The Geological Society of America
Field Guide 15
2009

Cenozoic paleobotany of the John Day Basin, central Oregon

Richard M. Dillhoff
Thomas A. Dillhoff
Evolving Earth Foundation, P.O. Box 2090, Issaquah, Washington 98027, USA

Regan E. Dunn
Department of Biology, University of Washington, Box 351800, Seattle, Washington 98195, USA

Jeffrey A. Myers
Department of Earth Sciences, Western Oregon University, 345 N. Monmouth Ave, Monmouth, Oregon 97361, USA

Caroline A. E. Strömberg
Department of Biology & Burke Museum of Natural History and Culture, University of Washington, Box 353010, Seattle, Washington 98195, USA

ABSTRACT

The John Day Basin of central Oregon contains a remarkably detailed and well-dated Early Eocene–Late Miocene sedimentary sequence, known for its superb fossils. This field trip examines plant fossil assemblages from throughout the sequence in the context of their geological and taphonomic setting and regional and global significance. The Early to Late Eocene (>54–39.7 Ma) Clarno Formation contains fossil plants and animals that occupied an active volcanic landscape near sea level, interspersed with meandering rivers and lakes. Clarno assemblages, including the ca. 44 Ma Nut Beds flora, record near-tropical "Boreotropical" rainforest, which was replaced during late Clarno time by more open and seasonal subtropical forest. The overlying John Day Formation (39.7–18.2 Ma) was deposited in a backarc landscape of low hills dotted with lakes and showered by ashfalls from the Western Cascades. Fossils and paleosols record the advent of the "Icehouse" Earth during the earliest Oligocene, with decreasing winter temperature and more seasonal rainfall that supported open deciduous and coniferous forest, much like that of the southern Chinese highlands today. Sixteen and a half million years ago the Picture Gorge flood basalt covered the region. Animals and plants fossilized in the overlying (ca. 16 to >12 Ma) Mascall Formation occupied a relatively flat landscape during a warm and moist period known as the Middle Miocene Climatic Optimum. In total this sequence preserves a detailed series of time slices illustrating regional biotic and landscape evolution during the Cenozoic that is highly relevant for deciphering regional and global biotic, climatic, and geological trends.

Dillhoff, R.M., Dillhoff, T.A., Dunn, R.E., Myers, J.A., and Strömberg, C.A.E., 2009, Cenozoic paleobotany of the John Day Basin, central Oregon, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 135–164, doi: 10.1130/2009.fld015(07). For permission to copy, contact editing@geosociety.org. ©2009 The Geological Society of America. All rights reserved.

HISTORY OF PALEONTOLOGICAL COLLECTION AND STUDY IN THE JOHN DAY BASIN

The John Day Basin of central Oregon preserves an astonishingly rich fossil record of Cenozoic vertebrates, plants (macrofossils, pollen and spores, and, more recently discovered, phytoliths), and fossil soils. The basin contains an almost uninterrupted 2200-m-thick sequence of richly fossiliferous Early Eocene–Late Miocene (ca. 54–7 Ma) deposits. These provide an extraordinary window into Cenozoic ecosystem evolution in the context of climate and environmental change. Congress recognized the importance of the John Day Basin sequence by designating John Day Fossil Beds National Monument in 1975. This field trip will visit key localities in the Clarno, John Day, and Mascall Formations, and visit the Thomas Condon Paleontology Center of John Day Fossil Beds National Monument, which houses important paleobotanical and vertebrate collections and scientifically informed artist reconstructions of the region through the Cenozoic (Fig. 1).

The John Day Basin has interested many prominent U.S. and foreign students of Cenozoic paleontology and geology for a century and a half (Fig. 2). In 1861, a company of soldiers returning to Fort Dalles (now The Dalles, Oregon) from the Crooked River area after searching the area for a railroad route to the Pacific discovered fossilized bones and teeth eroding from outcrops of what is now known as the John Day Formation. Their fossil collections caught the eye of Thomas Condon, then a pastor of the Congregational Church at Fort Dalles. Condon, having an interest in paleontology and geology, recognized the significance of the soldiers' finds and in the following year, joined a company of soldiers heading back to the Harney Valley. On their return trip, Condon collected specimens of fossil plants from the Bridge Creek area.

