (Merriam 1906; Wood et al. 1941; Enlows 1976; Walker 1979, 1990; Retallack et al. 2002; Prothero et al. 2006b; Samuels and Zancanella 2011; Samuels and Cavin 2013). The formation consists of ignimbrite and fanglomerate, which is a rock composed of a mixture of sediments originally deposited in an alluvial fan. The most recognizable unit in the Rattlesnake Formation is the dense, welded Rattlesnake Ash Flow Tuff, which is 12.5 m (41.3 ft) thick at the type section (Martin and Fremd 2001) and is composed of rhyolite, an extrusive igneous rock containing a high percentage of quartz (Streck and Grunder 1997; Streck et al. 1999). Vertebrate fossils dominate the Rattlesnake Formation collections, with mammalian fossils representing numerous taxa from 25 families (Fremd et al. 1994; Fremd 2010; Joshua Samuels, written communication, 11 April 2013; see the "Stratigraphic Features and Paleontological Resources" section).

An unconformity, which represents a period of time in which no deposition occurred or in which erosion removed sediments and rock units, separates the Rattlesnake Formation from the underlying Mascall Formation and Picture Gorge Basalt in the Picture Gorge area (Merriam et al. 1925). This unconformity is classified "angular" because the angle of the beds (layers) in the Mascall Formation is steeper than that of the beds in the Rattlesnake Formation. This tilting resulted from an episode of deformation that occurred prior to deposition of the Rattlesnake Formation.

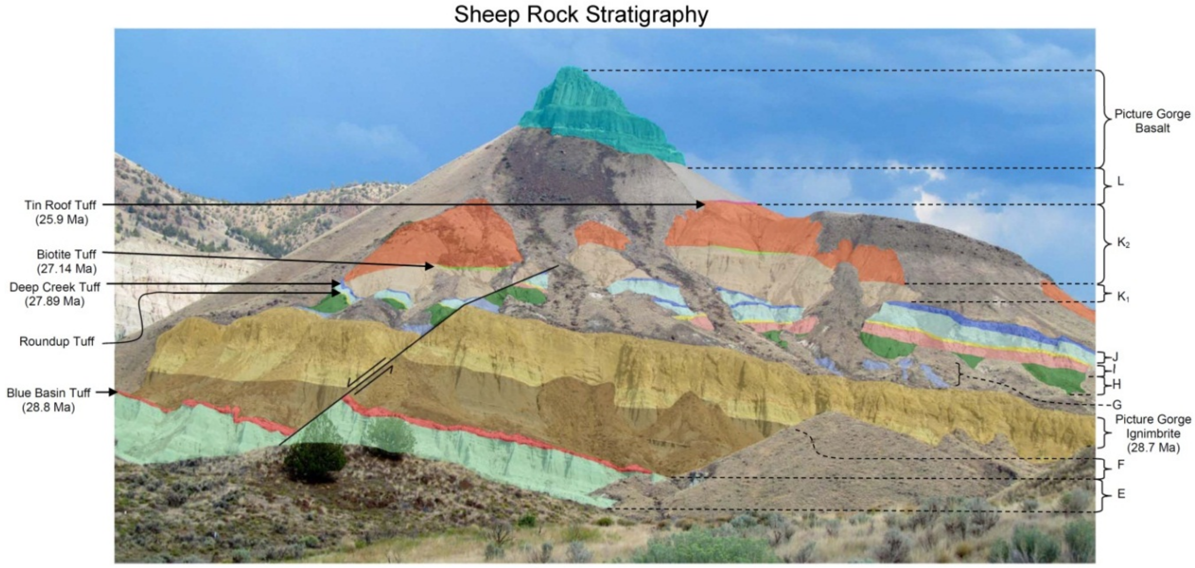

Figure 6. Sheep Rock stratigraphy, Sheep Rock Unit of John Day Fossil Beds National Monument. Picture Gorge Basalt (Columbia River Basalt Group) caps Sheep Rock. Fossiliferous, erodible siltstones, claystones, and tuffs of the John Day Formation comprise the slopes. Ma = millions of years ago. Photograph courtesy of Joshua Samuels (John Day Fossil Beds National Monument), stratigraphy based on Albright et al. (2008), annotations by Meghan McKnight (John Day Fossil Beds National Monument).

The Mascall Formation (Tm) lies above the Dayville Basalt Formation, which is the uppermost unit of the Picture Gorge Basalts Subgroup (Tcrbp) in the Picture Gorge area, and consists of volcaniclastic claystone, siltstone, sandstone, and tuff. As with the Rattlesnake Formation, more vertebrate than plant fossils are found in this formation in the Sheep Rock Unit. Age-equivalent strata occur throughout central and eastern Oregon (Bailey 1989; Bestland 1998; Bestland et al. 2008; Nash and Perkins 2012).

The John Day Formation (Tjd) forms the slopes and benches beneath the erosion-resistant Picture Gorge Basalt capping Sheep Rock and the badlands found at Blue Basin (Turtle Cove) and Foree (fig. 7). The strata consist of volcaniclastic siltstones and claystones, with interspersed airfall and welded tuff layers. Ignimbrites (pyroclastic flows), including the Picture Gorge Ignimbrite (Tji), are interlayered with the volcaniclastic sedimentary layers and tuffs. Although the John Day Formation is not subdivided in the Sheep Rock Unit on the GRI GIS map, a new geologic map based on fieldwork conducted in the summer of 2013 identifies the Big Basin, Turtle Cove, and Kimberly and Rose Creek members within the monument boundaries (Baker et al. 2013).

Plant fossils from Big Basin Member deposits near Goose Rock are part of the famous Bridge Creek Flora. The type localities and sources of most animal fossils discovered in the Turtle Cove Member of the John Day Formation are in the Sheep Rock Unit. A vast array of animal fossils has been discovered and collected from Oligocene-age deposits of the John Day Formation in the Sheep Rock, Blue Basin, and Foree areas of the Sheep Rock Unit. Many of these fossils are housed in the Thomas Condon Paleontology Center, located across the John Day River from Sheep Rock (fig. 8).

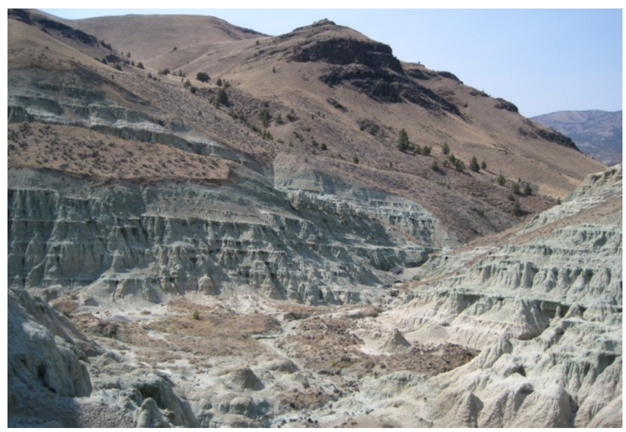

Figure 7. Badlands topography of Blue Basin, Sheep Rock Unit of John Day Fossil Beds National Monument. This area, also known as Turtle Cove, is the type area for the Turtle Cove Member of the John Day Formation. National Park Service photograph.

Figure 8. Thomas Condon Paleontology Center, John Day Fossil Beds National Monument. An alluvial fan is visible from the Center, on the opposite side of the John Day River. National Park Service photograph, available online: http://www.nps.gov/joda/photosmultimedia/index.htm (accessed 6 June 2014).

Few exposures of the Clarno Formation (Tcl) are mapped in the Sheep Rock Unit, and no fossils are known from them. The Clarno Formation is not subdivided into members in this unit, as it is in the other two administrative units. The strata consist of volcanic breccia containing silicified wood fragments, volcanic tuff, and lava flows of rhyolite and andesite. The flows contain phenocrysts of feldspar, hornblende, and augite.

The older, Cretaceous Mitchell Group (Kc), mapped adjacent to an east–west-trending fault that cuts through the Sheep Rock Unit north of the James Cant Ranch Historic District, is part of the Mitchell Inlier, which contains the largest exposures of Cretaceous sedimentary rocks in the region.

The John Day River flows through Picture Gorge and then north through the Sheep Rock Unit. The Rattlesnake Creek, Rock Creek, Dick Creek, Squaw Creek, and Johnny Creek tributaries join the John Day River before flowing along the western boundary of the Foree Area of the unit.

Clarno Unit

The approximately 54–39-million-year-old (Early-to-Middle Eocene–aged) Clarno Formation dominates the Clarno Unit, located 29 km (18 mi) west of Fossil, Oregon. The Clarno Formation is approximately 1,800 m (5,900 ft) thick, laterally discontinuous, and contains a heterogeneous sequence of volcanic rocks and sedimentary rock layers that include the Clarno Nut Beds, Hancock Mammal Quarry, and Fern Quarry (Retallack et al. 1996). Fossils have been discovered primarily in the Clarno Nut Beds and Hancock Mammal Quarry.

Plant fossils from this unit include a rich variety of fruits, nuts, seeds, leaves, and petrified wood from more than 170 species of trees, vines, shrubs, and other plants. Flora from the Nut Beds represents 145 genera and 173 species of fruits and seeds (Manchester 1994). Vertebrate fossils from the Nut Beds and the Hancock Mammal Quarry include alligator, creodonts, anthracotheres (hippopotamus-like ungulates), clawed oreodonts, rhinoceroses, tapirs, and horses (Hanson 1996; see the "Stratigraphic Features and Paleontological Resources" section).

The unit also contains the Palisades, cliffs of solidified volcanic mudflows (lahars) that were deposited approximately 44 million years ago and now dominate the surrounding landscape (Bestland and Retallack 1994a). Along Pine Creek, erosion of the Conglomerates of the Palisades (Tccp) has resulted in spectacular hoodoo (rock pillar) formation (fig. 9). Abundant andesite and basalt flows in the Clarno Formation suggest that the jungle was alive not only with the vibrant clamor of animal life, but also with the violent explosions of volcanic eruptions.

The claystones of Red Hill (Tcrh), a thick sequence of reddish and grayish-purple claystones that overlies the Conglomerates of Hancock Canyon (Tcch) are prone to landslides (Qls). This is especially true along the western border of the Clarno Unit where the claystones are overlain by the welded tuff of Member A, which marks the base of the John Day Formation (Tja).

Figure 9. The Clarno Palisades. Hoodoos formed in the Conglomerates of the Palisades (Tccp) along the John Day River and Pine Creek in the Clarno Unit, John Day Fossil Beds National Monument. National Park Service photograph by Jason Kenworthy (NPS Geologic Resources Division).

Painted Hills Unit

Most strata in the Painted Hills Unit, named for bare hills with colorful hues of red, orange, black, and tan volcaniclastic rock, are from the John Day and Clarno formations. The Big Basin Member of the John Day Formation dominates the Painted Hills Unit; it consists primarily of volcaniclastic sedimentary rocks interspersed with volcanic layers of basalt, andesite, and tuff, such as the Member A welded tuff and the Overlook Tuff. A diverse assemblage of leaf fossils (the Bridge Creek Flora) and a few animal fossils are known from old lake deposits that are intermixed with volcaniclastic claystones. The exceptional collection of fossils from the Bridge Creek Flora records the beginning of a cooling trend in the Paleogene and Neogene (see "Stratigraphic Features and Paleontological Resources" section).

The pale-brown and olive tuffaceous siltstones and claystones of the lower Turtle Cove Member (Tjl) form the slopes of Carroll Rim in the northern part of the Painted Hills Unit. This Carroll Rim location is not necessarily the same as that marked as Carroll Rim on other maps. For example, on the 1981 US Geological Survey map of Stephenson Mountain (1:100,000 scale), Carroll Rim is marked as the southeast rim of Sutton Mountain, about 10 km (6 mi) east of Carroll Rim's location in the Painted Hills Unit. The 2011 US Geological Survey map of Painted Hills, Oregon (1:24,000 scale), however, locates Carroll Rim in the Painted Hills (Joshua Samuels, written communication, 5 December 2013).

The lower Turtle Cove Member on the slopes of Carroll Rim in the Painted Hills Unit has produced a small assemblage of fossil mammals. Taxa include *Agriochoerus*, *Hypertragulus*, *Miohippus*, and *Diceratherium*. Carroll Rim is capped by the 28.7-million-year-old (Bestland and Retallack 1994b) Picture Gorge Ignimbrite (Tji), the middle unit in the Turtle Cove Member and the most widespread ash-flow tuff sheet in the John Day Formation (fig. 5). The upper part of the Turtle Cove Member (Tju) is represented by a few small exposures of "popcorn"-textured claystones on the north side of Carroll Rim (Joshua Samuels, written communication, 5 December 2013).

Alternating layers of claystone and volcanic rock of the Clarno Formation are mapped along the western border of the Painted Hills Unit. The uppermost Clarno unit in the Painted Hills Unit consists of the Claystones of Brown Grotto (Tcg); andesite and rhyolite beds comprise the other lithologic units. The dark–grayish-blue lower Clarno andesite lava flow (Tcla) marks the base of the section.

Paleogene and Neogene Global Climate Change

Through time, Earth's climate can be very broadly categorized as "greenhouse" (little or no "permanent" ice on the poles) or "icehouse" ("permanent" ice on the poles). Only about five transitions from one climate to the other occurred during the Phanerozoic Eon (the past 541 million years; Frakes et al. 1992). The most recent transition occurred during the Cenozoic Era and is remarkably well documented in John Day Fossil Beds National Monument (fig. 10).

The world was quite warm during the Mesozoic Era, the age of dinosaurs, but global temperatures reached a maximum in the Eocene, approximately 52 million years ago (fig. 10). Average annual temperatures in the western United States rose to 20–25°C (68–77°F) and Arctic Ocean temperatures were about 23°C (74°F; Woodburne et al. 2009; Kunzig 2011).

Fossils and paleosols from the Clarno Formation in John Day Fossil Beds National Monument document a subtropical jungle environment in the region of present-day central Oregon during the early Eocene (fig. 2). Around the Eocene–Oligocene boundary, the tropics became more temperate. Seasonal precipitation became more pronounced and the regional climate became 3–6°C (5–10°F) cooler (Wolfe 1993; Myers 2003; Dillhoff et al. 2009). Global triggering events may have included a global decrease in atmospheric carbon dioxide, changes in the Earth's axial tilt (obliquity) that resulted in a drier northern hemisphere, and the formation of the Antarctic circumpolar current and persistent Antarctic continental ice sheets as Antarctica separated from Tasmania and South America (Zachos et al. 2001).

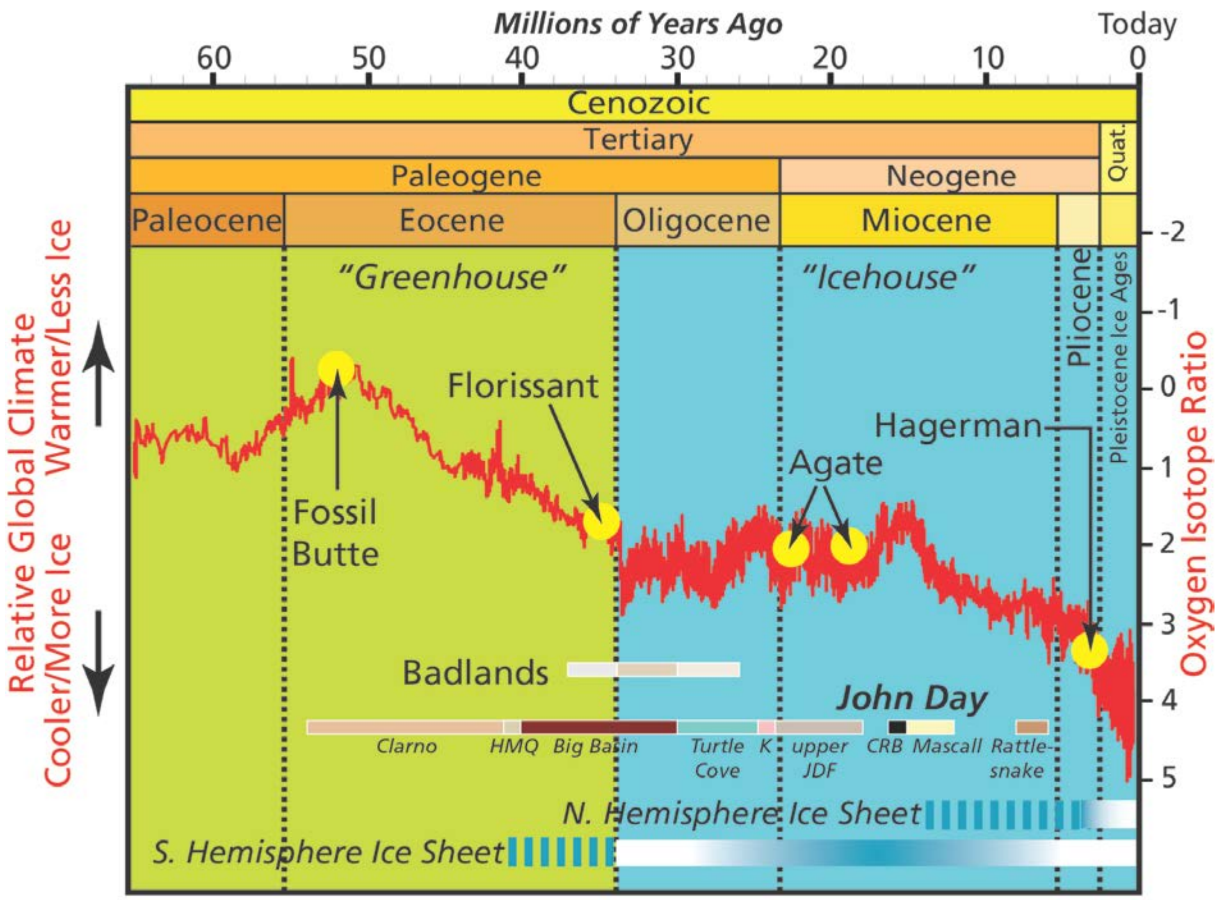

Figure 10. Relative global climate during the Paleogene and Neogene periods. The red line was plotted using ocean temperature data from Zachos et al. (2001, 2008a). The yellow dots and horizontal bars indicate the geologic ages or age ranges represented in six NPS units established to preserve scientifically significant Paleogene and Neogene fossils and strata: John Day Fossil Beds (Oregon), Fossil Butte (Wyoming), Florissant Fossil Beds (Colorado), Agate Fossil Beds (Nebraska), and Hagerman Fossil Beds (Idaho) national monuments and Badlands National Park (South Dakota). The transition from global "greenhouse" conditions with minimal polar ice sheets to "icehouse" conditions with ice sheets at one or both poles occurred near the Eocene–Oligocene boundary. Spans of eight fossil assemblages and the Columbia River Basalts in John Day Fossil Beds National Monument are depicted. Quat. = Quaternary; HMQ = Hancock Mammal Quarry; K = Kimberly Member; upper JDF = upper John Day Formation (Haystack Valley, Balm Creek, Johnson Canyon, and Rose Creek members); CRB = Columbia River Basalts. Graphic adapted from Kenworthy (2010) by Jason Kenworthy (NPS Geologic Resources Division).

The tropical to subtropical flora of the Eocene Nut Beds contrast sharply with the temperate, 33-million-year-old (around the Eocene–Oligocene boundary) Bridge Creek Flora (Bestland et al. 1999; Meyer and Manchester 1997; Retallack et al. 1999; Dillhoff et al. 2009). With the onset of this temperate climate, open woodlands began to dominate the landscape.

Grasslands and open forests continued to expand in the late Oligocene and Miocene, as evidenced by the presence of burrowing beavers, gophers, and animals adapted to running over open areas, such as camels and “stilt-legged” horses. Fossils from the Mascall Formation (Tm) document the possible return of grasslands and riparian habitats following the deposition of the Columbia River Basalt Group.

A warming trend in the Pliocene ended approximately during the period in which the Isthmus of Panama joined North and South America and ocean currents in the Caribbean Sea changed. As global temperatures began to decline, the wet climate of the western United States continued to support a wide range of habitats common to savanna-like grassland. By the end of the Pliocene, global climate had cooled and the stage was set for the Pleistocene ice ages.

The Pleistocene ice ages were followed by a transition to the Holocene greenhouse climate. Although the Holocene may be another interglacial period, the anthropogenic influx of greenhouse gases is producing rapid and dramatic climate change, which may ultimately raise global temperatures to levels that have not occurred since the early Eocene. John Day Fossil Beds National Monument offers a glimpse into habitat and ecosystem responses to such marked changes in global climate.

Early Discoveries

The John Day Fossil Beds have attracted paleontologists and geologists for almost 150 years. Cenozoic nonmarine fossils have been recognized in central Oregon since at least the 1860s, when soldiers discovered fossil plants near the Painted Hills on the military road from John Day to The Dalles (Retallack et al. 1996). In 1865, Thomas Condon, a minister and self-taught scientist in The Dalles, made the first scientifically useful collection of plant and mammal fossils and shipped them to prominent paleontologists in the eastern United States, including Joseph Leidy (University of Pennsylvania) and Othneil Charles Marsh (Yale University), for identification. At the beginning of the 20th century, expeditions from the University of California at Berkeley discovered plant fossils in the Clarno area. Amateurs initially developed the Nut Beds site beginning in 1943 and the Hancock Mammal Quarry in 1955.

Paleontological research continues today, with new material providing additional evidence for Paleogene and Neogene paleoclimatic and evolutionary change over approximately 44 million years (fig. 10; Retallack et al. 1996).

Continuing Research Opportunities

The cumulative number of animal species described from the John Day Formation has increased steadily since Joseph Leidy (University of Pennsylvania) published the first paper on this formation in 1870 (figs. 11 and 12). Following Leidy’s paper, paleontologists, especially Marsh, Cope, and William Berryman Scott, published an exceptional number of papers at the end of the 19th century that described a large number of fossil fauna (fig. 11). A steady number of papers were published throughout the 20th century, and the rate of publication increased in 2004 (fig. 12). Researchers continue to discover new species and new parts of known plants and animals, and their research continues to help define the Paleogene and Neogene ecosystems in the region of present-day Oregon. According to Joshua Samuels (written communication, 11 April 2013), documentation of newly described species from formations throughout the John Day Basin will be published in the next few years. Research has expanded to include examination of the relationships of fauna and flora to their ecosystems; reporting of data on the stratigraphic layers, including non-fossiliferous sedimentary and volcanic rocks; and analysis of the abundant paleosols in the stratigraphic column at the monument.

John Day Fossil Beds National Monument offers diverse research opportunities in addition to paleontological research, including the investigation of the following items as prepared by Joshua Samuels (written communication, 11 April 2013):

- The Mesozoic graben in the Painted Hills Unit
- The erosive shift in the mid-Miocene associated with plume uplift
- Paleogene volcanism, especially caldera formation in the region of present-day Oregon
- Neogene structural shifts, faulting, and tectonics
- Origin, structure, and differentiation processes in the Rattlesnake Tuff
- The Late Miocene river in the Rattlesnake area and Cottonwood Canyon
- The effects of Miocene and Pliocene erosion on the John Day River
- Pleistocene pediment features and outwash from glaciers in the Strawberry Mountains and terracing on the southeastern side of Picture Gorge
- The extent of the Mazama ash from the Mount Mazama eruption
- Radiometric age-dating of a white vitric tuff bed, referred to as “Ted’s Tuff,” located approximately 16 m (52 ft) above the base of the Rattlesnake Formation. The tuff is a candidate for age-date analysis through a Cooperative Ecosystem Studies Unit agreement with Boise State University (Retallack 1999; Retallack et al. 2002).

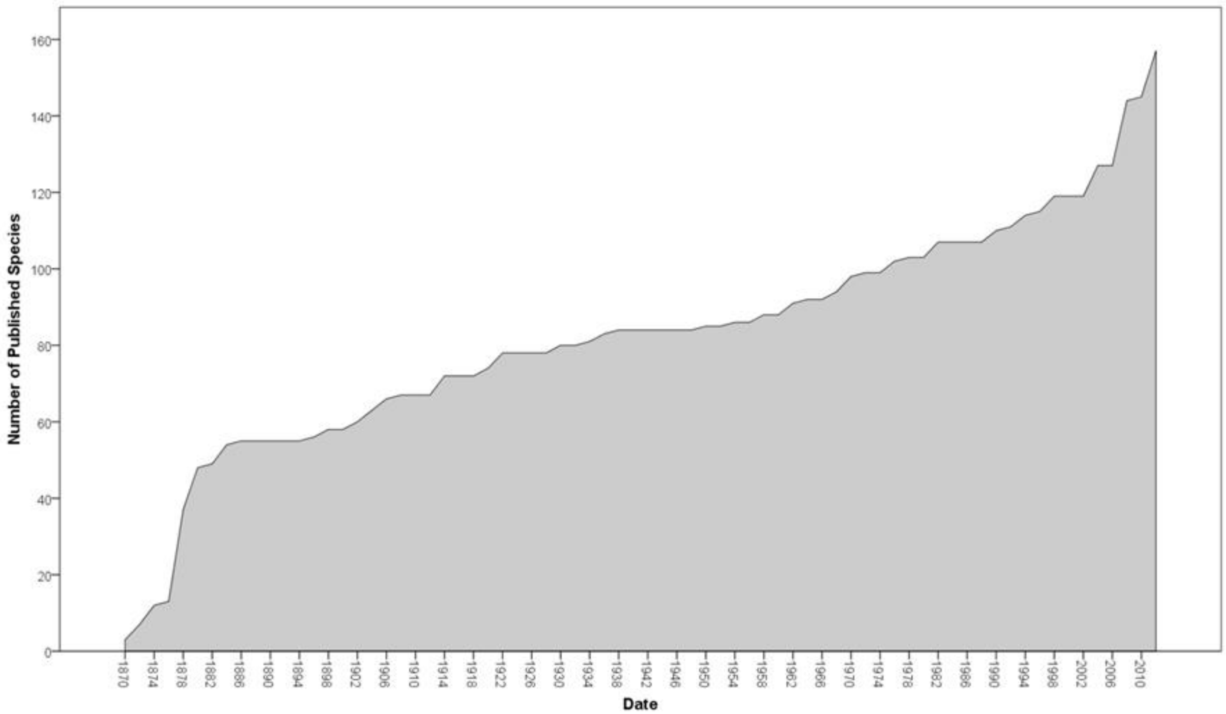

Figure 11. Cumulative number of animal species described from the John Day Formation through time. Graphic by Joshua Samuels (John Day Fossil Beds National Monument).

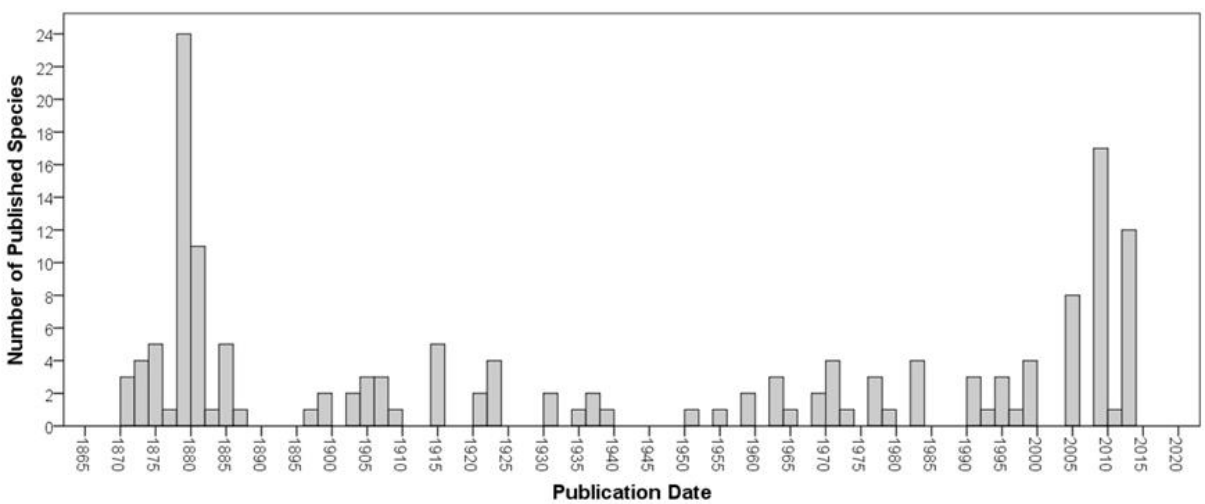

Figure 12. Number of animal species from the John Day Formation described by year. Graphic by Joshua Samuels (John Day Fossil Beds National Monument).

Geologic Features and Processes

This section describes noteworthy geologic features and processes in John Day Fossil Beds National Monument.

Geologic features and processes in John Day Fossil Beds National Monument cover a highly diversified spectrum. Extreme geologic processes, such as cataclysmic volcanic eruptions and lahars, dramatically altered the landscape throughout the approximately 44 million years represented in the monument. Paleosols developed from volcanic ash. The environments in the region of present-day eastern and central Oregon supported a myriad of plant and animal life. Global climate change resulted in a transition from greenhouse to icehouse ecosystems. While the climate changed and volcanoes erupted, tectonic processes continued to transform the western margin of North America. Ancient and recent geologic processes created a variety of features, including:

- Stratigraphic features and paleontological resources
- Paleosols
- Volcanic features in the John Day Formation
- Folds and faults
- Cave and karst features
- Fluvial geomorphic features
- Exceptional geologic landscape features

Most of the information in the "Stratigraphic Features and Paleontological Resources" and "Exceptional Geologic Landscape Features" sections was compiled by Joshua Samuels (John Day Fossil Beds NM, museum curator/chief of paleontology, written communication, 13 April 2013) for this report. The "Exceptional Geologic Landscape Features" section contains lists of notable features and locations in each unit.

Stratigraphic Features and Paleontological Resources

Sedimentary and volcanic features in rock layers at John Day Fossil Beds National Monument provide useful information about past depositional environments. Used in conjunction with paleontological resources, this information provides a relatively clear picture of Paleogene and Neogene environments in the region of present-day eastern and central Oregon. In addition, exposures of the Gable Creek Formation in the Sheep Rock Unit provide evidence that the region was part of a submarine depositional complex during the Cretaceous.

Regardless of the age of the rock, volcanic features signal specific processes that may have resulted in ash-fall deposits, pyroclastic flows, or lava flows. Features in the deposits may also indicate the locations of volcanic eruptions and the chemical compositions of magmas. Volcanic layers provide minerals for determing the layers ages via radiometric (using radioactive mineral ratios) or magenetostratigraphic (using magnetic "signature" of minerals) methods. These layers provide essential datums for determing the age of fossils and strata between volcanic layers (table 2). See also the "Volcanic Features in the John Day Formation" section.

Likewise, stratigraphic features represent processes common to specific depositional environments. For example, "conglomerate" sedimentary rock is prevalent in strata at the monument. A conglomerate consists of rounded bedrock clasts that were once angular pieces of bedrock. As the clasts were transported, commonly by water, they knocked against each other and their edges eventually became rounded. A conglomerate thus represents a significant amount of mechanical (physical) weathering and transportation. These processes may occur all at once or in a series of episodes of various magnitudes spread over a substantial period of time. Other features, such as ripple marks and cross-bedding, represent specific modes of transportation, such as wind, rivers, or waves. In this section, features in stratigraphic units at the monument are described in order from the oldest to the youngest unit.

Paleontological resources (fossils) include any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are non-renewable. Body fossils are remains of organisms, such as bones, teeth, shells, and leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, and coprolites (fossil dung). Fossils in NPS units occur in rocks and unconsolidated deposits, museum collections, and cultural contexts, such as building stones or archeological resources. As of August 2014, 246 NPS units had documented paleontological resources in at least one of these contexts. The NPS Geologic Resources Division Paleontology website, http://www.nature.nps.gov/geology/paleontology/index.cfm, provides more information.

Fossils are the most significant geologic feature in John Day Fossil Beds National Monument (see "Paleontolgical Resource Inventory, Monitoring, and Protection" section). Fossils discovered at the monument span approximately 44 million years of time, encompassing most of the Cenozoic Era (figs. 3 and 10). Fossil-bearing formations in the monument include the Clarno Formation (geologic map unit Tcl), John Day Formation (Tjd), Mascall Formation (Tm), and Rattlesnake Formation (QTr; fig. 5).

The fossil lists accompanying this GRI report (in pocket) were compiled by Joshua Samuels, museum curator/chief of paleontology at John Day Fossil Beds National Monument. The lists include fossils from the John Day Basin, not solely from John Day Fossil Beds National Monument.

Table 2. Radiometric and magnetostratigraphic age dates from Paleogene and Neogene volcanic rocks.

Age	Formation/Member (map symbol)	Volcanic Layer (map symbol)	NALMA (age range; millions of years)	Age (millions of years)
Miocene	Rattlesnake Formation (QTr)	Rattlesnake Ash-Flow Tuff	Hemphillian (10.39–4.9)	7.05 ± 0.01
		paleomagnetic study of type section		Chron C3Bn–C3Br2n (6.9–7.3)
	Mascall Formation (Tm)	Kangaroo Tuff	Barstovian (16.0–12.5)	13.564 ± 0.009
		Mascall Tuff		15.297 ± 0.009
		ash bed below Mascall Tuff		15.77 ± 0.048
		Lower Member		16.2 (tuff) Chron C5Br–C5Br1n (16.0–14.8)
	Columbia River Basalt (Tcrbu)	Picture Gorge Basalt Subgroup (Tcrbp): Dayville Basalt Fm.	Hemingfordian (18.8–16.0)	16.5–16.3
		Picture Gorge Basalt Subgroup (Tcrbp)		16.5–15.6 16.0 ± 0.2
	John Day Formation: Rose Creek Member	magnetostratigraphic ages		Chron C5Er or C5Dr 18.7–18.5 18.1–17.6
	John Day Formation: Johnson Canyon Member	Across the River Tuff at the contact with Balm Creek Member	Arikareean (30.0–18.8)	22.6 ± 0.13
Oligocene	John Day Formation: Haystack Valley Member (Tjh)	JD-BC-3 tuff at the contact with Balm Creek Member		23.79 ± 0.18
	John Day Formation: Kimberly Member (Tjk)	Tin Roof Tuff at the contact with Turtle Cove Member		25.9 ± 0.03
	John Day Formation: Turtle Cove Member, upper (Tjut)	Biotite Tuff		27.14 ± 0.13
		Deep Creek Tuff		27.89 ± 0.57
	John Day Formation: Turtle Cove Member, Picture Gorge Ignimbrite (Tji)	Member H		28.7 ± 0.05 28.7 ± 0.07
	John Day Formation: Turtle Cove Member, lower (Tjl)	Blue Basin Tuff		28.8
		A/B Tuff		29.75 ± 0.02
	John Day Formation: Big Basin Member, middle (Tjmb)	Overlook Tuff (Tjmbot)	Orellan (33.7–32.0)	32.66 ± 0.03
Eocene		biotite tuff		32.99 ± 0.11
	John Day Formation: Big Basin Member, lower (Tjlb)	andesite of Sand Mountain (Tjan)	Chadronian (36.9–33.7)	37
		Member A welded tuffs (Tja)	Duchesnean (40.1–36.9)	39.22 ± 0.03 39.72 ± 0.03
	Clarno Formation (Tcl)	stony tuff	Uintan (46.3–40.1)	42.7 ± 0.3
		amygdaloidal basalt (Tcab)		43.8 ±0.5
		Nut Beds		44 43.76 ± 0.29
		andesite of Pine Creek (Tcap)	Wasatchian (55.4–50.1)	51.2 ± 0.50

NALMA: North American Land Mammal Ages (from Woodburne 2004); Fm: formation. Most John Day Formation radiometric age dates were acquired using $^{40}Ar/^{39}Ar$ single-crystal laser-fusion dating of sanidine (Swisher 1992; Bestland and Retallack 1994a; Bestland et al. 1999, 2008; Albright et al. 2008). Additional information obtained from Joshua Samuels (John Day Fossil Beds NM, museum curator/chief of paleontology, written communications, 2013).

Gable Creek Formation

Goose Rock, a distinctive exposure along the John Day River within the Sheep Rock Unit, is part of the 95-million-year-old (Cretaceous) Gable Creek Formation, which is included in the Mitchell Group (Kc; Kleinhans et al. 1984; Dorsey and Lenegan 2007). The exposure at Goose Rock consists of more than 90 m (300 ft) of Cretaceous conglomerate, interbedded sandstone, and mudstone layers (Kleinhans et al. 1984; Dorsey and Lenegan 2007). Clasts in the conglomerate range from sand-sized particles to cobbles and include a wide variety of rock types, such as white quartzite, black chert, granite, basalt, schist, and carbonates (Lenegan 2001; Dorsey and Lenegan 2007).

The coarse-to-fine-textured Goose Rock layers may represent submarine landslides that incorporated a variety of clasts from various original bedrock sources. These turbidites are associated with a submarine fan system that may have been similar to those that currently transport terrestrial sediments off the Oregon coast (Kleinhans et al. 1984; Dorsey and Lenegan 2007).

In the Mitchell area, the Eocene Clarno Formation overlies the Cretaceous Gable Creek Formation (fig. 5; Housen and Dorsey 2005). This contact, known as an unconformity, represents a significant gap in time in which deposition did not occur or for which erosion has removed any sediments and rock units that were once present. A more extensive gap in time may exist at Goose Rock in the Sheep Rock Unit, where the Big Basin Member of the John Day Formation may overlie the Gable Creek Formation (Fisher 1964; Baker et al. 2013).

Clarno Formation

The Clarno Formation (Tcl) consists of nonmarine volcanic and volcaniclastic layers that were deposited near sea level (White and Robinson 1992; Bestland et al. 1999; Dillhoff et al. 2009; McClaughry et al. 2009b). These strata suggest the existence of a landscape flanked by active volcanoes (Bestland et al. 1999). The formation is not divided into units in the Sheep Rock Unit, but consists of lava flow deposits similar to rocks found in the monument's other two administrative units (Niewendorp et al. 2006).

Features in the sedimentary units of this formation are associated primarily with debris flows, floodplain deposition, and fluvial point bar/channel deposition (table 3). Debris flows deposited conglomerates, some with cobble- or boulder-sized clasts, while flood events produced the layered mudstone in the floodplains, upon which paleosols developed.

In the Clarno Unit, weathering of the 55-m- (180-ft-)-thick sequence of the Conglomerates of the Palisades (Tccp) produced the distinctive hoodoos and cliffs of the Palisades (fig. 9; Bestland et al. 1999). The Hancock Canyon conglomerates (Tcch) also contain the Nut Beds, fine sediment deposited in floodplains or deltas, tuff beds, and paleosols (Fremd 2010). The distribution of fossil remains in the Hancock Mammal Quarry, paleosol evidence, and enclosing sediments (Tcq) suggest that animal carcasses accumulated and subsequently disarticulated in a fluvial point bar, which is a bend in the river where the current slows and larger debris falls out of suspension (Pratt 1988; Bestland et al. 1999).

Table 3. Features and processes in the Clarno Formation.

Feature	Process	Map Unit
Sedimentary Rock Layers		
Conglomerates	Debris flows	Tclc, Tcch, Tccp, Tcq
Claystones	Flooding of floodplain	Tcch, Tcrh
		Tcm, Tcs, Tcg
Accumulation of Mammal Quarry bones	Accumulation of carcasses on point bars	Tcq
Volcanic (Extrusive) Rock Layers		
Volcanic debris cemented together	Lahar	Tcch
Basalt layer	Lava flow	Tcch
Tuff	Welded volcanic ash	Tcch, Tcrh
Andesite layer	Lava flow	Tcah
		Tcla, Tca, Tcr
Rhyolite layer	Lava flow	Tcr
Dacite dome	Subsurface cooling of magma	Tcd

The discontinuously exposed claystones of Meyers Canyon (Tcm) in the Painted Hills Unit may represent Lakayx paleosols (see the "Paleosols" section), which developed on lowland, well-drained, old-growth rain forest.

Volcanic features (table 3) include volcanic debris deposited in lahars (volcanic mudflows), basaltic and andesitic lava flows, and tuff (volcanic ash). In the Clarno Unit, the widespread amygdaloidal basalt flow in the Conglomerates of Hancock Canyon (Tcch; fig. 13) can be traced for 14 km (9 mi) along the cliffs of the John Day River. Locally, columnar jointing and pahoehoe flow structures are present, and vesicles (holes) at the base of the basalt indicate that the molten lava flowed over moist ground. The heat from the lava turned the moisture to steam, which penetrated upward into the molten lava. Once the lava solidified, the gas left holes, many of which are now filled with agate (Bestland et al. 1999).

The Hancock dacite dome (Tcd) intrudes the lower Clarno conglomerates (Tclc). The igneous intrusion contains phenocrysts (large crystals) of plagioclase and hornblende, suggesting that at least part of the magma cooled slowly, providing time for these large crystals to form. Because the dome is onlapped by the Conglomerates of Hancock Canyon (Tcch) and the Conglomerates of the Palisades (Tccp), it must have been

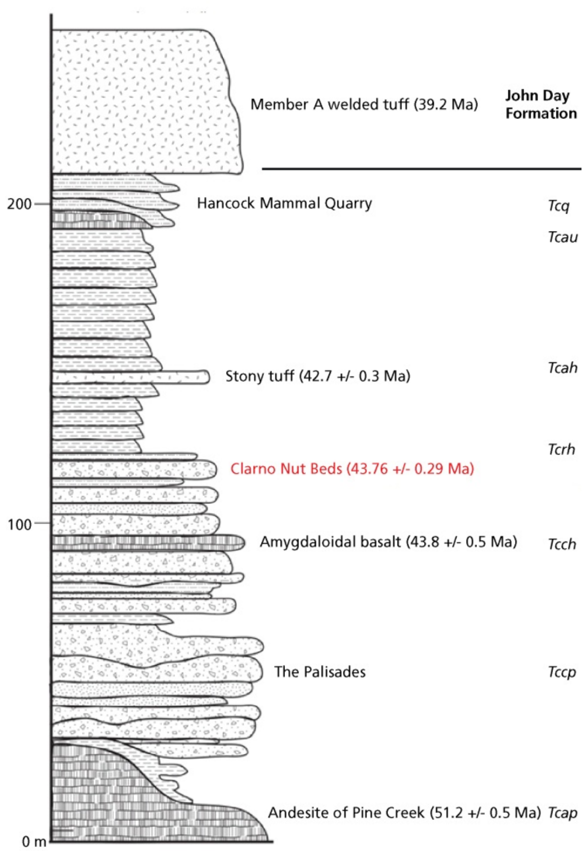

Figure 13. Simplified stratigraphic column of the Clarno Formation in the Clarno Unit of John Day Fossil Beds National Monument. Column redrafted by Trista Thornberry-Ehrlich (Colorado State University), based on Bestland et al. 1999 and modified from Fremd 2010, p. 101, with revised radiometric ages supplied by Joshua Samuels (John Day Fossil Beds National Monument). The shape of this column reflects the erosion resistance and sediment grain size of individual units (increasing to the right). Ma: millions of years ago.

a positive topographic feature when these conglomerates were deposited during the Eocene.

Radiometric ages for the Clarno Formation range from 51.2 million years for the andesite of Pine Creek (Tcap), near the base of the Clarno Formation, to 42.7 million years for the stony tuff bed above the Clarno Nut Beds in the Conglomerates of Hancock Canyon (Tcch; table 2; Bestland et al. 1999). Plagioclase minerals in a tuff bed in the Clarno Nut Beds were dated to 44 million and 43.76 million years old, and an amygdaloidal basalt unit within the Conglomerates of Hancock Canyon was dated to 43.8 million years old (Swisher 1992; Manchester 1994; Bestland et al. 1999).

In the Clarno Unit, the Member A welded tuff at the base of the John Day Formation (Tja) overlies the siltstone of Hancock Mammal Quarry. In the Painted Hills Unit, the red and ocher-colored claystones of Brown Grotto (Tcg) separate the rhyolite of Bear Creek (Tcr) from this welded tuff. The Brown Grotto claystones are difficult to distinguish from the Big Basin Member of the John Day Formation where the Member A tuff is absent. On the other hand, the Brown Grotto claystones are difficult to differentiate from other, underlying red claystones at sites in the region where the rhyolite of Bear Creek is absent.

Among the many claystone, conglomerate, and volcanic units in the Clarno Formation (see the Map Unit Properties Table), fossils are found in the Conglomerates of the Palisades (Tccp), the younger Conglomerates of Hancock Canyon (Tcch), and the siltstone of the Mammal Quarry (Tcq), which is the youngest unit in the Clarno Formation in which fossils have been discovered (Tables 4–8). These strata are mapped in the Clarno Unit of the monument. The world-class fossils of the Clarno Nut Beds are found in the Conglomerates of Hancock Canyon.

Fossils in the Conglomerates of the Palisades

Leaf impressions of angiosperms (flowering plants) and ferns characterize the Conglomerates of the Palisades assemblage from Fern Quarry. Ferns (*Acrostichum hesperium*) dominate the assemblage and are found in growth position, as are horsetails (*Equisetum clarnoi*). The angiosperms are dicots (*Joffrea speirsii*, *Quercus* sp., *Cinnamomophyllum* sp., cf. "*Cryptocarya*" *eocenica*), and their leaf litter is found in brown and red claystones interpreted as weakly-developed paleosols (ancient soils) that formed in volcanic ash deposited above layers of conglomerate (Retallack et al. 1996; Bestland et al. 1999; Dilloff et al. 2009). Modern species similar to those represented in Fern Quarry are found today in tropical and near-tropical estuaries and floodplains.