In a letter to J.S. Newberry, Condon wrote:

> On my last visit to the place of the outcrops I found some new things, new leaves, new fruit…as the region when I was there was infested with hostile Indians whose fresh tracks were on the trail I traveled, I could examine but little of the surroundings…. (Recounted in Clark, 1989).

Some of these specimens were given to John Strong Newberry of Columbia University who described several fossil plants from the John Day Basin in 1883, with additional descriptions in 1898. The collections also sparked the interest of other paleobotanists and vertebrate paleontologists. Collecting parties under O.C. Marsh (Yale University), E.D. Cope (U.S. Geological Survey), W.B. Scott (Princeton University), and John C. Merriam (University of California) visited the region between 1871 and 1900 to collect, in particular, mammal fossils. Merriam also deserves credit for first describing the lithostratigraphic units in the John Day Basin (Merriam 1901). Condon's Bridge Creek plant fossils are now housed at the U.S. National Museum, Smithsonian Institution.

A collection made by C.D. Voy, a collector from San Francisco, in 1870, was acquired by the University of California and studied by Leo Lesquereux. Lesquereux, too, published descriptions

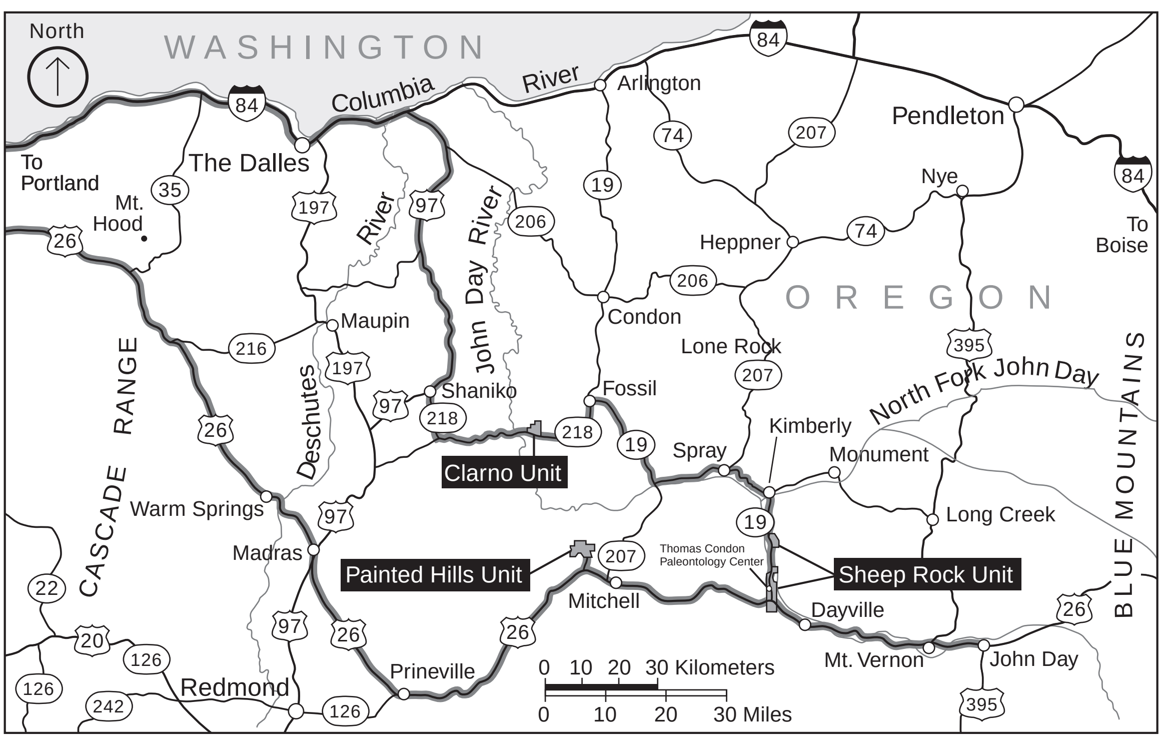

Figure 1. The field trip route through the John Day Basin.

of species from the Bridge Creek Flora. Some of these were the same taxa as described by Newberry but were given different names, thus making nomenclature priority somewhat ambiguous (Meyer and Manchester, 1997). Both Lesquereux and Newberry considered the Bridge Creek Flora to be Miocene in age.

In 1901, Frank Hall Knowlton traveled to the John Day Basin with Merriam and, in 1902, included the Bridge Creek flora in a monograph of floras exclusively from the John Day Basin. Knowlton was the first to document other sites in the area including those from the Clarno and Mascall Formations. Knowlton considered the Bridge Creek Flora to be part of the Clarno Formation, and Eocene in age.

Ralph Works Chaney from the University of California, Berkeley, began working in the John Day Basin in the early 1920s and coined the name Bridge Creek flora. Many of his studies included work on the flora at the type locality near Bridge Creek, a tributary of the John Day River that flows north through the Painted Hills (Chaney, 1925a), as well as other sites that he deduced to be equivalent in the Crooked River Basin (Chaney, 1927). He published extensively on the flora, which he considered Oligocene in age, and he was the first to use quantitative methods of collection to determine the floral composition, taphonomy, and paleoclimate of the assemblage (Chaney, 1925a). He made comparisons of the Bridge Creek floral assemblage to modern Muir Woods in the redwoods of northern California (Chaney, 1924). Later, after the discovery of *Metasequoia* growing in China, leading to the realization that most of the Bridge Creek fossils that had been assigned to *Sequoia* were instead *Metasequoia*, Chaney recognized the similarity of the Bridge Creek flora to modern Asian floras (Chaney, 1948a, 1951). The Bridge Creek