Fossils in the Conglomerates of Hancock Canyon

Approximately 12 fossil plant assemblages occur in central and eastern Oregon, but the most impressive assemblages are found in the Clarno Nut Beds in the Conglomerates of Hancock Canyon (fig. 14; Dillhoff et al. 2009). The Nut Bed fossils are found in a 7-m- (23-ft-) thick by 300-m- (1,000-ft-) wide layer of silica-cemented sandstone and conglomerate that lies above several volcanic mudflows (Retallack et al. 1996; Bestland et al. 1999). Table 4 lists the components of the exceptionally diverse assemblage of nuts, seeds, and petrified wood that make the Clarno Nut Beds a world-class fossil site (Scott 1954; Manchester 1981, 1990, 1994; Wheeler and Manchester 2002; Dillhoff et al. 2009).

Figure 14. Wood and seeds from the Clarno Nut Beds, John Day Fossil Beds National Monument. National Park Service photograph courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

The fossil assemblages in the Clarno Nut Beds have excellent three-dimensional preservation. Examination of approximately 20,000 specimens of fruits and seeds has provided data on the evolution, biogeography, and paleoecology of 145 genera and 173 species (Manchester 1994). Comparison of internal structures showed that 75 genera and 102 species were related to 35 living families. Detailed preservation of reproductive structures of seeds, nuts, and fruits has enabled the identification of 14 families (Dillhoff et al. 2009). These assemblages also contain petrified wood representing 66 genera and 77 species, more than any other known petrified wood locality on Earth (Scott and Wheeler 1982; Wheeler and Manchester 2002). One herbaceous angiosperm (a flowering plant with no woody stem) has been identified as *Ensete* (genus in the banana family) (Manchester 1994). Vines are well represented among the fossil plants. Of the 69 species for which growth form can be identified, 43% represent lianas, woody vines that are rooted in the ground and climb vertically (Manchester 1994). In addition, two species of wood-rotting fungus have been discovered in the Clarno Nut Beds (table 5; Scott 1956). No other North American Paleogene floral assemblage site is characterized by such exceptional preservation (Joshua Samuels, written communication, 11 April 2013).

The Conglomerates of Hancock Canyon (Tcch), which are dominated by debris flows containing boulder-sized clasts, also preserve petrified trees in Hancock Canyon. The upright Hancock Tree, a local landmark, is one of seven fossil trees found within a single volcanic mudflow (lahar) in the canyon. The trees represent part of an extensive fossil forest in an intermediate stage between old growth and secondary regrowth (Retallack et al. 1996). The diameter of the Hancock Tree is 39 cm (15 in) and its total preserved length is 4.22 m (13.8 ft), with 2.79 m (9.15 ft) of trunk exposed above the volcanic mudflow in which it is encased (Retallack et al. 1996). Elizabeth Wheeler recently identified this tree as *Exbucklandia* sp., a pipli tree belonging to the Cercidiphyllaceae family (Joshua Samuels, written communication, 11 April 2013). Today, the natural range of *Exbucklandia* extends from eastern India through southern China and southward to the Malay Peninsula. The existence of the Hancock Tree, and other vertically-oriented petrified tree trunks suggest that these trees were not uprooted by debris flows and are preserved in a growth position, or they were transported in an upright position (Dillhoff et al. 2009).

The Clarno Nut Beds also preserve fragments of vertebrate fossils, and are thus the oldest Cenozoic vertebrate locality in the Pacific Northwest (table 6; Stirton 1944; Hanson 1996; Robinson et al. 2004; Fremd 2010). The most common vertebrate fossils are molars from a newly defined genus of brontothere (Retallack et al. 1996; Mihlbachler and Samuels in preparation). Other mammalian vertebrate fragments include skull fragments and teeth from the "running rhino" *Hyrachyus eximius*, teeth and jaw fragments from the primitive horse *Orohippus major*, and a single jaw fragment from the cat-like creodont *Patriofelis ferox* (Stirton 1944; Carroll 1988; Retallack et al. 1996). Reptiles are represented by fragments of the crocodile *Pristichampsus* and a carapace fragment of the thick-shelled land tortoise, *Hadrianus* sp., a member of the family Testudinidae, which includes the well-known Galapagos tortoises (Carroll 1988; Retallack et al. 1996; Joshua Samuels, written communication, 11 April 2013).

Vertebrate fossil fragments from the Clarno Nut Beds were compared to relatively complete skeletons of fauna discovered in Bridger and Washakie basins, Wyoming. Fossil skeletons from Wyoming and Utah were used to determine the Bridgerian faunal stage, an age interval within the North American Land Mammal Ages (NALMAs) that extends from 55.4 million to 50.1 million years ago (Woodburne 2004). *Patriofelis*, *Orohippus*, and *Hyrachyus* are considered to be characteristic of Bridgerian fauna. Although fossil fragments from the Clarno Nut Beds resemble faunal remains from Bridgerian-aged localities in Wyoming, the Clarno Nut Beds are approximately 44 million years old, which falls within the Uintan faunal stage (46.3–40.1 million years ago; Woodburne 2004). The presence of Bridgerian fauna in an assemblage dating to the Uintan faunal stage is atypical among Uintan faunal assemblages from other North American sites (Joshua Samuels, written communication, 11 April 2013).

Fossils in the Siltstone of the Mammal Quarry

The Hancock Mammal Quarry is the only other Eocene vertebrate fossil locality in the Pacific Northwest, and the only vertebrate quarry in John Day Fossil Beds National Monument (Hanson 1996; Fremd 2010). The quarry lays near the upper contact of the Clarno Formation with the 39.2-million-year-old Member A ash-flow tuff at the base of the John Day Formation. Thus, the quarry also represents the oldest known mammalian fauna of the Duchesnean NALMA, which ranges from 40.1 million to 36.9 million years ago (Lucas 1992, 2006; Retallack et al. 1996; Lucas et al. 2004). However, the lower strata of the Hancock Quarry have been radiometrically age-dated to 42.7 million years ago, within the Uintan NALMA (Lucas et al. 2004).

Mammals represented in the quarry include creodont carnivores, saber-toothed cats, rodents, anthracotheres, oreodonts, rhinoceroses, and horses (table 7; Retallack et al. 1996). Most fossils come from a few large mammals, primarily an early rhino (*Teletaceras*). Skull fragments and teeth of the tapir *Plesiocolopirus hancocki* are common, as are fossils from the "clawed oreodont" *Agriochoerus*, the "marsh rhino" *Zaisanamynodon*, and the brontothere *Eubrontotherium clarnoensis*, which was one of the largest North American mammals in the Late Eocene (table 7; Hanson 1989, 1996; Mihlbachler 2007, 2011). One horse species (*Epihippus gracilis*) and the clawed oreodont (*Agriochoerus antiquus*) are Uintan taxa, whereas the other horse species (*Haplohippus texanus*), tapir (*Plesiocolopirus hancocki*), and creodont (*Hemipsalodon grandis*) belong to the Duchesnean NALMA (Robinson et al. 2004). Fossils from the Hancock Quarry thus represent a mixed Uintan–

Duchesnean fauna (Hanson 1996; Robinson et al. 2004; Lucas 2006).

Similar to the plant fossils in the Clarno Nut Beds, the vertebrate fossils in the Hancock Mammal Quarry offer insights into this younger Eocene ecosystem. Tapirs, for example, are forest browsers, and the assemblage also includes crocodilian fossils. Horses, rhinoceroses, and oreodonts, represented by fossil teeth, are also browsers (Retallack et al. 1996). Relatively complete, although disarticulated, skeletons found in river deposits suggest that some of the carcasses accumulated on a point bar of a meandering river while their bones were still encased in flesh (Pratt 1988; Retallack et al. 1996). The current slackened as it was diverted around the point bar, and the coarser, heavier material, including animal carcasses, settled out of the river's sediment load. The carcasses eventually decayed and the bones became disarticulated. Shale in the quarry, which may represent overbank flood deposits, contains fossils of leaves, fish, and amphibians (Bestland and Retallack 1994a; Fremd 2010).

River processes may also explain the scarcity of smaller bones and those from small mammals in Hancock Mammal Quarry. During flood events or times of high water, smaller bones would have been washed away by the current and deposited downstream, away from the quarry location. As of April 2013, collections from the quarry include only a few rodent incisors (Hanson 1996); however, careful washing of the matrix through screens during future excavations may yield more material (Joshua Samuels, written communication, 11 April 2013).

The mammals of Hancock Quarry may also provide details of global paleogeography. Like the fossil plants in the Clarno Nut Beds, some animals from the quarry are found outside of the Oregon region. The Hancock Quarry mammals *Zaisanamynodon*, *Eubrontotherium*, and *Teletaceras* were roaming parts of Asia at the same time that they were present in the region of present-day Oregon (fig. 15; Hanson 1996; Lucas 2006; Mihlbachler 2007, 2008).

A few fossil fruits and seeds have also been found in the Hancock Mammal Quarry, but they are not the thermophilic species found in the Clarno Nut Beds (table 8). The floral assemblage includes tropical vines,

Figure 15. *Eubrontotherium clarnoensis* fossil from the Hancock Mammal Quarry, John Day Fossil Beds National Monument. National Park Service photograph courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

sycamores, dogwoods, alangiums, cashews, and walnuts (McKee 1970; Bestland and Retallack 1994a; Retallack et al. 1996).

Mammalian browsers, alligators, temperate flora, and associated paleosols suggest that the climate was cooler, albeit still free of frost, and drier in the later Eocene compared with the climate represented in the Clarno Nut Beds (Retallack et al. 1996; Bestland et al. 1999; Dilloff et al. 2009).

John Day Formation

The John Day Formation unconformably overlies the Clarno Formation in the Clarno and Painted Hills Units, while it unconformably overlies the Gable Creek Formation in the Sheep Rock Unit (Fisher and Rensberger 1972; Albright et al. 2008; Joshua Samuels, written communication, 10 December 2013). The Columbia River Basalts nonconformably overlie the John Day Formation. Interbedded fine-grained sedimentary rocks and volcanic units dominate the members of the John Day Formation and provide marker beds with which to physically correlate discontinuous exposures of the formation over great distances (fig. 5; Albright et al. 2008). Many of the volcanic units have been radiometrically age-dated and thus provide chronostratigraphic control (table 2). The features and associated processes represented in these units are summarized in table 9.

Radiometric ages for the John Day Formation in the John Day Fossil Beds National Monument area help place the stratigraphy, fauna, and flora within a timeframe that spans about 21 million years (table 2; Peck 1964; Robinson 1975; Long and Duncan 1982; Robinson et al. 1984; Prothero and Rensberger 1985; Baksi 1989; Hooper and Swanson 1990; Swisher 1992; Bestland and Retallack 1994a; Fremd et al. 1994; Retallack et al. 1999; Hunt and Stepleton 2004; Sheldon 2006; Albright et al. 2008; McClaughry et al. 2009b).

The seven members of the John Day Formation—Big Basin, Turtle Cove, Kimberly, Haystack Valley, Balm Creek, Johnson Canyon, and Rose Creek—and their many stratigraphic units record approximately 20 million years of the Eocene, Oligocene, and Miocene epochs (fig. 5). Abundant plant fossils and fossils from more than 150 vertebrate species have been recovered from the members (tables 10–17). Almost all of the fossil plants belong to the Eocene-aged Bridge Creek Flora of the Big Basin Member (table 10), which contains very few vertebrate remains (table 11). In contrast, few fossil plants are found in the Oligocene Turtle Cove and Kimberly members, but these members contain an exceptional collection of fauna and some of the most well-renowned Oligocene vertebrate sites in North America (table 12). Fossil sites in the Eocene and Oligocene members of the John Day Formation are common throughout central and eastern Oregon, but few Miocene sites have been documented (Joshua Samuels, written communication, 11 April 2013).

Table 9. Features and processes in John Day Formation members (younger to older) mapped in the monument.*

Feature	Process	Map Unit
Upper John Day Formation (Haystack Valley, Balm Creek, Johnson Canyon, Rose Creek members)*		
Conglomerates	Clasts rounded in river channel	Tjh
Siltstones	Flooding of floodplain	
Kimberly Member		
Tuff (thin)	Ash-flow	Tjk
Claystones and siltstones	Flooding of floodplain	
Turtle Cove Member		
Tuff (thin)	Ash-flow	Tjut, Tjl
Ignimbrite tuff (thick unit)	Pyroclastic ash-flow	Tji
Claystones and siltstones	Flooding of floodplain	Tjut, Tjl
Big Basin Member		
Welded tuff	Fused volcanic ash	Tja
Andesite and basaltic tuff	Volcanic ash-flow	Tjb, Tjft
		Tjan, Tjmb Tjmbot
Andesite breccia (colluvium)	Erosion at slope margin of ash-flow	Tjanb
Claystones	Flooding of floodplain	Tjlb, Tjmb, Tjub
Lignite	Organic decomposition in marshes	Tjmblg

These units are being updated based on new mapping by Baker et al. (2013).

Interest in the John Day Formation fossils has existed since the 1860s, when Union soldiers presented some of these fossils to Thomas Condon, who turned them over to interested scientists. Notable 19th century paleontologists, such as Othniel Charles Marsh (from Yale's Peabody Museum) and Edward Drinker Cope (from Academy of Natural Sciences in Philadelphia) and their colleagues collected massive amounts of fossils, but unfortunately did not document their localities in as much detail as paleontologists do today. For example, some of the only known specimens for some taxa come from unknown locations and/or strata (Joshua Samuels, written communication, 11 April 2013).

In 1884, Cope produced an epic summary of Tertiary vertebrate fossils in the American West, which included fossils from what would later become John Day Fossil Beds and Fossil Butte national monuments, among other significant sites. In this tome, informally referred to as "Cope's Bible," Cope described fossils (including many type specimens) collected primarily from the Turtle Cove Member vaguely defined locations (Cope 1884). Most of these sites were in the Blue Basin, Foree, and Sheep Rock areas of the monument's Sheep Rock Unit.

Ongoing research is being conducted with the aim of placing the John Day Formation fossils not only within the detailed stratigraphy of the John Day Formation, but also within a specific time sequence. This sequencing will allow a more detailed analysis of climate change and its effects on habitats, whole ecosystems, and biodiversity during the Paleogene and Neogene (Albright et al. 2008). Continuing research is also being carried out in the attempt to explain the lack of plant fossils from extensive stratigraphic intervals and the uneven distribution of small vertebrates in the John Day Formation (Joshua Samuels, written communication, 11 April 2013). Larger-scale, detailed geologic mapping of the Sheep Rock Unit is underway to facilitate such efforts (e.g., Baker et al. 2013).

Big Basin Member

In the southern part of the Painted Hills Unit, the discontinuous welded tuff of Member A (Tja), which marks the base of the Big Basin Member, is extensively exposed above red beds of the Clarno Formation (fig. 16; Bestland and Retallack 1994b). A thick sequence of volcanic tuffs is present at the base of the John Day Formation, including the Member A tuff (Tja), the 37.5-million-year-old andesite of Sand Mountain (Tjan) exposed in the Painted Hills Unit, and distinctive aphanitic (very fine-grained) columnar-jointed basaltic andesite flows of the Member B basalts (Tjb) in the Clarno Unit (Bestland et al. 1999; see the Map Unit Properties Table for more detail).

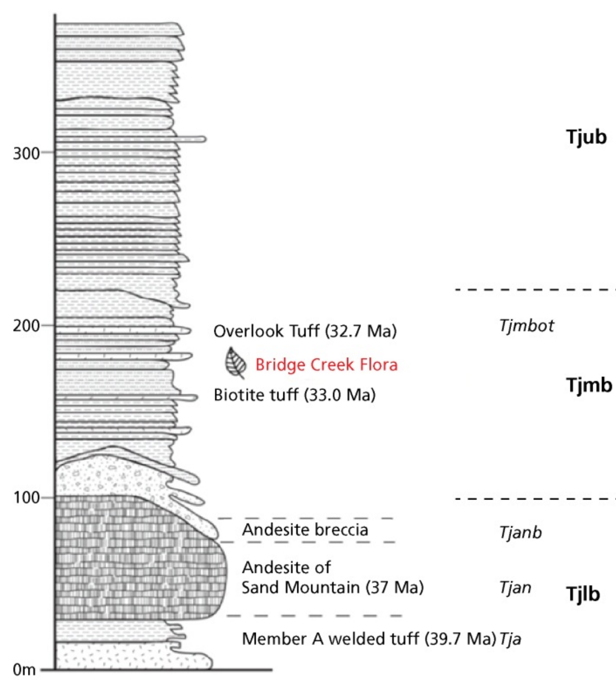

Figure 16. Composite stratigraphic column of the Big Basin Member, John Day Formation. Column redrafted by Trista Thornberry-Ehrlich (Colorado State University), modified from Fremd (2010, p. 93), with revised radiometric ages supplied by Joshua Samuels (John Day Fossil Beds National Monument). The shape of this column reflects the erosion resistance and sediment grain size of individual units (increasing to the right). Ma: millions of years ago.

The andesite breccia (Tjanb) above the andesite of Sand Mountain was deposited at the base of the slope of an andesite flow (fig. 16). A "breccia" is similar to a conglomerate, except that the rock clasts have angular edges, indicating deposition near their origin.

Most fossil plants in John Day Fossil Beds National Monument belong to the Bridge Creek Flora, found in the middle Big Basin Member (Tjmb; fig. 16). The fossils are preserved in a series of pale-olive and pale-yellow claystones that formed in the floodplains as a result of the settling out of fine sediment from floodwaters. The claystones are interlayered with lignite beds (Tjmblg) that developed in an ancient swamp.

In the Painted Hills area, the Overlook Tuff (Tjmbot) marks a significant break in the stratigraphic sequence. The tuff truncated and buried an ancient landscape consisting of swamps, poorly-drained marsh, and well-drained, forested soils. Prior to deposition of the tuff, ancient channels had incised into the claystones of the lower Big Basin Member and filled with conglomerate. The abrupt contact between the claystones and the tuff approximates the Eocene–Oligocene boundary (Bestland et al. 1999).

Fossil plants in the lower Big Basin Member (Tjlb) from localities outside the Clarno Unit boundaries include fruits of walnut-like plants and eucommia, extinct malvalean flowers, and seeds of cigar-tree, elm, Oregon grape, and dawn redwood (Bestland and Retallack 1994a; Retallack et al. 1996). These plant fossils were discovered in lake beds 5 m (16 ft) below a 38-million-year-old volcanic tuff, indicating that the fossils are Late Eocene and within the Duchesnean NALMA (Retallack et al. 1996). The flora are primarily temperate taxa, although thermophilic broad-leaved plants also occur, suggesting a warm, temperate climate (Manchester 2000; Manchester and McIntosh 2007; Wheeler et al. 2006).

In the middle Big Basin Member (Tjmb), fossil alder and dawn redwood (*Metasequoia*), which is Oregon's state fossil, have been discovered from the tuffaceous lake beds of the well-known "Slanting Leaf Beds" (fig. 17; Bestland and Retallack 1994a; Retallack et al. 1996). These beds are part of the Bridge Creek Flora (table 10) and have been dated to 33.62 million years ago, very early in the Oligocene (fig. 3; Retallack et al. 1996). In the Painted Hills, the age of the Bridge Creek Flora ranges from 32.99 million to 32.66 million years (Bestland and Retallack 1994a; Retallack et al. 1999).

The remarkably diverse Bridge Creek Flora from many localities within and adjacent to John Day Fossil Beds National Monument have been studied since the 19th century (Knowlton 1902; Chaney 1924, 1948, 1952, 1956; Meyer and Manchester 1997; DeVore and Pigg 2009). Meyer and Manchester (1997) documented 91 genera, identifying 110 species from leaves and 58 species from fruits, seeds, and cones. At a site east of the Clarno Unit, they identified a floral assemblage that included species belonging to genera that are no longer native to the Pacific Northwest (Manchester and Meyer 1987). The

Figure 17. Metasequoia (dawn redwood) from the Big Basin Member, John Day Formation. Metasequoia is the state fossil of Oregon. Increments on scale bar are 1 cm. National Park Service photograph courtesy Joshua Samuels (John Day Fossil Beds National Monument).

Bridge Creek Flora include a myriad of broad-leaved deciduous trees, such as alder, maple, beech, walnut, birch, and an extinct hornbeam, as well as tropical vines (table 10; Manchester and Meyer 1987; Meyer and Manchester 1997). The floral assemblages also include abundant samples from conifers (Chaney 1952; Meyer and Manchester 1997). Early in the 20th century, the first quantitative census of fossil plants was conducted at "Leaf Hill," a Bridge Creek Flora site in the Painted Hills Unit (Chaney 1924).

The deciduous hardwood forest represented by the Bridge Creek Flora is comparable to today's Mixed Northern Hardwood forest in eastern Asia and marks the transition from a warmer Eocene tropical to subtropical climate to a cooler, more temperate climate in the Early Oligocene (Manchester and Meyer 1987; Wolfe 1993; Meyer and Manchester 1997; Bestland et al. 1999; Manchester 2000; Myers 2003; Zachos et al. 2001, 2008a; Retallack 2007; Dillhoff et al. 2009).

Fossil fauna are scarcer than fossil flora in the Big Basin Member (table 11). In 1959, Brown documented fossil remains of a bat associated with the Bridge Creek Flora. The Bridge Creek Floral assemblage from this member also contains remnants of invertebrates, fish, and amphibians (Coleman 1949). In the Painted Hills, mammal fossils include fragments of mouse deer, oreodonts, rhinoceros, and the giant, hog-like entelodont (Retallack et al. 1996). In the upper Big Basin Member, fossil fragments from weathered claystones include those of horses, rhinoceroses, oreodonts, and entelodonts (Merriam 1901; Merriam and Sinclair 1907; Fremd 2010).

The mammalian material recovered from Big Basin strata is not sufficient to specify a NALMA affiliation for the Big Basin Member (Joshua Samuels, written communication, 11 April 2013). Radiometric dates and magnetostratigraphy, however, indicate an Orellan (33.7–32.0 million years ago) age (Albright et al. 2008). No fossil potentially representing the Chadronian

NALMA (36.9–33.7 million years ago) has been recovered from a lower Big Basin Member stratum. Research continues at several widely scattered sites in the lower Big Basin Member in an attempt to fill this major faunal gap (Fremd 2010; Joshua Samuels, written communication, 11 April 2013).

Turtle Cove Member

The Turtle Cove Member, the thickest in the John Day Formation, overlies the Big Basin Member (fig. 18; Fisher and Rensberger 1972). The Turtle Cove Member forms the prominent badlands topography in the Sheep Rock area. The green tuffaceous claystones have been zeolitized and very widely in texture and color (Fremd 2010). About 24 million years ago, before the extrusion of the Columbia River Basalt, the zeolite mineral clinoptilote replaced glassy material that had dissolved to form cavities in most of the claystones and tuffs of the lower part of the John Day Formation (Hay 1963; Albright et al. 2008; Fremd 2010). The zeolites contribute to the colorful beds in the John Day Formation, especially those in the Turtle Cove Member, and they also may distrupt paleomagnetism in the Picture Gorge region (Albright et al. 2008).

These zeolitized green and tan claystones are the source of the most diverse fossil fauna in Oregon and most of the monument's museum collection (Joshua Samuels, written communication, 10 December 2013). Fossils are found throughout the Turtle Cove Member, although some layers are more productive than others. Ted Fremd, a retired paleontologist from John Day Fossil Beds National Monument, developed an informal system of units based on the appearance of distinctive fauna and the presence of tuff beds and tuffaceous sediments to help explain the chronology of this member (fig. 18; Fremd et al. 1994; Albright et al. 2008; Fremd 2010). This informal division and the Turtle Cove fauna have proven critical in revising the early Arikareean (Ar1 and Ar2) intervals of the Arikareean land mammal stage, which extends from 30.0 million to 18.8 million years ago (Albright et al. 2008).

The lowest part of the Turtle Cove Member contains the 29.75-million-year-old A/B Tuff (Sanidine Tuff of Bestland and Retallack 1994b) and the 28.8-million-year-old Blue Basin Tuff. The A/B Tuff is exposed on the northern side of Blue Basin and the southern side of Carroll Rim, and the Blue Basin Tuff is exposed at Blue Basin (fig. 7), Foree, Cathedral Rock, Sheep Rock, and Carroll Rim (fig. 19; Albright et al. 2008).

The Picture Gorge Ignimbrite (Tji) is the middle unit of the Turtle Cove Member and the most widespread ash-flow tuff sheet in the John Day Formation (fig. 18; Fisher 1966). Approximately 28.7 million years ago, superheated gases, volcanic ash, and pulverized rock from a volcanic eruption fused to form this dense, welded ignimbrite, which has a maximum thickness of nearly 80 m (260 ft; Fisher and Rensberger 1972). Multiple eruptions produced distinctive cooling units in the tuff (Tji1 and Tji2) and indicate that several ignimbrites occurred over an unknown period of time

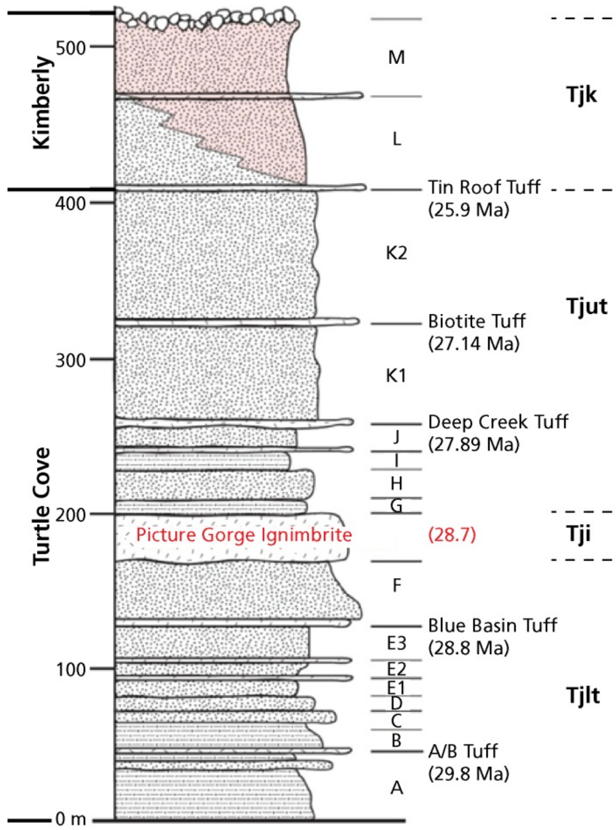

Figure 18. Stratigraphic section, including faunal divisions A–M, of the Turtle Cove and Kimberly members of the John Day Formation. Column redrafted by Trista Thornberry-Ehrlich (Colorado State University), modified from Fremd (2010, p. 87), with revised radiometric ages supplied by Joshua Samuels (John Day Fossil Beds National Monument). The shape of this column reflects the erosion resistance and sediment grain size of individual units (increasing to the right). Ma: millions of years ago.

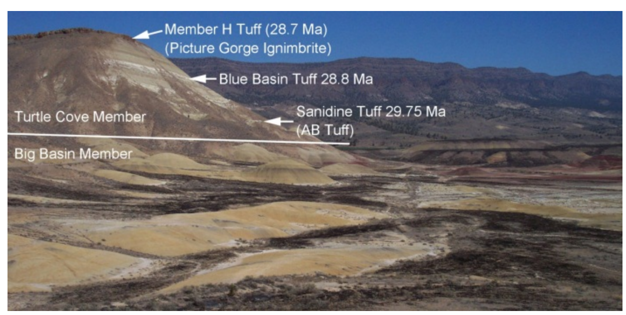

Figure 19. Turtle Cove Member volcanic tuffs exposed at Carroll Rim in the Painted Hills Unit of John Day Fossil Beds National Monument. View is to the east, with Carroll Rim on the left and Sutton Mountain visible in the background. Age dates are from Albright et al. (2008). Ma: million years ago. Annotated photograph courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

(Fisher 1966; Bestland and Retallack 1994b; Bestland 1995). The Picture Gorge Ignimbrite forms a well-recognized layer in many areas, including the crest of Carroll Rim, the distinctive brown layer in the middle of Sheep Rock, and the bright red layer that caps cliffs at Foree and Cathedral Rock.

A complete section of the upper Turtle Cove Member (Tjut) is exposed on Sheep Rock, and partial sections are exposed at Blue Basin and Foree. The alternating claystones, siltstones, and tuff suggest nonmarine deposition on alluvial floodplains punctuated with volcanic activity. Volcanic activity is represented by several prominent tuff beds, including the Roundup, Deep Creek, and Biotite tuffs (figs. 6 and 18). All of these tuff layers are exposed on Sheep Rock and at localities beyond the monument's boundaries (Bestland 1995; Albright et al. 2008). The 25.9-million-year-old Tin Roof Tuff, exposed near the top of Sheep Rock, forms the top of the Turtle Cove Member (fig. 6; Albright et al. 2008).

The upper part of this member contains an impressive collection of mammalian fossils from 36 families, including three-toed horses (*Miohippus*), mouse-deer, burrowing beavers, oreodonts (fig. 20), giant pig-like entelodonts, and carnivores (fig. 22), such as dogs, bear-dogs and cat-like nimravids (table 12).

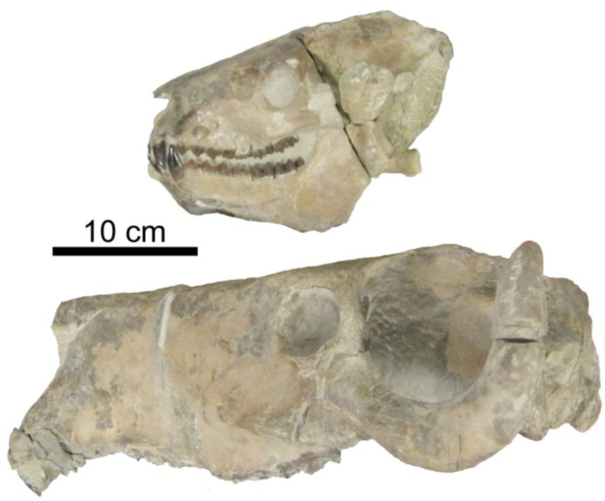

Figure 20. Oreodont fossils from the Turtle Cove Member, John Day Formation. Oreodonts are a common mammal fossil in the Turtle Cove Member. Upper image: *Eporeodon occidentalis* (specimen JODA 15637). Lower image: *Promerycochoerus chelydra* (JODA 7795). National Park Service photographs courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

Nearly 100 mammal species had been identified by April 2013, and new species continue to be added to the list of the assemblage from this member. Some of the more noteworthy mammals include *Miohippus*, which paleontologists have long considered to be critical in understanding horse evolution (Marsh 1874; MacFadden 1994). Saber-toothed cats of the family Nimravidae range from the bobcat-sized (*Dinictis*, *Nimravus*) to leopard-sized (*Eusmilus*) (fig. 22; Bryant 1996; Martin 1998). *Ekgmowechashala* is the only known Late Oligocene/Early Miocene North American primate and the last primate in North America until the arrival of humans about 25 million years later (Albright et al. in preparation, noted by Joshua Samuels, written communication, 11 April 2013). The Turtle Cove Member includes 12 species of dogs (Canidae), which is the most diverse canid faunal assemblage from any period of Earth's history (fig. 22; Wang 1994; Wang et al. 1999; Wang and Tedford 2008; Tedford et al. 2009).

Burrows of earthworms (*Edaphichnium*) and tortoises (*Stylemys*) are well-represented in the Turtle Cove Member, but few specimens of fish, amphibians, reptiles, and birds are documented from the unit (Hay 1908; Brattstrom 1961; Auffenberg 1964; Berman 1976). Plant fossils are uncommon in the Turtle Cove Member, although striking green leaf fossils have been discovered (fig. 21).

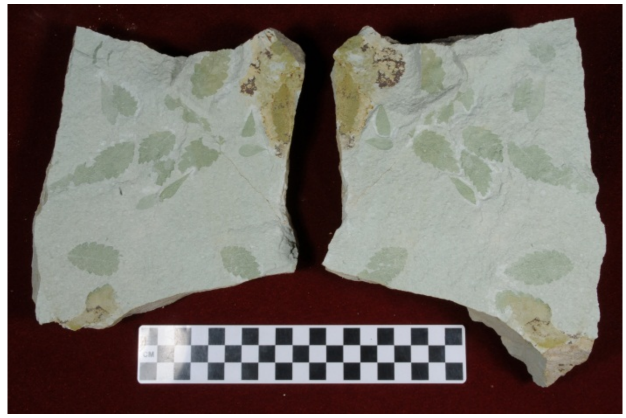

Figure 21. *Zelkova* sp. (from the elm and hackberry family) leaf fossils from the Turtle Cove Member, John Day Formation. These striking green leaf fossils in green claystones of the Turtle Cove Member are rare (specimen JODA 13070). Increments on scale bar are 1 cm. National Park Service photograph courtesy of Joshua Saumuels (John Day Fossil Beds National Monument).

The Turtle Cove fauna and associated paleosols document significant environmental changes in the Oligocene (see the "Paleosols" section). As the climate became cooler and drier, woodlands opened up. Paleosols indicate the presence of woodlands on hills, grassy woodlands and wooded grassland in valley bottoms, and local grassy woodlands in wet bottomlands (Retallack et al. 1996). These woods and grasslands provided for compatible fauna including arboreal squirrels, the first burrowing mammals in the region of present-day Oregon (*Palaeocastor*, *Entoptychus*, *Proscalops*), browsing horses, grazing rhinoceroses, and oreodonts, as well as rabbits (*Archaeolagus*) and camels (*Paratylopus*), Oregon's first running-adapted mammals (Retallack et al. 1996; Zachos et al. 2001, 2008a; Retallack 2007; Samuels and Janis 2010).

Kimberly Member

The unzeolitized buff and brown tuffaceous sediments (primarily siltstones) of the Kimberly Member (Tjk) on Sheep Rock lie between the Tin Roof Tuff at the top of the Turtle Cove Member and the overlying Columbia Basalts (Tcrbp; fig. 18; Fisher and Rensberger 1972; Albright et al. 2008). At many localities, the top of the Kimberly Member is marked by an erosional surface. Burrows, rhizoliths (cylindrical or conical structures that resemble roots), and airfall tuffs in a succession of paleosols suggest the gradual accumulation of sediments punctuated by periods of airfall events. Sandstones, siltstones, and occasional conglomerates in river channels suggest that deposition occurred in both intense flood events and prolonged periods of channel filling in which winnowing produced well-sorted sediments (Hunt and Stepleton 2004).

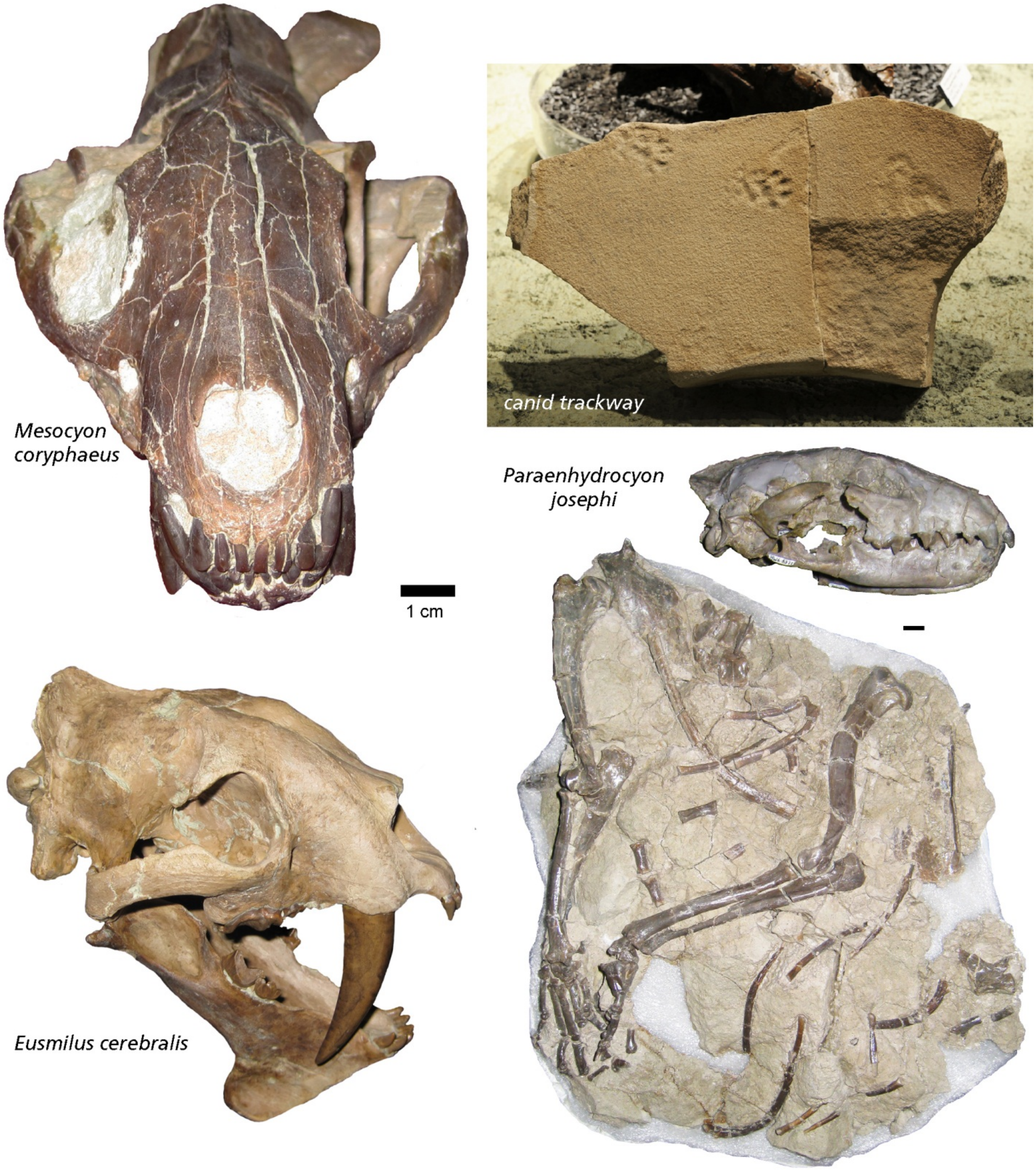

Figure 22. Carnivore fossils from the Turtle Cove Member, John Day Formation. Clockwise from upper left: *Mesoyon coryphaeus* (dog, specimen number JODA 3366), canid trackway (dog, JODA 283), *Paraenhydrocyon josephi* (dog, JODA 761), and *Eusmilus cerebralis* (nimravid, JODA 7047). There is no scale bar for the *Eusmilus* specimen. National Park Service photographs courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

Fossil locations in the Kimberly Member (Tjk) fall outside the monument's boundaries (Fremd et al. 1994; Fremd 2010). Classic sites include those in the Fossil Creek area, in the Southern Region, and at Lonerock (Fremd 2010). In John Day Fossil Beds National Monument, the buff-to-pink layers of the Kimberly Member are exposed only on and near Sheep Rock (Joshua Samuels, written communication, 11 April 2013). Fremd expanded his informal designation system to include the Kimberly Member, defining units L and M, which are early Late Arikareean in age (fig. 18; Fremd et al. 1994; Albright et al. 2008; Fremd 2010). Fauna such as the bear-dog *Daphoenodon*, which first appeared in the region of present-day Oregon at this time; the "stilt-legged" horse *Kalobatippus*; and *Moropus*, a horse-sized, herbivorous, odd-toed ungulate (chalicothere) helped to

Figure 23. Reconstructions of animals in the Late Oligocene Kimberly Member, John Day Formation. Stilt-legged horses (*Kalobatippus*, upper) and wolf-like emphicyonid (*Daphoenodon*, lower). Extracted from murals by Roger Witter, photographed by Will Landon.

further refine age intervals within the Arikareean NALMA (fig. 23; table 13; Tedford et al. 2004; Albright et al. 2008). Similar genera are present in Agate Fossil Beds National Monument in Nebraska (Vincent Santucci, NPS Geologic Resources Division, senior geologist, written communication, 19 August 2013; see GRI report by Graham 2009a).

Most fossil fauna in the Kimberly Member are small mammals (table 13). Gophers dominate the collections, and the presence of specimens from multiple *Entoptychus* species allowed Rensberger (1971) to detail the evolution of the genus (Joshua Samuels, written communication, 11 April 2013). However, large mammals, including *Enhydrocyon* (canid; fig. 24) and the pig-like entelodonts *Archaeotherium calkinsi* and *Daeodon shoshonensis*, have also been recovered (table 13). Many of the large nodules in classic exposures at Sutton Mountain enclose complete oreodont (*Merycochoerus superbus*) skulls (Fremd 2010).

Burrowing beavers (*Palaeocastor*), gophers, running-adapted herbivores such as camels and horses, and the

Figure 24. *Enhydrocyon* sp. (dog) skull from the Late Oligocene Kimberly Member, John Day Formation. Scale bar is 1 cm. National Park Service photograph courtesy Joshua Samuels (John Day Fossil Beds National Monument).

first running-adapted predator in the region of present-day Oregon (*Daphoenodon*) suggest that the area covered by open habitats continued to increase during the period represented by the Kimberly Member (Rensberger 1971; Hunt 2009; Samuels and Van Valkenburgh 2009). Skeletal material is often found in river deposits, where it has been strongly abraded, scavenged and disarticulated, buried by ashfalls, and reworked by subsequent fluvial processes (Hunt and Stepleton 2004). This environment may have been similar to those of open deciduous forests populated with oak, elm, birch, maple, fir, spruce, and pine in today's eastern United States (National Park Service 2014).

Haystack Valley, Balm Creek, Johnson Canyon, and Rose Creek Members

Stratigraphic revision for the Haystack Valley Member of the uppermost John Day Formation resulted in the definition of four lithologic members separated by regional unconformities (fig. 25; Fisher and Rensberger 1972; Hunt and Stepleton 2004). The Haystack Valley, Balm Creek, and Johnson Canyon members are absent in the monument (Hunt and Stepleton 2004; Albright et al. 2008). Their sediments, however, record uplift, fluvial incision, and valley filling due to regional compression about 24 million to 19 million years ago (Fisher and Rensberger 1972; Bestland and Retallack 1994b; Hunt and Stepleton 2004).

The Rose Creek Member (fig. 25) is exposed only at the southern end of Foree in the Sheep Rock Unit, where it unconformably overlies the Turtle Cove Member (Joshua Samuels, written communication, 10 December 2013). Like the Balm Creek and Johnson Canyon members, it is not differentiated on the enclosed GRI GIS map because the source map is older than the 2004 stratigraphic revisions. The Rose Creek Member consists

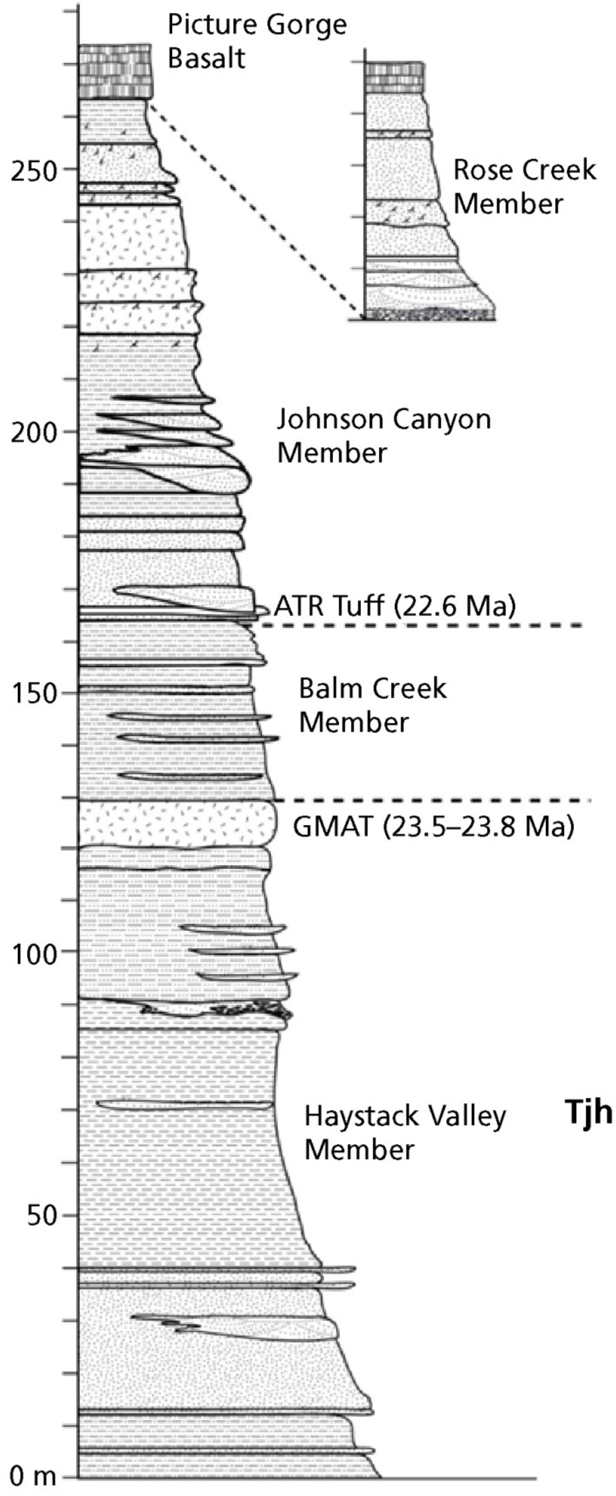

Figure 25. Composite stratigraphic section of the Haystack Valley, Balm Creek, Johnson Canyon, and Rose Creek members of the John Day Formation. Column redrafted by Trista Thornberry-Ehrlich (Colorado State University), modified from Fremd (2010, p. 79), with revised radiometric ages supplied by Joshua Samuels (John Day Fossil Beds National Monument). The shape of this column reflects the erosion resistance and sediment grain size of individual units (increasing to the right). Ma: millions of years ago. GMAT: gray massive airfall tuff.

of fluvial sediments that record incision into underlying rocks of the John Day Formation. Deposits include pebble-to-cobble-sized, welded tuff conglomerates, cross-stratified fluvial sandstones, and debris flows (Hunt and Stepleton 2004).