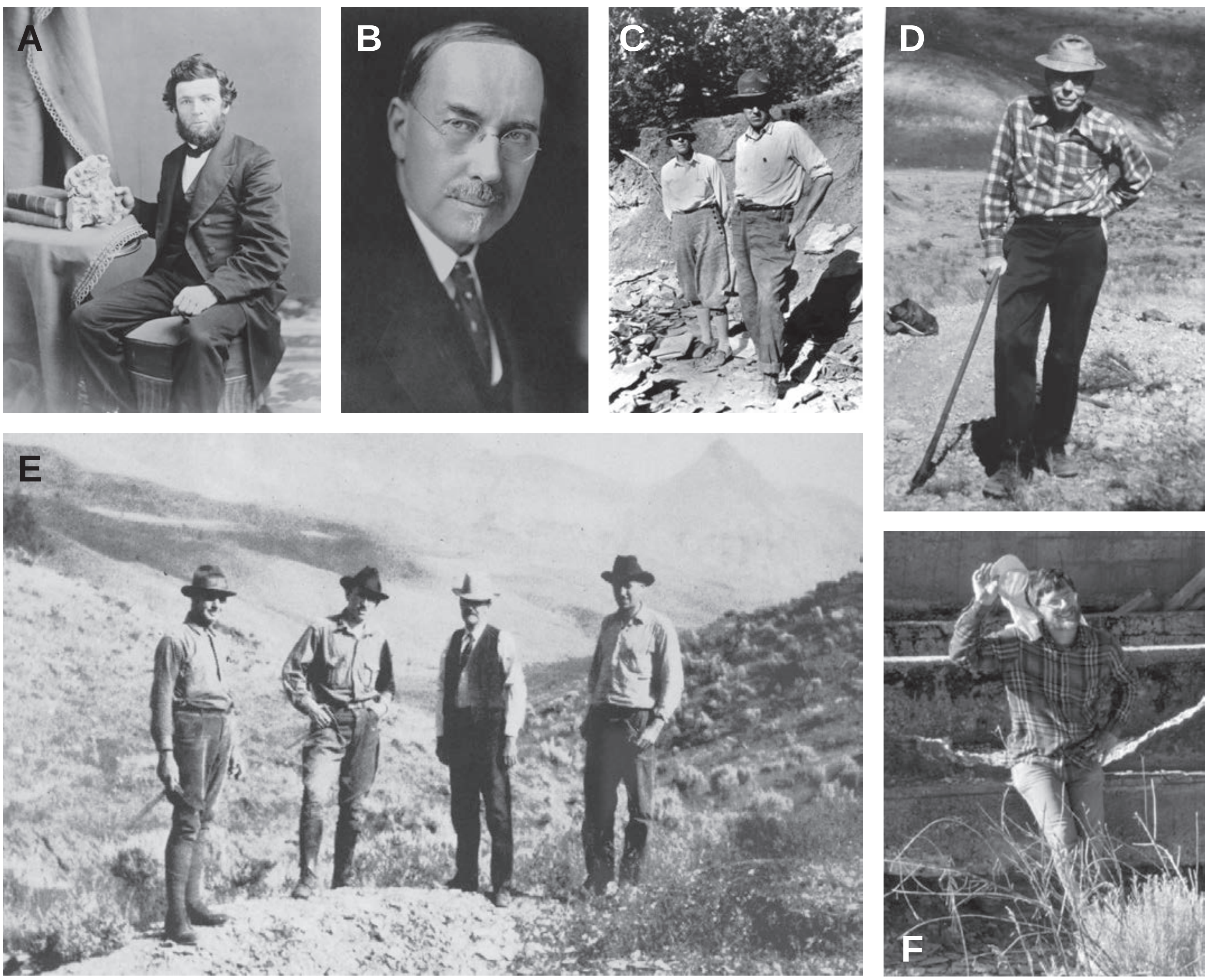

Figure 2. Pioneers of John Day Paleobotany and their successors. (A) Rev. Thomas Condon. (B) J.C. Merriam. (C) R.W. Chaney and Elizabeth Oliver. (D) Thomas Bones. (E) Left to right: E. Furlong, C. Stock, J. Merriam, R. Chaney (photo from Chaney, 1948b). (F) Steven R. Manchester.

assemblage has henceforth figured prominently in discussions of Chaney's hypothesized Arcto-Tertiary flora.

Since Chaney, the Bridge Creek flora has figured prominently in studies of specific lineages or taxa by many paleobotanists, including H.L. Mason (1927, 1947), R.W. Brown (1959), H.E. Schorn (1966), T. Tanai and J.A. Wolfe (1977), Wolfe and Tanai (1987), and Wolfe (1977). More recent work includes several species descriptions by Steven R. Manchester (1987a, 1987b, 1992, 1994a) and Manchester and Crane (1987) and autecological studies (Retallack et al., 1996; Retallack, 2004c). Most recently, Meyer and Manchester (1997) published a monograph of the Bridge Creek Flora that included the examination of nearly 20,000 specimens from at least seven fossil sites in the region. Their monograph contains detailed taxonomic descriptions of 110 species belonging to 91 genera. Fruits and seeds (Manchester, 1994b) and wood (Wheeler and Manchester, 2002) of the Clarno Nut Beds flora have also been thoroughly monographed. Ongoing work by Manchester and others focuses on other localities of the Clarno flora, including highly fossiliferous and well-preserved floras in lacustrine deposits at Red Gap, John Day Gulch, Alex Canyon, White Cliffs, Horse Heaven Mine, and West Branch Creek. Jane Gray collected samples for palynological studies of the Bridge Creek flora, but never published her work.

In addition to the Clarno and Bridge Creek floras, the Middle Miocene Mascall Formation is an important component of the John Day basin. Major plant fossil localities of the Mascall lie east of the town of Dayville, Oregon, along the John Day River and Highway 26. Most of the sites are on private property and very little collecting has been done in recent years. The Mascall Formation was formally named by Merriam in 1901, although fossils from the area had been known since the 1870s (Knowlton, 1902) and described along with other fossil plants from the John Day area (Lesquereux. 1878, 1888; Newberry, 1883; Merriam, 1901).