These upper John Day Formation members were largely ignored until recently (Hunt and Stepleton 2004; Fremd 2010). Although fossils from these members have been recovered from locations north of the Sheep Rock Unit and near the Painted Hills Unit (Tables 14–17), no skeletal material has been recovered in John Day Fossil Beds National Monument (Joshua Samuels, written communication, 11 April 2013).

The Late Arikareean Haystack Valley Member (Tjh) contains more fluvial deposits with diagnostic bone fragments than any other member of the John Day Formation (Albright et al. 2008; Fremd 2010). The complex series of sands, gravels, volcanic ash layers, and paleosols contain evidence of hardwood forests that supported massive, browsing rhinoceroses and chalicotheres (horse-like animals with claws), as well as open grassy areas suited to smaller grazers, such as camels and horses (table 14; Albright et al. 2008; Fremd 2010; National Park Service 2014). Although the Haystack Valley and Kimberly members contain many of the same faunal taxa, the former contains some more advanced species, such as the gopher *Entoptychus* and the mountain beaver *Allomys*, suggesting a slightly younger age (Hunt and Stepleton 2004; Albright et al. 2008).

As of April 2013, the Balm Creek Member had produced only a peccary skull (table 15; Hunt and Stepleton 2004; Joshua Samuels, written communication, 11 April 2013). Diagnostic fauna of the late Late Arikareean Johnson Canyon Member include horned "gophers" (*Mylagauodon*), the first appearance of a palaeomerycid (even-toed ungulate), the musk deer (moschid) *Pseudoblastomeryx*, and advanced species of pocket mice (*Schizodontomys*), oreodonts, and camels (table 16; Hunt and Stepleton 2004; Albright et al. 2008).

Large, undamaged fossil jaws have been found *in situ* and recovered from conglomerate layers at the base of the Rose Creek Member (table 17; Hunt and Stepleton 2004; Albright et al. 2008; Fremd 2010). Many fauna discovered at this Bone Creek site are part of the early Hemingfordian NALMA (18.8–16.0 million years ago) of Nebraska (Hunt and Stepleton 2004; Albright et al. 2008). Diagnostic fauna include species of rodent, dog, camel, horse, chalicothere, musk-deer, rhinoceros, and oreodont (table 17; Albright et al. 2008).

Although Oligocene–Miocene fossil plants are scarce in the John Day Formation, floral remains of sweetgum (*Liquidambar*), plane tree (*Platanus*), elm (*Cedrelospermun* and *Ulmus*), oak (*Quercus*), and cypress (*Taxodium*) have been donated to the John Day Fossil Beds National Monument collections. These fossils were reportedly collected from an "upper" John Day Formation locality in the Western Region of central

Oregon (Joshua Samuels, written communication, 11 April 2013).

Picture Gorge Basalt Subgroup

Features in the Picture Gorge Basalt (Tcrbp) formed during the Miocene, when floods of basalt flowed into the Columbia River Basin (fig. 5). Features include fine-grained basalt, the result of rapid cooling of magma on the surface, as well as phenocrysts, which indicate a period of less rapid cooling. The rough zones of scoriaceous (containing large holes) basalt resulted from escaping gas. In the vicinity of Picture Gorge (Sheep Rock Unit; see fig. 35), the basalt flows currently tilt at an angle of approximately 22° to the south-southwest (Bestland 1998).

The basalts are typically overlain by the Mascall Formation (Tm), but they are unconformably overlain by the Rattlesnake Formation (QTr) where the Mascall Formation is absent. Near Sheep Rock and Blue Basin, the basalts may unconformably overlie the Kimberly and Turtle Cove members of the John Day Formation; at the south end of Foree, they overlie the Rose Creek Member.

Data from multiple studies using a combination of dating methods suggest that the Picture Gorge Basalt is 16.0 million to 16.5 million years old (table 2; Long and Duncan 1982; Baksi 1989; Hooper and Swanson 1990; Sheldon 2006). The Dayville Basalt Formation of the Picture Gorge Basalt Subgroup is conformable with the base of the Mascall Formation (Long and Duncan 1982; Bestland et al. 2008).

Mascall Formation

The Mascall Formation overlies the Dayville Basalt Formation of the Picture Gorge Basalt Subgroup (fig. 26). Features of all tuffs in the Mascall Formation (Tm) are consistent with fluvial deposition or paleosol development (Bestland et al. 2008). Deposited in a fluvial basin on the southern flank of the Columbia River Plateau, the claystones and siltstones lack coarse clasts and contain burrows and root traces, consistent with overbank flooding (fig. 26; Bestland 1998; Bestland et al. 2008). The homogeneous quality of the volcanic tuffs and the lack of pyroclastic deposits suggest a distant volcanic source, perhaps associated with the Cascade volcanic arc (Rytuba and McKee 1984; Bestland et al. 2008). The Lower Member contains siltstones and claystones composed of diatoms, single-celled algae that secrete silica, which represent deposition in lake or marsh environments (Bestland et al. 2008).

The Mascall Formation has been subdivided into Lower, Middle, and Upper members (Bestland et al. 2008). Fossils are sparse in the Upper Member. The Lower Member produces the majority of leaves and diatomite units from layers of lake sediments beneath the 15.3-million-year-old Mascall Tuff, which marks the base of the Middle Member (Chaney 1925, 1952, 1956, 1959; Chaney and Axelrod 1959; Kuiper 1988; Krull 1998; Bestland et al. 2008; Dillhoff et al. 2009; Fremd 2010).

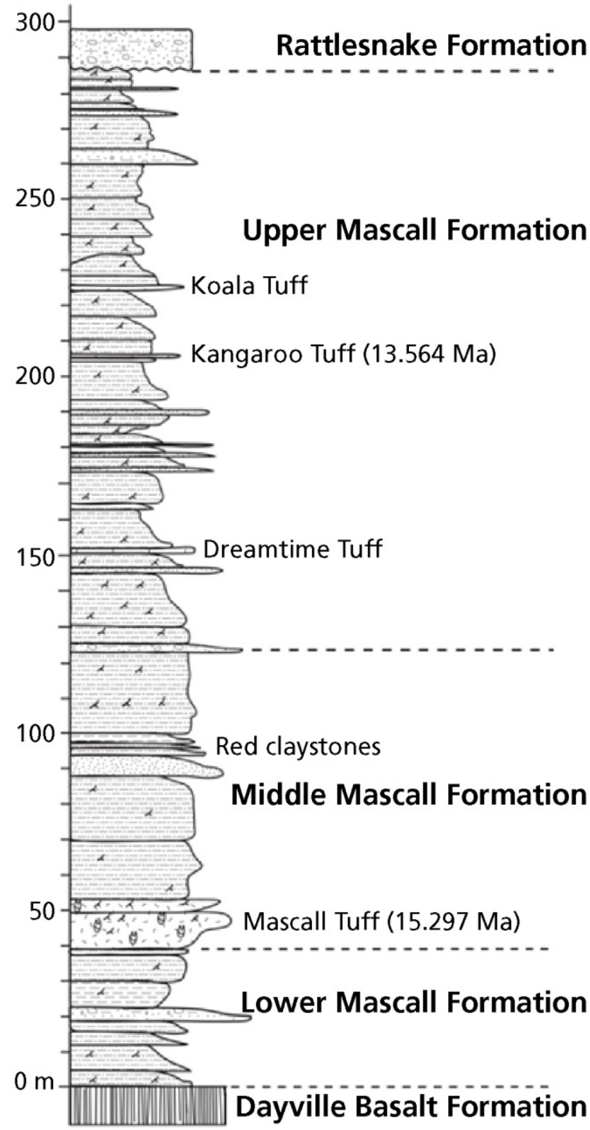

Figure 26. Composite stratigraphic section of the Mascall Formation (Tm). The section is based on deposits in and around the Sheep Rock Unit. Column redrafted by Trista Thornberry-Ehrlich (Colorado State University), modified from Fremd (2010, p. 75) and Bestland et al. (2008, figs. 3 and 4) with updated age-dates supplied by Joshua Samuels (John Day Fossil Beds National Monument). Fm: formation. Ma: millions of years ago.

The Middle Member has produced vertebrate fossils from fauna characteristic of the Barstonvian NALMA, which extends from 16.0 million to 12.5 million years ago (Tedford et al. 2004; Fremd 2010).

The Mascall Tuff is a massive, tuffaceous siltstone consisting of stratified tuffs and conglomerate lenses. Relatively resistant to erosion, the tuff is the primary source of *in situ* vertebrate fossils in the formation. The tuffaceous clasts that formed the conglomerates were rounded and deposited in fluvial channels.

Some lithological characteristics and features of the Upper Member are similar to those of the other two members. This member also contains the Dreamtime, Kangaroo, and Koala tuff beds (fig. 26), which may serve as regional marker beds to help correlate the type section with other Mascall-like sections (Bestland et al. 2008).

The Dayville Basalt Formation has been radiometrically dated to 16.5 million to 16.3 million years old (Long and Duncan 1982; Hooper and Swanson 1990; Bestland et al. 2008). A tuffaceous paleosol near the base of the basalt flows was dated to 16.0 million years, a tuff bed in the Lower Mascall Formation was dated to 15.8 million years, the Mascall Tuff was dated to 15.297 million years, and the Kangaroo Tuff in the Upper Mascall Formation was dated to 13.564 million years (table 2; Swisher 1992; Bestland 1998; Sheldon 2006; Schmitz and Lovelock 2012). Paleomagnetic data have been used to correlate the lower part of the Mascall Formation with magnetic chrons C5Br to C5Br1n, or 16.0 million to 14.8 million years ago (Prothero et al. 2006a).

Mammalian fossils from 24 families and plant fossils from at least 70 genera have been found in the Mascall Formation (Tables 18 and 19; Chaney 1959; Chaney and Axelrod 1959; Fremd 2010; Joshua Samuels, written communication, 11 April 2013). Most fossils from the Miocene Mascall Formation (Tm) in John Day Fossil Beds National Monument have been recovered from the historic Mascall Ranch locality, the designated type section for the formation, located in the Sheep Rock Unit.

Although equids (horses), palaeomerycids (ruminants, even-toed ungulates), and other large mammals dominate the Mascall fauna, the assemblage also includes relatively abundant specimens of rodents (table 18). The elephant-like *Gomphotherium* and the mastodon, *Zygolophodon*, which helped define the Barstovian NALMA, were some of the earliest of their kind in North America, and *Pseudaelurus* was the first documented cat in the Pacific Northwest (fig. 27; Tedford et al. 2004; Joshua Samuels, written communication, 11 April 2013).

Most floral fossils from the Mascall Formation (table 19) are leaf impressions from plants similar to those found in temperate forests in the eastern United States that include cypress swamps, lowland deciduous forests, and upland coniferous forests (Chaney 1959; Chaney and Axelrod 1959; Dillhoff et al. 2009).

The shallow lake and marsh sediments beneath the Mascall Tuff Bed, which marks the base of the Middle Member, contain most of the 70 species of fossil plants (table 19; Bestland et al. 2008; Fremd 2010). Fossils of the sunfish *Arcoplites* (table 18) are also found in the Lower Member, as are diatoms (a major group of algae) from diatomaceous siltstone (table 20). The planktic diatom *Melosira* represents slightly alkaline freshwater lakes under eutrophic conditions (Taylor et al. 1990; Bestland et al. 2008).

The diversity of plants and animals in the Mascall Formation, combined with paleosol evidence (see the "Paleosols" section), suggests that the Middle Miocene climate in the region of present-day central Oregon was humid and temperate, with dry, warm summers and cool

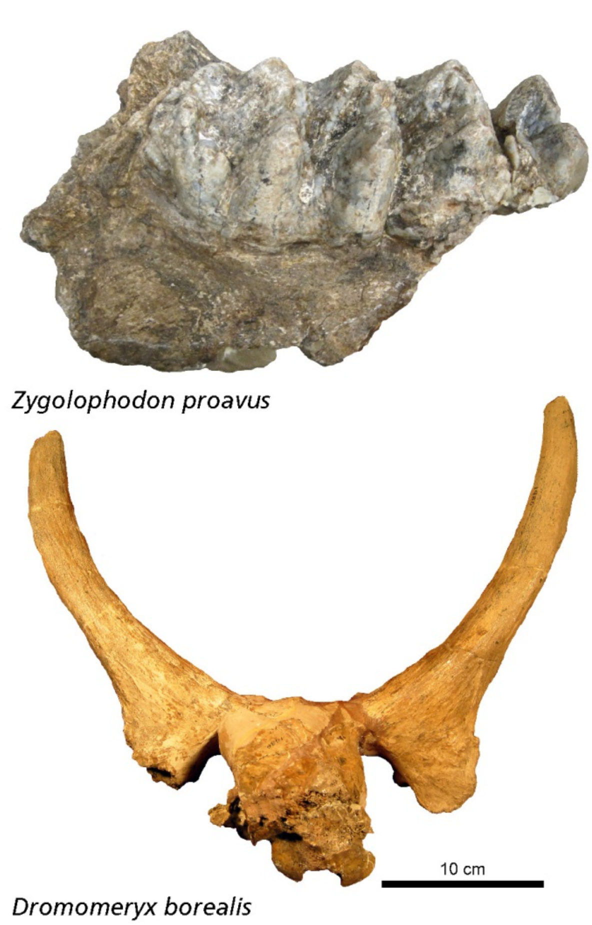

Figure 27. Fossils from the Mascall Formation. This maxilla of Zygolophodon proavus (mastodon, top) and partial skull of Dromomeryx borealis (giraffe-deer, bottom) are two of the many fossils from the Mascall Formation. Scale bar refers to the Dromomeryx specimen. National Park Service photographs of specimens JODA 1322 (upper) and UCMP 1486 (lower) courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

to cold winters (Bestland et al. 2008). Fauna such as mastodons, horses, camels, rabbits, burrowing ground squirrels, gophers, and an arboreal ringtail (*Bassariscus lycopotamicus*) suggest that the landscape consisted of both open, grass-dominated habitats and forested areas (Downs 1956; Retallack 2004b, 2007; Bestland et al. 2008). River and lake systems supported aquatic plants, such as cypress trees and water-lillies, as well as pond turtles and *Monosaulax*, the semi-aquatic beaver (Tables 18 and 19).

The hackberry, *Celtis* sp., is the only plant fossil that occurs in deposits ranging from the Eocene (Clarno Nut Beds) through the Middle Miocene (Mascall Formation). This deciduous tree grows in the monument today and thrives in warm, temperate regions. *Celtis* fossils are better preserved than those of other plants, and berries of this tree have been found in paleosols throughout central and eastern Oregon. One reason for its preservation may be the highly mineralized endocarp of its berries, which includes aragonite and opal (Cowan et al. 1997).

Rattlesnake Formation

In the Sheep Rock Unit, the Rattlesnake Formation (QTr) unconformably overlies the Mascall Formation and Picture Gorge Basalts. Abundant conglomerate, claystone, siltstone, and the massive Rattlesnake Ash Flow Tuff characterize the Rattlesnake Formation (fig. 28). The fine-grained claystones and siltstones in the lower Rattlesnake Formation were deposited by a stream flowing to the northeast in the ancestral John Day Valley (Retallack et al. 2002). Composed primarily of basaltic gravel, the conglomerates in the lower part of the formation filled river channels (Merriam et al. 1925; Enlows 1976; Martin 1983, 1996; Martin and Fremd 2001).

Fanglomerates in the upper part of the Rattlesnake Formation formed in extensive alluvial fan settings. Alluvial fan deposits commonly form as streams emerge from mountainous areas and into valleys or plains. As a stream's gradient and velocity decrease in these settings, it can no longer transport coarser sediments. As a result, coarse sediments choke the stream's channel, which shifts laterally. This continuous back-and-forth lateral migration of the channel forms the familiar fan shape (fig. 8). In the Miocene, alluvial fans developed due to the northward growth of the Picture Gorge Basalt anticline (Retallack et al. 2002). Vertebrate fossils occur in the fanglomerate.

Erupted from volcanoes in the Harney Basin, southwest of present-day Burns, Oregon, and deposited as a single cooling unit, the Rattlesnake Ash Flow Tuff originally covered as up to 40,000 km^2 (15,000 mi^2) of area in present-day eastern and central Oregon and consisted of 280 km^3 (67 mi^3) of magma (Streck and Grunder 1997; Streck et al. 1999). Spectacular banded pumices and a salt-and-pepper matrix of white and gray glass shards distinguish the tuff.

Radiometric and paleomagnetic analyses of the Rattlesnake Formation record magnetic Chrons C3Bn to C3Br2n, or 6.9 million to 7.3 million years ago, and an age of 7.05 million years for the Rattlesnake Ash Flow Tuff (table 2; Streck and Grunder 1997; Prothero et al. 2006b).

In the Sheep Rock Unit, fossils from the Rattlesnake Formation (QTr) come primarily from alluvial fan (fanglomerate) deposits approximately 25 m (82 ft) below the 7.05-million-year-old Rattlesnake Ash Flow Tuff (Fremd 2010). Mammal fossils represent at least 41 species from 25 families (table 21), whereas plant fossils record only 8 families and 9 species (table 22; Fremd et al. 1994; Kenworthy et al. 2005; Fremd 2010).

Although sparse, the mammal fossils in the Rattlesnake Formation were chosen as the reference fauna for the Hemphillian NALMA, which ranges from 9.0 million to 4.9 million years ago (fig. 29; Wood et al. 1941). Some of the fauna, such as the ground sloth (*Megalonyx*) and *Simocyon*, an extinct mountain-lion–sized member of the red panda family, indicate immigration events (Qiu 2003; Tedford et al. 2004; Woodburne 2004; Samuels and Zancanella 2011). *Megalonyx* immigrated from South America, and the *Simocyon* specimen is one of only two found on the North American continent (Joshua

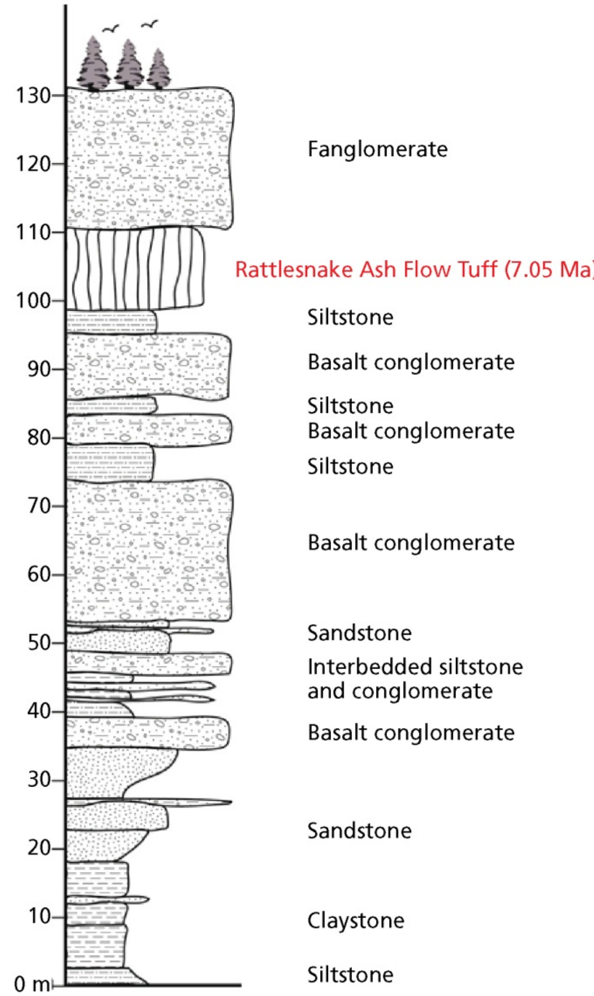

Figure 28. Composite stratigraphic section of the Rattlesnake Formation (QTr). This section is based on deposits in and around the Sheep Rock Unit (Martin and Fremd 2001). Column redrafted by Trista Thornberry-Ehrlich (Colorado State University), modified from Fremd (2010, p. 71), with updated age-dates supplied by Joshua Samuels (John Day Fossil Beds National Monument). Ma: millions of years ago.

Figure 29. *Borophagus* (dog) jaw from the Rattlesnake Formation. National Park Service photograph courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

Samuels, John Day Fossil Beds NM, written communication, 11 April 2013).

Plant fossils are rare in the Rattlesnake Formation (table 22; Dillhoff et al. 2009). The only documented floral fossil site is near Dayville, Oregon, in lower fanglomerate deposits beneath the Rattlesnake Ash Flow Tuff (Chaney 1948, 1956). In addition to eudicot leaves, petrified wood fragments may be found in these fanglomerates (Samuels and Cavin 2013).

Paleosols beneath the Rattlesnake Ash Flow Tuff record a transition from riparian woodland and seasonally waterlogged riparian meadow at the base of the Rattlesnake Formation (7.5–7.3 million years ago) to tall grassland (7.3–7.2 million years ago; Retallack et al. 2002; see the "Paleosols" section). The shift from woodland to grassland approximately 7.3 million years ago is supported by the Rattlesnake Formation faunal assemblage, which includes running animals such as horses and pronghorns. However, the recent discovery of a fisher (*Pekania*) and fossil remains of beavers and a tapir suggest that the landscape also included forested river systems (Samuels and Cavin 2013).

Paleosols

The color-banded claystones in John Day Fossil Beds National Monument are paleosols (fossil soils) that contain a relatively detailed paleoclimatic record of stepwise cooling and drying during the Paleogene and Neogene, including the dramatic climatic change at the Eocene–Oligocene boundary (table 23; Retallack et al. 1999, 2002). Each pedotype listed in table 23 represents a specific kind of paleosol, each representing a different environment. The names of the pedotypes were derived from the American Indian Sahaptin language, which was spoken in the region prior to English settlement.

Clarno Formation

In general, paleosols in the Eocene Clarno Formation developed in humid, forest environments (Retallack et al. 1999). Some paleosols reflect waterlogged lowlands in which peat developed, whereas other paleosols developed in well-drained forested landscapes (table 23). Lakayx pedotypes are exposed in the claystones of Meyers Canyon (Tcm), southeast of the Painted Hills Unit. In the Clarno Unit, the claystones of Red Hill (Tcrh) contain Lakayx and Luca pedotypes. In a lower part of the cliffs along the John Day River, the Conglomerates of the Palisades (Tccp) contain Scat and Sitaxs pedotypes. Nukut paleosols are present in the Clarno Formation at Brown Grotto, Painted Cove, and possibly Red Scar Knoll.

Lakayx, Luca, and Nukut pedotypes represent humid forested environments in which the mean annual precipitation (MAP) may have reached 135 cm (53 in; table 23; Retallack et al. 1999). In comparison, the MAP in present-day Eugene, Oregon, is approximately 127 cm (50 in), and that of the Amazon Basin, which has a warm, humid climate perhaps similar to that of the Eocene in the region of present-day central Oregon, is about 203 cm (80 in).

Lakayx, Luca, Scat, and Sitaxs pedotypes developed on alluvial terraces. The Luca pedotype, a red paleosol, and the Lakayx pedotype formed on well-drained alluvial terraces above the regional water table (Retallack et al. 1999). Scat paleosols also formed in well-drained paleogeomorphic settings, but lower on the alluvial terraces than Luca paleosols. The weakly developed Scat paleosols formed on conglomerates interpreted as fluvial paleochannel deposits, possibly originating from catastrophic floods and mudflows (Retallack et al. 1999). The Sitaxs pedotype, distinctively purple and mottled, formed in lowland topographic settings susceptible to seasonal waterlogging.

John Day Formation

Abundant paleosols have been recognized in the John Day Formation (table 23). Retallack et al. (1999) identified 435 successive paleosols of 15 pedotypes within 430 m (1,400 ft) of the lower John Day Formation. Apax and Tiliwal paleosols are found at Brown Grotto and Red Scar Knoll. Tiliwal paleosols are also found at Painted Cove. The John Day Formation in the Painted Hills contains a variety of paleosols, including Kskus, Luca, Lakim, and Ticam.

Woodlands or forests of the middle Big Basin Member (Tjmb) evolved into increasingly grassy woodlands in the upper Big Basin Member (Tjub). In the Painted Hills Unit, the Red Cap beds (Tjmbrc) at the contact between the middle and upper Big Basin Member contain a double set of paleosols. The lower set is composed primarily of thin, reddish-brown Ticam paleosols, whereas the upper set contains thick, deep-red, Luca paleosols. The juxtaposition of the two pedotypes suggests that sedimentation rates slowed toward the end of middle Big Basin Member deposition, and incision events may have transformed floodplains into well-drained terraces upon which Luca paleosols developed.

The paleosols in the lower Turtle Cove Member (Tjl) differ significantly from those in the Big Basin Member and signal a change in paleoenvironment. In the Painted Hills Unit, the change from Skwiskwi and Ticam paleosol types to Maquas paleosol types marks the boundary between the upper Big Basin Member (Tjub) and the lower Turtle Cove Member (Tjl). Green Xaxus and Xaxuspa pedotypes dominate the upper Turtle Cover Member claystones in the Sheep Rock Unit and on Carroll Rim and Sutton Mountain. Yapas and Maqas pedotypes signal an increase in grassy woodlands and wooded grasslands in the region. Xaxus and Xaxuspa pedotypes developed in seasonally wet alluvial lowlands and represent slightly weeded, seasonally wet meadows (Xaxus) and sagebrush desert grassland (Xaxuspa) environments (Retallack et al. 1999).

The Oligocene and Early Miocene paleosols of Oregon document changes in the ecosystem that are not captured by plant fossils. During this time, a cooler, drier climate supported the evolution of grasslands and the

Table 23. Paleogene and Neogene pedotypes (paleosols) of central Oregon.

Age (Epoch)	Pedotype	Sahaptin meaning	Formation	Paleoclimate	Ancient Vegetation Interpretation
Miocene	Xaus	root	Rattlesnake Upper John Day	Insufficiently developed.	Riparian woodlands of sand bars and point bars.
	Cmti	new		Insufficiently developed.	Riparian woodlands of streamside levees.
	Tnan	cliff		Semi-arid; seasonal; MAP 20–60 cm (7.9–24 in).	Dry wooded shrubland.
	Tatas	basket		Drier than Kalas. MAP 50–85 cm (20–33 in).	Tall wooded grassland.
	Kalas	raccoon		Associated with Skwiskwi pedotype	Seasonally waterlogged riparian meadow.
	Patu	fine	Mascall Upper John Day	Temperate climate with dry, warm summers (Mediterranean aspects) and cool to cold winters (continental aspects).	Grassy woodland (associated with Maqas).
	Walasx	resin			Grassy woodland; hardwood forest.
	Monana	underneath	Mascall Picture Gorge Basalt	Subhumid, seasonally dry.	Peat swamp.
	Ilukas	firewood	Picture Gorge Basalt	Humid. MAP 60–120 cm (10–47 in).	Upland old-growth forest.
	Kwalk	drab		Humid; MAP > 50 cm (20 in). Seasonally dry.	Riparian swale woodland.
	Skaw	scare			Woodland.
	Nuqwas	throat			Shrubs.
Late Oligocene–Early Miocene	Abiaxi	bitter root	Upper John Day	Insufficiently developed.	Saline scrub.
	Iscit	path		Semiarid, seasonally dry.	Grassy woodland.
	Plas	white		Semiarid. MAP 40–50 cm (16–20 in).	Sagebrush shrubland.
	Plaspa	in white		Semiarid. MAP 30–40 cm (12–16 in).	Desert scrub.
	Tima	write		Semiarid, seasonally dry.	Dry woodland.
	Yapaspa	in grease		Semiarid. MAP 35–60 cm (14–24 in).	Sagebrush shrubland.
Late Oligocene–Middle Miocene	Yapas	grease	John Day	Subhumid; MAP 35–105 cm (14–41 in). Dry season.	Open grassy woodland and wooded grassland.
Late Eocene–Middle Miocene	Micay	root	John Day Clarno	Insufficiently developed.	Early successional woodland.
Late Oligocene	Maqas	yellow, orange	Mascall John Day	Subhumid; MAP 35–75 cm (14–30 in). Dry season.	Grassy woodland.
	Xaxus	green	John Day	Subhumid; MAP 25–60 cm (10–24 in). Wet season.	Lightly wooded seasonally wet meadow.
	Xaxuspa				
Middle Oligocene–Late Miocene	Skwiskwi	brown	Rattlesnake Mascall John Day	Subhumid; MAP 40–95 cm (16–37 in). Dry season.	Riparian woodland.
Early–Middle Oligocene	Ticam	earth	John Day	Subhumid; MAP 60–120 cm (24–47 in). Dry season.	Colonizing woodland.
Early Oligocene	Wawcak	split	Mascall John Day	Marked dry season.	Open woodland.
	Yanwa	weak, poor	Mascall John Day	Humid, temperate, seasonally cool and dry.	Swamp woodland.
Late Eocene – Late Oligocene	Lakim	soot	John Day Clarno	Insufficiently developed.	Waterlogged bottomland forest.

Table 23. Paleogene and Neogene pedotypes (paleosols) of central Oregon (continued).

Age (Epoch)	Pedotype	Sahaptin meaning	Formation	Paleoclimate	Ancient Vegetation Interpretation
Late Eocene–Middle Oligocene	Luca	red	Mascall John Day Clarno	Humid, MAP 41–135 cm (16–53 in). Short dry season.	Woodland or forest with good ground cover.
	Kskus	small	John Day	Insufficiently developed.	Early successional vegetation.
Late Eocene	Acas	eye		Humid; MAP 75–120 cm (30–47 in). Short dry season.	Tall tropical forest with good ground cover.
	Apax	skin		Warm, tropical climate; MAP 100–135 cm (39–53 in). Short dry season.	Tropical colonizing forest.
Late Eocene	Sak	onion	John Day	Humid; MAP 95–130 cm (37–51 in). Tropical. Short dry season.	Tall tropical forest.
	Tiliwal	blood		Humid; MAP 105–140 cm (41–55 in). Tropical. Dry season.	Tall tropical forest with little ground cover.
	Tuksay	cup, pot		Humid; MAP 90–135 cm (35–53 in). Tropical. Dry season.	
	Cmuk	black	Clarno	Insufficiently developed.	Swamp woodland.
	Sitaxs	liver		Insufficiently developed.	Seasonally waterlogged lowland forest.
Middle–Late Eocene	Nukut	flesh		Humid; MAP 105–140 cm (41–55 in). Tropical. Short dry season.	
Middle Eocene	Lakayx	shine		Humid; MAP 95–130 cm (37–51 in).	Lowland well-drained old-growth rainforest.
	Luquem	decayed fire		Insufficiently developed.	Early successional herbs.
	Pasct	cloud		Humid; MAP 85–120 cm (33–47 in).	Lowland poorly drained forest.
	Patat	tree		Insufficiently developed.	Mid-successional forest (Hancock Tree).
	Pswa	stone, clay		Humid; MAP 75–110 cm (30–43 in). Dry season.	Well-drained old-growth forest.
	Sayayk	sand		Insufficiently developed.	Early successional woodland.
	Scat	dark		Insufficiently developed.	Humid mid-successional woodland.

Note: Detailed descriptions of pedotypes, including soil profiles, parent material, alteration after burial, evidence of former animal life, topography, time of formation, and comparison to modern soil types are available in Retallack et al. (2000, 2002), Retallack (2004a), Bestland et al. (2008), and Sheldon (2003, 2006). An expanded, more thorough discussion of features supporting the paleoprecipitation estimates and paleoclimate interpretations is also available from these references. MAP: mean annual precipitation.

spread of sagebrush steppe, with a corresponding decrease in the expanse of forests, woodlands, and swamps, which dominated the landscape through the Eocene and earliest Oligocene (Sheldon et al. 2002; Retallack 2004a, 2007; Dillhoff et al. 2009). Bunch grasslands, the earliest form of grass-dominated habitat, may have appeared in the region of present-day Oregon approximately 30 million to 27 million years ago, during the Early Oligocene (Retallack 2004a, 2004b, 2007). Plas and Plaspa paleosols dominate the Miocene Haystack Valley Member of the John Day Formation and represent semiarid sagebrush and desert scrub environments that received 30 cm to 50 cm (12–20 in) annual precipitation (Retallack et al. 1999). The spread of grasslands provided open habitats for burrowing and cursorily adapted taxa, which appear in the Turtle Cove Member (Webb 1977; Janis and Wilhelm 1993; Janis et al. 2002, 2008; Hunt 2009, 2011; Samuels and Van Vlakenburgh 2009; Samuels and Janis 2010). Early Miocene (19–16 million years ago) paleosols document the appearance and expansion of short sod grasslands into regional ecosystems (Retallack 2004a, 2007).

Picture Gorge Basalt Subgroup

Red, clay-rich paleosols in the Picture Gorge Basalt Subgroup record significant intervals of time between the emplacement of basalt flows. Originally considered to be “baked zones” resulting from basalt flow emplacement, these zones show evidence of soil formation during a short-lived warming event, known as the Middle Miocene climatic optimum, that occurred between 16.0 million and 15.4 million years ago (fig. 2; Sheldon 2003, 2006; Bestland et al. 2008). During this climatic optimum, conditions became nearly tropical in middle latitudes around the Pacific Rim as global temperatures warmed. Geochemical evidence and mass-balance characteristics of paleosols in the Picture Gorge Basalt indicate that MAP was 50 cm to 90 cm (20–35 in), mean annual temperature was 8°C to 16°C (46–61°F), and general cooling and aridification occurred from 16 million to 15 million years ago. These estimates are consistent with evidence from fossil plants and paleosols in the Miocene Mascall Formation and marine isotopic records (Sheldon 2006).

Five pedotypes have been identified from exposures in Picture Gorge (Table 23). Except for the Ilukas pedotype, these pedotypes are weakly developed, with very little soil structure. Monana paleosols are weakly developed but have a peat horizon. The very weakly developed Skaw paleosols developed from volcanic ash. Kwalk paleosols represent reworking of this volcanic ash, but lack distinctive subsurface horizons or soil structure. Thin, weakly developed Nuqwas paleosols are considered to be an early stage in the development of Ilukas paleosols. Ilukas paleosols are the most common, thickest, and most developed of the paleosols in the Picture Gorge Basalt Subgroup. All of these paleosols indicate that the John Day region received more than 50 cm (20 in) precipitation annually in a humid, temperate paleoclimate (Sheldon 2003).

Mascall Formation

In general, the paleosols in all three members of the Mascall Formation formed within a low-relief floodplain environment in a humid temperate climate (Bestland et al. 2008). The six major pedotypes in the Mascall are the Maqas, Patu, Skwiskwi, Luca, Wawcak, and Walasx pedotypes (Table 23). Less-developed paleosols include the Maqas, Patu, and Walasx pedotypes, which typically formed from volcanic ash in humid to subhumid regions (Bestland et al. 2008). Grasslands, grassy woodlands, and hardwood forests are associated with the development of Skwisksi, Wawcak, and Luca paleosols over longer periods of time from volcanic material (basalt, tuff) deposited within stable floodplains. Luca paleosols are common in the Middle Member of the Mascall Formation (Bestland et al. 2008).

Yanwa and Monana pedotypes (Table 23) occur in the Mascall Formation, but are not areally extensive. Pale-yellow Yanwa pedotypes occur at the base of the formation in the thin interval of diatomaceous and lignitic beds. They developed from coniferous leaf debris and represent forested swamp soils that formed near lakes or ponds. Monana pedotypes occur in the upper part of the formation, and their darker color suggests that they formed from both coniferous and dicot leaf debris (Retallack 2004b; Bestland et al. 2008).

The volcanic ages (Table 2) and the paleosol sequence suggest that the entire Mascall Formation at John Day Fossil Beds National Monument represents the Middle Miocene climatic optimum (Bestland et al. 2008).

Rattlesnake Formation

Paleosols in the Miocene Rattlesnake Formation document the existence of three different climates prior to the deposition of the 7.05-million-year-old Rattlesnake Ash-Flow Tuff (Table 23). Kalas and Skwiskwi paleosols at the base of the formation indicate that the paleoclimate in the region of present-day Oregon was subhumid from approximately 7.5 million to 7.3 million years ago (Retallack et al. 2002). The tall, wooded grassland vegetation represented by the Tatas paleosols signals a shift to a semi-arid paleoclimate from approximately 7.3 million to 7.2 million years ago. From approximately 7.2 million to 7.1 million years ago, aridification continued, with semi-arid conditions and vegetation (desert bunch grass) similar to those of present-day eastern Oregon (Tnan, Xaus, and Cmti paleosols).

Changes in paleosol type correspond to changes in vegetation, topography, and mammalian fauna. Aridification and a shift to shrubland about 7.2 million years ago (Early Hemphillian) coincide with a continent-wide mass extinction of most remaining browsing mammals (Retallack et al. 2002).

Volcanic Features in the John Day Formation

All units in John Day Fossil Beds National Monument contain significant and noteworthy volcanic features, including lahars in the Clarno Formation, features documenting the evolution of the ancient Cascades, the Rattlesnake Ash-Flow Tuff, and the Columbia River Basalts. Some of these features are described in the “Stratigraphic Features and Paleontological Resources” section. The origin of the widespread sequence of ash-flow and airfall tuffs in the John Day Formation, however, is the subject of active research. Previously thought to be the product of now-buried eruptive centers in or along the margins of the Cascade Range, the volcanic tuffs may rather be the product of caldera complexes originating along the northeast-trending axis of the Blue Mountains (McClaughry and Ferns 2007; McClaughry et al. 2009b). A caldera forms following a tremendous volcanic eruption that removes large volumes of magma from the underlying magma chamber, causing the volcano to collapse as rubble into the chamber. Calderas differ from volcanic craters, which form at the summit of volcanic cones following eruptions. Most craters are the remnants of the conduits, or volcanic vents, through which magma flowed. The diameter of a caldera is many times greater than that of a volcanic vent.

Three large-scale rhyolite caldera complexes have recently been identified in the Blue Mountains: (1) the 41.50–39.35-million-year-old Wildcat Mountain Caldera exposed in the Ochoco Mountains, (2) the 29.56-million-year-old Crooked River Caldera at Prineville, and (3) the

29.8–28.1-million-year-old Tower Mountain Caldera near Ukiah in northeastern Oregon (McClaughry and Ferns 2007; McClaughry et al. 2009b). Until recently, the pyroclastic rocks in the John Day Formation were thought to come from the ancestral Cascade Range, but recent work on the older Wildcat Mountain Caldera suggests that this volcano was the likely source area for the volcanic rocks in the Clarno Formation and the Member A welded tuff of the John Day Formation (McClaughry et al. 2009b). In John Day Fossil Beds National Monument, the picturesque tuffs of the Turtle Cove Member range in age from approximately 30.4 million to 25.9 million years ago. The age, stratigraphic sequence, and lithological and geochemical characteristics of the tuffs suggest that they resulted from eruptions that produced the Crooked River Caldera (McClaughry and Ferns 2007; McClaughry et al. 2009b).

Prominent tuff marker beds are interlayered with fossil-bearing strata in the Turtle Cove Member, providing a timeline for the fossil record (McClaughry et al. 2009b). A succession of paleosols beneath Carroll Rim in the Painted Hills is punctuated by at least three distinct tuff marker beds (fig. 19). The AB and Blue Basin tuffs have ages of 29.75 million and 28.8 million years, respectively (Bestland and Retallack 1994b; Retallack et al. 1999; Albright et al. 2008; Fremd 2010). The Picture Gorge Ignimbrite caps Carroll Rim and forms a prominent marker bed throughout the eastern and western regions of the John Day Formation (Fisher 1966). The ignimbrite is also clearly visible in the middle of Sheep Rock (fig. 6) and at the tops of the sections at Foree and Cathedral Rock. The eruption that created the Crooked River Caldera produced the Tuff of Barnes Butte in Prineville, which is stratigraphically equivalent to the Western Region Member H tuff. The Member H tuff is equivalent to the Picture Gorge Ignimbrite, suggesting that the Crooked River Caldera also produced the ignimbrite (McClaughry et al. 2009b).

Further radiometric age-dating of additional tuff beds in the John Day Formation will refine the ages of the strata and associated fossils. Source areas for the volcanic units will be refined with further geochemical analyses, which may also allow direct comparison and correlation between widely separated exposures of the units (Joshua Samuels, written communication, 10 December 2013).

Folds and Faults

Mesozoic and Cenozoic deformation events produced folds and faults that deform or cut the strata in John Day Fossil Beds National Monument. The geologic structures reflect several major deformational processes, including plate collision during the Mesozoic and early Paleogene, Paleogene and Neogene volcanism, and Miocene extension.

Clarno Unit

A fold divides the Clarno Unit into two distinct areas: (1) Horse Mountain, characterized by relatively flat-lying, undeformed strata, and (2) an area in which these same strata are exposed along a northeast–southwest-trending fold limb (fig. 30). The fold terminates in the northeastern section of the Clarno Unit. The geologic sequence in the area of the northeast–southwest-trending fold limb is complicated by the intrusion of a dacitic (igneous) dome, evidence of an older folding event, and remains of episodic volcanic activity (Bestland and Retallack 1994a).

Prior to the deformation event that produced the northeast–southwest-trending fold, the debris flow deposits of the lower Clarno conglomerates (Tclc) were folded and then intruded by the Hancock dacite dome (Tcd). The floodplain paleosols in the claystones of Red Hill (Tcrh) represent a significant hiatus in coarse-grained volcanogenic sedimentation. Volcanism resumed with the eruption that produced the extensive deposits of andesite of Horse Mountain (Tcah) and corresponding deposition of the Mammal Quarry beds (Tcq; Bestland and Retallack 1994a).

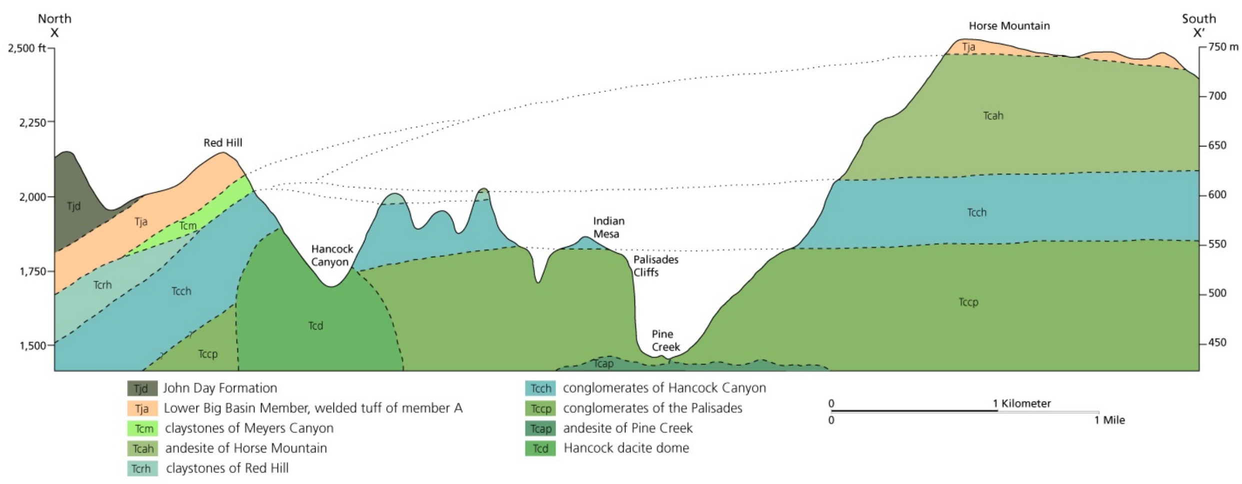

Figure 30. North–south geologic cross-section (X–X′) illustrating the two basic structures in the Clarno Unit: 1) relatively flat-lying strata and 2) strata tilted along a westward-dipping fold limb. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after Bestland and Retallack (1994a, fig. 2.2).

Painted Hills Unit

The Painted Hills Unit lies within a small southwest-trending basin that approximately follows the Sutton Mountain (also known as Mitchell) syncline (U-shaped fold). The syncline was present in the Eocene, and subsidence during deposition produced locally thick sections of lower John Day Formation units (Bestland and Retallack 1994a).

The Sand Mountain Fault is a normal fault that transects the southern part of the Painted Hills Unit (fig. 31). The fault offsets the andesite of Sand Mountain (Tjan) by as much as 60 m (200 ft) and extends on the surface for approximately 11 km (6.6 mi). The Sand Mountain Fault is part of a larger system of en echelon, down-to-the-south normal faults that may be related to the right-lateral strike-slip Mitchell Fault (Bestland and Retallack 1994a). A southward bend in the Mitchell Fault produced compressional structures consisting of small thrust faults and folds.

Two small domes and a short plunging fold occur in the middle and upper Big Basin members in the central part of the Painted Hills. The two domes are adjacent to each other and are located east and west of the north–south-trending ridge along which the Overlook hiking trail passes (Bestland and Retallack 1994a). The fold transects Yellow Basin, trends northeast–southwest, and plunges to the northeast as do the two domes.

Minor normal and thrust faults with no obvious predominant orientation also occur in the Painted Hills Unit. These features include the prominent north–south-striking normal fault that cuts Carroll Rim and Painted Ridge and the reverse fault visible from the Overlook Trail in Painted Ridge (Bestland and Retallack 1994a).

Sheep Rock Unit

The dominant structure in the Sheep Rock Unit is the east–west-trending Middle Mountain Fault, which transects the unit just north of Goose Rock (fig. 32; see Map Graphic [in pocket]). Previous mapping of the fault juxtaposed the John Day Formation (Tjd) to the north of the fault with the Cretaceous Mitchell Group (Kc). Mapping conducted during the summer of 2013 placed the Middle Mountain Fault within the John Day Formation east of the John Day River (Baker et al. 2013). The new map shows the Big Basin Member capping the Goose Rock Conglomerate on the south side of the fault, juxtaposed with the Turtle Cove Member on the north side. West of the John Day River, the John Day Formation is on the south side of the fault and the Picture Gorge Basalt is on the north side (Coleman 1949; Fisher and Rensberger 1972). Although the Middle Mountain Fault and the Goose Rock conglomerate are exposed in the same area, the fault is not directly responsible for the juxtaposition of the conglomerate with the John Day Formation deposits (Baker et al. 2013).

In the Picture Gorge area, the Rattlesnake Formation lies in angular unconformity above the Mascall Formation. Mapping in the area of the western edge of the John Day

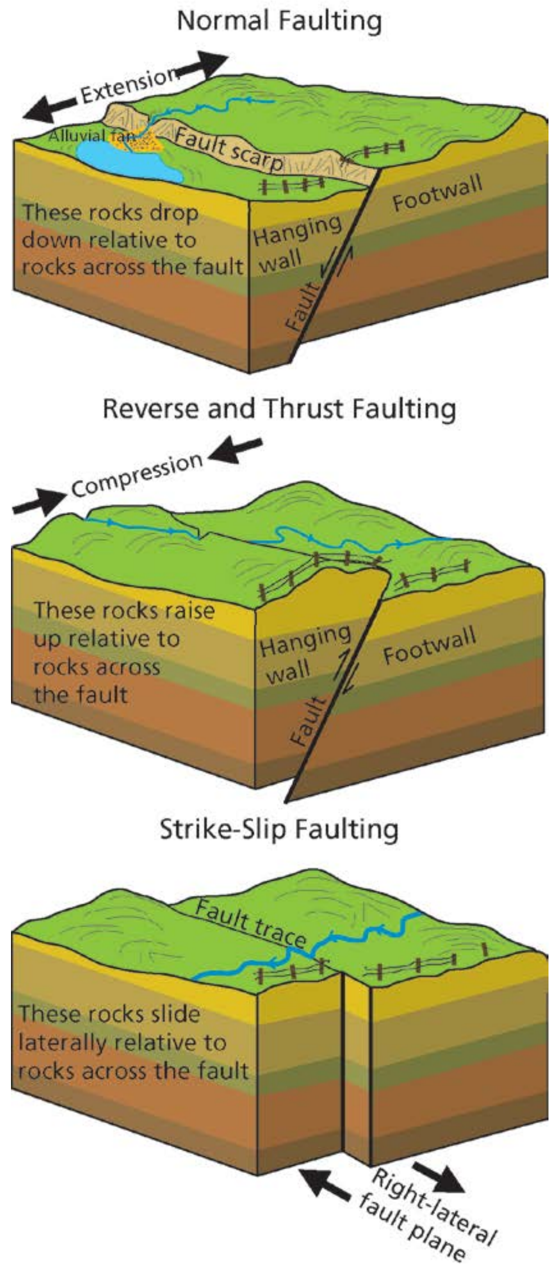

Figure 31. Schematic illustrations of fault types. Footwalls are below the fault plane and hanging walls are above it. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle <45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

fault zone, which follows the south side of the John Day Valley from Prairie City to near Dayville, Merriam et al. (1925) identified a narrow east–west-trending syncline 8 km (5 mi) wide and 19 km (12 mi) long (Merriam et al. 1925; Brown and Thayer 1966). The northern limb dips 18° south and the southern limb dips 30° north. Faults in this area displace the Rattlesnake Ash Flow Tuff as much as 60 m (200 ft) (Merriam et al. 1925; Brown and Thayer 1966).

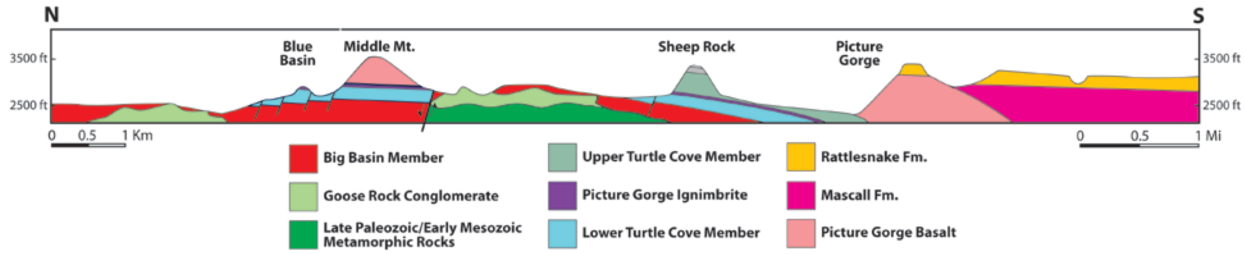

Figure 32. North–south geologic cross-section of the Sheep Rock Unit, from the area south of Picture Gorge to Big Basin. The cross-section illustrates the most prominent structural features of the unit, including: (1) the prominent Middle Mountain Fault, (2) strata dipping to the south, and (3) several unconformities between the John Day Formation, Picture Gorge Basalts, and overlying strata. Fm: formation. Graphic from Baker et al. (2013).

A northwest–southeast-trending normal fault lies within Sheep Rock (fig. 6), and similar faults are present in Blue Basin. Offset along these faults varies, but appears to involve only Turtle Cove Member strata (Baker et al. 2013). Southeast of Sheep Rock and in the Blue Basin area, larger northwest–southeast-trending faults juxtapose Picture Gorge Basalt (Tcrbp) with the John Day (Tjd) and Mascall (Tm) formations.

Cave and Karst Features

Sinkholes and pseudokarst features occur in many areas of John Day Fossil Beds National Monument, including Blue Basin and Sheep Rock in the Sheep Rock Unit, Carroll Rim in the Painted Hills Unit, and at Clarno. Variously sized holes, lava tubes, and overhangs occur within the Picture Gorge Basalt (Tcrbp). Some of these lava tubes extend to depths of approximately 15 m (50 ft). Tree molds occur in the Palisades of the Clarno Unit (Joshua Samuels, written communication, 11 April 2013). Officer's Cave, located outside the Sheep Rock Unit, is a massive pseudokarst feature in John Day Formation rocks, it is the largest of its kind in North America (Parker et al. 1964; Fremd 2010).

Fluvial Geomorphic Features

The few fluvial processes occurring today in the monument modify the geomorphic landscape in much the same ways as they did during the Paleogene and Neogene in the region of present-day central Oregon. Classic fluvial geomorphic features, such as point bars, cutbanks, and natural levees, occur along the rivers and their tributaries that meander through John Day Fossil Beds National Monument (fig. 33). In a meandering stream, the maximum velocity of the main current migrates from bank to bank. Point bars form on the inside of a meander curve as the current wanes and sediment drops out of suspension. In the Paleogene and Neogene, point bars were excellent natural accumulation points for dead animals and bones. Near-death animals sought water and their bones were transported downstream, where they dropped out of the current at point bars (fig. 34). The current increases on the outside of bends, laterally eroding the bank to form a cutbank. In this way, meandering streams migrate laterally across valley floors. Floods spread sediment on the rivers' floodplains. Should a river's gradient increase, its channel may incise and begin to erode a new floodplain, leaving the old one as a terrace. If a meander is impeded

Figure 33. Fluvial geomorphic features viewed from the top of Sheep Rock. The Thomas Condon Paleontology Center is visible on the opposite side of the John Day River. National Park Service photograph, courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

Figure 34. Reconstruction of how bones may have accumulated on point bars in the Paleogene and Neogene. Extracted from the Clarno Hancock Mammal Quarry mural in John Day Fossil Beds National Monument and based on an actual fossil skull on display at the museum that shows evidence of being trampled (such as the one near the foot of the juvenile brontothere). Extracted from a mural by Roger Witter, photographed by Will Landon. A key to the images in the mural may be found in Fremd (2010, p. 99).

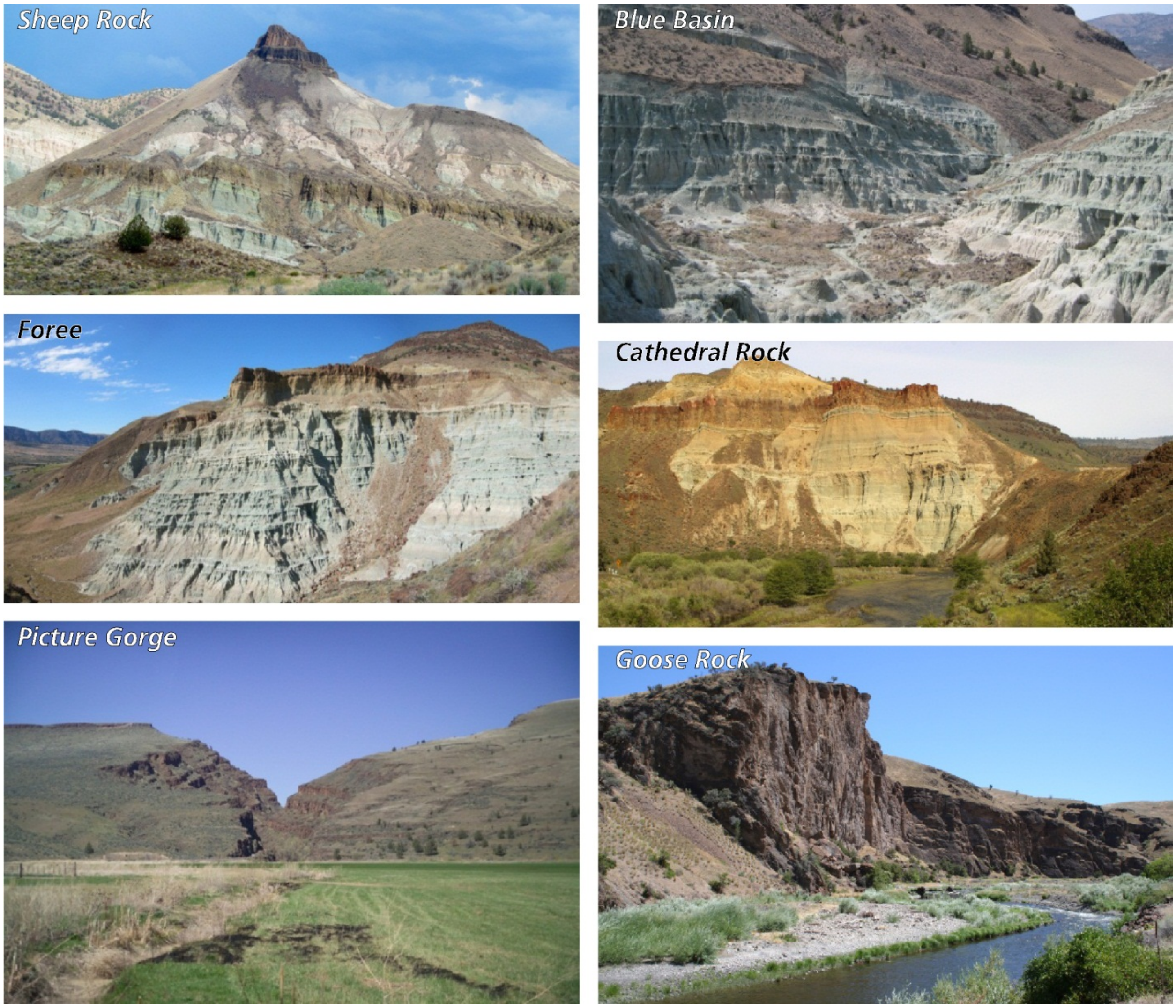

Figure 35. Exceptional geologic landscape features in the Sheep Rock Unit of John Day Fossil Beds National Monument. National Park Service photographs courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

by a cliff of erosion-resistant rock, the channel tends to incise vertically.

With periodic flooding, overbank deposits accumulate and form natural levees along channels. Riffles and associated pools form when the channel gradient changes, stream velocity decreases, and larger cobbles and boulders are left behind.

The primary river in John Day Fossil Beds National Monument is the John Day River, which flows south–north through the Sheep Rock Unit (fig. 1). Pine Creek flows past the talus slopes of the Palisades along the southern border of the Clarno Unit, and Bridge Creek flows past Picture Gorge Ignimbrite (Tji) in the northeastern section of the Painted Hills Unit.

Exceptional Geologic Landscape Features

Exceptional geologic features occur in all three units of John Day Fossil Beds National Monument (figs. 35, 36, and 37).The information was compiled by Joshua Samuels (written communication, 10 December 2013).

Sheep Rock Unit

Sheep Rock

Located opposite the Thomas Condon Paleontology Center and rising nearly 365 m (1,200 ft) above the John Day River, Sheep Rock contains nearly all layers of the Turtle Cove Member of the John Day Formation (figs. 6 and 35). More of the Turtle Cove section is exposed at Sheep Rock than at any other site. The landmark is capped by Picture Gorge Basalt (Tcrbp) and includes the prominent Picture Gorge Ignimbrite (Tji), as well as five other clearly recognizable tuffs on its slope (fig. 6).

Blue Basin

The stark topography in the Blue Basin consists of blue-green and tan Turtle Cove Member strata that include classic fossil localities (fig. 35). Known as “Turtle Cove” to early paleontologists, the basin may have produced more vertebrate specimens than any other site in the region (Joshua Samuels, written communication, 10 December 2013). The Island in Time Trail leads to the center of the basin, ascending to an amphitheater carved in Turtle Cove rocks. The Overlook Trail loops around and above the basin, offering expansive views of the badlands, as well as Cathedral Rock and Foree to the north.

Foree

In addition to the Turtle Cove strata found at Sheep Rock and Blue Basin, Foree includes prominent cliffs capped by Picture Gorge Ignimbrite (fig. 35). The 0.40-km- (0.25-mi-) long Flood of Fire Trail leads to a viewpoint overlooking a 90-m- (300-ft-) high cliff of Turtle Cove strata and offers the monument's best view of the John Day River Valley and the many Picture Gorge Basalt flows on the ridges high above. The fossiliferous blue-green siltstones and claystones of the Turtle Cove Member can be viewed up close along the 0.40-km- (0.25-mi-) long Story in Stone Trail, which has badlands cliffs and is flanked by a prominent faulted butte.

Cathedral Rock

A nearly 90-m- (300-ft-) high sheer cliff of Turtle Cove strata forms this bluff along the John Day River (fig. 35). The same Turtle Cove layers visible in Blue Basin and Foree can be seen here.

Picture Gorge

At the southern end of the Sheep Rock Unit, the John Day River cuts a deep gorge through 17 distinct flows of Picture Gorge Basalt (Tcrbp; fig. 35). This location is the type area for these strata, and the flows form part of the Columbia River Basalt Group. The flows likely erupted from a series of fissures near present-day Monument, Oregon, approximately 16 million years ago. Picture Gorge was named for the many American Indian pictographs found throughout the gorge.

Goose Rock

The conglomerates of Goose Rock, which rises more than 60 m (200 ft) above the John Day River, consist of rounded pebbles that were deposited by a river emptying into the Pacific Ocean approximately 95 million years ago (fig. 35). The exposures are part of the Cretaceous Mitchell Inlier, which represents marine rocks that were deposited unusually far to the east of the established Cretaceous shoreline.

Middle Mountain Fault

The east–west-trending Middle Mountain Fault juxtaposes the middle Turtle Cove Member, exposed north of the fault, with the lower Big Basin Member, exposed to the south (Baker et al. 2013).

Clarno Unit

Palisades

The cliffs of the Palisades form the most prominent landform in the Clarno Unit (fig. 36). The volcanic mudflows that formed the Palisades preserved a wide variety of plant fossils, including leaves and petrified wood. Features include erosional hoodoos carved from

Figure 36. Exceptional geologic landscape features in the Clarno Unit of John Day Fossil Beds National Monument. National Park Service photographs courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

the Conglomerates of the Palisades (Tccp). Plant fossils in boulders below the Palisades cliffs can be seen along the 0.40-km- (0.25-mi-) long Trail of the Fossils.

Nut Beds

The Clarno Nut Beds site is one of the most spectacular paleobotanical sites in the world (see the Paleontological Resources section; fig. 36). Volcanic mudflows (lahars) preserved a myriad of plant fossils, including three-dimentional fossils of seeds, nuts, and wood (Joshua Samuels, written communication, 10 December 2013). Tuff layers within the mudflows have enabled precise dating of the lahars.

Hancock Mammal Quarry

This site is the only vertebrate fossil quarry in John Day Fossil Beds National Monument, and the most representative Late Eocene vertebrate fossil site in the Pacific Northwest. Preservation of animals and plant fossils in the quarry offers the potential for a greater understanding of Late Eocene ecosystems.

Red Hill

The colorful red, white, and gray paleosols that overly the Clarno Nut Beds are exposed at Red Hill, located at the far western edge of the Clarno Unit (fig. 36). The newly constructed Red Hill Trail (0.40 km [0.25 mi] long), located northwest of the Hancock Field Station, leads to Red Hill and provides scenic views of the entire Clarno Unit.

Hancock Canyon

The trail in Hancock Canyon passes through the Conglomerates of Hancock Canyon (Tcch) of the Clarno Formation. Large petrified trees, including the Hancock Tree (see the “Stratigraphic Features and Paleontological Resources” section), are exposed throughout the canyon (fig. 36). The trees, some in apparent life position, were preserved because they were rapidly buried by volcanic mudflows.

Painted Hills Unit

Painted Hills

The brightly colored slopes of the Painted Hills contain an assortment of yellow, gold, black, and red layers from the lower John Day Formation (fig. 37). Alternating red and yellow paleosol units record fluctuations in climate, and some darker bands contain petrified wood or manganese concentrations.

Brown Grotto

The Rhyolite of Bear Creek, the uppermost lava flow of the Clarno Formation, is exposed in the small red and brown gully known as Brown Grotto (fig. 37). The gully also contains excellent examples of laterites, which are heavily weathered paleosols that developed along rhyolitic lava flows, including the Rhyolite of Bear Creek. The colorful rocks in Brown Grotto include lavender rhyolite, gray and white saprolites, brown laterites, and red claystones.

Red Scar Knoll

A short trail loops around this brightly colored hill on the southern border of the Painted Hills Unit (fig. 37). This area is important because it contains exposures of the lowest part of the John Day Formation. The red and tan lower Big Basin Member claystones (Tjlb) overly the breccia from the andesite of Sand Mountain (Tjan) and the Member A welded tuff (Tja).

Painted Cove

In this area, the margin of a lavender rhyolite flow from the Clarno Formation is overlain by dark-red and tan claystones of the Big Basin Member of the John Day Formation. The 0.40-km- (0.25-mi-) long Painted Cove Trail provides access to these colorful hills and rocks of the Clarno and John Day Formations.

Leaf Hill

This hill is the type locality of the Bridge Creek Flora. In 1924, Ralph W. Chaney conducted the first quantitative census in the field of paleobotany at this site. Samples of leaf fossils are exhibited along the 0.40-km- (0.25-mi-) long Leaf Hill Trail.

Carroll Rim

The Picture Gorge Ignimbrite (Tji) caps this large ridge, which includes the youngest rocks in the Painted Hills Unit (fig. 37). The Turtle Cove strata of Carroll Rim are the same as those present in Blue Basin and Foree, allowing comparison of fossils and paleosols separated by 80 km (50 mi). The 2.4-km- (1.5-mi-) long Carroll Rim Trail, which ascends 90 m (300 ft) in elevation, provides a bird’s-eye view of the Painted Hills.

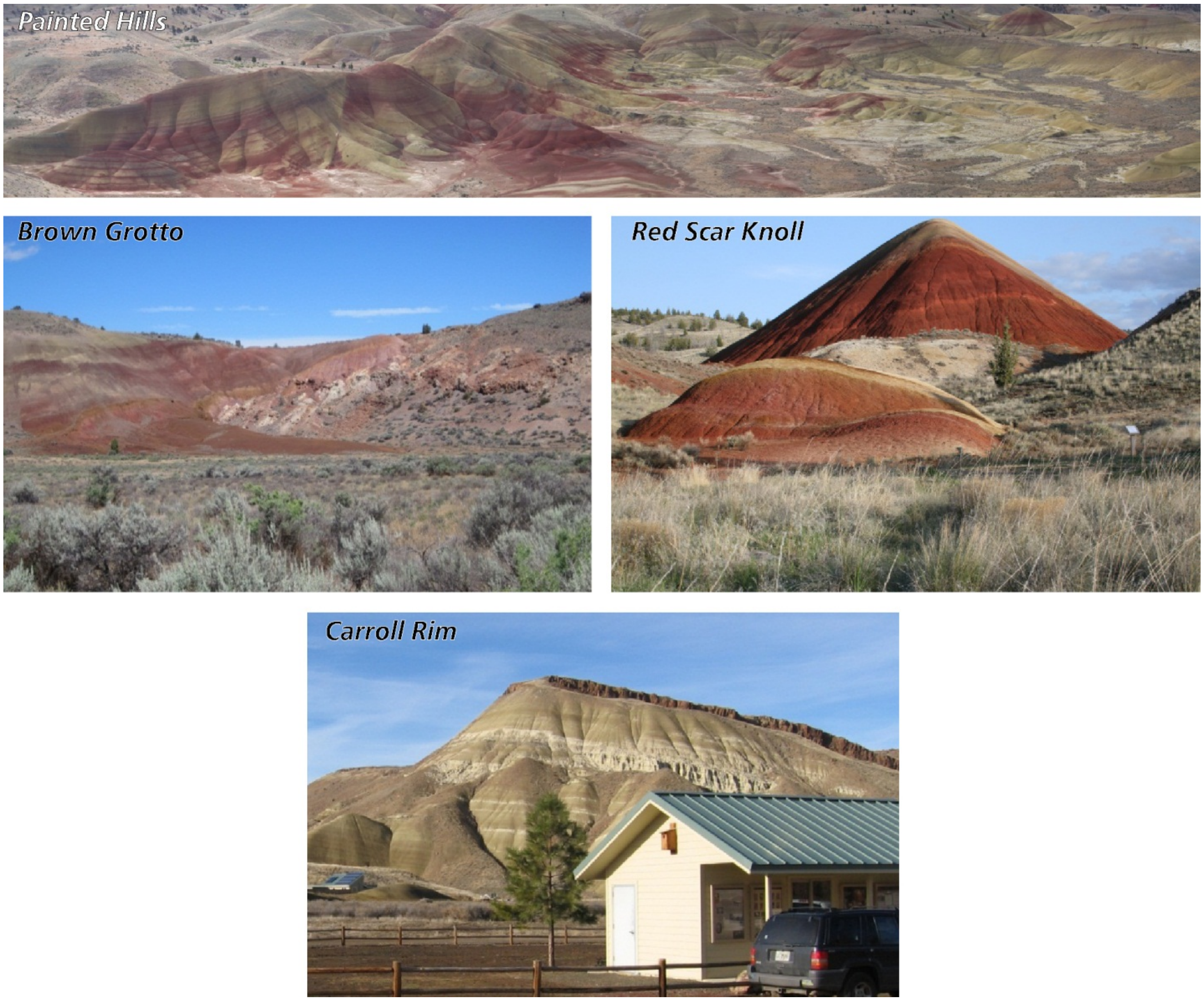

Figure 37. Exceptional geologic landscape features in the Painted Hills Unit of John Day Fossil Beds National Monument. National Park Service photographs courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

Geologic Resource Management Issues

This section describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in John Day Fossil Beds National Monument. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 30 January 2013 conference call, the following geologic resource management issues of significance at John Day Fossil Beds National Monument were identified:

- Paleontological resource inventory, monitoring, and protection
- Flooding and subsequent erosion
- Slope movements
- Cave and karst inventory and monitoring
- Disturbed lands
- Potential seismic (earthquake) activity
- Potential volcanic hazards

Resource managers may find *Geological Monitoring* (http://go.nps.gov/geomonitoring; Young and Norby 2009) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring.

Paleontological Resource Inventory, Monitoring, and Protection

Paleontological resources are non-renewable. The primary resource management responsibilities at John Day Fossil Beds National Monument are the inventory, monitoring, and protection of paleontological resources (Joshua Samuels, John Day Fossil Beds NM, museum curator/chief of paleontology, written communication, 11 April 2013). The 2009 Paleontological Resources Preservation Act (Public Law 111-11; see Appendix B) directs the NPS and other federal land-management agencies to implement comprehensive, science-based paleontological resource management programs. Such programs must include plans for inventory, monitoring, research, and education, as well as the protection of resource and locality information. As of August 2014, Department of the Interior regulations associated with the act were being developed. Fossils in the monument are inventoried, monitored, excavated, identified, and cataloged. According to the State of the Park report for John Day Fossil Beds National Monument (National Park Service 2013c), paleontological resources in the monument are considered in good condition with respect to knowledge, inventory and conservation, and resource stability.

Figure 38. In situ fossils within John Day Fossil Beds National Monument. The highly eroded claystones represent a paleontological resource management challenge at the monument. Upper fossil is a *Stylemys* tortoise shell; a *Hypertragulus herperius* maxilla is below. National Park Service photographs courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

Because many strata in John Day National Monument undergo rapid erosion, resource managers have used a management program for more than 25 years known as "cyclic prospecting," in which fossil sites are periodically monitored and specimens threatened by erosion are collected and preserved (figs. 38 and 39; Fremd 1995). Some sites, such as the Clarno Nut Beds, contain more indurated, less erodible strata and do not require cyclic prospecting as frequently as do the more erodible claystones of the John Day Formation. Fossils within these claystones are hard and brittle. Moisture trapped in the fossils may freeze and expand in the winter, causing specimens to break apart and generally degrade when the

Figure 39. Cyclic prospecting. Cyclic prospecting is a primary strategy for paleontological resource management within John Day Fossil Beds National Monument. Photograph by Robert J. Lillie (Oregon State University).

ice melts in the spring (Joshua Samuels, written communication, 11 April 2013).

Scientifically significant fossils are found throughout the John Day Basin. John Day Fossil Beds National Monument covers only a fraction (approximately 5,700 ha [14,000 ac]) of the basin's total area of 200,000 ha (500,000 ac). In addition, some sites outside the monument's boundaries contain fossils representing paleoenvironments and periods of time that are not represented in the monument. For more than 25 years, the paleontological resources in the region have been managed through the cooperative efforts of the NPS, Bureau of Land Management (BLM), and Forest Service. This cooperative arrangement has helped facilitate staff training, complete scientific research projects, and improve education and outreach. Cooperative Areas for the Management of Paleontology (CAMPs) have been established in some areas, such as the BLM Prineville District, to help preserve critical areas containing paleontological resources. Unfortunately, many more sites in the basin still need protection (Joshua Samuels, written communication, 11 April 2013). Fossils collected from all federal lands in the John Day Basin are currently housed at John Day Fossil Beds National Monument.

In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs used to monitor *in situ* paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Fossil theft in John Day Fossil Beds National Monument and surrounding BLM lands is a continuing problem (Ramsayer 2007). Santucci (1992) and Santucci et al. (2009) identified three categories of illegal fossil collecting on NPS lands: (1) inadvertent casual collecting, (2) intentional casual collecting, and (3) illegal commercial collecting. Collecting for research purposes without a permit is also illegal. Fossil theft at John Day Fossil Beds National Monument falls primarily into the first two categories. In the Clarno Unit, visitors can see plant fossils in the large boulders strewn below the Palisades along the Trail of Fossils. At the base of Leaf Hill in the Painted Hills Unit, visitors have been seen crossing a low wooden fence to pick up the bleached rocks containing fossil plant imprints. Theft of fossilized bones also occurs. Given the size of the monument, staff rely on educating the public about the significance of the fossils to help prevent theft (Ramsayer 2007).

Flooding and Subsequent Erosion

Flood hazards do not appear to be significant in Wheeler and Grant counties, according to Oregon's statewide geohazard map (Oregon Department of Geology and Mineral Industries 2014). However, the John Day region of central Oregon is subject to short bursts of intense rainfall. These storms may produce flooding of the rivers and their tributaries that transect John Day Fossil Beds National Monument (fig. 40). Vegetation is scarce on the badlands topography of the John Day Formation, and flooding may increase erosion, which may expose or remove fossils. Conference call participants indicated that flooding is an important issue for resource management at the monument.

Figure 40. High water from the John Day River encroaches on the road in Picture Gorge, 16 May 2011. National Park Service photograph.

The John Day River, the primary river in the monument, flows through the Sheep Rock Unit. Most of the river and its tributaries within the monument's boundaries are bordered by alluvium and landslide deposits (geologic map unit Qls), which occur in the John Day Formation throughout the monument, alluvium (Qae), the Mascall Formation (Tm), Picture Gorge Basalt (Tcrbp), and the

Mitchell Group (Kc). Some river banks, however, encroach on the fossiliferous John Day Formation (Tjd).

The US Geological Survey's Oregon Water Science Center records real-time and historical water flow data for the John Day River and Bridge Creek, which flows adjacent to the Turtle Cove Member in the Painted Hills Unit (USGS 2014). In 2011, the average monthly base flow discharge on the John Day River was 1.1 cubic meters per second ([cms]; 40 cubic feet per second [cfs]), and the average peak flow discharge, recorded in May, was 12.7 cms (449 cfs; National Park Service 2011). At John Day, Oregon, flood stage for the John Day River is 2.4 m (8.0 ft). The largest historical flood crest of the John Day River near John Day was 3.29 m (10.80 ft) on 9 June 1969 (National Weather Service 2014).

For Bridge Creek, a tributary to the John Day River, the average monthly base flow discharge, recorded in September 2011, was 0.10 cms (3.3 cfs), and the average peak flow discharge, recorded in May, was 2.2 cms (79 cfs). The creek is usually less than 0.3 m (1 ft) deep and is subject to occasional flash floods. For example, between 7:00 pm and midnight on 1 August 2009, Bridge Creek rose from approximately 0.5 m (1.8 ft) to 1.8 m (6 ft) before quickly returning to approximately 0.49 m (1.6 ft). Silt-laden floodwaters killed an estimated 4,000 smallmouth bass in the John Day River (Oregon Department of Fish and Wildlife 2009).

In the *Geological Monitoring* chapter about fluvial geomorphology, Lord et al. (2009) described methods for inventorying and monitoring geomorphology-related vital signs, including: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile.

Slope Movements

Slope movement is the downslope transfer of soil, regolith, and/or rock under the influence of gravity. Soil creep, rockfalls, debris flows, and avalanches are common types of slope movement. These processes and the resultant deposits are known as "mass wasting" and commonly grouped as "landslides." Slope movements occur on time scales ranging from seconds to years and create geologic hazards and associated risks in many NPS units.

Landslides (Qls) are mapped throughout the Sheep Rock Unit. According to conference call participants, large blocks of Picture Gorge Basalt (Tcrbp) fall from the walls of Picture Gorge periodically, and a block fell from the top of Sheep Rock in 2012. The factors triggering these landslides are not known. In the spring, they may be related to rainfall, erosion, and subsequent undercutting of the less-resistant John Day Formation siltstones and claystones beneath the basalt caprock. Undercutting may result in collapse of the overlying cliff. In the winter, water may freeze in cracks and fractures, expanding them slightly and making them less stable when the ice melts. Over time, this freeze/thaw process may contribute to cliff collapse. The monument's staff is concerned that stabilization of the cliffs in Picture Gorge by may scar the cliff and impact or destroy culturally significant American Indian pictograph resources, for which the gorge is named. Slope movements remain a constant problem, and the road through Picture Gorge is closed periodically to remove rockfall debris.

Landslides also occur in the claystones of Red Hill (Tcrh) in the Clarno Unit. These landslides are shallow and do not cut deeply into the claystones (Bestland et al. 1999).

Slope movement is a potential hazard to trails at John Day Fossil Beds National Monument, but is not currently impacting trails significantly. If rainfall saturates the sparsely vegetated slopes of John Day Formation in the Sheep Rock Unit, debris flows may cover the Island of Time Trail (fig. 41).

In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring these processes: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. Wieczorek and Snyder (2009), Highland and Bobrowsky (2008), the US Geological Survey landslides website, http://landslides.usgs.gov/, and the NPS geohazards website, http://nature.nps.gov/geology/hazards/index.cfm, and slope movement monitoring website, http://nature.nps.gov/geology/monitoring/slopes.cfm, provide detailed information regarding slope movements, monitoring, and mitigation options.

Figure 41. Island of Time Trail at Blue Basin in the Sheep Rock Unit. The trail winds through sparsely vegetated badlands topography in the John Day Formation. Rainfall that saturates the slopes may cause small landslides that temporarily close the trail. Note the alcoves in the slope to the left of the bridge. National Park Service photograph courtesy of Joshua Samuels (John Day Fossil Beds National Monument).

Potential Seismic (Earthquake) Hazards

Earthquakes are rare in central Oregon. Although the Cascadia Subduction Zone off the coast of Oregon presents the potential for damaging earthquakes and tsunamis along the Oregon coast, the earthquake

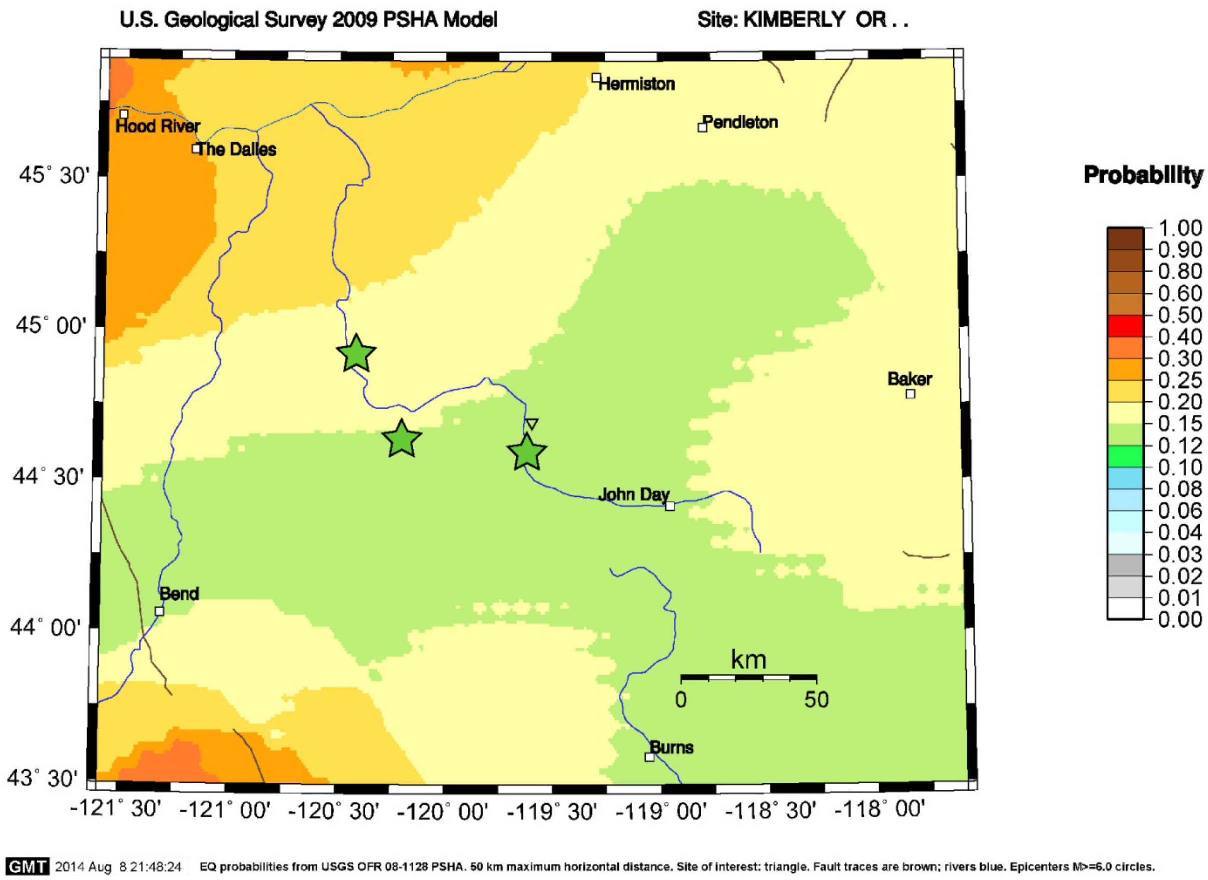

Figure 42. Map showing probability of magnitude 5.5 or greater earthquake within 100 years for John Day Fossil Beds National Monument and the surrounding area. Triangle in center of image is Kimberly, Oregon. Green stars make the locations of John Day Fossil Beds National Monument units. Map created by the US Geological Survey 2009 Earthquake Probability Mapping tool, available at: http://geohazards.usgs.gov/eqprob/2009/index.php (accessed 8 August 2014).

potential in central Oregon is slight according to the US Geological Survey earthquake hazards program (USGS 2013a) and the Pacific Northwest Seismic Network (Pacific Northwest Seismic Network 2014). The US Geological Survey maintains an online application to estimate the probability of a particular magnitude earthquake occurring over a specified time period. The tool is available at: http://geohazards.usgs.gov/eqprob/2009/index.php (accessed 8 August 2014). According to that tool, there is between a 0.12 and 0.15 probability (between 12% and 15%) of a magnitude 5.5 earthquake (considered moderate) occurring near Sheep Rock or Painted Hills units of John Day Fossil Beds National Monument during the next 100 years (fig. 42). The probability is slightly higher (0.15-0.20 [15%-20%]) for the Clarno Unit.

Quaternary faults exist along the eastern border of the Cascade Range, but no such faults appear to intersect John Day Fossil Beds National Monument, further reducing the potential for earthquake damage (USGS 2010).

In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs useful for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonic processes.

Potential Volcanic Hazards

Evidence from the Paleogene and Neogene stratigraphic record indicates that volcanic activity in the past greatly impacted John Day Fossil Beds National Monument. Ash from more recent eruptions of Mount Mazama (7,700 years ago, forming Crater Lake; see GRI report by KellerLynn 2013) and Newberry Volcano are present in the monument (Joshua Samuels, written communication, 10 December 2013; Fremd 2010). The Mazama ash deposits near Deer Gulch are more than a meter (3 ft) thick (Joshua Samuels, written communication, 10 December 2013). The US Geological Survey Cascades Volcano Observatory (CVO) monitors the volcanoes in Oregon and Washington and issues updates and changes in alert level as needed. Real-time volcano alert status and monitoring information is available at the CVO website: http://volcanoes.usgs.gov/observatories/cvo/ (accessed 11 August 2014). From north-to-south, the four most active volcanoes in the Cascade Range of Oregon that lie west of the park include Mount Hood,

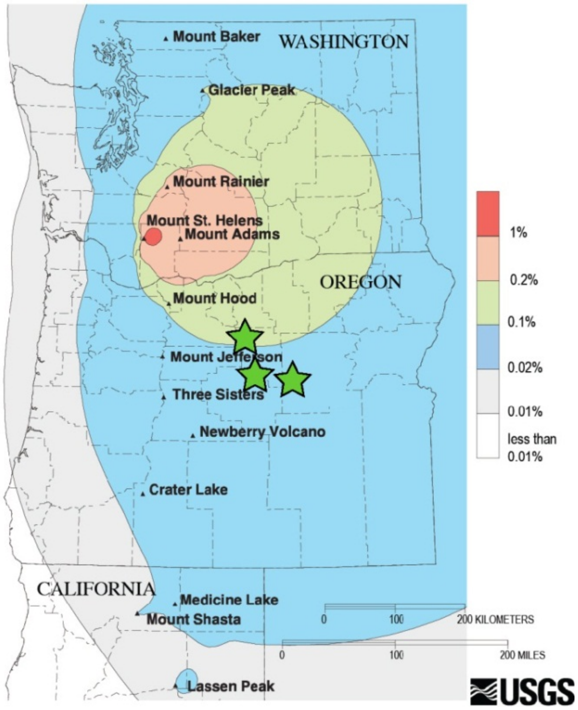

Figure 43. Map showing one-year probability of accumulation of 1 cm (0.4 in) or more of tephra from eruptions of volcanoes in the Cascade Range. Green stars mark the locations of John Day Fossil Beds National Monument units. US Geological Survey graphic by Manny Nathensen in 2013. Available at: http://volcanoes.usgs.gov/volcanoes/newberry/newberry_gallery_18.html (accessed 8 August 2014).

Mount Jefferson, South Sister, and Newberry. The CVO considers Mount Hood, South Sister, and Newberry volcanoes with a high to very high threat potential while Mount Jefferson is considered to have a low to very low threat potential.

Mount Hood, Oregon's highest peak, erupted twice during the past 1,500 years. Lava domes, pyroclastic flows, and lahars occurred during both eruptive periods (USGS 2013). About 2,000 years ago, two closely spaced eruptive episodes at South Sister produced small pyroclastic flows, volcanic ash, and lava from two vent areas on the volcano's south flank. Less than 1 cm (0.5 in) of ash fell near Bend, Oregon. Much larger eruptions occurred at South Sister just before the most recent ice age, approximately 30,000 to 15,000 years ago. The most recent eruption of the Newberry Volcano, the largest volcano in the Cascades volcanic arc, occurred about 1,300 years ago. Covering an area the size of Rhode Island (approximately 3,100 km^2 or 1,200 mi^2), the Newberry Volcano has a broad shield-shape, rather than the typical cone-shaped Cascade volcano, and formed from repeated eruptions of ash, pyroclastic flows, and lava over the past 400,000 years. An explosive eruption about 75,000 years ago created a large depression in its summit, which now hosts two lakes. Although tephra from a Cascades volcano eruption may reach the monument, the probability of such an event in any given year is low, between 0.1% and 0.2% for the Clarno Unit and between 0.02% and 0.1% for the Sheep Rock and Painted Hills units according to US Geological Survey projections (fig. 43).

Disturbed Lands

Mining activities can produce disturbed areas that require remediation. No abandoned mineral land (AML) site at John Day Fossil Beds National Monument is documented in the NPS Geologic Resources Division AML database, although a very small coal mine that is currently less than 5 m (16 ft) deep is present in the Painted Hills Unit (Joshua Samuels, written communication, 20 August 2013). The monument should consider documenting this site for inclusion in the NPS AML database. Exploratory hydrocarbon wells, which are now completely closed, are present in the Clarno Unit. Consequently, potential hazards resulting from mining are not issues at John Day Fossil Beds National Monument. Bentonite in the Mascall Formation (Tm) is mined in Crook County, south of Wheeler County. The Mascall Formation is mapped south of US Highway 26 in the Sheep Rock Unit. The NPS AML Program website, http://www.nature.nps.gov/geology/aml/index.cfm, and Burghardt et al. (2014) provide further information.

Cave and Karst Inventory and Monitoring

No systematic cave inventory or monitoring is being conducted for the sinkholes and pseudokarst features that occur throughout John Day Fossil Beds National Monument, although conference call participants confirmed that research on the relationship between bats and caves in the monument continues. The cave and karst features in the monument are highly unstable and dangerous, which may render an inventory of such features in the back country infeasible. The features change regularly and are not localized in scope (Joshua Samuels, written communication, 20 August 2013).

Caves are non-renewable geologic resources with considerable variation in complexity. They may contain paleontological and cultural remains. In the chapter in *Geological Monitoring* about caves and associated landscapes, Toomey (2009, p. 27) defined a cave as any "naturally occurring underground void." He described methods for inventorying and monitoring cave-related vital signs, including the following: (1) cave meteorology, such as microclimate and air composition; (2) airborne sedimentation, including dust and lint; (3) direct visitor impacts, such as breakage of cave formations, trail use in caves, graffiti, and artificial cave lighting; (4) permanent or seasonal ice; (5) cave drip and pool water, including drip locations, drip rate, drip volume, drip water chemistry, pool microbiology, and temperature; (6) cave microbiology; (7) stability associated with breakdown, rockfall, and partings; (8) mineral growth of speleothems, such as stalagmites and stalactites; (9) surface expressions and processes that link the surface and the cave environment, including springs, sinkholes, and cracks; (10) regional groundwater levels and quantity; and (11) fluvial processes, including underground streams and rivers. Should the cave and karst features become more stable, some of these methods may prove useful for management at the monument.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of John Day Fossil Beds National Monument.

Rocks in the Blue Mountains physiographic province, which includes the Sheep Rock Unit, document a geologic history that extends back into the Paleozoic Era (fig. 3). With a basement composed of a collage of displaced Paleozoic and Mesozoic terranes, the province resulted from subduction that sutured volcanic archipelagos and ocean crust to the western margin of North America. Accretion of these landmasses provided the framework for the tropical landscape that emerged in the Paleogene and Neogene and is well represented at John Day Fossil Beds National Monument. Volcanic strata, paleosols, and plant and animal fossils in the monument and surrounding John Day Basin capture an exquisitely detailed, nearly continuous history of approximately 44 million years, during which the region was subjected to episodic volcanic eruptions, including massive outpourings of Columbia River Basalt, and a dramatic climate change from warm, "greenhouse" to cooler "icehouse" conditions that preceded the onset of Pleistocene glaciation (fig. 10).

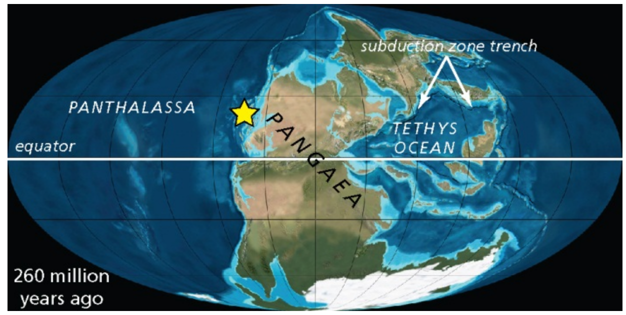

Figure 44. Triassic paleogeographic map, approximately 260 million years ago (mya). All major landmasses had come together to form the supercontinent Pangaea. The C-shaped landmass stretched from pole to pole and surrounded much of the Tethys Ocean. The spine of the "C" was adjacent to a long subduction zone. Much of Earth's surface was covered by a large ocean called Panthalassa. The terranes that would accrete to North America and create the Blue Mountains lay offshore. The yellow star marks the approximate location of the present-day John Day Fossil Beds National Monument. Annotated by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic image by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 14 June 2013).

Preamble to the Age of Mammals and the Emergence of Central Oregon: Cretaceous Period

Paleozoic and Mesozoic rocks of the Baker (geologic map units PZul, MZPZm, TRsp) and Olds Ferry (TRv) terranes, along with the Wallowa and Izee terranes (not mapped), form the foundation of the 140,000-km^2 (55,000-mi^2) landscape of the Blue Mountains (fig. 4). Each terrane originated as a separate fault-bounded block containing strata of different ages that primarily formed in volcanic island arc settings, probably similar to the modern Mariana Islands in the South Pacific (Housen and Dorsey 2005; Dorsey and Lenegan 2007; Orr and Orr 2012). These terranes originated far south of their present latitude.

By the Middle–Late Triassic, Earth's major landmasses had united to form the supercontinent Pangaea (fig. 44). The volcanic sandstone, conglomerate, graywacke, shale, and basalt of the Olds Ferry Terrane (TRv) had accreted to the North American continent while the Wallowa volcanic arc still lay some distance to the west. The submarine Izee basin and the igneous, metamorphic, and sedimentary rocks of the emergent Baker Terrane (TRsp, MZPZm, PZul) separated the accreted Olds Ferry Terrane from the Wallowa terrane (Orr and Orr 2012).

By the Cretaceous, all major terranes except the Siletz Terrane, which would collide with North America to form the Coast Range in the Eocene, had been accreted to the North American continent (Bishop 2003; Dorsey and Lenegan 2007; Gray and Oldow 2007). Arc–continent collision, thrusting, and metamorphism in the Early Cretaceous (about 130–120 million years ago) were followed by strike-slip displacement, continued metamorphism, and igneous pluton emplacement in the Middle Cretaceous (approximately 118–90 million years ago; Dorsey and Lenegan 2007).

Continued subduction produced the Sevier Orogeny, which deformed the western margin of North America into a north–south-trending belt of folds and thrusts that extends from the Brooks Range in Alaska to the Sierra Madre Oriental in Mexico. The orogeny lasted from approximately 140 million to 50 million years ago and is responsible for the voluminous magma that formed the Sierra Nevada Batholith and emplaced continental-margin plutons from Mexico to the Alaskan peninsula (Oldow et al. 1989; Lageson and Schmitt 1994; Lawton 1994; DeCelles 2004). These plutons are particularly well-exposed in the iconic cliffs and valleys of Yosemite National Park (summarized in GRI report by Graham 2012b). The Western Interior Seaway formed east of the fold-and-thrust belt and the region of present-day eastern Oregon (fig. 45). This seaway, which extended about 4,800 km (3,000 mi) from today's Gulf of Mexico to the Arctic Ocean, became the most extensive interior seaway ever to bisect the North American continent (Kauffman 1977; Steidtmann 1993). During periods of maximum sea-level rise, the width of the basin reached 1,600 km (1,000 mi).

The Mitchell Inlier forms the largest area (180 km^2 [69 mi^2]) of exposed Cretaceous sedimentary rocks in the region of present-day central Oregon. The Mitchell Group (Kc) has been divided into two intertonguing formations, the Hudspeth and Gable Creek formations (Wilkinson and Oles 1968; Oles and Enlows 1971;

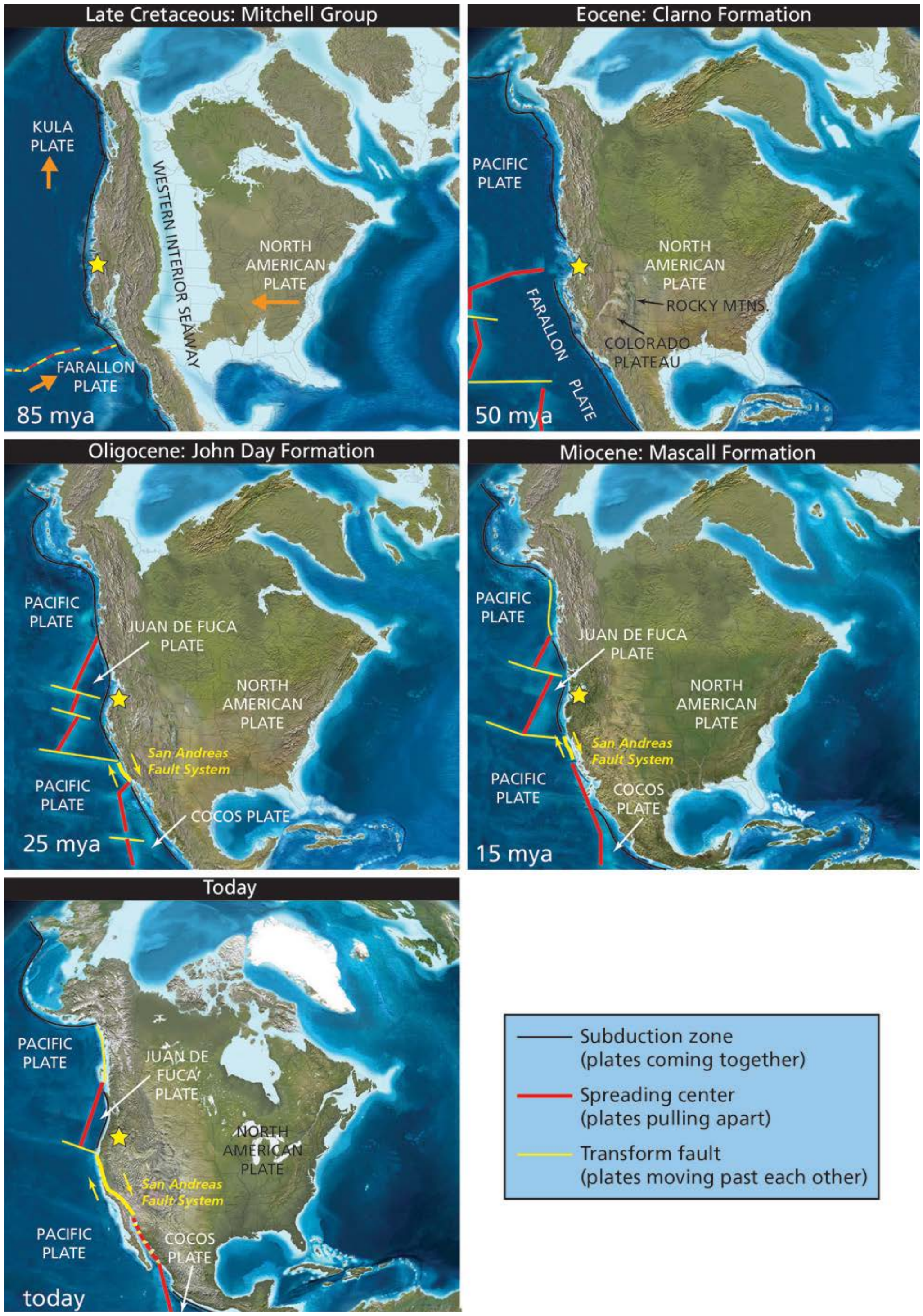

Figure 45. Mesozoic, Paleogene, and Neogene paleogeographic maps of North America. The age of each time frame is in million years ago (mya). In the Cretaceous, the Sevier Orogeny deformed the west coast of North America into a series of north–south-oriented mountain ranges. The Mitchell Inlier formed in in the region of present-day central Oregon and the Western Interior Seaway bisected the North American continent. From the Late Cretaceous into the Eocene, the angle of the subducting Farallon Plate became less steep and pressure from the collision with North America produced the Rocky Mountains. The Clarno Formation was deposited in subtropical jungles in the region of present-day central Oregon. When the spreading center between the Pacific and Farallon plates intersected the North American Plate in the Oligocene, a transform fault (San Andreas Fault zone) formed, causing strike-slip (transpressional) movement. The Farallon Plate was subdivided into the Juan de Fuca Plate to the north and the Cocos Plate to the south. The subducting angle of the Juan de Fuca Plate steepened, resulting in volcanic activity along the western margin of North America. The forests in the region of present-day Oregon began to change into open woodlands and grasslands and the climate began to cool. Strike-slip faulting and high heat flow caused crustal extension beneath the Great Basin and the subsequent development of Basin and Range horsts and grabens in the Miocene. Grasslands occupied the region of central Oregon and the Earth experienced a global cooling trend. The yellow stars mark the approximate location of today's John Day Fossil Beds National Monument. Arrows represent the direction of plate movement. Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 14 June 2013).

Kleinhans et al. 1984). Currently considered to be part of the Mitchell Inlier, Goose Rock exposes approximately 90 m (300 ft) of the Gable Creek Formation in the Sheep Rock Unit (Dorsey and Lenegan 2007). Originally interpreted as a fluvial-deltaic deposit (Wilkinson and Oles 1968), the Gable Creek Formation is now believed to represent sediment-gravity flow deposits in a submarine fan system (Kleinhans et al. 1984; Little 1987; Lenegan 2001; Dorsey and Lenegan 2007).

Oblique subduction of the Farallon Plate beneath the North American Plate deformed the Cretaceous rocks of the Mitchell Inlier, resulting in northeast-trending folds and strike-slip faults. Deformation features and recently acquired paleomagnetic data suggest that the Blue Mountains were displaced about 1,200 to 1,700 km (750–1,100 mi) north of their original location (Housen and Dorsey 2005; Dorsey and Lenegan 2007). Reconstruction of their original position indicates that the Blue Mountains were adjacent to the Sierra Nevada in present-day California prior to 93 million years ago, when they began their northward journey.

Global Greenhouse to Global Icehouse: Paleogene and Neogene Periods

Global Greenhouse: Eocene Epoch

Near the Paleocene–Eocene boundary, about 56 million years ago, global temperatures increased abruptly. This event is known as the Paleocene–Eocene Thermal Maximum (PETM). Global temperatures were already much warmer than today (fig. 10), but average annual temperatures in the region of the present-day western United States rose to 20° to 25°C (68–77°F) and Arctic Ocean temperatures were 23°C (74°F; Zachos et al. 2001, 2008a, 2008b; Woodburne et al. 2009; Kunzig 2011). Debate about the cause of the PETM continues, but an estimated 4.5 trillion tons of carbon and an unknown amount of methane entered the atmosphere at that time (Kunzig 2011). This amount of carbon is roughly equivalent to that available in the Earth's present reserves of coal, oil, and natural gas.

The PETM lasted about 170,000 years and coincided with the earliest Eocene mammalian fauna and mammalian immigration in the region of present-day western United States (Woodburne et al. 2009). This dramatic climatic episode prompted significant changes in the composition and extent of ecosystems, including animal and plant diversity and habitat complexity in the Eocene. A second major climatic episode occurred between 53 million and 50 million years ago, when average annual temperatures reached 23°C (74°F) in interior North America and the diversity and extent of vegetation increased markedly. This episode is referred to as the Early Eocene Climatic Optimum (Zachos et al. 2001, 2008a). The fossils at Fossil Butte National Monument represent this time period (fig. 10) (see GRI report by Graham 2012a). The ocean record also documents a temperature increase from approximately 42 million to 40 million years ago, which is known as the Middle Eocene Climatic Optimum (Zachos et al. 2008b).

Fossil plants in the Clarno Nut Beds provide detailed data that suggest the existence of a near sea-level paleolandscape that included volcanoes, meandering rivers, and lakes during this period (Dillhoff et al. 2009). An andesitic stratovolcano erupted to the east and was the source for the lahars that inundated the Clarno region (Retallack et al. 1996). Clarno Nut Bed fossils include plants whose modern relatives require the relatively high temperatures found in near-tropical to tropical environments, such as palms, cycads, and banana (*Ensete*), as well as plants that grow in more temperate climates, such as sycamores, maples, birches, elms, and walnuts (Manchester 1994, 1995; Wheeler and Manchester 2002). Today, lianas, similar to fossil vines found in the Clarno Nut Beds, characterize tropical and temperate rainforests. Leaf litter from paleosols underlying the petrified tree trunks in Hancock Canyon derives from plants common to temperate climates, whereas paleosols in conglomerates underlying the Clarno Nut Beds have yielded leaf fossils consistent with tropical climates (Retallack et al. 1996).

Paleotemperature analyses and the compositions of fossil floral assemblages suggest that the mean average temperature in the Clarno Nut Bed region was about 16°C to 17°C (61–63°F; Wiemann et al. 1999). Annual rainfall may have been as much as 300 cm (120 in) (Wolfe 1992; Fremd et al. 1994; Manchester 1995; Wheeler and Manchester 2002; Myers 2003). The fossil plants, leaf impressions, fossil insects, and a crocodilian discovered among the vertebrate fossils record the transition from near-tropical rainforest approximately 44 million years ago to a more open and seasonal subtropical forest in late Clarno time (Wheeler and Manchester 2002; Dillhoff et al. 2009).

Comparison of the Clarno Nut Bed flora with fossil plants in Europe and Asia suggests that similar temperate to tropical environments existed in all of these regions in the Early to Middle Eocene (Manchester 1994). The global distribution of the flora suggests that North America, Europe, and Asia may have been connected by land bridges, perhaps across the Bering Sea or North Atlantic, in the Eocene (Manchester 1981, 1994; Bestland and Retallack 1994a; Retallack et al. 1996; Wing 1998; Graham 1999; Tiffney and Manchester 2001; Wheeler and Manchester 2002; Dillhoff et al. 2009).

Leaf impressions, including those of angiosperms and ferns, from the Conglomerates of the Palisades' (Tccp) Fern Quarry also support the existence of a tropical or near-tropical Eocene environment in the region of present-day central Oregon (Dillhoff et al. 2009). Modern species similar to those represented in the Fern Quarry assemblage are found today in tropical and near-tropical estuaries and floodplains.

As with global climate, the tectonic regime along the western margin of North America also underwent a dramatic change. From the Late Cretaceous through the Middle Eocene, approximately 70 million to 35 million years ago, the angle of subduction off the western margin of North America became flatter (fig. 46). This "flat-slab"

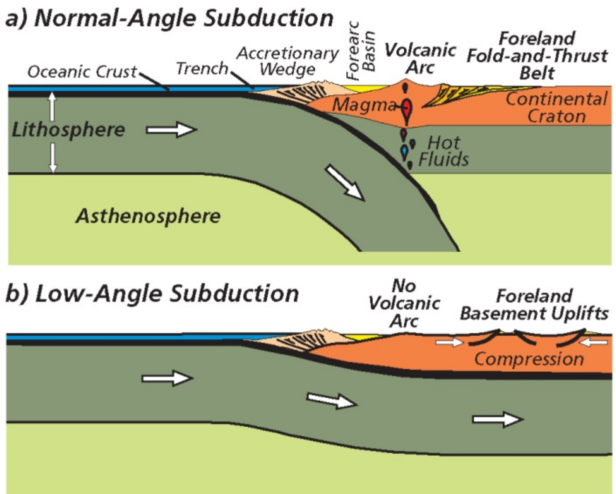

Figure 46. Schematic illustrations of normal-angle and low-angle (flat-slab) subduction. A) In a normal plate-tectonic setting, a relatively steep angle of subduction causes melting above the down-going slab. Magma rises to the surface and erupts, forming a chain of volcanoes (volcanic arc) along the continental margin, similar to the present Andes Mountains of South America. Sedimentary strata are folded and thrust toward the continental craton in a "foreland fold-and-thrust belt." The terranes that accreted to the North American continent and formed the Blue Mountains consisted of volcanic arcs forming above a normal-angle subduction zone. B) During the Laramide Orogeny (Late Cretaceous to Eocene), the subducting slab flattened out and deformation occurred farther inland. As the down-going slab does not extend sufficiently deep to heat up and produce magma in low-angle subduction, volcanism ceases or migrates toward the craton. The subducting slab transmits stress farther inland, causing hard rock in the crust to compress and break along reverse faults, forming basement uplifts such as those in today's Rocky Mountains. Diagram modified from Lillie (2005) by Jason Kenworthy (NPS Geologic Resources Division).

subduction marked a pronounced eastward shift in tectonic activity and produced the Laramide Orogeny, which gave rise to the Rocky Mountains and caused the Western Interior Seaway to recede from the continent (fig. 45). In the region of present-day Oregon, a broad arc of volcanoes formed, which produced the basalt and andesite lava flows, lahars, and ash-fall tuffs that characterize the Clarno Formation (White and Robinson 1992; Dillhoff et al. 2009). The paleosols in the upper Clarno Formation developed from repeated deposits of volcanic ash.

The approximately 1,800-m (6,000-ft) area of Clarno Formation rocks represents deposition in an extensional basin, or series of basins, that formed near sea level (White and Robinson 1992). The section consists primarily of andesitic volcanic and volcaniclastic rocks that were deposited in alluvial fans and floodplains that flanked active volcanoes in the Blue Mountains Province (Bestland et al. 1999; McClaughry et al. 2009b). Periodically, lahars (volcanic mudflows) and debris flows entombed the Clarno-aged animals and plants. A nearby volcanic source generated the Conglomerates of Hancock Canyon (Tcch), which buried the 44-million-year-old Nut Beds.

Between 41.50 million and 39.35 million years ago, voluminous ash-flow tuff and pyroclastic material were ejected from the Wildcat Mountain Caldera, located 19 km (12 mi) northeast of Prineville, Oregon, in the Ochoco Mountains (McClaughry et al. 2009b, 2009c). Recent mapping suggests that the volcanic blast formed a northeast-trending caldera about 16 km (10 mi) long by 11 km (7 mi) wide. When the volcanic vent complex collapsed, more than 90 km^3 (21.5 mi^3) of rhyolitic ash-flow tuff filled the depression (McClaughry et al. 2009c).

The Wildcat Mountain Caldera and the younger (Oligocene) Tower Mountain and Crooked River calderas may represent northward extension of the Middle Eocene to Oligocene magmatic activity that flared up in the Great Basin region of the present-day southwestern United States from approximately 43 million to 23 million years ago (Best et al. 1989; Christiansen and Yates 1992; Honn and Smith 2007; McClaughry et al. 2009b, 2009c). One of these Great Basin calderas, the 26.9-million-year-old Turkey Creek Caldera, is preserved in Chiricahua National Monument in Arizona (see GRI report by Graham 2009c).

The claystones of Red Hill (Tcrh) capture a hiatus in volcanic activity that occurred from 44 million years to about 40 million years ago (Bestland et al. 1999). The andesite of Horse Mountain (Tcah) records renewed volcanism, which rejuvenated the alluvial system that deposited the beds of Mammal Quarry (Tcq).

The welded tuff of Member A of the lower Big Basin Member marks the base of the John Day Formation and the transition from andesitic detritus to rhyodacite ash in the later Eocene. Paleosols in the lower Big Basin Member are similar to those in the upper Clarno Formation, suggesting that the climate was similar in late Clarno and early John Day times (Bestland et al. 1999). The inclusion of both temperate and thermophilic evergreen broad-leaved plant taxa in the lower Big Basin Member indicates the existence of a warm-temperate environment in the Late Eocene (Manchester 2000; Manchester and McIntosh 2007).

Global Icehouse: Oligocene–Miocene Epochs

The 33-million-year-old Overlook Tuff (Tjmbot) marks the base of the middle Big Basin Member of the John Day Formation and the boundary between the Eocene and Oligocene epochs. With the dawn of the Oligocene, the climate dramatically changed from subtropical to temperate conditions (fig. 10; Zachos et al. 2001, 2008a, 2008b; Dillhoff et al. 2009). The tropical to subtropical flora of the Eocene Nut Beds contrast sharply with the temperate, 33-million-year-old Bridge Creek flora, which represent a period near the Eocene–Oligocene boundary (Table 10; Meyer and Manchester 1997; Bestland et al. 1999; Retallack et al. 1999; Dillhoff et al. 2009).

In the Oligocene (fig. 45), seasonal precipitation became more pronounced and the regional temperature became 3°C to 6°C (5–10°F) cooler (Wolfe 1993; Myers 2003; Dillhoff et al. 2009). Several global-scale events probably contributed to this climate change: (1) the amount of carbon dioxide in the atmosphere decreased, (2) the Earth's axial tilt (obliquity) changed so that the northern hemisphere became drier, and most significantly, (3) Antarctica separated from Tasmania and South America, resulting in the Antarctic circumpolar current and the Antarctic continental ice sheets (Zachos et al. 2001).

The landscape not only supported wooded grasslands, but also featured towering stratovolcanoes. The 29.56-million-year-old Crooked River Caldera and 29.8 million to 28.1-million-year-old Tower Mountain Caldera have recently been identified as the sources of the abundant tuffaceous deposits and ash-flow tuffs in the Oligocene Turtle Cove Member of the John Day Formation (McClaughry et al. 2009b). The massive, 41-by-27-km (25 x 17-mi) Crooked River Caldera formed a semi-elliptical depression that filled with more than 580 km^3 (139 mi^3) of rhyolitic ash-flow tuff between the present-day cities of Prineville and Redmond in central Oregon (McClaughry et al. 2009a). Rocks of the Crooked River Caldera correlate with Members G and H of the western region of the John Day Formation. Member H is equivalent to the Eastern Region Picture Gorge Ignimbrite (Tji), the middle unit of the Turtle Cove Member. The widespread, 29-million-year-old Picture Gorge Ignimbrite once covered an area of approximately 5,000 km^2 (2,000 mi^2), and the combined thickness of its two cooling units is about 30 m (100 ft) in the Painted Hills Unit (Robinson 1987).

The eruption of the Tower Mountain Volcano produced a 15- km- (9-mi)- wide, roughly circular caldera exposed approximately 30 km (19 mi) southeast of Ukiah, in the foothills of the Blue Mountains. The caldera is part of the Tower Mountain volcanic field, which covers more than 500 km^2 (190 mi^2) in the Blue Mountains (Ferns et al. 2001; McClaughry et al. 2009b).

The regional appearance of the first animals adapted to open habitats occurred in the Middle Oligocene and is represented by fauna from the Turtle Cove Member of the John Day Formation. The fauna include the first animals with higher-crowned teeth and the first burrowing (*Palaeocastor*, *Entoptycush*, *Proscalops*) and running-adapted (*Archaeolagus*, *Paratylopus*) mammals (Samuels and Janis 2010). Fauna in the Kimberly Member (Tjk) of the John Day Formation, such as gophers, burrowing beavers, camels, and “stilt-legged” horses, suggest that open habitats expanded in the Late Oligocene (Rensberger 1971; Fremd and Whistler 2009; Samuels and Van Valkenburgh 2009; Samuels and Janis 2010).

Paleosols document the spread of bunch grasslands and sagebrush from the Middle to Late-Oligocene (Retallack 2004a, 2007). Fauna in the Haystack Valley (Tjh), Balm Creek, Johnson Canyon, and Rose Creek members of the John Day Formation are similar to those found in the Kimberly Member and suggest that open grasslands continued to evolve. Paleosol evidence also supports the evolution of grasslands, including the development of short-sod grasslands, in the Early Miocene (19–16 million years ago; Retallack 2004a, 2007).

The lower and middle units of the John Day Formation represent deposition on a relatively flat landscape, whereas the upper units of the formation record tectonic events, regional uplift, episodes of stream incision, and lacustrine deposition just prior to the outpouring of the Columbia River basalts. The upper John Day Formation rocks have varying lithological characteristics, contain multiple unconformity-bounded subunits, and are punctuated by numerous paleosols. In contrast to the fine-grained volcaniclastic sediments in the lower John Day rocks, these upper units are characterized by increasingly coarse fluvial channel fills, massive air-fall and coarse-shard tuffs, well-developed paleosols, and topographic relief (Hunt and Stepleton 2004).

Fauna in the upper John Day Formation members provide biochronologic control enabling the dating of this complex sequence of tectonic, sedimentation, and erosional events (Hunt and Stepleton 2004). For example, volcanic tuffs and abundant early Late Arikareean mammalian fauna (Table 14) suggest an approximate age of 23.8 million to 23.5 million years ago, or the earliest Miocene, for the revised Haystack Valley Member. Following deposition of this member, the region was folded and faulted by northwest–southeast-directed compression that produced the northeast–southwest-trending anticlines (convex folds) and synclines (concave folds) common in the region southeast of the Blue Mountains. The Balm Creek Syncline and associated low-angle reverse faults also developed at this time. The graben (fault-bounded basin) that currently contains the Haystack Valley and Balm Creek members formed during a later interval of extensional faulting.

The Johnson Canyon Member contains late or latest Arikareean fauna (Table 16) and a tuff that suggests an age range of 22.6 million to possibly 19.2 million years ago. An erosional disconformity separates the horizontal beds in this member from the underlying Kimberly Member, but the deformation in the Kimberly and Turtle Cove members is missing in the Johnson Creek Member strata. Johnson Canyon Member strata are disturbed only by normal faulting, which must have occurred after the unit was deposited (Hunt and Stepleton 2004).

Faunal and paleosol evidence from the Rose Creek Member (Table 17) suggests that a heterogeneous savannah-like environment was present approximately 18.8 million to 18.2 million years ago. Because the beds of the Rose Creek Member are oriented differently from the underlying strata (angular unconformity), the regional compression that folded the Haystack Valley Member must have occurred prior to 18.8 million years ago. An angular unconformity also separates the Rose Creek Member from underlying, tilted Turtle Cove and Kimberly members along the east and west walls of the John Day Valley (Hunt and Stepleton 2004).

Paleosol development and stream incision into underlying Rose Creek Member sediments mark the end of John Day deposition in the region. Normal faulting then occurred prior to the inundation of the John Day topography by the earliest Columbia River Basalt flows. The earliest flows (Twickenham Basalt) are perhaps 17 million years old, which means that only 1 million years

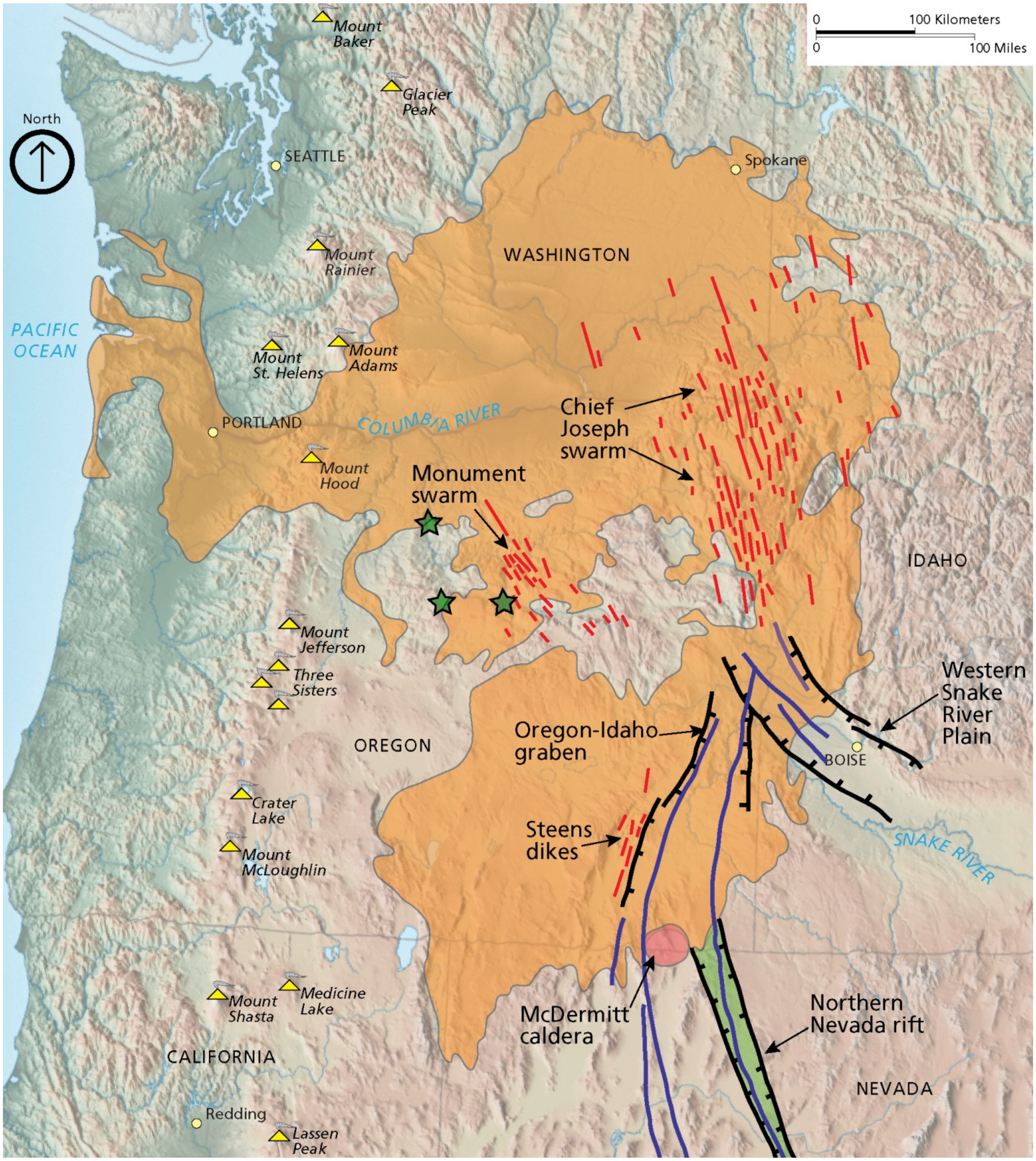

Figure 47. Distribution of the Columbia River Flood Basalt. Cascade volcanoes are indicated by yellow triangles. Location of John Day Fossil Beds National Monument units are indicated by green stars. Map by Trista Thornberry-Ehrlich (Colorado State University) after a graphic by Camp and Ross (2004), available at http://www.largeigneousprovinces.org/04nov (accessed 4 June 2013). Basemap by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 10 June 2014).

(an extraordinarily short period of geologic time) elapsed between the initiation of paleosol development in the Rose Creek Member and the basalt floods that dramatically altered the landscape (Hunt and Stepleton 2004).

Global Warming and Flood Basalts: Middle Miocene Epoch

During the Middle Miocene, approximately 16 million years ago, global climate warmed significantly (fig. 10). This geologically short-lived warming event, known as the Middle Miocene Climatic Optimum, coincides with the eruption of the Picture Gorge Basalt (Tcrbp; Wolfe 1981; Sheldon 2003, 2006). The Picture Gorge Basalt Subgroup of the Columbia River Basalt erupted from fissures near Picture Gorge, Monument, Kimberly, and Courtrock. These fissures were part of the Monument dike swarm (fig. 47). The basalt flows covered 10,680 km^2

(4,124 mi^2) of present-day central Oregon with 2,400 km^3 (580 mi^3) of lava (Camp and Ross 2004).

Almost half of the landscape in the region of present-day Oregon must have been on fire during the Middle Miocene. Basalts flooded the Columbia Basin and much of present-day southeastern Oregon. Calderas exploded throughout the Owyhee Mountains, currently located along the Oregon/Idaho border. The region surrounding John Day and Baker City was inundated by volcanic ash and andesite lava flows. Volcanoes erupted from the Cascade Range.

Between 17 million and 6 million years ago, basaltic lava flooded approximately 160,000 km^2 (63,000 mi^2) of the Pacific Northwest (US Geological Survey 2002; Liu and Stegman 2012). More than 300 high-volume individual lava flows and countless small flows accumulated into a thickness of more than 1,800 m (6,000 ft). The flows are collectively known as the Columbia River Basalt Group.

Debate on the origin of the Columbia River basalts continues. A mantle plume hypothesis suggests that the outpouring of basalt was caused by the mantle upwelling that gave rise to the Yellowstone hot spot. In this scenario, the mantle plume caused the rapid, radial migration (10–100 cm [4–40 in]/year) of volcanic activity approximately 15 million years ago, followed by a shearing off of the plume head as the hot spot tracked more slowly (1–5 cm [0.4–2 in]/year) across the Snake River Plain. Today, the mantle plume head is marked by high heat flow in the subsurface near the Idaho/Oregon border, young Cascade volcanism, and seismic waves that decrease when passing through zones of higher temperatures (Camp and Ross 2004).

A recent explanation for the origin of these flood basalts involves a slab tear event that began in the Steens Mountain area of present-day eastern Oregon approximately 17 million years ago (Liu and Stegman 2012). As the Farallon Plate was subducted beneath the North American Plate, a piece broke off and the resulting slab tear and upwelling of subducted oceanic mantle and crust led to a 900-km- (600-mi-) long rupture in the area of present-day eastern Oregon and northern Nevada. Beginning about 16.6 million years ago, flood basalts erupted from this slab tear and spread from the Steens Mountain area, with flows forming the Imnaha and Grande Ronde magmatic provinces between 16.3 million and 15 million years ago (Camp and Ross 2004; Liu and Stegman 2012). These flood basalt eruptions terminated in the region of present-day Oregon and Washington approximately 13 million to 14 million years ago, but eruptions continued east through the Snake River Plain (Liu and Stegman 2012).

The eruption of the Columbia River Basalt Group also coincides with a change in the tectonic regime that occurred along the western margin of North America approximately 15 million years ago. Complex rearrangement of the tectonic plates resulted in the stretching of the continental crust to produce the Basin and Range Province of the present-day southwestern United States. Normal faults formed as the crust pulled apart, creating the province's distinctive landscape of uplifted ranges (horsts) and down-dropped basins (grabens). The High Lava Plains form a structural boundary with the Basin-and-Range-style block faulting in southeastern Oregon (Streck et al. 1999). The north–south-trending normal faults die out in southeastern Oregon and intersect the Brothers Fault zone, a major northwest-trending zone of faults.

Paleosols that developed in the intervals between and above basalt flows, as well as fossil plants from the contemporaneous Mascall Formation (Table 19), indicate a paleoenvironment of savannah-like habitats that supported grazing-adapted mammals, such as camels and horses (*Merychippus*), abundant rabbits (*Hypolagus* spp.), and burrowing-adapted ground squirrels (*Protospermophilus*) and horned gophers (Downs 1956; Retallack 2004b, 2007; Sheldon 2006; Bestland et al. 2008). The flora in the Mascall Formation flourish in modern settings in which the mean annual temperature is 8°C to 16°C (46° to 61°F) and the mean annual precipitation is 50 to 90 cm (20 to 35 in; Wolfe 1981; Sheldon 2006).

Tectonic changes occurred between the deposition of the Mascall and Rattlesnake formations. Although it overlies the Picture Gorge Basalt, the Mascall Formation contains only rare fragments of basalt (Bestland et al. 2008). In the Rattlesnake Formation, on the other hand, conglomerates contain abundant basalt fragments (Merriam 1901; Retallack et al. 2002; Bestland et al. 2008). An angular unconformity also separates the Rattlesnake Formation from underlying strata (Merriam 1901; Merriam et al. 1925; Downs 1956). The contrasts between the Mascall and Rattlesnake formations suggest that the Mascall Formation was deposited in a low-relief, tectonically inactive area, which was transformed into an active tectonic zone along the John Day Fault in the Late Miocene, prior to deposition of the Rattlesnake Formation (Brown and Thayer 1966; Ehret 1981; Bestland et al. 2008).

The Cool Down: Late Miocene and Pliocene Epochs

The upper Rattlesnake Formation (QTr) documents the continuation of open tall grassland and shrubland habitats in the Late Miocene, although evidence of fishers (*Pekania*), beavers (*Dipoides* and *Castor*), and a tapir suggest that forest environments survived along river systems (Table 21; Samuels and Zancanella 2011; Samuels and Cavin 2013).

About 7.05 million years ago, the landscape was incinerated by an ignimbrite erupting from a vent near Capehart Lake, 19 km (30 mi) southwest of the present-day city of Burns. This single eruptive event produced about 290 km^3 (70 mi^3) of ash in less than 1 week and formed the Rattlesnake Tuff (Bishop 2003). For comparison, the volume of this eruption was almost 100 times that erupted from Mount Mazama and about five times the volume of ash from the 1815 Tambora eruption in Indonesia, the most powerful eruption in modern times. Mount St. Helens produced 0.1% the volume of ash represented by the Rattlesnake Tuff. The tuff erupted unusually rapidly and at hot temperatures, rising through a narrow conduit at a rate of 16 to 24 km (10–15 mi) per hour, in contrast to the typical rate of centimeters (inches) per hour. In a matter of days, 35,000 km^2 (13,500 mi^2) of the landscape lay barren, buried beneath 10 to 30 m (33–98 ft) of welded tuff that represented approximately 280 km^3 (67 mi^3) of magma (Streck and Grunder 1997; Streck et al. 1999).

Pliocene (5.3–2.5 million years ago) rocks are scarce in Oregon. At the beginning of the epoch, Earth's climate was warmer and wetter than it is today. Ice was rare in the Arctic, and at maximum Pliocene temperatures, approximately 3 million to 4 million years ago, sea level was 20 to 30 m (70–100 ft) higher than current. Average annual temperatures may have been 3°C to 5°C (5–7°F) higher in the region of present-day Oregon, and a wetter climate in its eastern portion allowed conifer forests to cover the southeastern part of the region about 2.9 million years ago (Bishop 2003).

Erosion, volcanic eruptions, extension, and compression characterized the region of present-day Oregon in the Pliocene. Headward erosion of a north-flowing tributary of the Salmon River drainage system breached the natural dam containing the massive Lake Idaho, which reached its highest level of about 1,100 m (3,600 ft) in the Pliocene (Wood 2000; Greg McDonald, NPS, museum curator/chief of paleontology, written communication, 27 October 2008). The erosive power of the channel began to carve Hells Canyon, currently one of the deepest gorges in North America. Stream erosion also excavated the gorge of the Deschutes River.

In the region of present-day central and eastern Oregon, volcanic eruptions along the Brothers fault zone produced isolated peaks, such as Glass Buttes (4.9 million years old) and Frederick Butte (3.7 million years old). In the Cascades, low and volatile volcanoes continued to erupt. They deposited ash, lahars, and occasional lava in the Deschutes Basin for another 500,000 years. These volcanoes also built the foundation for the High Cascades, which dramatically altered the regional topography in the Middle Pleistocene.

Basin-and-range extension in the region of present-day southeastern Oregon down-dropped the Alvord Desert, Klamath Basin, and Warner Valley (Bishop 2003). Tectonic collision between the North American and Juan de Fuca plates continued to deform the area of present-day western Oregon.

Hagerman Fossil Beds National Monument in Idaho preserves and protects one of the world's best records of Pliocene life forms (McDonald et al. 1996; Ruez 2009a, 2009b; see GRI report by Graham 2009b). In the lush savanna grassland, a rich variety of animals flourished, including Hagerman horses, pronghorn, camels, and saber-toothed cats (McDonald 1993; Kiver and Harris 1999; Ruez 2009b). The climate, twice as wet as today's semiarid conditions, supported a wide range of habitats and an ecosystem teeming with life (Ruez 2007).

At the end of the Pliocene, glaciers began to expand and polar ice caps began reflecting an increasing amount of solar heat away from Earth. Ocean currents changed and temperatures became increasingly unstable. The stage was set for the ice ages of the Pleistocene.

Global Icehouse to Global Greenhouse: Quaternary Period

Fire, Ice, and Floods: Pleistocene Epoch

The Pleistocene (2.6 million to 11,700 years ago) was a time of extreme contrasts in the region of present-day Oregon. Glaciers repeatedly advanced and retreated as climate fluctuated (fig. 48). Oblique convergence of the North American and Juan de Fuca plates off the coast of present-day Oregon and Washington continued to maintain the north–south-trending Cascade Range. Although the extensive continental ice sheets of the present-day Midwest and New England did not impact the Oregon region, alpine glaciers altered its mountainous landscape. Such glaciers, for example, flowed down the canyons in the Blue and Wallowa mountains and the Cascade Range (Orr and Orr 2012). Both glaciation and episodic volcanic activity left their marks on the landscape. Immense lakes, unlike any occurring previously in the region of the western United States, formed in the wet Pleistocene climate. Monumental flood events occurred that dwarfed any such previous or subsequent event in western North America.

Too low and too far east to collect glacial ice, the Newberry Volcano began erupting ash and basaltic lava

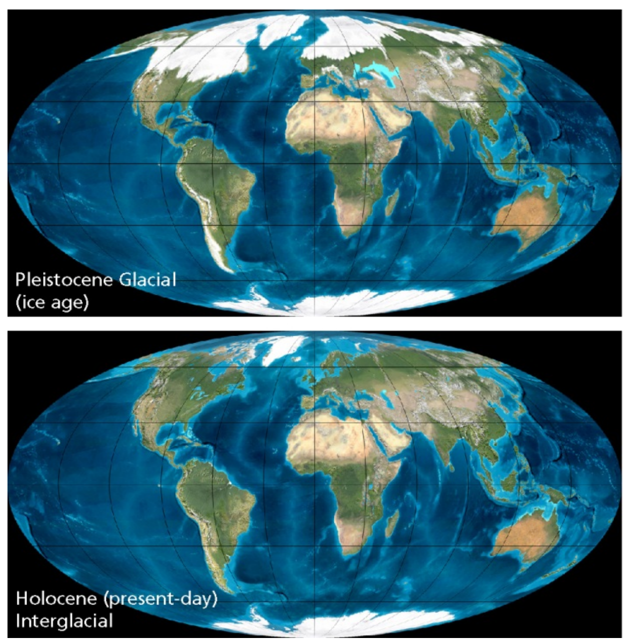

Figure 48. Pleistocene and Holocene paleogeographic maps illustrate the difference in ice cover between glacial and interglacial periods. The Earth is on a path of global climate change to a greenhouse state, wherein the remaining Arctic ice and the Antarctic ice sheet may disappear. Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 14 June 2013).

about 1.2 million years ago and continued erupting periodically throughout the Pleistocene, until about 12,000 years ago. Although commonly considered to be a Cascade volcano, the Newbery volcanic system may be tied more directly to the High Lava Plains and extensional tectonism of the Basin and Range Province (Luedke and Smith 1991).

In the region of present-day southeastern Oregon, abundant Pleistocene precipitation produced large lakes that formed in internally drained basins. The streamflow of major rivers in the west was at least three-fold that of today's rivers (Kukla 1991).

Between 15,000 and 13,000 years ago, ice dammed the Snake River in present-day Idaho and created Lake Missoula, which contained as much water as today's lakes Erie and Ontario combined (Booth et al. 2004). When the ice dam failed, water suddenly poured out of Lake Missoula at a rate of about 64 million liters (17 million gallons) per second. During this time, at least 40 ice dams formed and failed, and cataclysmic floodwaters scoured the Columbia Basin, rampaged through the Columbia River Gorge, and backed up into the Willamette Valley on their way to the Pacific. The exceptional agricultural conditions in today's Willamette Valley are due to the accumulation of silt from the region of present-day Montana and eastern Washington as a result of these colossal floods.

A second noteworthy flood occurred when the dam containing Lake Bonneville, the Lake Michigan-sized precursor to the Great Salt Lake, ruptured. Lake Bonneville overtopped its rim at Red Rock Pass in present-day southeastern Idaho about 14,500 years ago, and floodwaters roared through Hells Canyon. The Bonneville Flood likely lasted at least 8 weeks, although attenuated flow through the canyons may have increased this duration (Malde 1991).

The Pleistocene did not comprise a single, long ice age. Global temperatures rise and fall depending on such factors as the amount of carbon dioxide in the atmosphere, the distribution of solar radiation on Earth, and the amount of radiation retained in the atmosphere. Variations in Earth's orbit change the amount of solar radiation that impacts the planet. Interglacial periods tend to occur when intense summer solar radiation increases in the Northern Hemisphere (National Oceanic and Atmospheric Administration [NOAA] 2008). A feedback loop occurs wherein solar radiation melts ice, which exposes more land capable of absorbing solar radiation, which causes temperatures to rise. The Holocene began as one of these interglacial periods.

The Hot House: Holocene Epoch

Pleistocene glaciers, volcanic activity, and mega-floods irrevocably changed the landscape of present-day Oregon, but the global climate was warming and the glaciers had retreated by about 10,000 years ago. The Oregon Cascades, with the exception of Mount Mazama, have remained relatively quiet since the end of the Pleistocene. In the later part of the Pleistocene, the eruptive cycles of Mount Mazama grew more explosive. About 7,700 calendar years before present, Mount Mazama culminated in a catastrophic eruption that produced a caldera, which presently contains the 9-km- (6-mi-)- diameter Crater Lake (Luedke and Smith 1991; Scott 2004; KellerLynn 2013). The most recent eruption of an Oregon Cascade volcano occurred in fall of 1781 or winter of 1781–1782, when a significant amount of ash and gas erupted from a vent on the southwestern slope of Mount Hood (Bishop 2003).

Early in the Holocene, probably somewhat less than 10,000 years ago, basalt erupted from vents associated with the Brothers fault zone on the High Lava Plains. These eruptions involved the maars, cinder cones, and lava flows in and adjacent to Fort Rock and Christmas Lake valleys, an area west of Harney Basin, the Diamond Craters area southeast of Harney Basin, and the Jordan Craters area near the Oregon/Idaho border (Luedke and Smith 1991).

Small eruptions (insignificant by Mount Mazama standards) that produced cinder cones, ash, and minor basalt flows erupted from the Oregon Cascades between 3,000 and 1,000 years ago. A relatively recent phase of Mount Hood eruptions began about 18,000 years ago, ejecting primarily ash from a vent on the volcano's southwestern side. Volcanic activity resulted in cinder cone formations and lava deposition around Three Sisters, Sand Mountain, and Belknap Crater about 3,000 years ago.

Perhaps the most significant aspect of the Holocene, especially with regard to John Day Fossil Beds National Monument, occurred in the 19th century, with the initiation of the Industrial Revolution and the beginning of massive and increasing release of anthropogenic greenhouse gases (GHGs) into the atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC), it is extremely likely (>95% certainty) that human activities caused more than half of the observed increase in global average surface temperature from 1951 to 2010 (Stocker et al. 2013). As temperatures continue to increase, glaciers retreat and sea levels rise. The four long-lived GHGs responsible for global warming are carbon dioxide, methane, nitrous oxide, and halocarbons, which are a group of gases containing fluorine, chlorine, or bromine. Anthropogenic emissions of GHGs have caused atmospheric concentrations of nitrous oxide to far exceed pre-industrial values spanning many thousands of years, and concentrations of methane and carbon dioxide now far exceed the natural range over the last 650,000 years (fig. 49; Stocker et al. 2013). Regional climate changes are now influencing many natural systems on all continents and in some oceans.

In the Pacific Northwest, average annual temperatures have risen about 0.7°C (1.3°F) since 1895, with some areas experiencing increases of 2°C (4°F). Average temperatures are expected to increase another 1.8°C to 5.4°C (3.3°–9.7°F) by 2100 (Mote et al. 2014). Warming is projected to exacerbate the demand for over-allocated

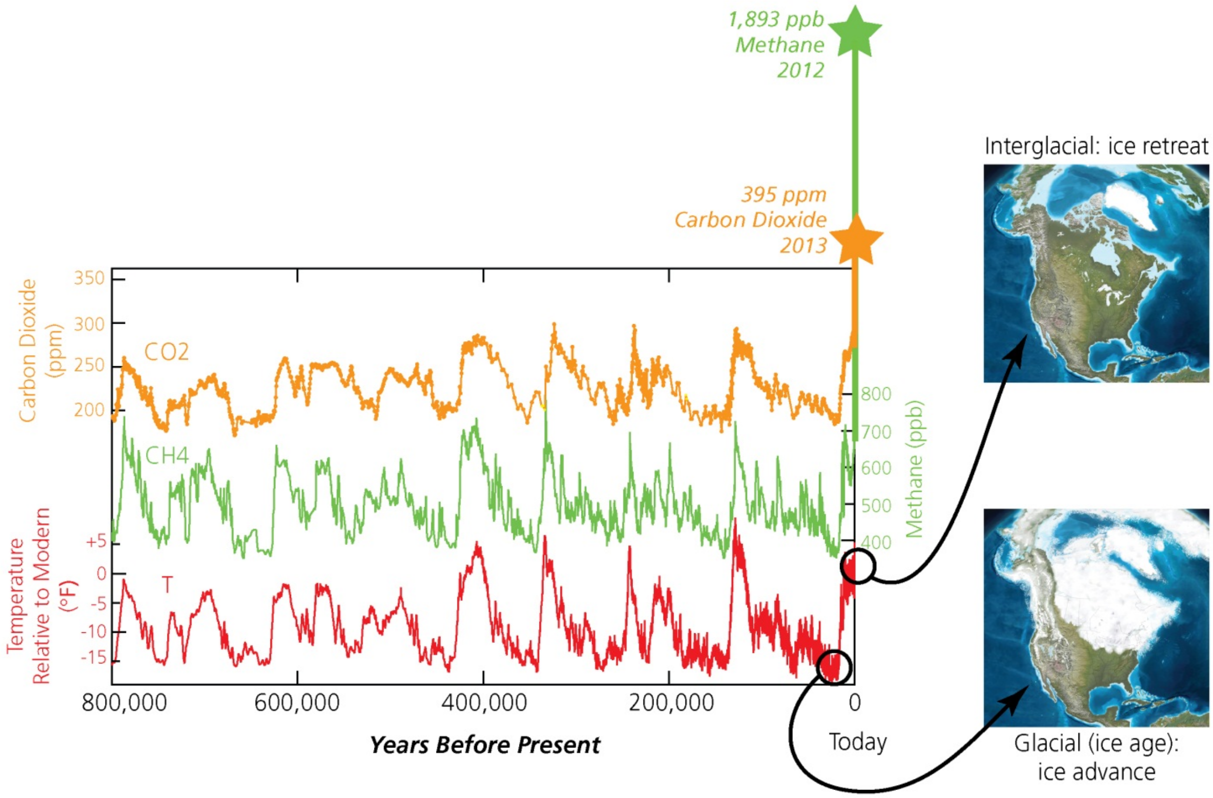

Figure 49. Graph of temperature, carbon dioxide and methane concentrations over the past 800,000 years. Earth's temperature (°F), amount of carbon dioxide (orange line, parts per million [ppm]), and methane (green line, parts per billion [ppb]) were determined by ice core studies. Note the direct relationship among temperature, carbon dioxide, and methane. Amounts of carbon dioxide and methane are considerably higher today than they have been in the last 800,000 years. National Park Service graphic by Jason Kenworthy (NPS Geologic Resources Division), updated from Kenworthy (2010). Ice core data compiled by Edward Brook (Oregon State University Department of Geosciences) from information in Luthi and others (2008) and Loulergue and others (2008). Modern carbon dioxide and methane concentrations compiled by Blasing (2014). Maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 14 June 2013).

water resources as snowpack decreases in the mountains, more flooding occurs in winter, and summer flows are reduced (Mote et al. 2014). The average April 1 snowpack in the Cascade Range, for example, has decreased by about 20% since 1950 (Mote et al. 2014). As approximately 70% of Oregon's electricity comes from hydropower, variability in water quantity and seasonal streamflow, combined with domestic, agricultural, and other industrial demands, may profoundly impact Oregon communities. According to the Oregon Climate Research Institute (2010), most of the more dramatic impacts of global warming will occur west of the Cascade Range and along Oregon's coast, but streamflow in the John Day River, Bridge Creek, and Pine Creek may also be affected, thereby influencing riparian habitats, incision rates, and cliff erosion in John Day Fossil Beds National Monument. Additional potential impacts of global climate change are detailed in the references cited above.

The current interglacial period is characterized by dramatic climate change, and the icehouse conditions of the Pleistocene may well be followed by greenhouse conditions in the Holocene as the Earth continues to warm. Whether the Earth will cycle back into a glacial period remains to be determined, but an understanding of the climatic transitions of the Paleogene and Neogene may help researchers model expected changes in the ensuing centuries. Ecosystem responses to climate change are well recorded in the fossils of John Day Fossil Beds National Monument. Along with the five other NPS units established to preserve Paleogene and Neogene fossils, the monument offers the opportunity to study potential changes in ecosystems due to climate change over millions of years (fig. 10). Migration, adaptation (evolution), and extinction will occur in modern ecosystems as Earth's climate continues to warm.

Geologic Map Data

This section summarizes the geologic map data available for John Day Fossil Beds National Monument. The Geologic Map Graphic (in pocket) displays the map data draped over imagery of the park and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.agiweb.org/environment/publications/mapping/index.html, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI digital geologic map product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, references, and figures. The GRI team used the following sources to produce the digital geologic data set for John Day Fossil Beds National Monument. These sources also provided information for this report.

Bestland, E. A., and G. J. Retallack. 1994. Geology and paleoenvironments of the Clarno Unit, John Day Fossil Beds National Monument, Oregon. Final report, NPS contract CX-9000-1-10009 (Clarno Unit).

- Plate I: Geologic map of the Clarno area, approximate scale 1:7,300
- Plate II: Geologic map of the Clarno Unit area, approximate scale 1:4,500
- Plate III: Sample location map for the Clarno area, approximate scale 1:34,000

Bestland, E. A. and G. J. Retallack. 1994. Geology and paleoenvironments of the Painted Hills Unit, John Day Fossil Beds National Monument, Oregon. Final report, NPS contract CX-9000-1-10009 (Painted Hills Unit).

- Plate I: Geologic map of the Painted Hills Area, approximate scale 1:7,300
- Plate II: Geologic map of the Painted Hills, approximate scale 1:4,700
- Plate III: Sample location map for the Painted Hill, approximate scale 1:34,000

Niewendorp, C. A., M. D. Jenks, M. L. Ferns, I. P. Madin, P. E. Staub, and L. Ma. 2006. Oregon geologic data compilation - release 3 (Sheep Rock Unit; scale 1:100,000). Oregon Department of Geology and Mineral Industries.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for John Day Fossil Beds National Monument using data model version 1.4. The GRI Geologic Maps website, http://www.nature.nps.gov/geology/inventory/geo_maps.cfm, provides more information about GRI map products.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the data set:

- A GIS readme file (PDF) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information
- Data in ESRI geodatabase and shapefile GIS format

- Layer files with feature symbology (table 24)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- An ancillary map information document (.hlp) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures.
- An ESRI map document (.mxd) that displays the digital geologic data

Table 24. Geology data layers in the John Day Fossil Beds National Monument GIS data.

Data Layer	Monument Unit	Map Code*	Data Layer Code	On GRI Poster?
Stratigraphic section line	Clarno Painted Hills	CLU1, CLU2, PHU1, PHU2	LIN	No
Geologic cross section indexes	Painted Hills	PHU1	SEC	No
Geologic attitude observation localities (strike and dip)	Clarno Painted Hills	CLU1, CLU2, PHU1, PHU2	ATD	Yes
Geologic sample localities (misc. rock, Ar/Ar samples, or add'l stratigraphic sections)	Clarno Painted Hills	CLU3, PHU3	GSL	No
Fault and fold symbology	Clarno	CLU2, PHU2	SYM	No
Folds	Clarno	CLU2, PHU2	FLD	No
Fault symbology	Clarno Painted Hills	CLU1, PHU1	SYM	Yes
Fault dip direction	Sheep Rock	SHRK	ATD	No
Faults	Clarno Painted Hills Sheep Rock	CLU1, CLU2, PHU1, PHU2, SHRK	FLT	Yes
Linear geologic units	Clarno	CLU1	GLN	Yes
Geologic marker beds	Painted Hills	PHU2	GLF	No
Geologic contacts	Clarno Painted Hills Sheep Rock	CLU1, CLU2, PHU1, PHU2, SHRK	GLGA	Yes
Geologic units	Clarno Painted Hills Sheep Rock	CLU1, CLU2, PHU1, PHU2, SHRK	GLG	Yes

CLU = Clarno Unit; PHU = Painted Hills Unit; SHRK = Sheep Rock Unit.

GRI Geologic Map Poster

A poster of the GRI digital geologic data draped over a shaded relief image of the park and surrounding area is included with this report. Not all GIS feature classes are included on the poster (table 24). Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Map Unit Properties Table

The Map Unit Properties Table lists the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the Geologic Map Graphic. Table 25 lists horizontal error margins in the John Day Fossil Beds National Monument GIS data, based on the source map scale and US National Map Accuracy Standards.

Table 25. Horizontal accuracy of GIS data.

Map Scale	Maps	Horizontal Accuracy
1:4,500	CLU2	2.3 m (7.5 ft)
1:4,700	PHU2	2.4 m (7.8 ft)
1:7,300	CLU1, PHU1	3.7 m (12 ft)
1:34,000	CLU3, PHU3	17 m (57 ft)
1:100,000	SHRK	51 m (167 ft)

Glossary

This section contains brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.
accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.
active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."
adit. A horizontal passage from the surface into a mine.
alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.
alluvium. Stream-deposited sediment.
alpine glacier. A glacier occurring in a mountainous region; also called a valley glacier.
amygdule. A gas cavity or vesicle in an igneous rock, which is filled with secondary minerals ("amygdaloidal" describes rocks with amygdules).
andesite. Fine-grained volcanic rock commonly associated with subduction zone volcanoes. Named for the subduction zone volcanoes of the Andes Mountains.
angular unconformity. An unconformity where the rock layers above and below are oriented differently. Also see "unconformity."
anticline. A convex-upward ("A" shaped) fold. Older rocks are found in the center.
aphanitic. Describes the texture of fine-grained igneous rocks where the different components are not distinguishable with the unaided eye.
arc. See "volcanic arc" and "magmatic arc."
ash (volcanic). Fine material ejected from a volcano (also see "tuff").
asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.
augite. A dark-green to black pyroxene mineral that contains large amounts of aluminum, iron, and magnesium. Found in igneous and high-temperature metamorphic rocks.
axis (fold). A straight line approximation of the trend of a fold which divides the two limbs of the fold. "Hinge line" is a preferred term.
badlands. Eroded topography characterized by steep slopes and surfaces with little or no vegetative cover, composed of unconsolidated or poorly cemented clays or silts.
basalt. A dark-colored, often low-viscosity, extrusive igneous rock.
basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.
basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.
basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.
bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.
bedding. Depositional layering or stratification of sediments.
bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.
bentonite. A soft clay or greasy claystone composed largely of smectite. Formed by the chemical alteration of glassy volcanic ash in contact with water.
block (fault). A crustal unit bounded by faults, either completely or in part.
biotite. A widely distributed and important rock-forming mineral of the mica group. Forms thin, flat sheets.
bioturbation. The reworking of sediment by organisms.
breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).
breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material such as tuff or ash.
calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).
caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.
carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.
carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).
cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.
chemical sediment. A sediment precipitated directly from solution (also called nonclastic).
chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.
chert. A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It

consists chiefly of interlocking crystals of quartz Also called "flint."

cinder. A glassy pyroclastic fragment that falls to the ground in an essentially solid condition.

cinder cone. A conical volcanic feature formed by the accumulation of cinders and other pyroclasts, normally of basaltic or andesitic composition.

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).

columnar joints. Parallel, prismatic columns, polygonal in cross section, in basaltic flows and sometimes in other extrusive and intrusive rocks; they form as a result of contraction during cooling.

colluvium. A general term applied to any loose, heterogeneous, and incoherent mass of rock fragments deposited by unconcentrated surface runoff or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

convergent boundary. A plate boundary where two tectonic plates are colliding.

cordillera. A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

creep. The slow, imperceptible downslope movement of mineral, rock, and soil particles under gravity.

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

cutbank. A steep, bare slope formed by lateral erosion of a stream.

cycad. An ancient group of extant seed plants that flourished during the Jurassic, characterized by a large crown of compound leaves and a stout trunk; resembles palms or ferns in appearance, but is unrelated to either.

dacite. A fine-grained extrusive igneous rock similar to andesite but with less calcium-plagioclase minerals and more quartz.

debris flow. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

delta. A sediment wedge deposited where a stream flows into a lake or sea.

detritus. A collective term for lose rock and mineral material that is worn off or removed by mechanical means.

diatom. A microscopic, single-celled alga that secretes walls of silica, called frustules. Diatoms live in freshwater or marine environment.

diatomite. A light-colored, soft silica-rich sedimentary rock, consisting chiefly of diatoms.

differential erosion. Erosion that occurs at irregular or varying rates, caused by differences in the resistance and hardness of surface material.

diorite. A type of plutonic igneous rock. It is the approximate intrusive equivalent of andesite.

dip. The angle between a bed or other geologic surface and horizontal.

disconformity. An unconformity where the bedding of the strata above and below are parallel.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

dome. General term for any smoothly rounded landform or rock mass. More specifically refers to an elliptical uplift in which rocks dip gently away in all directions.

downcutting. Stream erosion process in which the cutting is directed in primarily downward, as opposed to lateral erosion.

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix; many estuaries are drowned river valleys caused by sea-level rise (transgression) or coastal subsidence.

extension. A type of strain resulting from forces "pulling apart." Opposite of compression.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

fanglomerate. A sedimentary rock of heterogeneous materials that were originally deposited in an alluvial fan and have since been cemented into solid rock.

fault. A break in rock along which relative movement has occurred between the two sides.

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

felsic. Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic."

flat slab subduction. Refers to a tectonic plate being subducted beneath another tectonic plate at a relatively shallow angle.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

fold. A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

graben. A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").

graywacke. A term commonly used in the field for a dark gray to dark green, very hard, dense sandstone of any composition but with a chlorite-rich matrix; these rocks have undergone deep burial.

groundmass. The material between the large crystals in a porphyritic igneous rock. Can also refer to the matrix of a sedimentary rock.

hanging wall. The mass of rock above a fault surface (also see "footwall").

hardpan. A general term for a relatively hard, impervious, and often clayey layer of soil lying at or just below the surface, produced as a result of cementation of soil particles by precipitation of relatively insoluble materials such as silica, iron oxide, calcium carbonate, and organic matter.

hoodoo. A pillar of rock developed by erosion of horizontal strata of varying hardness. Typically found in climatic zones where most rainfall is concentrated during a short period of the year.

hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").

hot spot. A volcanic center that is thought to be the surface expression of a rising plume of hot mantle material.

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

ignimbrite. A pyroclastic flow deposit.

incision. The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.

intercalated. Layered material that exists or is introduced between layers of a different type.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

kaolinite. A common clay mineral with a high aluminum oxide content and white color.

karst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of rocks containing calcium carbonate.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

lahar. A mudflow composed primarily of volcaniclastic materials on the flank of a volcano. The debris carried in the flow includes pyroclasts, blocks from primary lava flows, and clastic material.

lamination. Very thin, parallel layers.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

lapilli. Pyroclastics in the general size range of 2 to 64 mm (0.08 to 2.5 in.).

lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

left lateral fault. A strike slip fault on which the side opposite the observer has been displaced to the left Synonymous with "sinistral fault."

levee. Raised ridge lining the banks of a stream. May be natural or artificial.

lignite. A brownish-black coal that is intermediate in coalification between peat and subbituminous coal.

limb. Either side of a structural fold.

lithic. A sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.

lithic tuff. A dense deposit of volcanic ash in which the fragments are composed of previously formed rocks that first solidify in the vent and are then blown out.

lithification. The conversion of sediment into solid rock.

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.

maar. A low-relief, broad volcanic crater formed by multiple shallow explosive eruptions; it may contain a lake.

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

magmatic arc. Zone of plutons or volcanic rocks formed at a convergent boundary.

mantle. The zone of Earth's interior between the crust and core.

mantle plume. A rising pipe-shaped volume of mantle that is either abnormally hot or wet or both, such that during decompression it partially melts more than normal mantle material.

marker bed. A distinctive layer used to trace a geologic unit from one geographic location to another.

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

meander. Sinuous lateral curve or bend in a stream channel. An entrenched meander is incised, or carved downward into the surface of the valley in which a meander originally formed. The meander preserves its original pattern with little modification.

mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with "physical weathering."

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.

mica. A prominent rock-forming mineral of igneous and metamorphic rocks. It has perfect basal cleavage meaning that it forms flat sheets.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

muscovite. A mineral of the mica group. It is colorless to pale brown and is a common mineral in metamorphic rocks such as gneiss and schist, igneous rocks such as granite, pegmatite, and sedimentary rocks such as sandstone.

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.

oblique fault. A fault in which motion includes both dip-slip and strike-slip components (also see "dip-slip fault" and "strike-slip fault").

oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

orogeny. A mountain-building event.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

overbank deposit. Alluvium deposited outside a stream channel during flooding.

paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

paleosol. A ancient soil layer preserved in the geologic record.

Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.

parent material. The unconsolidated organic and mineral material in which soil forms.

parent rock. Rock from which soil, sediments, or other rocks are derived.

passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").

pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.

pediment. A gently sloping, erosional bedrock surface at the foot of mountains or plateau escarpments.

phenocryst. A coarse (large) crystal in a porphyritic igneous rock.

plagioclase. An important rock-forming group of feldspar minerals.

plastic. Describes a material capable of being deformed permanently without rupture.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.

plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.

platy. Refers to a sedimentary particle whose length is more than 3 times its thickness. Also refers to a sandstone or limestone that splits into thin layers having thicknesses in the range of 2 to 10 mm (0.08 to 0.4 in).

plume. A persistent, pipe-like body of hot material moving upward from Earth's mantle into the crust.

pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

pluvial. Describes geologic processes or features resulting from rain.

point bar. A low ridge of sand and gravel deposited in a stream channel on the inside of a meander where flow velocity slows.

porphyritic. Describes an igneous rock wherein the rock contains conspicuously large crystals in a fine-grained groundmass.

potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).

provenance. A place of origin. The area from which the constituent materials of a sedimentary rock were derived.

pull-apart basin. A topographic depression created by an extensional bend or extensional overstep along a strike-slip fault.

pumice. Solidified "frothy" lava. It is highly vesicular and has very low density.

pumiceous. Volcanic vesicular texture involving tiny gas holes such as in pumice. Finer than scoriaceous.

pyroclast. An individual particle ejected during a volcanic eruption.

pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.

pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.

quartzite. Metamorphosed quartz sandstone.

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

red beds. Sedimentary strata composed largely of sandstone, siltstone, and shale that are predominantly red due to the presence of ferric iron oxide (hematite) coating individual grains.

relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

rhyodacite. A volcanic rock intermediate between rhyolite and dacite. Extrusive equivalent to quartz monzonite.

rhyolite. A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.

rock. A solid, cohesive aggregate of one or more minerals.

rock fall. Slope movement process where rocks are dislodged and move downslope rapidly; it is the fastest Slope movement process.

sandstone. Clastic sedimentary rock of predominantly sand-sized grains in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

saprolite. Soft, often clay-rich, decomposed rock formed in place by chemical weathering.

schist. A strongly foliated metamorphic rock that can be readily be split into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity" to the rock.

scoria. A bomb-size pyroclast that is irregular in form and generally very vesicular.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

shield volcano. A volcano in the shape of a flattened dome, broad and low, built by flows of very fluid basaltic lava. The Hawaiian Mauna Loa volcano is one example.

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

silicic. Describes a silica-rich igneous rock or magma.

siltstone. A variably lithified sedimentary rock composed of silt-sized grains intermediate in size between fine-grained sand and coarse clay.

slope movement. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

slump. A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.

soil. Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

strata. Tabular or sheet-like masses or distinct layers of rock.

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stratovolcano. A volcano that is constructed of alternating layers of lava and pyroclastic deposits, along with abundant dikes and sills.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

suture. The linear zone where two continental landmasses become joined via obduction.

syncline. A downward curving (concave-up) fold with layers that dip inward; the core of the syncline contains the stratigraphically-younger rocks.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.

tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected into the air during a volcanic eruption.

terrane. A large region or group of rocks with similar geology, age, or structural style.

terrestrial. Relating to land, Earth, or its inhabitants.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

till. Unstratified drift, deposited directly by a glacier without reworking by meltwater, and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

transform fault. A strike-slip fault that links two other faults or two other plate boundaries (e.g. two segments of a mid-ocean ridge). A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.

trend. The direction or azimuth of elongation of a linear geologic feature.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

tuffaceous. A non-volcanic, clastic sedimentary rock that contains mixtures of ash-size pyroclasts.

turbidite. A sediment or rock deposited from a turbidity current (underwater flow of sediment) and characterized by graded bedding, moderate sorting, and well-developed primary structures in the sequence noted in the Bouma cycle.

type locality. The geographic location where a stratigraphic unit (or fossil) is well displayed, formally defined, and derives its name. The place of original description.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

undercutting. The removal of material at the base of a steep slope or cliff or other exposed rock by the erosive action of falling or running water (such as a meandering stream), of sand-laden wind in the desert, or of waves along the coast.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

vent. An opening at Earth's surface where volcanic materials emerge.

vesicle. A void in an igneous rock formed by a gas bubble trapped when the lava solidified.

vesicular. Describes a volcanic rock with abundant holes that formed from the expansion of gases while the lava was still molten.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

volcaniclastic. Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment.

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

weathering. The physical, chemical, and biological processes by which rock is broken down.

welded tuff. A glass-rich pyroclastic rock that has been indurated by the welding together of its glass shards under the combined action of the heat retained by particles, the weight of overlying material, and hot gases.

zircon. A common accessory mineral in siliceous igneous rocks, crystalline limestone, schist, and gneiss, also in sedimentary rocks derived from and in beach and river placer deposits. When cut and polished, the colorless varieties provide exceptionally brilliant gemstones. Very durable mineral, often used for age-dating.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of July 2014. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

NPS Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm

NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/

NPS Resource Management Guidance and Documents

1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

Management policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html

NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Young, R. and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/index.cfm

Climate Change Resources

NPS Climate change response program resources: http://www.nps.gov/subjects/climatechange/resources.htm

US Global Change Research Program: http://globalchange.gov/home

Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

Oregon Department of Geology and Mineral Industries: http://www.oregongeology.org/sub/default.htm

US Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geophysical Union: http://sites.agu.org/

American Geosciences Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

National geologic map database (NGMDB): http://ngmdb.usgs.gov/

Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”)

Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Conference Call Participants

The following people participated in the GRI conference call for John Day Fossil Beds National Monument, held on 30 January 2013. Discussions during the conference call supplied a foundation for this GRI report.

Name	Affiliation	Position
Bilderback, Eric	NPS Geologic Resources Division	Geomorphologist
Connors, Tim	NPS Geologic Resources Division	Geologist
Fremd, Ted	NPS John Day Fossil Beds National Monument (retired)	Chief Paleontologist
Graham, John	Colorado State University	Geologist
Hall, Shelley	NPS John Day Fossil Beds National Monument	Superintendent
Kenworthy, Jason	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Mack, Greg	NPS Pacific West Region	GIS specialist
Samuels, Joshua	NPS John Day Fossil Beds National Monument	Museum curator/paleontologist

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of July 2014. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009**, **16 USC § 470aaa *et seq.*** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (May 2014).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act**, **16 USC § 1 *et seq.*** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law. **Exception: 16 USC § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone).	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 CFR § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** 16 USC §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with **Part 6** standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**)	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 *et. seq.*** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. **Part 610** governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. **Part 611** governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).

NPS 177/126139, August 2014

National Park Service
US Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
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www.nature.nps.gov

Species lists were compiled by Joshua Samuels, John Day Fossil Beds NM museum curator/chief of paleontology (written communication, 12 April 2013).

Table 4. Floral List – Clarno Nut Beds and conglomerates of the Palisades, Clarno Formation

(note - some plant species are represented by multiple elements [leaves, seeds, etc.], these sometimes bear distinct names)

Clade	Order	Family	Species
Equisetopsida			
	Equisetales		
		Equisetaceae	
			Equisetum clarnoi
Pteridopsida			
	Cyatheales		
		Cyatheaceae [tree ferns]	
			Cyathea pinnata
	Polypodiales [polypod ferns]		
		Saccolomataceae	
			Saccoloma gardneri
Cycadopsida			
	Cycadales [cycads]		
		Zamiaceae	
			Dioon sp.
Ginkgophyta			
	Ginkgoales		
		Ginkgoaceae [ginkgos]	
			Ginkgo bonesi
Pinophyta			
	Cupressales		
		Taxaceae [yews]	
			Diploporus torreyoides
			Taxus masonii
			Torreya clarnensis
	Pinales		
		Pinaceae [pines]	
			Pinus sp.
'Basal Angiosperms'			
	Austrobaileyales		
		Schisandraceae [star anise]	
			Schisandra oregonensis
Magnoliids			
	Magnoliales		
		Annonaceae [custard apples]	
			Annonaspermum bonesii
			Annonaspermum cf. pulchrum
			Annonaspermum rotundum
		Magnoliaceae [magnolias, tulip trees]	
			Liriodendroxylon multiporosum
			Magnolia muldoonae
			Magnolia parablonga
			Magnolia tiffneyi
Monocots			
	Arecales		
		Arecaceae [palms, palmettos]	
			Sabal bracknellense
			Sabal jenkinsi
			Sabalites eocenica
	Poales		
		Poaceae [grasses]	
			Graminophyllum sp.
	Zingiberales		
		Musaceae [bananas]	
			Ensete oregonense
Eudicots			
	Apiales		
		Araliaceae [ivy and ginseng]	
			Paleopanax oregonensis
	Cornales		
		Cornaceae [dogwoods, tupelos]	
			Alangium eydei
			Alangium oregonensis
			Alangium rotundicarpum
			Cornus clarnensis
			Langtonia bisulcata
			Mastixia sp.
			Mastixicarpum occidentale
			Mastixiodiocarpum oregonense
			Nyssa scottii
			Nyssa spatulata
			Nyssa sp.
		Hydrangeaceae [hydrangeas]	
			Hydrangea knowltonii
	Crossomotales		
		Staphyleaceae ['bladdernuts']	
			Tapiscia occidentalis
	Ericales		
		Actinidiaceae [kiwi fruit]	
			Actinidia oregonensis
		Sapotaceae [chicle family]	
			Bumelia? globosa
			Bumelia? subangularis
			Sideroxylon sp.
		Symplocaceae [lodh bark family]	
			Symplocos nooteboomii
		Theaceae [tea family]	
			Cleyera grotei
			Fabales
		Fabaceae [legumes]	
			Leguminicarpon sp.
			(*Tetrapleuroxylon sp.*)
Eudicots (continued)			
	Fagales		
		Betulaceae [alder, birch]	
			Alnus clarnoensis
			Betula clarnoensis
			Coryloides hancockii
			Kardiasperma parvum
		Fagaceae [beeches, oaks]	
			Castanopsis crepetii
			(*Fagaceoxylon ostryopsoides*)
			Quercus palaeocarpa
			(*Quercinium crystallifera*)
		Juglandaceae [walnuts]	
			Cruciptera simsonii
			Engelhardioxylon nutbedensis
			cf. Hooleya lata
			(*Clarnoxylon blanchardi*)
			Juglans clarnensis
			Palaeocarya clarnensis
			Palaeoplatycarya? hickeyi
	Gentianales		
		Rubiaceae [coffee and gardenia family]	
			Emmenopterys dilcheri
	Huerteales		
		Tapisciaceae ['false pistachio']	
			Tapiscia occidentalis
	Laurales		
		Lauraceae [laurels]	
			Cinnamomophyllum sp.
			Laurocarpum hancockii
			Laurocarpum nutbedensis
			Laurocarpum raisinoides
			Laurocalyx wheelerae
			Lindera clarnensis
			Litseaphyllum praelingue
			Litseaphyllum presanguinea
			Litseaphyllum cf. merrilli
			Ulminium scalariforme
	Malpighiales		
		Salicaceae [willows, cottonwoods]	
			Saxifragispermum tetragonalis
	Malvales		
		Malvaceae [mallows, cocoa, linden]	
			Chattawaya paliformis
			Triplochitioxylon oregonensis
	Myrtales		
		Lythraceae [crape myrtle, waterwillow]	
			Decodon sp.
	Proteales		
		Platanaceae [plane trees, sycamores]	
			Macginicarpa glabra
			(*Platananthus synandrus,*
			Macginistemon mikanoides,
			Macginitea angustiloba,
			Platanoxylon haydeni)
			Platanus hirticarpa
			Tanyoplatanus cranei
	Ranunculales		
		Menispermaceae [moonseeds]	
			Anamirta leiocarpa
			Atriaecarpum clarnense
			Calycocarpum crassicrustae
			Chandlera lacunose
			Curvitinospora formanii
			Daviscarpum limacioides
			Diploclisia auriformis
			Eohypserpa scottii
			Odontocaryoidea nodulosa
			Palaeosinomenium venablesii
			Thanikaemonia geniculata
			Tinospora elongata
			Tinospora hardmanae
			Tinomiscoidea occidentalis
	Rosales		
		Moraceae [figs]	
			Castilla sp. (*Ficoxylon sp.*)
		Rhamnaceae [buckthorn family]	
			Berhamnophyllum sp.
		Rosaceae [apples, roses]	
			Prunus olsonii
			Prunus weinsteinii
		Ulmaceae [elms, hackberries]	
			Aphananthe maii
			Cedrelospermum lineatum
			Celtis burnhamae
			Celtis sp.
			Trema nucilecta
	Sapindales		
		Anacardiaceae [cashews, sumacs]	
			Astronium sp.
			Pentoperculum minimus
			Rhus rooseae
			Tapiriria clarnoensis
		Burseraceae [torchwoods]	
			Bursericarpum oregonense
Eudicots (continued)			
	Sapindales (continued)		
		Sapindaceae [maple, soapberry family]	
			Acer clarnoense
			Deviacer wolfei
			Palaeoallophyllus globosa
			Palaeoallophyllus gordonii
	Saxifragales		
		Cercidiphyllaceae [katsura trees]	
			Exbucklandia sp.
			Joffrea spersii
			(*Cercidiphyllum alalongum,*
			(Cercidiphyllum crenatum)
		Hamamelidaceae [sweetgums]	
			Fortunearites endressii
			Hamamelidoxylon uniseriatum
	Vitales		
		Vitaceae [grapes]	
			Ampelocissus auriforma
			Ampelocissu scottii
			Ampelopsis rooseae
			Parthenocissus angustisulcata
			Parthenocissus clarnensis
			Vitis magnisperma
			Vitis tiffneyi
	Unplaced Dicots		
		Icacinaceae [tropical vines]	
			Comicilabium atkinsii
			Goweria dilleri
			Iodes chandlerae
			Iodes multireticulata
			Iodicarpa ampla
			Iodicarpa lenticularis
			Palaeophytocrene hancocki
			Palaeophytocrene pseudopersica
			Pyrenacantha occidentalis
		Sabiaceae [aguacatilla]	
			Meliosma beusekomii
			Meliosma bonesii
			Meliosma elongicarpa
			Meliosma cf. jenkinsii
			Meliosma leptocarpa
			Sabia prefoetida
Incertae Sedae			
			Ankistrosperma spetzerae
			Anonymocarpa ovoidea
			Ascophaera eocenis
			Axinosperma agnostum
			Bonesia spatulata
			Comminicarpa friisae
			Cuneisemen truncatum
			Dentisemen parvum
			Durocarpus cordatus
			Ferrignocarpus bivalvis
			Fimbrialata wingii
			Fragarites ramificans
			Clobulicarpium levigatum
			Hexacarpellites hallii
			Joejonesia globosa
			Lignicarpus crassimuri
			Ligniglobus sinuosifibrae
			Lunaticarpa curvistriata
			Microphallus perplexus
			Nephrosemen reticulatus
			Omsicarpium striatum
			Pasternakia pusilla
			Pileosperma minutum
			Pileosperma ovatum
			Pistachioides striata
			Pollostosperma dictyum
			Polygrana nutbedense
			Pruniticarpa cevallosii
			Pteronepelys wehrii
			Pulvinisperma minutum
			Pyrisemen attenuatum
			Quintacava velosida
			Sambucuspermites rugulosus
			Scabraecarpium clarnense
			Scalaritheca biseriata
			Scaphicarpium radiatum
			Sphaerosperma riesii
			Sphenosperma baccatum
			Stockeycarpa globosa
			Striatisperma coronapunctatum
			Tenuisperma ellipticum
			Tiffneycarpa scleroidea
			Trigonostela oregonensis
			Tripartisemen bonesii
			Triplascapha collinsonae
			Triplexivalva rugata
			Trsepticarpium minutum
			Truncatisemen sapotoides
			Ulospermum hardingae
			Wheelera lignicrusta
			Carpolithus bellispermus
			Carpolithus spp. (21 unnamed)

Species lists were compiled by Joshua Samuels, John Day Fossil Beds NM museum curator/chief of paleontology (written communication, 12 April 2013).

Table 5. Fungal List – Clarno Nut Beds, Clarno Formation

Clade	Order	Family	Species
Eurotiomycetes			
	Eurotiales [molds]		
		Trichocomaceae	
			Cryptocolax clarnensis
			Cryptocolax parvula

Table 6. Faunal List – Clarno Nut Beds, Clarno Formation

Clade	Order	Family	Species
Insecta			
	Coleoptera		
		Adephaga [water beetles]	
			unidentified species
		Buprestidae [metallic wood-boring beetles]	
			unidentified species
		Scarabaeidae [dung beetles]	
			Oryctoantiquus borealis
	Hemiptera		
		Cicadidae [cicadas]	
			unidentified species
	Phasmida [stick insects] – ichnofossils		
		Pseudophasmatidae	
			Eophasma minor
			Eophasma oregonense
			Eophasmina menchesteri
"Reptilia"			
	Crocodilia		
		Crocodylidae [crocodiles]	
			Pristichampsus sp.
	Chelonia (Testudines)		
		Testudnidae [tortoises]	
			Hadrianus sp
Mammalia			
	Creodonta [creodonts]		
		Oxyaenidae	
			Patriofelis ferox
	Perissodactyla		
		Brontotheriidae [brontotheres]	
			new genus
		Equidae [horses]	
			Orohippus major
		Hyrachyidae ['running rhinos']	
			Hyrachyus eximius
	Artiodactyla		
		Oromerycidae	
			unidentified oromerycid?

Table 7. Faunal List – Hancock Mammal Quarry, Clarno Formation

Clade	Order	Family	Species
Actinopterygii			
	Siluriformes		
		Hypsidoridae [catfish]	
			Hypsidoris oregonensis
"Reptilia"			
	Crocodilia		
		Alligatoridae [alligators]	
			unidentified species
	Chelonia (Testudines)		
		Chelydridae [snapping turtles]	
			unidentified chelydrid
Mammalia			
	Creodonta [creodonts]		
		Hyaenodontidae	
			Hemipsalodon grandis
	Perissodactyla		
		Amynodontidae ['marsh rhinos']	
			Zaisanamynodon protheroi
		Brontotheriidae [brontotheres]	
			Eubrontotherium clarnoensis
Mammalia (continued)			
	Perissodactyla (continued)		
E		quidae [horses]	
			Epihippus gracilis
			Haplohippus texanus
		Hyracodontidae	
			Hyracodon sp.
		Rhinocerotidae [rhinoceroses]	
			Teletaceras radinskyi
		Tapiridae [tapirs]	
			Plesiocolopirus hancocki
	Artiodactyla		
		Achaenodontidae	
			Achaenodon fremdi
		Agriochoeridae [clawed oreodonts]	
			Agriochoerus antiquus
		Anthracotheriidae	
			Heptacodon sp.
	Rodentia		
		unidentified rodent	

Table 8. Floral List – Hancock Mammal Quarry, Clarno Formation

Clade	Order	Family	Species
Eudicots			
	Cornales		
		Cornaceae [dogwoods]	
			Alangium sp.
			Mastixia oregonense
	Fagales		
		Juglandaceae [walnuts]	
			Juglans clarnensis
	Proteales		
		Platanaceae [plane trees, sycamores]	
			Platanthus synandrus
	Ranunculales		
		Menispermaceae [moonseeds]	
			Diploclisia sp.
			Eohypserpa sp.
			Odontocaryoidea nodulosa
Eudicots (continued)			
	Sapindales		
		Anacardiaceae [cashews, sumacs]	
			Pentoperculum minimus
	Vitales		
		Vitaceae [grapes]	
			Ampelocissus sp.
			Tetrastigma sp.
			Vitis sp.
	Unplaced		
		Icacinaceae [icacinas]	
			Iodes sp.
			Jodicarpa sp.
			Palaeophytocrene cf. foveolata

Species lists were compiled by Joshua Samuels, John Day Fossil Beds NM museum curator/chief of paleontology (written communication, 12 April 2013).

Table 10. Floral List – Bridge Creek Flora, Big Basin Member, John Day Formation

(note: some plant species are represented by multiple elements [leaves, seeds, etc.], these sometimes bear distinct names)

Clade	Order	Family	Species
Equisetopsida			
	Equisetales		
		Equisetaceae	
			Equisetum sp.
Pteridopsida			
	Polypodiales [polypod ferns]		
		cf. Dyropteridaceae	
			unidentified species
		Polypodiaceae	
			cf. Polypodium
		Pteridaceae [brakes]	
			"Pteris" silvicola
Pinophyta			
	Cupressales		
		Cupressaceae [cypress, dawn redwood]	
			Calocedrus schornii
			Cunninghamia chaneyi
			Fokieniopsis praedecurrens
			Metasequoia sp.
			Sequoia affinis
			Tetraclinis potlachensis
		Taxaceae [yews]	
			Torreya masonii
	Pinales		
		Pinaceae [pines]	
			Abies sp.
			Keteleeria ptesimosperma
			Pinus johndayensis
'Basal Angiosperms'			
	Nymphaeales		
		Nymphaeaceae [water-lilies]	
			Nuphar sp.
Monocots			
	Poales		
		Typhaceae [cattails]	
			Typhoides buzekii
	Zingiberales		
		Zingiberaceae [ginger]	
			Zingiberopsis sp.
	Unplaced Monocots		
			"Potamogeton" parva
			unidentified leaf species
Eudicots			
	Cornales		
		Cornaceae [dogwoods, tupelos]	
			Cornus sp.
		Hydrangeaceae [hydrangeas]	
			Hydrangea sp.
	Dipsacales		
		Caprifoliaceae [honeysuckle]	
			Diplodipelta reniptera
	Ericales		
		Styracaceae [silverbells, snowbells]	
			Flectorivus microdontos
	Fabales		
		Fabaceae [legumes]	
			Cercis maurerae
			Cladrastis oregonensis
			Cladrastis sp.
			Micropodium ovatum
Eudicots (continued)			
	Fagales		
		Betulaceae [alder, birch]	
			Alnus heterodonta
			Alnus newberryi
			Alnus sp.
			Asterocarpinus perplexans
			Betula angustifolia
			Ostrya oregoniana
			Paracarpinus chaneyi
		Fagaceae [beeches, oaks]	
			Fagus pacifica
			Quercus berryi
			Quercus consimilis
			Quercus sp.
		Juglandaceae [walnuts]	
			Carya sp.
			Cruciptera sp.
			Juglandiphyllites cryptatus
			Juglans wheelerensis
			Pterocarya occidentalis
			Pterocarya sp.
		Myricaceae [sweetfern]	
			Comptonia columbiana
	Garryales		
		Garryaceae [silktassels, aucubas]	
			Aucuba smileyi
	Gentianales		
		Rubiaceae [coffee and gardenia family]	
			Pinckneya dilcheri
	Lamiales		
		Bignoniaceae [bignonias, catalpas]	
			Catalpa sp.
		Oleaceae [ashes, lilacs, olives]	
			Fraxinus sp.
	Laurales		
		Lauraceae [laurels]	
			Cinnamomophyllum bendirei
			Cinnamomophyllum knowltonii
			Litseaphyllum presanguinea
	Malvales		
		Malvaceae [mallows, cocoa, linden]	
			Cragia oregonensis
			Florissantia speirii
			Plafkeria obliquifolia
			Tilia aspera
			Tilia circularis
			Tilia fossilensis
			Tilia lamottei
			Tilia pedunculata
	Myrtales		
		Combretaceae [leadwood, bushwillow]	
			Terminalia oregona
		Lythraceae [crape myrtle, waterwillow]	
			Decodon sp.
	Proteales		
		Platanaceae [plane trees, sycamores]	
			Platanus condone
			Platanus exaspera
			Platanus sp.
	Ranunculales		
		Berberidaceae [barberries, mayapples]	
			Mahonia simplex
		Menispermaceae [moonseeds]	
			cf. Menispermum
Eudiconts (continued)			
	Rosales		
		Rhamnaceae [buckthorn family]	
			Hovenia oregonensis
			Paliurus blakei
		Rosaceae [apples, roses]	
			Amelanchier covea
			Amelanchier grayi
			Crataegus merriami
			cf. Malus or Pyrus
			cf. Pyracantha
			Rosa hilliae
			Rosa sp.
			Rubus ameyeri
			Rubus fremdii
			Rubus sp.
		Ulmaceae [elms, hackberries]	
			Cedrelospermum lineatum
			Ulmus shaneyi
			Ulmus speciosa
			Ulmus spp. (4 unnamed)
			"Zelkova" hesperia
	Sapindales		
		Anacardiaceae [cashews, sumacs]	
			Rhus lesquereuxii
			Rhus sp.
			Toxicodendron wolfei
		Meliaceae [mahoganies]	
			Cedrela merrillii
		Sapindaceae [maple, soapberry family]	
			Acer ashwilli
			Acer cranei
			Acer glabroides
			Acer kluckingii
			Acer manchesteri
			Acer oligomedianum
			Acer osmontii
			Acer sp. (5 unnamed)
			Aesculus sp.
			Dipteronia sp.
	Saxifragales		
		Cercidiphyllaceae [katsura trees]	
			Cercidiphyllum crenatum
		Grossulariaceae [edible currants, gooseberry]	
			Ribes sp.
		Hamamelidaceae [sweetgums]	
			Fothergilla praeovata
			Liquidambar sp.
			Parrotia brevipetiolata
	Vitales		
		Vitaceae [grapes]	
			Vitis sp.
	unplaced dicots		
		Icacinaceae [tropical vines]	
			Palaeophytocrene sp.
		Incertae Sedae	
			unknown dicot leaves (31 species)
			Beckerosperma ovalicarpa
			Potanospira fryi
			Saportaspermum occidentalis
			unknown fruits (5 species)

Table 11. Faunal List – Big Basin Member, John Day Formation

Clade	Order	Family	Species
Bivalvia [clams and mussels]			
			unidentified clams
Gastropoda [snails]			
	Stylommatophora		
		Polygyridae	
			Polygyra dalli
		Megomphicidae	
			Ammonitella lunata
	Eupulmonata		
		Helicidae	
			Helix marginicola
Insecta			
	Trichoptera [caddisflies]		
		Phryganeidae	
			unidentified species
Actinopterygii			
	Amiiformes		
		Amiidae [bowfin]	
			Amia sp.
	Cypriniformes		
		Cyprinidae [carp and minnows]	
			unidentified cyprinid
	Esociformes		
		Umbridae [mudminnows]	
			Novumbra oregonensis
	Perciformes		
		Centrarchidae [sunfish]	
			Plioplarchus septemspinosus
"Amphibia"			
	Anura		
		unidentified anuran	
	Caudata		
		Salamandridae [salamanders]	
			Taricha (Palaeotaricha) lindoei
Aves			
		unidentified bird	
Mammalia			
	Perissodactyla		
		Equidae [horses]	
			Mesohippus cf. bairdi
		Rhinocerotidae [rhinoceroses]	
			Subhyracodon sp.
			Diceratherium sp.
		Tapiridae [tapirs]	
			unidentified tapir
	Artiodactyla		
		Entelodontidae [giant "pigs"]	
			Archaeotherium sp.
	Chiroptera		
		unidentified bat	

Species lists were compiled by Joshua Samuels, John Day Fossil Beds NM museum curator/chief of paleontology (written communication, 12 April 2013).

Table 12. Faunal List – Turtle Cove Member, John Day Formation

Clade	Order	Family	Species
Oligochaeta			
	Haplotaxida [earthworms] - ichnofossils		
			Edaphichnium sp.
Bivalvia [clams and mussels]			
			unidentified clams
Gastropoda [snails]			
	Basommatophora		
		Lymnaeidae	
			Lymnaea stearnsi
	Neritopsina		
		Helicinidae	
			Helicina oregona
	Stylommatophora		
		Bradybaenidae	
			Monadenia sp.
		Megomphicidae	
			Ammonitella lunata
		Polygyridae	
			Polygyra dalli
			Vespiricola sp.
	Eupulmonata		
		Helicidae	
			Helix dubiosa
Insecta			
	Coleoptera		
		Scarabaeoidea [dung beetles] - ichnofossils	
	Hymenoptera		
		Formicidae [ants] - ichnofossils	
		Halictidae [sweat bees] - ichnofossils	
		Isoptera [termites] - ichnofossils	
"Reptilia"			
	Chelonia (Testudines)		
		Testudinidae [tortoises]	
			Stylemys capax
			Stylemys conspecta
			Stylemys oregonensis
	Squamata		
		Boidae [constrictors]	
			Ogmophis oregonensis
		Rhineuridae [worm lizards]	
			Dyticonastis rensbergeri
Aves			
	Charadriiformes		
		Laridae [gulls]	
			Larus pristinus
		Scolopacidae [sandpipers]	
			Limicolavis pluvianella
	Falconiformes		
		Cathartidae [New World vultures]	
			unidentified teratorn
	Galliformes		
		Phasianidae [pheasants]	
			Phasianus americanus
	Pelicaniformes		
		Phalacrocoracidae [cormorants]	
			Phalacrocorax marinavis
	Podicipediformes		
		Podicipedidae [grebes]	
			Podiceps oligoceanus
Mammalia			
	Marsupialia		
		Herpetotheriidae [opossums]	
			Copedelphys sp.
			Herpetotherium merriami
Mammalia (continued)			
	Lipotyphla [insectivores]		
		Erinaceidae [hedgehogs]	
			Ocajila sp.
		Micropternodontidae	
			Micropternodus morgani
		Proscalopidae	
			Proscalops sp.
		Soricidae [shrews]	
			Domnina sp.
	Carnivora		
		Amphicyonidae [bear-dogs]	
			Daphoenus transversus
			Daphoenus sp.
			Paradaphoenus cuspigerus
			Temnocyon altigenis
			Temnocyon ferox
			Temnocyon subferox
		Arctoidea [uncertain classification]	
			Nothocyon geismarianus
		Canidae [dogs]	
			Archaeocyon pavidus
			Cormocyon copei
			Cynarctoides lemur
			Enhydrocyon stenocephalus
			Leptocyon mollis
			Mesocyon brachyops
			Mesocyon coryphaeus
			Paraenhydrocyon josephi
			Paraenhydrocyon wallovianus
			Philotrox condoni
			Phlaocyon latidens
			Rhizocyon oregonensis
		Mustelidae [weasels, otters, etc.]	
			Plesictis sp.
		Nimravidae [nimravids]	
			Dinaelurus crassus
			Dinictis cyclops
			Eusmilus cerebralis
			Nimravus brachyops
			Pogonodon platycopis
		Ursidae [bears]	
			Allocyon loganensis
			Parictis primaevus
		Viverravoidea [uncertain classification]	
			Palaeogale sp.
	Perissodactyla		
		Equidae [horses]	
			Mesohippus cf. bairdi
			Miohippus equiceps
		Rhinocerotidae [rhinoceroses]	
			Diceratherium annectens
			Diceratherium armatum
		Tapiridae [tapirs]	
			Nexuotapirus sp.
	Artiodactyla		
		Agriochoeridae [clawed oreodonts]	
			Agriochoerus
		Anthracotheriidae	
			Elomeryx sp.
		Camelidae [camels]	
			Gentilicamelus sternbergi
			Paratylopus sp.
		Entelodontidae [giant "pigs"]	
			Archaeotherium caninus
		Hypertragulidae [mouse-deer]	
			Hypertragulus hesperius
			Hypertragulus minutus
			Nanotragulus planiceps
Mammalia (continued)			
	Artiodactyla (continued)		
		Leptocheridae [leptochoerids]	
			Leptochoerus sp.
			Stibarus sp.
		Merycoidodontidae [oreodonts]	
			Eporeodon occidentalis
			Eucrotaphus trigonocephalus
			Hypsiops johndayensis
			Promerycochoerus chelydra
			Merycoides pariogonus
			Merycoidodon bullatus
			Mesoreodon minor
			Oreodontoides oregonensis
			Paroreodon parvus
			Promerycochoerus superbus
		Tayassuidae [peccaries]	
			Perchoerus probus
			Thinohyus lentus
	Rodentia		
		Aplodontidae [mountain beavers]	
			Allomys cavatus
			Allomys nitens
			Allomys reticulatus
			Allomys simplicidens
			Allomys tesselatus
			Alwoodia magnua
			Haplomys liolophus
			Meniscomys editus
			Meniscomys hippodus
			Meniscomys uhtoffi
			Rudiomys mcgrewi
		Castoridae [beavers]	
			Capacikala gradates
			Palaeocastor peninsulatus
		Cricetidae [New World mice]	
			Leidymys lockingtonianus
			Leidymys nematodon
			Leidymys parvus
			Paciculus insolitus
		Eomyidae [dawn mice]	
			new species 1
.			new species 2
		Eutypomyidae	
			new genus
		Florentiamyidae	
			Florentiamys sp.
		Geomyidae [gophers]	
			Entoptychus–multiple species
			Gregorymys grantensis
			Pleurolicus sulcifrons
		Heteromyidae [pocket mice]	
			new species
		Sciuridae [squirrels]	
			Miosciurus ballovianus
			Miosciurs - new species
			Protosciurus condoni
			Protosciurus rachelae
			Protospermophilus vortmani
	Lagomorpha		
		Ochotonidae [pikas]	
			Desmatolagus sp.
		Leporidae [rabbits]	
			Archaeolagus ennisianus
			Palaeolagus sp.
	Primates		
		Omomyidae	
			Ekgmowechashala sp.
	uncertain		
		Apatemyidae	
			Sinclairella dakotensis

Species lists were compiled by Joshua Samuels, John Day Fossil Beds NM museum curator/chief of paleontology (written communication, 12 April 2013).

Table 13. Faunal List – Kimberly Member, John Day Formation

Clade	Order	Family	Species
"Amphibia"			
	Caudata		
		Salamandridae [salamanders]	
			unidentified salamander
"Reptilia"			
	Squamata		
		Boidae [constrictors]	
			Ogmophis oregonensis
		Anguidae	
			unidentified anguine
Mammalia			
	Marsupialia		
		Herpetotheriidae [opposums]	
			Copedelphys sp.
			Herpetotherium merriami
	Lipotyphla [insectivores]		
		Erinaceidae [hedgehogs]	
			cf. Amphechinus sp.
		Micropternodontidae	
			Micropternodus morgani
		Proscalopidae	
			Proscalops sp.
		Soricidae [shrews]	
			Domnina sp.
			Wilsonosorex sp.
		Talpidae [moles]	
			Domninoides sp.
			Scalopoides sp.
	Carnivora		
		Amphicyonidae [bear-dogs]	
			Daphoenus socialis
			Daphoenodon robustum
			Rudiocyon amplidens
		Canidae	
			Cormocyon copei
			Cynarctoides lemur
			Enhydrocyon sp.
Mammalia (continued)			
	Carnivora (continued)		
		Mustelidae [weasels, otters, etc.]	
			Oligobunis crassivultus
		Nimravidae [nimravids]	
			Pogonodon sp.
	Perissodactyla		
		Chalicotheriidae	
			Moropus oregonensis
		Equidae [horses]	
			Archaeohippus sp.
			Kalobatippus praestans
			Miohippus sp.
		Rhinocerotidae	
			Diceratherium annectens
			Diceratherium armatum
		Tapiridae [tapirs]	
			Nexuotapirus sp.
	Artiodactyla		
		Agriochoeridae [clawed oreodonts]	
			Agriochoerus guyotianus
		Camelidae [camels]	
			Gentilicamelus sternbergi
			Paratylopus sp.
		Entelodontidae [giant "pigs"]	
			Archaeotherium calkinsi
			Daeodon shoshonensis
		Hypertragulidae [mouse-deer]	
			Hypertragulus hesperius
			Nanotragulus planiceps
		Merycoidodontidae [oreodonts]	
			Eporeodon occidentalis
			Hypsiops johndayensis
			Oreodontoides oregonensis
			Paroreodon parvus
			Promerycochoerus superbus
Mammalia (continued)			
	Rodentia		
		Aplodontidae [mountain beavers]	
			Alwoodia magna
			cf. Ansomys sp.
			Campestrallomys sp.
		Castoridae [beavers]	
			Capacikala gradatus
			Palaeocastor peninsulatus
		Cricetidae [New World mice]	
			Leidymys lockingtonianus
			Leidymys nematodon
			Leidymys parvus
			Paciculus insolitus
		Dipodidae [jumping mice and jerboas]	
			Plesiosminthus-New Species
		Eomyidae [dawn mice]	
			Apeomys - New Species
			cf. Arikareeomys sp.
			Leptodontomys sp.
		Florentiamyidae	
			Florentiamys sp.
		Geomyidae [gophers]	
			Entoptychus-Multiple Species
		Heteromyidae [pocket-mice]	
			Proheteromys sp.
			Proheteromys thorpei
			Schizodontomys greeni
		Sciuridae [squirrels]	
			Petauristodon sp.
			Miosciurus ballovianus
			Protosciurus condoni
	Lagomorpha		
		Ochotonidae [pikas]	
			Desmatolagus sp.
		Leporidae [rabbits]	
			Archaeolagus sp.

Table 14. Faunal List – Haystack Valley Member, John Day Formation

Clade	Order	Family	Species
Mammalia			
	Carnivora		
		Amphicyonidae [bear-dogs]	
			Daphoenus socialis
			Mammacyon obtusidens
			Temnocyon fingeruti
		Canidae [dogs]	
			Cynarctoides sp.
			Desmocyon thomsoni
			Enhydrocyon basilatus
		Mustelidae [weasels, otters, etc.]	
			Promartes sp.
		Ursidae [bears]	
			Ursavus sp.
	Perissodactyla		
		Chalicotheriidae	
			Moropus oregonensis
Mammalia (continued)			
	Perissodactyla (continued)		
		Equidae [horses]	
			Kalobatippus praestans
			Miohippus sp.
		Rhinocerotidae [rhinoceroses]	
			Diceratherium sp.
		Tapiridae [tapirs]	
			Nexuotapirus robustus
	Artiodactyla		
		Camelidae [camels]	
			Paratylopus sp.
		Entelodontidae [giant "pigs"]	
			Daeodon humerosum
		Hypertragulidae [mouse-deer]	
			Nanotragulus planiceps
Mammalia (continued)			
	Artiodactyla (continued)		
		Merycoidodontidae [oreodonts]	
			Hypsiops breviceps
			Paroreodon cf. marshi
		Moschidae [musk deer]	
			Blastomeryx sp.
	Rodentia		
		Aplodontidae [mountain beavers]	
			Allomys tessellatus
		Castoridae [beavers]	
			Palaeocastor fossor
		Geomyidae [gophers]	
			Entoptychus–multiple species
			Tenudomys sp.
		Heteromyidae [pocket-mice]	
			new species

Table 15. Faunal List – Balm Creek Member, John Day Formation

Clade	Order	Family	Species
Mammalia			
	Artiodactyla		
		Tayassuidae [peccaries]	
			cf. Hesperhys sp.

Table 16. Faunal List – Johnson Canyon Member, John Day Formation

Clade	Order	Family	Species
Mammalia			
	Carnivora		
		Amphicyonidae [bear-dogs]	
			Mammacyon obtusidens
			Temnocyon fingeruti
		Canidae [dogs]	
			Cynarctoides cf. luskensis
			Desmocyon thomsoni
	Perissodactyla		
		Chalicotheriidae	
			Moropus oregonensis
		Equidae [horses]	
			Archaeohippus sp.
			Kalobatippus praestans
		Rhinocerotidae [rhinoceroses]	
			Diceratherium sp.
			cf. Menoceras sp.
Mammalia (continued)			
	Perissodactyla (continued)		
		Tapiridae [tapirs]	
			Miotapirus harrisonensis
	Artiodactyla		
		Camelidae [camels]	
			Paratylopus cameloides
		Entelodontidae [giant "pigs"]	
			Daeodon humerosum
		Merycoidodontidae [oreodonts]	
			Paroreodon sp.
			Promerycochoerus sp.
		Moschidae [musk deer]	
			Pseudoblastomeryx cf. advena.
Mammalia (continued)			
	Artiodactyla (continued)		
		Palaeomerycidae	
			Bouromeryx submilleri
		Tayassuidae [peccaries]	
			Hesperhys sp.
	Rodentia		
		Aplodontidae [mountain beavers]	
			Sewelleladon predontia
		Heteromyidae [pocket-mice]	
			Schizodontomys greeni
		Mylagaulidae [horned "gophers"]	
			Mylagaulodon angulatus
	Lagomorpha		
		Leporidae [rabbits]	
			Archaeolagus cf. macrocephalus

Species lists were compiled by Joshua Samuels, John Day Fossil Beds NM museum curator/chief of paleontology (written communication, 12 April 2013).

Table 17. Faunal List – Rose Creek Member, John Day Formation

Clade	Order	Family	Species
Mammalia			
	Carnivora		
		Amphicyonidae [bear-dogs]	
			cf. Amphicyon sp.
			Daphoenodon robustum
			Mammacyon obtusidens
		Canidae [dogs]	
			Cynarctoides cf. luskensis
			Desmocyon thomsoni
	Perissodactyla		
		Chalicotheriidae	
			Moropus oregonensis
		Equidae [horses]	
			Archaeohippus sp.
			Kalobatippus praestans
			Parahippus pawniensis
Mammalia (continued)			
	Perissodactyla (continued)		
		Rhinocerotidae [rhinoceroses]	
			Diceratherium sp.
	Artiodactyla		
		Camelidae [camels]	
			Paratylopus cameloides
			Protolabis sp.
		Merycoidodontidae [oreodonts]	
			Promerycochoerus magnus
		Moschidae [musk deer]	
			Parablastomeryx schultzi
		Palaeomerycidae	
			Barbouromeryx cf. trigonocorneus
Mammalia (continued)			
	Rodentia		
		Aplodontidae [mountain beavers]	
			Sewelleladon predontia
		Castoridae [beavers]	
			cf. Hystricops sp.
		Heteromyidae [pocket-mice]	
			Schizodontomys greeni
		Mylagaulidae [horned "gophers"]	
			Mesogaulus sp.
			Mylagaulodon angulatus
	Lagomorpha		
		Leporidae [rabbits]	
			Hypolagus sp.

Table 18. Faunal List – Mascall Formation *(data from Kaitlin Maguire, PhD candidate at the University of California – Berkeley)*

Clade	Order	Family	Species
Bivalvia [clams and mussels]			
			unidentified clams
Gastropoda [snails]			
	Basommatophora		
		Lymnaeidae	
			Lymnaea stearnsi
Actinopterygii			
	Perciformes		
		Centrarchidae [sunfish]	
			Arcoplites sp.
"Reptilia"			
	Chelonia (Testudines)		
		Emydidae [pond turtles]	
			Clemmys sp.
Aves			
			unidentified birds
Mammalia			
	Lipotyphla [insectivores]		
		Soricidae [shrews]	
			Pseudotrimylus mawbyi
	Carnivora		
		Amphicyonidae [bear-dogs]	
			Cynelos sinapius
			Pliocyon ossifragus
		Canidae [dogs]	
			Leptocyon cf. leidyi
			Tephrocyon rurestris
		Felidae [cats]	
			Pseudaelurus sp.
		Mustelidae [weasels, otters, etc.]	
			Leptarctus oregonensis
Mammalia (continued)			
	Carnivora (continued)		
		Procyonidae [raccoons and ringtails]	
			Bassariscus lycopotamicus
		Ursidae [bears]	
			Ursavus sp.
	Perissodactyla		
		Equidae [horses]	
			Acritohippus isonesus
			Archaeohippus ultimus
			Desmatippus avus
			cf. Kalobatippus sp.
			Merychippus relictus
			Merychippus seversus
		Rhinocerotidae [rhinoceroses]	
			Aphelops megalodus
			Teleoceras medicornutum
	Artiodactyla		
		Camelidae [camels]	
			Miolabis transmontanus
			Protolabis sp.
		Merycoidodontidae [oreodonts]	
			Ticholeptus zygomaticus
		Moschidae [musk deer]	
			Blastomeryx gemmifer
			Parablastomeryx sp.
		Palaeomerycidae [giraffe-deer]	
			Cranioceras cf. unicornis
			Dromomeryx borealis
			Rakomeryx sinclairi
Mammalia (continued)			
	Artiodactyla (continued)		
		Tayassuidae [peccaries]	
			Cynorca hesperia
			Prosthennops cf. xiphidonticu
	Rodentia		
		Castoridae [beavers]	
			Monosaulax sp.
		Cricetidae [New World mice]	
			Copemys sp.
		Geomyidae [gophers]	
			Mojavemys mascallensis
		Heteromyidae [pocket-mice]	
			Balantiomys oregonensis
		Mylagaulidae [horned "gophers"]	
			Alphagaulus vetus
			Hesperogaulus wilsoni
		Sciuridae [squirrels]	
			Arctomyoides oregonensis
			Protospermophilus malheurensis
			Tamias sp.
	Lagomorpha		
		Leporidae [rabbits]	
			Hypolagus cf.vetus
			Hypolagus fontinalus
			Hypolagus parviplicatus
	Chiroptera		
		unidentified bat	
	Proboscidea		
		Gomphotheriidae [gomphotheres]	
			Gomphotherium sp.
		Mammutidae [mastodons]	
			Zygolophodon proavus

Table 19. Floral List – Mascall Formation *(note - some plant species are represented by multiple elements [leaves, seeds, etc.], these sometimes bear distinct names)*

Clade	Order	Family	Species
Ginkgophyta			
	Ginkgoales		
		Ginkgoaceae [ginkgos]	
			Ginkgo adiantoides
Gnetophyta			
	Ephedrales		
		Ephedraceae	
			Ephedra sp.
Pinophyta			
	Cupressales		
		Cupressaceae [cypress, dawn redwood]	
			Libocedrus masoni
			Metasequoia occidentalis
			Taxodium dubium
			Thuja dimorphia
		Taxaceae [yews]	
			Cephalotaxus californica
	Pinales		
		Pinaceae [pines]	
			Abies chaneyi
			Abies klamathensis
			Keteleerea heterophylloides
			Picea magna
			Picea sonomensis
			Pinus harneyana
'Basal Angliosperms'			
	Nymphaeales		
		Nymphaeaceae [water-lilies]	
			Nymphaeites nevadensis
Monocots			
	Liliales		
		Smilacaceae [greenbriar, 'sarsaparilla']	
			Smilax magna
			Smilax wardii
	Poales		
		Typhaceae [cattails]	
			Typha lesquereuxi
Eudicots			
	Cornales		
		Cornaceae [dogwoods, tupelos]	
			Nyssa hesperia
		Hydrangeaceae [hydrangeas]	
			Hydrangea bendirei
	Ericales		
		Ebenaceae [ebony, persimmon trees]	
			Diospyros oregoniana
	Fabales		
		Fabaceae [legumes]	
			Albizia oregoniana
			Gymnocladus dayana
	Fagales		
		Betulaceae [alder, birch]	
			Alnus hollandiana
			Alnus relates
			Betula fairii
			Betula thor
			Ostrya oregoniana
		Fagaceae [beeches, oaks]	
			Fagus washoensis
			Quercus bretzi
			Quercus columbiana
			Quercus dayana
			Quercus merriami
			Quercus prelobata
			Quercus pseudolyrata
			Quercus smileyana
		Juglandaceae [walnuts]	
			Carya bendirei
			Juglans sp.
			Pterocarya mixta Lamiales
		Oleaceae [ashes, lilacs, olives]	
			Fraxinus coulteri
			Fraxinus dayana
	Laurales		
		Lauraceae [laurels]	
			Laurophyllum merrilli
			Lindera oregoniana
			Persea pseudocarolinensis
	Malpighiales		
		Salicaceae [willows, cottonwoods]	
			Populus lingreni
			Populus voyana
			Salix boisiensis
			Salix hesperia
	Ranunculales		
		Berberidaceae [barberries, mayapples]	
			Berberis? gigantea
			Mahonia simplex
	Proteales		
		Platanaceae [plane trees, sycamores]	
			Platanus dissecta
	Rosales		
		Rosaceae [apples, roses]	
			Amelanchier couleeana
			Amelanchier coveus
			Crataegus gracilens
		Ulmaceae [elms, hackberries]	
			Celtis dayana
			Ulmus paucidentata
			Ulmus speciosa
			Zelkova oregoniana
	Sapindales		
		Meliaceae [mahoganies]	
			Cedrela trainii
		Rutaceae [rues]	
			Ptelea miocenica
		Sapindaceae [maple, soapberry family]	
			Acer bendirei
			Acer bolanderi
			Acer columbianum
			Acer glabroides
			Acer minor
			Acer oregonianum
			Acer scottiae
		Simaroubaceae [corkwood]	
			Leitneria pacifica
	Saxifragales		
		Cercidiphyllaceae [katsura trees]	
			Cercidiphyllum crenatum
		Hamamelidaceae [sweetgums]	
			Hamamelis merriami
			Liquidambar pachyphyllum

Table 20. Diatom List – Mascall Formation

Clade	Order	Family	Species
Coscinodiscophyceae			
	Aulacoseirales		
		Aulacoseiraceae	
			Aulacoseira ambigua
			Aulacoseira granulate
	Thalassiosirales		
		Melosiraceae	
			Melosira teres
Bacillariophyceae			
	Cymbellales		
		Cymbellaceae	
			Cymbella sp.
		Gomphonemataeae	
			Gomphonema sp.
	Naviculales		
		Naviculaceae	
			Navicula sp.
Fragilariophyceae			
	Fragilariales		
		Fragilariaceae	
			Fragilaria sp.
			Synedra sp.
	Tabellariales		
		Tabellareaceae	
			Tetracyclus ellipticus

Table 21. Faunal List – Rattlesnake Formation

Clade	Order	Family	Species
"Amphibia"			
	Anura		
		Ranidae [frogs]	
			Rana sp.
"Reptilia"			
	Chelonia (Testudines)		
		Emydidae [pond turtles]	
			Actinemys marmorata
Aves			
	Falconiformes		
		Falconidae [falcons]	
			unidentified falconid
		Ralidae	
			unidentified rail
Mammalia			
	Lipotyphla [insectivores]		
		Soricidae [shrews]	
			Sorex edwardsi
		Talpidae [moles]	
			Scapanus sp.
	Xenarthra		
		Megalonychidae [sloths]	
			Megalonyx sp.
	Carnivora		
		Ailuridae [red pandas]	
			Simocyon primigenius
		Canidae [dogs]	
			Borophagus secundus
			Eucyon davisi
			Metalopex merriami
			Vulpes stenognathus
		Felidae [cats]	
			Lynx sp.
			Machairodus sp.
			unidentified machairodontine
		Mustelidae [weasels, otters, etc.]	
			Lutravus halli
			Martes sp.
			Mustela sp.
			Pekania occulta
		Ursidae [bears]	
			Indarctos oregonensis
			Plionarctos edensis
Mammalia (continued)			
	Perissodactyla		
		Equidae [horses]	
			Hippotherium sp.
			Neohipparion leptode
			Pliohippus spectans
		Rhinocerotidae [rhinoceroses]	
			Teleoceras cf. fossiger
		Tapiridae [tapirs]	
			unidentified tapir
	Artiodactyla		
		Antilocapridae [pronghorn antelope]	
			Ilingoceras sp.
			Sphenophalos sp.
		Camelidae [camels]	
			Hemiauchenia cf. vera
			Megatylopus sp.
			cf. Pliauchenia sp.
		Moschidae [musk deer]	
			cf. Parablastomeryx sp.
		Palaeomerycidae [giraffe-deer]	
			cf. Pediomeryx sp.
		Tayassuidae [peccaries]	
			Mylohyus longirostris
			Platygonus oregonensis
	Rodentia		
		Castoridae [beavers]	
			Castor californicus
			Dipoides stirtoni
		Cricetidae [New World mice]	
			Peromyscus antiquus
		Geomyidae [gophers]	
			Thomomys sp.
		Heteromyidae [pocket-mice]	
			Prodipodomys sp.
		Mylagaulidae [horned "gophers"]	
			Hesperogaulus gazini
		Sciuridae [squirrels]	
			Spermophilus gidleyi
	Lagomorpha		
		Leporidae [rabbits]	
			Hypolagus vetus
	Chiroptera		
		Vespertilionidae [evening bats]	
			Myotis sp.
	Proboscidea		
		Gomphotheriidae [gomphotheres]	
			Amebelodon sp.

Table 22. Floral List – Rattlesnake Formation

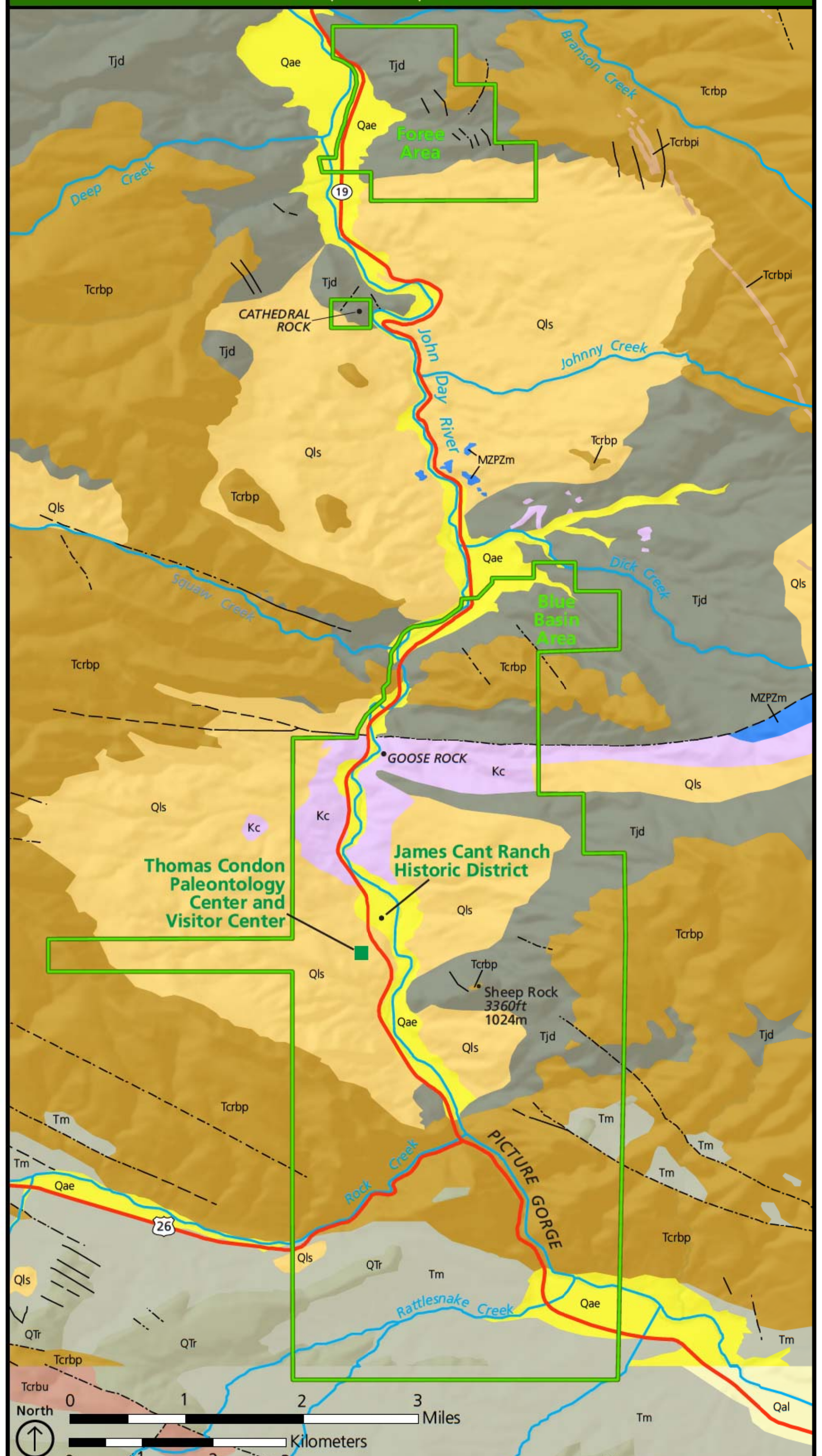
Clade	Order	Family	Species
Eudicots			
	Fagales		
		Fagaceae [beeches, oaks]	
			Quercus sp.
	Malpighiales		
		Salicaceae [willows, cottonwoods]	
			Populus sp.
			Salix sp.
	Proteales		
		Platanaceae [plane trees, sycamores]	
			unidentified species
Eudicots (continued)			
	Ranunculales		
		Berberidaceae [barberries, mayapples]	
			Mahonia sp.
	Rosales		
		Rosaceae [roses]	
			Rosa sp.
		Ulmaceae [elms, hackberries]	
			unidentified species
	Sapindales		
		Rutaceae [rues]	
			Ptelea sp.
		Sapindaceae [maple, soapberry family]	
			Acer sp.

Geologic Map of John Day Fossil Beds National Monument

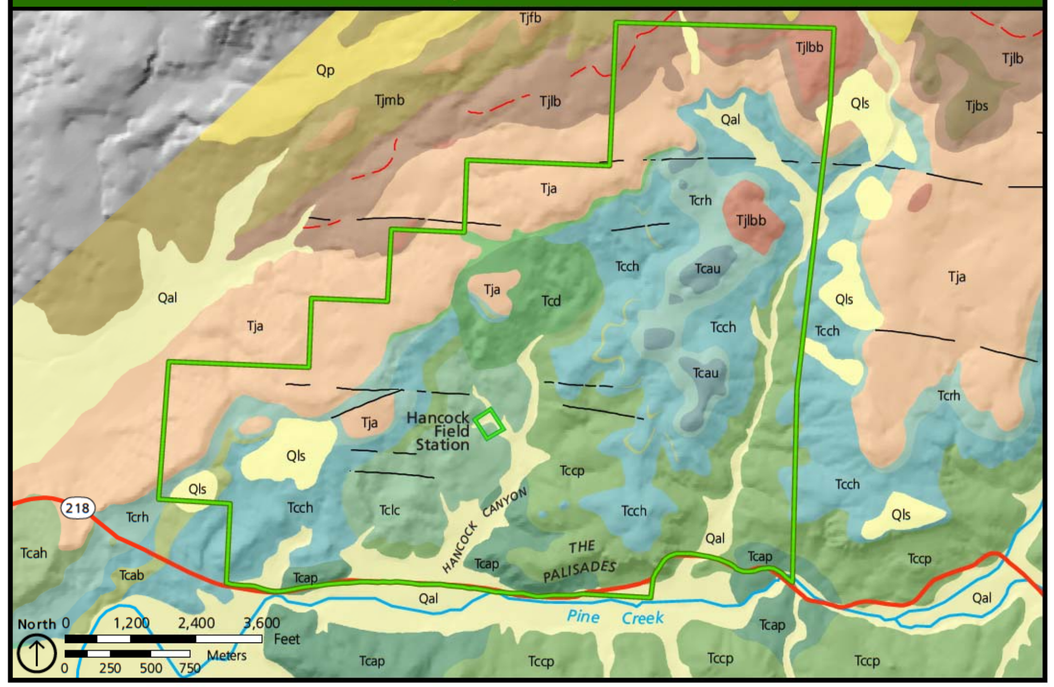
Oregon

National Park Service
U.S. Department of the Interior

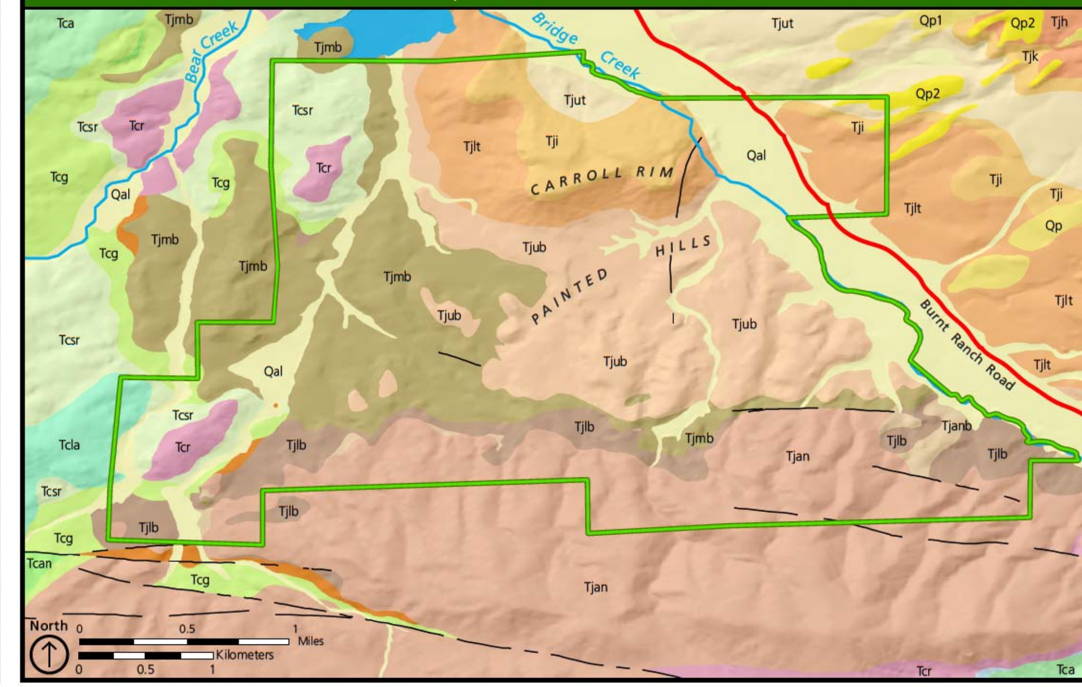
Map 1: Sheep Rock Unit



Map 2: Clarno Unit



Map 3: Painted Hills Unit



Map 4: Full Extent, Areas of Detail in Yellow

NPS Boundary

Infrastructure

- cities
- structures
- points of interest
- roads

Water

- rivers

Faults

- unknown offset/displacement, known or certain
- unknown offset/displacement, approximate
- unknown offset/displacement, concealed
- normal fault, known or approximate

Linear Geologic Units

- Tjft - Lower Big Basin Member, member F Tuff, approximate

Geologic Units

- water
- Qal Alluvium
- Qae Alluvium, eolian/fluvial
- Qp Pediments
- Qp1 Pediments, lower surface
- Qp2 Pediments, upper surface
- Qt Terrace alluvium
- Qls Landslides
- QTr Rattlesnake Formation, Ashflow Tuff
- Tm Mascall Formation
- Tcrb Columbia River Basalt Group
  - Tcrbu undivided
  - Tcrbp Picture Gorge Basalt
  - Tcrbpi Picture Gorge Basalt, basalt dikes
  - Tcrbpi Picture Gorge Basalt, basaltic irregular intrusion
- Tjd John Day Formation
  - Tjh Haystack Valley Member
  - Tjk Kimberly Member
  - Tjut Upper Turtle Cove Member
  - Tji Picture Gorge ignimbrite
  - Tjlt Lower Turtle Cove Member
  - Tjub Upper Big Basin Member
  - Tjmb Middle Big Basin Member
  - Tjfb Middle Big Basin Member; member F basalts
  - Tjmbb Middle Big Basin Member basalt
  - Tjlb Lower Big Basin Member claystones
  - Tjanb Lower Big Basin Member, andesite saprolite breccia
  - Tjan Lower Big Basin Member, andesite of Sand Mountain
  - Tjbs Lower Big Basin Member, volcaniclastic deposits
  - Tjlbb Lower Big Basin Member, member B basalts
  - Tja Lower Big Basin Member, welded tuff of member A
- Tcl Clarno Formation
  - Tcg claystones of Brown Grotto
  - Tcan andesite flows
  - Tcsr rhyolitic saprolite
  - Tcr rhyolite of Bear Creek
  - Tcs claystones of Sand Mountain
  - Tca andesite of Bridge Creek Canyon
  - Tcm claystones of Meyers Canyon
  - Tcla lower Clarno andesite flows
  - Tcq siltstones of the Mammal Quarry
  - Tcah andesite of Horse Mountain
  - Tcau andesite of Horse Mountain, upper andesite
  - Tcrc andesite of Horse Mountain, red claystones
  - Tcrh claystones of Red Hill
  - Tcrg claystones of Red Hill, cobble conglomerate
  - Tcch conglomerates of Hancock Canyon
  - Tct conglomerates of Hancock Canyon, welded tuff
  - Tcab conglomerates of Hancock Canyon, amygdaloidal basalt
  - Tcam conglomerates of Hancock Canyon, middle andesite
  - Tccp conglomerates of the Palisades
  - Tcap andesite of Pine Creek
  - Tcd Hancock dacite dome
  - Tclc lower Clarno conglomerates
- Krx Cretaceous rocks
- Kc Mitchell Group, conglomerate w/ intercalated sandstone lenses
- Ks Mitchell Group, sedimentary rocks
- KJi Nevadean Intrusives, dioritic intrusive rocks
- TRv Olds Ferry Terrane, Vester Formation
- TRsp Baker Terrane, igneous and metamorphic rocks
- MZPZm Baker Terrane, metamorphic rocks
- PZu1 Baker Terrane, sedimentary, volcanic, and metamorphic rocks

This map was produced by Ian Hageman (Colorado State University) and Georgia Hybels (NPS Geologic Resources Division) in August 2014. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source maps used in creation of the digital geologic data were:

Bestland, E.A. and Retallack, G.J. 1994. Geology and Paleoenvironments of the Clarno Unit, John Day Fossil Beds National Monument, Oregon (1:7,300 scale). Final Report NPS Contract CX-9000-1-10009.

Bestland, E.A. and Retallack, G.J. 1994. Geology and Paleoenvironments of the Painted Hills Unit, John Day Fossil Beds National Monument, Oregon (1:7,300 scale). Final Report NPS Contract CX-9000-1-10009.

Niewendorp, C.A., Jenks, M.D., Ferns, M.L., Madin, I.P., Staub, P.E., and Ma, L. 2006. Oregon Geologic Data Compilation - Release 3, State of Oregon (1:100,000 scale). Oregon Department of Geology and Mineral Industries OGDC-3.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 4 m (12 ft) (1:7,300 scale data) or 50 m (166 ft) (1:100,000 scale data) of their true location.

All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select a park from the unit list.

Map Unit Properties Table: John Day Fossil Beds National Monument

Gray units are not mapped within John Day Fossil Beds National Monument.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Holocene)	Alluvium (Qal)	Clarno and Painted Hills unit maps: Unconsolidated material deposited by running water (alluvium). Sheep Rock Unit map: Silt- to gravel-sized sediment deposited by rivers or streams. Mapped in Clarno and Painted Hills units.	**Fluvial Geomorphic Features**—Floodplains, point bars, cutbanks, natural levees.	**Flooding and Subsequent Erosion**—Intense cloudbursts and scarce vegetation on badlands topography may trigger flash flooding, which may increase erosion. Erosion may expose or remove fossils.	**The Hot House: Holocene Epoch**—Since the end of the Pleistocene, the Oregon Cascades have remained relatively quiet with the exception of Mount Mazama, which erupted about 7,700 years ago and produced the caldera that currently contains Crater Lake. Smaller volcanic eruptions have occurred in the Cascades as recently as 1,000 years ago, depositing ash within what is now the monument. Early in the Holocene, basalt erupted from vents associated with the Brothers fault zone on the High Lava Plains Province. The resources in John Day Fossil Beds National Monument may be impacted by global climate change. Changes in the timing, intensity, duration, and amount of precipitation may affect water quantity, riparian habitats, incision rates, and cliff erosion in the monument.
	Alluvium; aeolian/fluvial (Qae)	Sheep Rock Unit map: Silt, sand, pebbles, and boulders deposited by rivers. Clasts include a variety of igneous and sedimentary rocks. Gravel deposits up to 3 m (10 ft) thick. Volcanic ash deposits up to 2.7 m (9 ft) thick. Mapped in Sheep Rock Unit.			
	Pediments (Qp)	**Qp1**. Lower surface. **Qp2**. Upper surface. Mapped in Painted Hills Unit.	None reported.	None reported.	
	Terrace alluvium (Qt)	Painted Hills Unit map: Unconsolidated cobble conglomerate. Mapped in Painted Hills Unit.	**Fluvial Geomorphic Features**—Floodplains, point bars, cutbanks, natural levees.	None reported.	
	Landslides (Qls)	Sheep Rock Unit map: Landslides. Clarno Unit map: Most mapped landslides occur where thick exposures of Claystones of Red Hill (**Tcrh**) are overlain by the welded tuff of Member A of the basal John Day Formation (**Tja**). Mapped in Sheep Rock and Clarno units.	None reported.	**Slope Movements**—Landslides occur in John Day Formation (**Tjd**) claystones (Sheep Rock Unit) and in the claystones of Red Hill (**Tcrh**; Clarno Unit), especially where overlain by **Tja**.	
NEOGENE (Miocene)	Rattlesnake Formation (QTr)	Sheep Rock Unit map: The formation consists of densely welded tuff, ignimbrite (pyroclastic flow), siltstone, fine- to medium-grained sandstone, and fanglomerates, which are conglomerates that usually form on the upper end of an alluvial fan. The conglomerates consist of well-rounded, poorly-indurated pebbles to boulders in poorly-sorted, fine- to coarse-grained volcanic sandstone, basalt, quartz diorite, green chert, and white quartzite. Mapped in Sheep Rock Unit.	**Stratigraphic Features and Paleontological Resources**—Alluvial fans, conglomerate, and the Rattlesnake Ash Flow Tuff (RAFT), which is the most distinctive unit in **QTr**. RAFT is 7.05 ± 0.01 million years old. Contains primarily vertebrate fossils (table 21), including mammals, reptiles, and amphibians. Plant fossils (table 22; not found in the park) include sycamore, elm, and willow. Mammal fossils are reference fauna for Hemphillian North American Land Mammal Age (NALMA). The presence of the ground sloth *Megalonyx* suggests that North America was connected to South America. **Paleosols**—Kalas, Skwiskwi, Tatas, Tnana, Xaus, and Cmti paleosols suggest woodlands, shrublands, and grasslands (table 23). **Faults and Folds**—In the Picture Gorge area, the Rattlesnake Formation lies in angular unconformity above the Mascall Formation.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service.	**The Cool Down: Late Miocene and Pliocene Epochs**—Open tall grassland and shrubland habitats with forest environments along river systems. About 7.1 million years ago, the RAFT erupted and deposited about 290 km^3 (70 mi^3) of ash in less than 1 week. In contrast to **Tm**, **QTr** was deposited in an active tectonic zone. Volcanic eruptions along the Brothers fault zone produced isolated peaks, and in the Cascades, low and volatile volcanoes continued to erupt. At the end of the Pliocene, glaciers began to expand, polar ice caps began reflecting more solar heat away from Earth, ocean currents changed, and temperatures became increasingly unstable.

Gray units are not mapped within John Day Fossil Beds National Monument.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
NEOGENE (Miocene)	Mascall Formation (Tm)	Sheep Rock Unit map: Volcanic sandstone and siltstone, volcanic ash, welded rhyolite tuff, minor lignite, conglomerate, bentonitic clay and shale, and traces of sand and gravel. The volcanic sandstone and siltstone are white, fine-grained, poorly indurated, and porous, with black manganese oxidation and fragments of pumice. Mapped in Sheep Rock Unit.	**Stratigraphic Features and Paleontological Resources**—Diatom-rich claystones, lignite, conglomerate beds, and volcanic tuff. Ages determined from volcanic layers include 15.8 million years (ash bed below Mascall Tuff); 17.619 million and 15.297 million years (Mascall Tuff); and 13.564 million years (Kangaroo Tuff). Complete lists of animal and plant fossils are available in tables 18–20. Most fossils come from the Sheep Rock Unit. Cypress and oak are the most abundant plant fossils. Larger mammals, mainly equids and palaeomerycids, dominate the **Tm** fauna, but several smaller taxa are relatively abundant. The proboscideans *Gomphotherium* and *Zygolophodon* are among the earliest records of "elephants" in North America and helped define the Barstovian NALMA. *Pseudaelurus* is the earliest known true cat (Felidae) in the Pacific Northwest. Open grassland habitats are represented by grazing-adapted mammals, such as camels and horses (*Merychippus*), rabbits (*Hypolagus* spp.), ground squirrels (*Protospermophilus*), and horned gophers. **Paleosols**—Maqas, Patu, Skwiskwi, Luca, Wawcak, and Walasx are primary pedotypes (table 23) Paleosols characteristic of open, grassy habitats. **Folds and Faults**—In the Sheep Rock Unit, northwest–southeast-trending faults juxtapose **Tcrbp** with **Tjd** and **Tm**.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service. **Flooding and Subsequent Erosion**—Intense cloudbursts and scarce vegetation on badlands topography may trigger flash flooding, which may increase erosion. Erosion may expose or remove fossils. **Disturbed Lands**—Bentonite in **Tm** is mined in Crook County, south of Wheeler County.	**Global Warming and Flood Basalts: Middle Miocene Epoch**—Paleosols that developed between basalt flows indicate open grass-dominated habitats. Swamp cypress grew along bodies of water. Modern representatives of the **Tm** flora suggest mean annual temperature of 8°C to 16°C (46°–61°F) and mean annual precipitation of 50 to 90 cm (20–35 in). Volcaniclastic sediments were derived from eruptions to the west, south, and east and deposited in floodplains. **Tm** was deposited in a low-relief, tectonically inactive area.
NEOGENE (Miocene)	Columbia River Basalt Group: Columbia River Basalt Group; undivided (Tcrb, Tcrbu)	Painted Hills and Clarno Unit maps: **Tcrb**. Blocky, fine-grained basalt. Sheep Rock Unit map: **Tcrbu.** Basalt flows, with andesite to rhyolite.	**Stratigraphic Features and Paleontological Resources**—Many basalt flows ranging from fine-grained flows to flows with phenocrysts of plagioclase and augite, as well as zones of scoriaceous basalt. Flows tilt to the south-southwest in the vicinity of Picture Gorge. **Cave and Karst Features**—Lava tubes, some of which are 15 m (50 ft) deep.	**Slope Movements**—Potential for rockslides or rockfall.	**Global Warming and Flood Basalts: Middle Miocene Epoch**—A warming event, known as the Middle Miocene Climatic Optimum, occurred approximately 16 million years ago. Between 17 million and 6 million years ago, basalts flooded the Columbia Basin and much of the region of present-day southeastern Oregon. The Picture Gorge Basalt (**Tcrbp**) erupted from fissures associated with the Monument dike swarm and covered 10,680 km^2 (4,124 mi^2) of present-day central Oregon.
NEOGENE (Miocene)	Columbia River Basalt Group: Picture Gorge Basalt (Tcrbp)	Sheep Rock Unit map: Basalt flows, flow breccia, tuff, volcanic siltstone, sandstone, and basalt talus. The basalt flows are up to 412 m (1,353 ft) thick and contain phenocrysts of feldspar, plagioclase, augite, and olivine. Vesicles (gas holes) are filled with zeolite and calcite. The basalts are a portion of the larger Steens–Columbia River flood basalts of the Pacific Northwest. Mapped in Sheep Rock Unit. **Tcrbpi**. Very fine-grained basalt dikes with vesicles filled with calcite and veins of calcite. Not mapped in the monument. **Tcrbpii**. Irregular basaltic intrusion that has a crumbly appearance and contains stringers of calcite and nodules of violet-zoned calcite or reddish baked tuff. Not mapped in the monument.	**Stratigraphic Features and Paleontological Resources**—Many basalt flows ranging from fine-grained flows to flows with phenocrysts of plagioclase and augite, as well as zones of scoriaceous basalt. Flows tilt to the south-southwest in the vicinity of Picture Gorge. Ages determined from basalt include16.0 ± 0.2 million years; 15.6-16.5 million years and 16.5 to 16.3 million years for Dayville Basalt Formation. **Cave and Karst Features**—Lava tubes, some of which are 15 m (50 ft) deep. **Paleosols**—Monana, Ilukas, Kwalk, Skaw, Nuqwas paleosols suggest peat swamps, forest, woodlands, and shrublands (table 23). **Exceptional Geologic Landscape Features**—Sheep Rock is capped by **Tcrbp**. Picture Gorge is type area for **Tcrbp**.	**Slope Movements**—Large blocks of **Tcrbp** have dislodged in the Sheep Rock Unit. The road through Picture Gorge is periodically closed to remove rockfall and landslide debris. **Cave and Karst Inventory and Monitoring**—No systematic cave inventory or monitoring program exists for the monument.	

Gray units are not mapped within John Day Fossil Beds National Monument.

Age		Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PALEOGENE-NEOGENE (Oligocene-Miocene)	John Day Formation	Undivided (Tjd)	Sheep Rock Unit map: Ignimbrites, welded and non-welded tuff, lava flows of rhyolite and basalt, tuffaceous siltstone and mudstone, minor coarse-grained sandstone, and conglomerate. The extremely hard welded tuff is 15 m (50ft) thick and contains a variety of rock fragments. The non-welded tuff is 2–8 m (5–25 ft) thick. The thin basalt flows have vesicles filled with calcite, chlorite, chalcedony, and zeolite. The conglomerate is composed of very coarse pebbles to well-rounded boulders. Mapped in Sheep Rock Unit.	**Stratigraphic Features and Paleontological Resources**—Complex stratigraphy consisting of sedimentary and volcanic features (see individual units below). Plethora of fossil plants and animals (see individual units below and tables 10–17). **Paleosols**—Diverse paleosols (see individual units below and table 23). **Volcanic Features in the John Day Formation**—Tuffs are important marker beds throughout the formation (see individual units below). **Folds and Faults**—Minor normal and thrust faults throughout the unit. A prominent north–south-trending normal fault cuts Carroll Rim and Painted Ridge, and a small reverse fault is visible from the Overlook Trail. In the Sheep Rock Unit, an east–west fault juxtaposes **Tjd** with **Kc**, and northwest–southeast-trending faults juxtapose **Tcrbp** with **Tjd** and **Tm**. **Exceptional Geologic Landscape Features**—In Sheep Rock Unit, Sheep Rock, Foree, Blue Basin, Cathedral Rock are comprised of **Tjd**.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service. **Flooding and Subsequent Erosion**—Intense cloudbursts and scarce vegetation on badlands topography may trigger flash flooding, which may increase erosion. Erosion may expose or remove fossils. **Slope Movements**—Landslides occur in **Tjd** claystones (Sheep Rock Unit). Undercutting of less resistant units may cause the overlying cliff of **Tji** to collapse.	**Global Icehouse: Oligocene–Miocene Epochs**—See individual units below.
		Haystack Valley Member (Tjh)	Painted Hills Unit map: Pale-brown, nodular, tuffaceous siltstones and conglomerates. In Hatch's Gulch, outside the monument boundaries, **Tjh** is 14 m (46 ft) thick and consists of resistant nodular tuffaceous siltstones and coarse clastic and conglomeratic deposits containing rounded and welded tuff fragments, and, more rarely, reworked bone fragments. Much of the conglomeratic material consists of reworked clasts of silica-cemented paleosols (fossil soils). Some brecciated nodular paleosol horizons contain abundant silica-cemented rhizoconcretions (branching, cylindrical structures resembling plant or tree roots). Balm Creek, Johnson Canyon, and Rose Creek members are now differentiated from Haystack Valley. This nomenclature is not reflected on GRI source maps that preceded the differentiation. Only the Rose Creek member is present in the monument, although not differentiated on source map.	**Stratigraphic Features and Paleontological Resources**—Sandstone and conglomerates record stream incision into the underlying Kimberly Member. Air-fall tuff serves as a regional marker bed separating **Tjh** from overlying Balm Creek, Johnson Canyon, and Rose Creek members. JD-BC-3 tuff at contact with Balm Creek Member yielded an age of 23.79 ± 0.18 million yeas. No fossil material has been recovered in John Day Fossil Beds National Monument (Joshua Samuels, NPS, written communication, 11 April 2013). Fossils (table 14) beyond the monument boundaries indicate hardwood forest habitats and include massive rhinoceroses, chalicotheres (horse-like animals with claws), and smaller grazers, such as camels and horses. Fossils from Balm Creek, Johnson Canyon, and Rose Creek members are listed on tables 15–17. **Paleosols**—Abiaxi, Iscit, Plas, Plaspa, Tima, and Yapaspa paleosols are present in the "upper John Day Formation" and represent scrub, shrubland, and woodland (table 23).	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service. **Slope Movements**—Potential for landslides.	**Global Icehouse: Oligocene–Miocene Epochs**—The mammalian fauna of the Rose Creek Member suggest an age of 18.8–18.2 million years. Prior to deposition of the Rose Creek Member and following deposition of **Tjh**, the region was folded and faulted by northwest–southeast-directed compression, which produced anticlines and synclines, such as the Balm Creek syncline, and low-angle reverse faults. Normal faulting offset the Johnson Canyon Member following its deposition 22.6–19.2 million years ago. The abundance of gophers, burrowing beavers, running-adapted herbivores, such as camels and "stilt-legged" horses, and fossils from hardwood trees suggest open grassy habitats and forest environments similar to those in today's eastern United States. Ages determined from volcanic layers indicate that **Tjh** is approximately 24 million years old.

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Age	Map Unit (Symbol)			Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PALEOGENE (Oligocene)	John Day Formation	Kimberly Member (Tjk)		Painted Hills Unit map: Volcanic tuffs and tuffaceous siltstones. Although similar to **Tjut**, **Tjk** tuffs are generally thicker, fresher, and form bulbous jointed cliffs that are commonly crumbly, dangerous, and overhanging in places. The abundance of weather-resistant non-calcareous nodules, root traces, and rhizoconcretions increases toward the top of the formation. Although not differentiated on the source map, Kimberly Member strata are present in the Sheep Rock Unit (as **Tjd**).	**Stratigraphic Features and Paleontological Resources**—Erosion-resistant nodules. Ash-flow tuff. Cliff-forming tuffaceous siltstones. A complete list of animal fossils is available in table 13. Dominated by small mammals, including massive samples of gophers, such as *Entoptychus* and *Meniscomys*, but also includes new predators (i.e., first true dogs) and some of the largest John Day Formation mammals, such as the entelodonts *Archaeotherium calkinsi* and *Daeodon*, and the large oreodont *Promerychochoerus*. *Moropus*, *Daphoenodon*, and *Kalobatippus* appear in Oregon for the first time. Fossilized oak, elm, birch, maple, fir, spruce, and pine. **Paleosols**—Succession of paleosols present in **Tjk**. **Exceptional Geologic Landscape Features**—Kimberly Member layers exposed on and near Sheep Rock.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service. **Slope Movements**—Cliffs of tuffaceous siltstones are jointed. Overhangs may be unstable and susceptible to rockfall.	**Global Icehouse: Oligocene–Miocene Epochs**—The abundance of gophers, burrowing beavers, running-adapted herbivores, such as camels and "stilt-legged" horses, and fossils from hardwood trees suggest open grassy habitats and forest environments similar to those in today's eastern United States.
		Turtle Cove Member	Upper Member (Tjut)	Painted Hills Unit map: Alternating clayey siltstones and tuffaceous siltstones that form densely dissected steep badlands. Tuffaceous layers are more resistant and weather to a darker shade of pale olive, whereas the more clayey layers weather to form lower-angle slopes of very pale olive with popcorn-textured surfaces. Most of the section consists of weakly developed paleosols. Thickness ranges from 0 to 63.5 m (0–208 ft). A *Promerycochoerus* skull was found *in situ* toward the top of the unit in a resistant, massive horizon of tuffaceous siltstone. The entombing siltstone is interpreted as an ashy flood deposit that was subjected to only minimal soil-forming processes and bioturbation. Mapped in Painted Hills Unit.	**Stratigraphic Features and Paleontological Resources**—Erosion-resistant tuffaceous siltstones and erodible clay-rich siltstones form a stair-step landscape of badlands topography. Ages of **Tjut** determined from volcanic layers include 27.89 million years (Deep Creek Tuff), 27.14 million years (biotite tuff), and 25.9 million and 25.3 million years (Tin Roof Tuff). A complete list of animal fossils for the entire Turtle Cove Member is available in table 12. The most abundant mammals are three species of hypertragulid ("mouse deer") and many species of oreodonts. Among the most notable and significant mammals are: 1) the three-toed horse *Miohippus*, a key species in understanding horse evolution; 2) five species of saber-toothed nimravids, ranging in size from bobcat to jaguar; 3) the last primate known from North America, until the arrival of humans more than 25 million years later; and 4) an incredible diversity of dogs, with as many as 10 co-occurring species, making this the most diverse canid fauna in the history of Earth. Unusual fossils from **Tjut** include three-toed horses, mouse-deer, beavers, oreodonts, and carnivores, such as bear-dogs, cat-like nimravids, and giant pig-like entelodonts. **Paleosols**—Most of **Tjut** consists of non-distinct paleosols (see table 23). **Volcanic Features in the John Day Formation**—Tuffs may have originated from eruptions that produced the Crooked River Caldera (30.4–22.6 million years ago).	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service.	**Global Icehouse: Oligocene–Miocene Epochs**—In the Oligocene, temperate conditions replaced a subtropical climate. Seasonal precipitation became more pronounced and the regional climate became 3–6°C (5–10°F) cooler. The landscape not only included wooded grasslands, but also featured towering stratovolcanoes. The 29.56-million-year-old Crooked River Caldera and 29.8–28.1-million-year-old Tower Mountain Caldera contributed abundant tuffaceous deposits and ash-flow tuffs to the Turtle Cove Member. Fauna and flora of **Tjut** indicate an environment of mixed wooded and open areas.

Gray units are not mapped within John Day Fossil Beds National Monument.

Age	Map Unit (Symbol)			Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PALEOGENE (Oligocene)	John Day Formation	Turtle Cove Member	Picture Gorge Ignimbrite (Tji)	Painted Hills Unit map: The most widespread ash-flow tuff sheet in the John Day Formation and the middle unit of the Turtle Cove Member. It forms the crest of Carroll Rim. In places, as at Carroll Rim, the unit has two cooling units, indicating multiple eruptions and emplacement over some period of time. **Tji1**: Lower cooling unit. **Tji2:** Upper cooling unit. Mapped in Painted Hills Unit.	**Stratigraphic Features and Paleontological Resources**—Welded tuff formed from superheated gases, volcanic ash, and pulverized rock. Two distinctive cooling units (**Tji1**, **Tji2**). **Tji** yielded an age of 28.7 million years ago. **Volcanic Features in the John Day Formation**—Forms a prominent marker bed. Equivalent to the Member H tuff. Crooked River Caldera eruption may have produced **Tji**. **Exceptional Geologic Landscape Features**—**Tji** is a prominent marker bed on Sheep Rock. Caps cliffs in Foree and Carroll Rim.	**Slope Movements**—Undercutting of less resistant units may cause overlying **Tji** to collapse.	**Global Icehouse: Oligocene–Miocene Epochs—** Approximately 28.7 million years ago, volcanic activity produced the Picture Gorge Ignimbrite, which is about 30 m (100 ft) thick in the Painted Hills Unit.
PALEOGENE (Oligocene)	John Day Formation	Turtle Cove Member	Lower Member (Tjlt)	Painted Hills Unit map: Pale-brown and olive siltstones and tuffaceous siltstones. The boundary between **Tjub** and **Tjlt** is well exposed in the lower slopes of Carroll Rim and is marked by a change from brown (**Tjub**) to pale-olive and pale-yellow (**Tjl**; primarily Maquas and Yapas paleosols) paleosol types, which signals a change in paleoenvironment. Carbonate nodules appear for the first time in the Painted Hills section. This calcareous material is probably one reason for the preservation of vertebrate fossils at this level. **Tjltst**. Sanidine tuff (Member G). Mapped in Painted Hills Unit.	**Stratigraphic Features and Paleontological Resources**—Clay-rich and tuffaceous siltstones and ash-flow tuff. Ages of **Tjl** determined from volcanic layers include 29.75 million years (A/B Tuff), 28.9 million years (Blue Basin Tuff), and 28.7 million years (white tuff). Because the Turtle Cove Member preserves about 5 million years of the Oligocene Epoch, the diverse fauna (table 12) document significant faunal and evolutionary changes due to changes in the regional environment. **Paleosols**—Grassy woodland (Yapas, Maqas, Micay), waterlogged bottomland forest (Lakim), and lightly wooded, seasonally wet meadow (Xaxus) pedotypes. **Volcanic Features in the John Day Formation**—Tuffs may have originated from eruptions that produced the Crooked River Caldera (30.4–22.6 million years ago). **Exceptional Geologic Landscape Features**—Turtle Cove strata are exposed at Sheep Rock, Blue Basin, Foree, and Cathedral Rock, as well as Carroll Rim.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service.	**Global Icehouse: Oligocene–Miocene Epochs—** Paleosols, which differ markedly from those of the Big Basin Member, signal a change in paleoenvironment from woodlands to more grassy habitats.

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Age	Map Unit (Symbol)			Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PALEOGENE (Oligocene)	John Day Formation	Big Basin Member	Upper Member (Tjub)	Painted Hills Unit map: Evenly-spaced, thin, red to brown claystone beds. A distinct truncation surface marked by a thick, red clayey paleosol occurs in the upper part of Candy Cane Canyon and abruptly juxtaposes thicker, closely-spaced and well-developed Luca paleosols of **Tjmb** against the thin, more widely-spaced Ticam paleosols of **Tjub**. Mapped in Painted Hills Unit.	**Stratigraphic Features and Paleontological Resources**—Complete lists of animal and plant fossils from the Big Basin Member are available in tables 10 and 11. Fragments of horses, rhinoceroses, and entelodonts have been recovered from **Tjub**. **Paleosols**—Variety of woodland paleosols (Skwiskwi, Micay, Kskus, Ticam, Lakim, and Luca; see table 23). **Folds and Faults**—**Tjub** and **Tjmb** contain two small domes and a short plunging fold in the Painted Hills. **Exceptional Geologic Landscape Features**—**Tjub** forms the iconic Painted Hills.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service.	**Global Icehouse: Oligocene–Miocene Epochs**—The temperate, 33-million-year-old Bridge Creek flora (**Tjmb**) contrast sharply with the tropical to subtropical flora of the Eocene Clarno Nut Beds (**Tcch**). Climate was cooler and more seasonal than in the Eocene. Seasonal precipitation became more pronounced and the regional climate became 3–6°C (5–10°F) cooler. The Overlook Tuff (**Tjmbot**), deposited near the Eocene–Oligocene boundary, buried an ancient landscape that consisted of swamps (lignite), poorly drained marsh, and well-drained, forested soils.
			Middle Member (Tjmb)	**Tjmb.** Painted Hills Unit map: Pale-olive and pale-yellow, smectite-rich, silty claystones and several distinctive tuff beds, such as the lowermost Biotite Tuff, the 1.5-m- (5-ft) thick Charcoal-Pumice Tuff, and the thick Overlook Tuff (**Tjmbot**). Approximately 91 m (300 ft) thick. A titania-rich basalt flow exposed along the Painted Hills access road is interbedded with the claystones and tuffs. Several subdivisions of **Tjmb** were mapped in the Painted Hills Unit and are described below. Clarno Unit map: Red-brown silty claystones, tuffs, and lacustrine shales with leaf impressions. Mapped in Painted Hills and Clarno units.	**Stratigraphic Features and Paleontological Resources**—Important stratigraphic marker beds. Overlook Tuff (**Tjmbot**) buries an ancient landscape. Truncation surface approximates the Eocene–Oligocene boundary. Basaltic ash-flow tuff. Lignite (**Tjmblg**) may represent an ancient swamp. Ages of **Tjmb** determined from volcanic layers include 32.66 million years (Overlook Tuff) and 32.99 million years (biotite tuff). **Tjmb** contains Bridge Creek Flora (table 10), which includes at least 91 genera of plants, with 110 species known from leaves and 58 species known from fruits, seeds, and cones. Fauna associated with the Bridge Creek Flora include invertebrates, fish, and amphibians from lake deposits and fragments of rhinoceros, entelodont, and bat (table 11). **Paleosols**—Variety of woodland paleosols (Micay, Luca, Kskus, Wawcak, Ticam, Lakim, and Yanwa; see table 23). **Exceptional Geologic Landscape Features**—**Tjmb** exposed at Leaf Hill (Bridge Creek Flora) and Painted Cove.		
				Middle–upper Big Basin Member boundary and marker beds. A Rainbow Hill Truncation Surface correlates with the Red Cap beds (**Tjmbrc)** and cuts out paleosols in the area.			
				Red Cap beds (Tjmbrc). A double set of paleosols. The upper set consists of two or three thick, closely-spaced, deep-red Luca paleosols and is more laterally persistent than the lower set of less well-developed paleosols, which tend to grade laterally into dark-gray Lakim paleosols and thin, reddish-brown Ticam paleosols. Mapped in Painted Hills Unit.			
				Overlook Tuff (Tjmbot). Tuff. A stratigraphic marker overlying red paleosols in Ruby Basin and **Tjmblg** in the Rainbow Hill–Yellow Basin area. Type locality is west of the visitor overlook. Mapped in Painted Hills Unit.			
				Lignite beds (Tjmblg). Occur below **Tjmbot** and pinch out into yellow cracked beds in the Rainbow Hill–Yellow Basin area. Mapped in Painted Hills Unit.			
				Member F basalts (Tjfb). Very dark-gray basalt. Mapped in Clarno Unit.			
				Basalt (Tjb). Dark-gray, fine-grained olivine basalt.			

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PALEOGENE (Eocene)	John Day Formation Big Basin Member Lower Member claystones (Tjlb)	**Tjlb**. <u>Painted Hills Unit map</u>: Red and ocher-colored claystones exposed between **Tjan** and **Tjmb**. Detailed mapping shows the claystones on-lapping the northern margin of **Tjan**. <u>Clarno Unit map</u>: Widespread, thick, clayey red beds. Subdivisions from the Painted Hills area are also recognized in the Clarno Unit. Mapped in Painted Hills and Clarno units. **Andesite saprolite breccia (Tjanb)**. <u>Painted Hills Unit map</u>: Bleached boulder horizon interbedded with deep-red claystones. Mapped in Painted Hills Unit. **Andesite of Sand Mountain (Tjan)**. <u>Painted Hills Unit map</u>: Dark-gray, fine-grained, non-porphyritic, blocky-jointed, extensive andesite flow unit up to100 m (330 ft) thick. A discontinuous red claystone separates **Tjan** from **Tja** locally. Mapped in Painted Hills Unit. **Member F tuff (Tjft)**. <u>Clarno Unit map</u>: Massive, white, weakly-welded, vitric tuff that is widespread but poorly exposed. Approximately 1–3 m (3–10 ft) thick. Mapped in Clarno Unit. **Volcaniclastic deposits (Tjbs)**. <u>Clarno Unit map</u>: Conglomerates with basalt clasts and sandstones. **Member B basalts (Tjlbb)**. <u>Clarno Unit map</u>: Distinctive fine-grained basaltic andesite flows that overlie **Tja**. The flows weather into cobble-sized blocks. A 21-m- (69-ft-) thick columnar-jointed lava flow crops out at the head of Indian Canyon and is the thickest occurrence of **Tjlbb** in the area. Mapped in the Clarno Unit. **Welded tuff of Member A (Tja)**. <u>Clarno Unit map</u>: Widespread ash-flow tuff that is useful for delineating the Clarno surface at the onset of John Day volcanism. A lower, red-purple, densely welded tuff forms prominent outcrops and is approximately 30 m (100 ft) thick. Unwelded tuff deposits are at the very base of the unit and also form the approximately 25-m- (82-ft-) thick slope on the Member A cuesta. **Tja-1**. Upper Member A. Poorly welded white tuff. **Tja-2**. Lower Member A. Welded tuff. Mapped in the Clarno Unit. <u>Painted Hills Unit map</u>: Welded tuff that occurs in many small white mounds above Clarno Formation red beds in the southern part of the unit. Up to 8 m (26 ft) thick. Mapped in Painted Hills Unit.	**Stratigraphic Features and Paleontological Resources**—Columnar-jointed lava flow (**Tjb**). Welded tuff (**Tja**). Ages of **Tjlb** determined from volcanic layers include 37 million years (andesite of Sand Mountain [**Tjan**]) and 39.72 million years (Member A welded tuff [**Tja**]) at the base of the John Day Formation). Late Eocene flora (**Tjlb**) are approximately 38–36 million years old, several million years younger than the Middle Eocene Clarno flora. **Paleosols**—Between the base of **Tjmb** and **Tjan**: tropical forest paleosols (Acas, Apax, Tuksay, and Sak; see table 23). Between **Tjan** and **Tja**: transition from tropical forest to early successional woodland (Tuksay, Lakim, Kskus, and Micay). **Volcanic Features in the John Day Formation—Tja**: welded tuff from the eruption that produced the Wildcat Mountain Caldera. **Folds and Faults**—Sand Mountain Fault, which offsets **Tjan** by as much as 60 m (200 ft). **Exceptional Geologic Landscape Features—Tjlb** exposed at Red Scar Knoll.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service.	**Global Greenhouse: Eocene Epoch**—Greenhouse conditions increased as the Paleocene–Eocene Thermal Maximum event caused global temperatures to rise. Average annual temperatures in the region of present-day western United States were 20–25°C (68–77°F) and Arctic Ocean temperatures were 23°C (74°F). Fossil plants in **Tjlb** indicate a warm, temperate climate similar to the upper Clarno Formation climate.
	Clarno Formation—<u>Sheep Rock Unit map</u> Undivided (Tcl)	Rock units include: 1) andesite breccia; 2) very hard aphanitic andesite flows; 3) basalt breccia with silicified wood fragments; 4) poorly-sorted, greenish basalt conglomerate; 5) basalt flows; 6) basaltic tuff; 7) dacite; 8) rhyolite flows, rhyolite tuff, and rhyolite breccia with silicified wood fragments; 9) fine ash; 10) volcanic boulder conglomerate; and 11) hard, well-rounded pebble conglomerate. Also includes veins of yellow limonite, thin layers of claystone, and soft hematite. Although not differentiated on the source map, Clarno Formation (undivided) strata are present in the Sheep Rock Unit.	**Stratigraphic Features and Paleontological Resources**—Sedimentary rock features include conglomerates, claystones, and accumulations of bones. Volcanic rock features include lahars, lava flows, and welded volcanic ash (tuff). Few exposures of the Clarno Formation are within the Sheep Rock Unit, and no fossils are known from them.	None reported.	**Global Greenhouse: Eocene Epoch**—See description below.

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Age	Formation	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PALEOGENE (Eocene)	Clarno Formation—Painted Hills Unit map	Claystones of Brown Grotto (Tcg)	Red claystones and ocher-colored claystone breccia that lie between **Tcr** and **Tja**. Hardpans are present locally and cover the underlying **Tcr**. Named for exposures in the Brown Grotto area. Mapped in Painted Hills Unit.	**Stratigraphic Features and Paleontological Resources**—Claystones, claystone breccia, and iron-bearing hardpan. Indistinguishable from the Big Basin Member of the John Day Formation without the presence of **Tja**. **Exceptional Geologic Landscape Features**—**Tcg** named for Brown Grotto exposures.	None reported.	**Global Greenhouse: Eocene Epoch**—Greenhouse conditions increased as the Paleocene–Eocene Thermal Maximum event caused global temperatures to rise. Average annual temperatures in the region of present-day western United States were 20° to 25°C (68°–77°F) and Arctic Ocean temperatures were 23°C (74°F). The fossil remains from **Tcl** represent three major pulses of global warming that resulted in significant mammalian reorganization, floral diversity, and habitat complexity in the Eocene. The Nut Beds (**Tcch**) and Mammal Quarry (**Tcq**) attest to the extensive variety of plants and animals that inhabited subtropical jungles in the region of present-day central Oregon. Fruits and seeds collected from the Nut Beds record a broad-leaved evergreen subtropical forest habitat. The flora and fauna suggest frost-free conditions. The angle of subduction of the Farallon tectonic plate beneath North America decreased, marking a dramatic eastward shift in tectonic activity. The Western Interior Seaway receded from the continent and the Rocky Mountains formed. A broad arc of volcanoes formed in the region of present-day Oregon, producing lava flows, lahars, and ash-fall tuff. Approximately 41.50–39.35 million years ago, the Wildcat Mountain Caldera formed, producing voluminous ash-flow tuff and pyroclastic material. **Tcrh** records a hiatus in volcanic activity 44–40 million years ago. **Tcah** records renewed volcanism that rejuvenated the alluvial system that deposited the Mammal Quarry beds (**Tcq**). Ages of the Clarno Formation determined from volcanic layers include 42.7 million years (stony tuff), 43.8 million years (**Tcab**), and 51.2 million years (**Tcap**).
		Andesite flows (Tcan)	Dark greenish-gray andesite.	**Stratigraphic Features and Paleontological Resources**—Rhyolite flows (**Tcr**), some of which have altered to a pebbly gravel (**Tcsr**). Andesite flows (**Tcan**) cap the sequence and contain phenocrysts of plagioclase and pyroxene. **Exceptional Geologic Landscape Features**—Margin of **Tcsr** exposed at Painted Cove. **Tcr** is exposed at Brown Grotto.		
		Rhyolite saprolite (Tcsr)	White, red, and purple rhyolite saprolite with clay infilling. **Tcsrrg**. Rhyolite cobble conglomerate. Mapped in Painted Hills Unit.			
		Rhyolite of Bear Creek (Tcr)	Platy to blocky, gray rhyodacite that weathers into grayish-purple to grayish-yellow pebbly gravel. Traced to the large rhyolite dome complex of Sheep Mountain. Mapped in Painted Hills Unit.			
		Claystones of Sand Mountain (Tcs)	Red and white claystones.	None reported.		
		Andesite of Bridge Creek Canyon (Tca)	At least three andesite flows in the canyon narrows. The upper flow contains white plagioclase crystals in a dark-gray groundmass. The entire section of weathered andesite and overlying claystones is up to 40 m (130 ft) thick.	**Stratigraphic Features and Paleontological Resources**—Three andesite flows with plagioclase phenocrysts.		
		Claystones of Meyers Canyon (Tcm)	Red claystones that are well exposed on the south-facing hill slope in Meyers Canyon just east of Bridge Creek. Approximately 20 m (70 ft) red claystone lies between resistant andesite lava flows (**Tca** and **Tcla**).	**Stratigraphic Features and Paleontological Resources**—Well-developed paleosol structure. **Paleosols**—Rainforest paleosols (Lakayx) in the Painted Hills area (table 23).		
		Lower Clarno andesite (Tcla)	Dark grayish-blue andesite lava flows. The flows are extensively exposed, dip to the northwest, and have a southwest–northeast-trending outcrop pattern. Correlation of the units in Bridge Creek Canyon with Clarno Formation units south of the canyon is not currently possible. Mapped in Painted Hills Unit.	**Stratigraphic Features and Paleontological Resources**—Platy to blocky-jointed andesite separated from **Tca** by the thick paleosols of **Tcm**.		
	Clarno Formation—Clarno Unit map	Siltstone of the Mammal Quarry (Tcq)	Tan, clayey siltstones and cobble conglomerates. A diverse accumulation of vertebrate fossils make **Tcq** paleontologically important. Several taxa have close affinities with Asiatic fauna and the early Duchesnean North American Land Mammal Age. East of the Mammal Quarry, siltstones of **Tcq** overlie Acas paleosols that cap the andesite breccia of **Tcah**, which overlies the red claystones of **Tcrh**. Mapped in Clarno Unit.	**Stratigraphic Features and Paleontological Resources**—Fossils and sediments that accumulated on a fluvial point bar. Hancock Mammal Quarry: leaves, fish, and amphibian fossils; disarticulated large mammal skeletons (tables 7 and 8). **Paleosols**—Tropical forest (Acas) pedotypes at the base of the unit (table 23). **Exceptional Geologic Landscape Features**—Hancock Mammal Quarry.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service.	
		Andesite of Horse Mountain (Tcah)	Platy to blocky andesite with abundant plagioclase phenocrysts. Caps much of Horse Mountain and overlies a thick red saprolite developed on **Tcab**. Ramp-like flow structures are common in lava flows exposed in the West Face Cliffs. Mapped in Clarno Unit.	**Stratigraphic Features and Paleontological Resources**—Lava flows. Plagioclase phenocrysts.	None reported.	
			Tcau. Upper andesite. Dark-gray basaltic andesite flow. Exposed on the top of the west part of Horse Mountain. Mapped in Clarno Unit.			
			Tcrc. Red claystones. Underlies **Tcau**.			

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Age	Map Unit (Symbol)		Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PALEOGENE (Eocene)	Clarno Formation—Clarno Unit map	Claystones of Red Hill (Tcrh)	Thick sequence of reddish and grayish-purple claystones with lower and upper paleosols separated by a stony tuff bed. Overlies **Tcch**. The unit is 59 m (190 ft) thick in the Red Hill area, but thins dramatically to the east. Mapped in Clarno Unit. **Tcrg**. Cobble conglomerate with rounded clasts of andesite and amygdaloidal basalt that is locally present in the claystones. The conglomerates cut into underlying units of **Tcch**.	**Stratigraphic Features and Paleontological Resources**—Primarily claystones with local conglomerates (**Tcrg**) containing rounded clasts of andesite and basalt. Conglomerates represent channels incised into **Tcch**. Claystones represent floodplain deposits. **Paleosols**—Rainforest (Lakayx) and forest (Luca) pedotypes (table 23). **Exceptional Geologic Landscape Features**—Red Hill.	**Slope Movements**—Claystones are prone to landslides (**Qls**), especially on the eastern side of Indian Canyon. Most landslides occur where thick exposures of claystones are overlain by **Tja**. The coherent blocks of **Tja** form shallow, rocky slides and do not appear to be deeply seated.	**Global Greenhouse: Eocene Epoch**—Greenhouse conditions increased as the Paleocene–Eocene Thermal Maximum event caused global temperatures to rise. Average annual temperatures in the region of present-day western United States were 20° to 25°C (68°–77°F) and Arctic Ocean temperatures were 23°C (74°F). The fossil remains from **Tcl** represent three major pulses of global warming that resulted in significant mammalian reorganization, floral diversity, and habitat complexity in the Eocene. The Nut Beds (**Tcch**) and Mammal Quarry (**Tcq**) attest to the extensive variety of plants and animals that inhabited subtropical jungles in the region of present-day central Oregon. Fruits and seeds collected from the Nut Beds record a broad-leaved evergreen subtropical forest habitat. The flora and fauna suggest frost-free conditions. The angle of subduction of the Farallon tectonic plate beneath North America decreased, marking a dramatic eastward shift in tectonic activity. The Western Interior Seaway receded from the continent and the Rocky Mountains formed. A broad arc of volcanoes formed in the region of present-day Oregon, producing lava flows, lahars, and ash-fall tuff. Approximately 41.50–39.35 million years ago, the Wildcat Mountain Caldera formed, producing voluminous ash-flow tuff and pyroclastic material. **Tcrh** records a hiatus in volcanic activity 44–40 million years ago. **Tcah** records renewed volcanism that rejuvenated the alluvial system that deposited the Mammal Quarry beds (**Tcq**). Ages of the Clarno Formation determined from volcanic layers include 42.7 million years (stony tuff), 43.8 million years (**Tcab**), and 51.2 million years (**Tcap**).
		Conglomerates of Hancock Canyon (Tcch)	Conglomerates with mostly andesite clasts. Dominated by matrix-supported boulder debris flows, but includes tuffaceous beds and a distinctive basalt flow. Contains the Nut Beds fossil site. A prominent bench of red claystone separates **Tcch** from the underlying **Tccp**. Fine-grained tuffs and medium-grained lahar deposits are common in Hancock Canyon. On-laps the Hancock dacite dome (**Tcd**) and the middle andesite unit (**Tcam**). Mapped in Clarno Unit. **Tct**. White pumice lapilli welded tuff. **Tclh**. Lavender lahar with abundant hornblende and andesite clasts. Light-colored boulders weather out of the matrix. Mapped in Clarno Unit. **Tcab**. Amygdaloidal basalt. A distinctive and widespread dark-grey vesicular amygdaloidal basalt flow that displays pahoehoe flow structures and local jointing. Mapped in Clarno Unit. **Tcam**. Middle andesite. Blocky, dark, pyroxene-plagioclase andesite. Locally present south of Clarno along the John Day River. On-lapped by **Tcch**. Fills a paleovalley cut into **Tccp** in the southern part of the area.	**Stratigraphic Features and Paleontological Resources**—Features associated with debris-flow, deltaic, and floodplain deposits. Lahars and lava flows. Paleosols. Clarno Nut Beds: diverse flora including nuts, seeds, and petrified wood representing at least 173 plant species (table 4); fungi (table 5); mammal and reptile fossils (table 6). Hancock Tree (*Exbucklandia* sp.): pipli tree that may be preserved in growth position. **Exceptional Geologic Landscape Features**—Nut Beds, Hancock Canyon.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service.	
		Conglomerates of the Palisades (Tccp)	Matrix-supported, laterally continuous conglomerates with abundant andesite clasts that form the Palisades Cliffs. Interpreted as floodplain debris-flows that on-lap the irregular surface of **Tcap**. Form the spectacular hoodoos along Pine Creek and in the lower part of the West Face Cliffs along the John Day River. Several thin, green, clayey paleosols with wood fragments and leaf impressions are exposed near the middle of the unit. Overlying the green paleosols is a massive debris flow that weathers brown-orange and crops out prominently along the West Face Cliffs. **Tcrp**. Red claystones. A continuous stratigraphic section exposed in the southern part of Cove Creek contains, in stratigraphic order from oldest to youngest: **Tccp**, **Tcrp**, **Tcch**, **Tcrh**, and **Tja**. Mapped in Clarno Unit.	**Stratigraphic Features and Paleontological Resources**—Conglomerates from debris flows form the cliffs and hoodoos of the Palisades. Fossil leaves and petrified wood are found in **Tccp**. The Clarno Fern Quarry preserves leaf impressions, including those of ferns and angiosperms. **Paleosols**—Paleosols represent humid woodland (Scat) and waterlogged lowland forest (Sitaxs) environments (table 23). **Exceptional Geologic Landscape Features**—Clarno Palisades.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service. **Slope Movements**—Potential collapse of hoodoos and cliffs.	

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Age	Map Unit (Symbol)		Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PALEOGENE (Eocene)	Clarno Formation—Clarno Unit map	Andesite of Pine Creek (Tcap)	Thick lava flows of dark andesite. Extensively exposed to the east of Cove Creek. The flows have very irregular upper surfaces. Paleorelief of this unit is best exposed in cliffs along Pine Creek between the Palisades Cliffs and the entrance to Hancock Field Station, where more than 40 m (130 ft) of andesite are on-lapped by debris flows over a lateral distance of 200 m (660 ft). **Tcrw**. Red and white claystones that occur at the top of the unit. Mapped in Clarno Unit.	**Stratigraphic Features and Paleontological Resources**—Andesite lava flows with phenocrysts of pyroxene and plagioclase. **Paleosols**—Paleosols (**Tcrw**) are preserved between **Tcap** and **Tccp**.	**Slope Movements**—Potential cliff collapse along Pine Creek. **Flooding and Subsequent Erosion**—**Tcrw**: The clayey saprolite and claystones erode to form an erosional bench, which is occupied in part by the modem Pine Creek floodplain. Erosion of cliffs along Pine Creek is in part due to the erodability of these claystones.	**Global Greenhouse: Eocene Epoch**—Greenhouse conditions increased as the Paleocene–Eocene Thermal Maximum event caused global temperatures to rise. Average annual temperatures in the region of present-day western United States were 20° to 25°C (68°–77°F) and Arctic Ocean temperatures were 23°C (74°F). The fossil remains from **Tcl** represent three major pulses of global warming that resulted in significant mammalian reorganization, floral diversity, and habitat complexity in the Eocene. The Nut Beds (**Tcch**) and Mammal Quarry (**Tcq**) attest to the extensive variety of plants and animals that inhabited subtropical jungles in the region of present-day central Oregon. Fruits and seeds collected from the Nut Beds record a broad-leaved evergreen subtropical forest habitat. The flora and fauna suggest frost-free conditions. The angle of subduction of the Farallon tectonic plate beneath North America decreased, marking a dramatic eastward shift in tectonic activity. The Western Interior Seaway receded from the continent and the Rocky Mountains formed. A broad arc of volcanoes formed in the region of present-day Oregon, producing lava flows, lahars, and ash-fall tuff. Approximately 41.50–39.35 million years ago, the Wildcat Mountain Caldera formed, producing voluminous ash-flow tuff and pyroclastic material. **Tcrh** records a hiatus in volcanic activity 44–40 million years ago. **Tcah** records renewed volcanism that rejuvenated the alluvial system that deposited the Mammal Quarry beds (**Tcq**). Ages of the Clarno Formation determined from volcanic layers include 42.7 million years (stony tuff), 43.8 million years (**Tcab**), and 51.2 million years (**Tcap**).
		Hancock dacite dome (Tcd)	Dacite intrusion that is overlain by claystone beds (Pswa paleosols). Exposed in the hills and gullies northeast of Hancock Field Station. Formed an erosional, topographic feature. Extensive alteration probably took place in the Eocene. Mapped in Clarno Unit.	**Stratigraphic Features and Paleontological Resources**—Igneous intrusion of dacite with plagioclase and hornblende phenocrysts. The dacite intruded into **Tclc** and was mantled by colluvium and soils of **Tcch** and **Tccp**.	None reported.	
		Lower Clarno conglomerates (Tclc)	Matrix-supported conglomerates with boulder- and cobble-sized clasts of andesite exposed just west of Hancock Canyon. Oldest and most deformed unit in the map area. The unit lacks tuff beds and paleosols. Stratigraphic relationships with overlying strata are not clear. Mapped in Clarno Unit.	**Stratigraphic Features and Paleontological Resources**—Boulders trapped within a fine-grained matrix (debris flows). **Folds and Faults**—**Tclc** was folded and then intruded by the Hancock dacite dome (**Tcd**) before subsequent deformation.		
CRETACEOUS	Cretaceous rocks (Krx)		Painted Hills Unit map: Iron-stained conglomerates and sandstone.	None reported.	None reported.	**Preamble to the Age of Mammals and the Emergence of Central Oregon: Cretaceous Period**—Units were deformed and accreted to the North American continent during the Cretaceous.
	Mitchell Group	Conglomerate with intercalated sandstone lenses (Kc)	Sheep Rock Unit map: Conglomerate and sandstone. Clasts consist of a wide variety of rock types and are as large as cobbles. Conglomerate has very low porosity. The sandstone is about 2 m (6 ft) thick and includes pebbles. It has poor-to-excellent porosity and permeability. Mapped in Sheep Rock Unit.	**Stratigraphic Features and Paleontological Resources**—Gable Creek Formation at Goose Rock contains sedimentary features associated with a submarine fan system. **Exceptional Geologic Landscape Features**—Goose Rock.	**Paleontological Resource Inventory, Monitoring, and Protection**—Management of paleontological resources includes inventory and monitoring, field recovery and excavation, stabilization, preparation, identification, cataloging of specimens, and cyclic prospecting of fossil localities, with more erodible strata visited more frequently. The monument manages John Day Basin paleontological resources cooperatively with Bureau of Land Management and Forest Service. **Flooding and Subsequent Erosion**—Intense cloudbursts and scarce vegetation on badlands topography may trigger flash flooding, which may increase erosion. Erosion may expose or remove fossils.	**Preamble to the Age of Mammals and the Emergence of Central Oregon: Cretaceous Period**—Turbidite (density-flow) deposits in a submarine fan system off the coast of present-day Oregon in the Cretaceous. Units were deformed and accreted to the North American continent.

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Age	Map Unit (Symbol)		Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
CRETACEOUS	Mitchell Group	Sedimentary rocks (Ks)	Sheep Rock Unit map: Fossiliferous conglomerate and sandstone.	None reported.	None reported.	**Preamble to the Age of Mammals and the Emergence of Central Oregon: Cretaceous Period**—Subduction-related intrusions (**Kil**) and submarine fan deposits (**Ks**). Units were deformed and accreted to the North American continent during the Cretaceous.
	Nevadan intrusives (Kil)		Sheep Rock Unit map: Diorite with quartz and biotite, porphyritic granodiorite, norite, and quartz monzonite.			
TRIASSIC	Olds Ferry Terrane	Vester Formation (TRv)	Sheep Rock Unit map: Mostly volcanic sandstone, conglomerate, graywacke, and shale with minor breccia and basalt flows.			**Preamble to the Age of Mammals and the Emergence of Central Oregon: Cretaceous Period**—**TRv** and **TRsp** form the foundation of the Blue Mountains. Each terrane originated as a separate fault-bounded block containing strata of different ages that formed primarily in volcanic island-arc, tropical settings well south of their present latitude.
	Baker Terrane	Igneous and metamorphic rocks (TRsp)	Sheep Rock Unit map: Igneous and metamorphic rocks. Serpentinite.			
PALEOZOIC and MESOZOIC ERAS		Metamorphic rocks (MZPZm)	Sheep Rock Unit map: Metamorphosed limestone, 270 m (900 ft) thick, with stringers of white secondary calcite. Serpentinite fills cavities and fractures.			
PALEOZOIC ERA		Sedimentary, volcanic, and metamorphic rocks (PZu1)	Sheep Rock Unit map: Unspecified Paleozoic rocks; granite; quartz diorite.			