Knowlton (1902) attempted the first comprehensive study on plant fossils from the Mascall Formation. He used earlier collections plus material that he gathered himself from a locality that he referred to as Van Horn's Ranch or Belshaw's Ranch (these are actually two localities separated by ~1 km), and included 80 taxa. He concluded that the plants indicated a Late Miocene age, supporting an earlier determination made by Merriam. Chaney (1925b) published a further investigation of the Mascall Formation in which he examined other floras in the northwest and noted the relationship of many of them to the Mascall flora. Based upon his observations, he reassigned the Mascall flora to the Middle Miocene.

The most extensive study of the Mascall flora was that by Chaney (1959) and Chaney and Axelrod (1959) in which all previous work, over 10,000 megafossils, plus the preliminary pollen work of Jane Gray were reviewed. Since the work of Chaney and Axelrod, most of the emphasis in recent paleobotanical studies of the John Day basin has been on Eocene and Oligocene floras, while floras of the Mascall Formation have received little attention.

GEOLOGICAL AND PALEOBOTANICAL OVERVIEW

The Cenozoic sequence in the John Day Basin rests on Mesozoic accreted tectonic terranes and consists, in successive order, of the Early-Middle Eocene Clarno Formation (ca. 54–39.7 Ma), Late Eocene–Early Miocene John Day Formation (39.7 to ca. 18.2 Ma), Early-Middle Miocene Picture Gorge Basalts (ca. 16.5–16 Ma), Middle-Late Miocene Mascall Formation (ca. 16 to >12 Ma), and Late Miocene Rattlesnake Formation (ca. 8–6 Ma) (Fig. 3).

The 1800-m-thick Clarno Formation, spanning much of the Eocene, crops out widely in central Oregon. The Columbia River Basalt series covers the most northern extent of the formation. White and Robinson (1992) and Myers (1998) extended the formation south to rocks at the base of the Lower Cedarville Formation in northeastern California. The Clarno Formation formed within a near sea level extensional basin or series of basins within a broad volcanic arc complex that followed a northwest-southeast trend from the Middle Eocene north coast of what is now Oregon southeast into northeast California and Nevada (White and Robinson, 1992). One notable silicic volcanic complex near Horse Heaven to the southwest of Camp Hancock generated thick ashfall deposits that inundated lakes to entomb fossils of the White Cliffs, Horse Heaven, Cherry Creek, Red Gap, and John Day Gulch fossil localities. While a large body of research recognizes that a major Middle Eocene river system crossed the region from Idaho to feed the Tyee Delta complex, recent work by D'Allura and Hopt (2009) indicates that the Klamath terranes remained steep enough to provide coarser pebbles and cobbles to the Tyee river system, as well.

The Middle Eocene Clarno volcanic arc appeared much like that of modern Central America, lying near sea level but interrupted by large, widely spaced active volcanic complexes and older inactive vents (White and Robinson, 1992). A very low angle "flat slab" subducted beneath far western North America from Late Cretaceous to late Middle Eocene time. The largest of these volcanoes included large andesitic stratocones that generated voluminous basaltic andesite flows and laharic breccias. As is typical of intra-arc basin sequences, beds in the Clarno Formation have limited lateral continuity. A 200-m-thick lava flow may abruptly buttress against older lahar deposits, and the formation is characterized by laterally discontinuous and lithologically varied rocks, including lava flows, pumicious tuff, laharic breccia and conglomerate and lacustrine mudstone.

Approximately 40 million years ago, the Clarno volcanic arc became inactive after the "flat slab" detached (e.g., Lipman et al., 1972, Noble, 1972). This event produced several major consequences for central Oregon. Steepening of the subduction zone resulted in formation of the Western Cascades far to the west of Camp Hancock. The oldest dated Western Cascades volcanics from the Late Eocene Fisher Formation line the east side of the Willamette Valley between Eugene and Cottage Grove, and yield ages between 34 and 38 Ma. Western Cascades volcanoes, like those of the Clarno arc, appear to have been widely

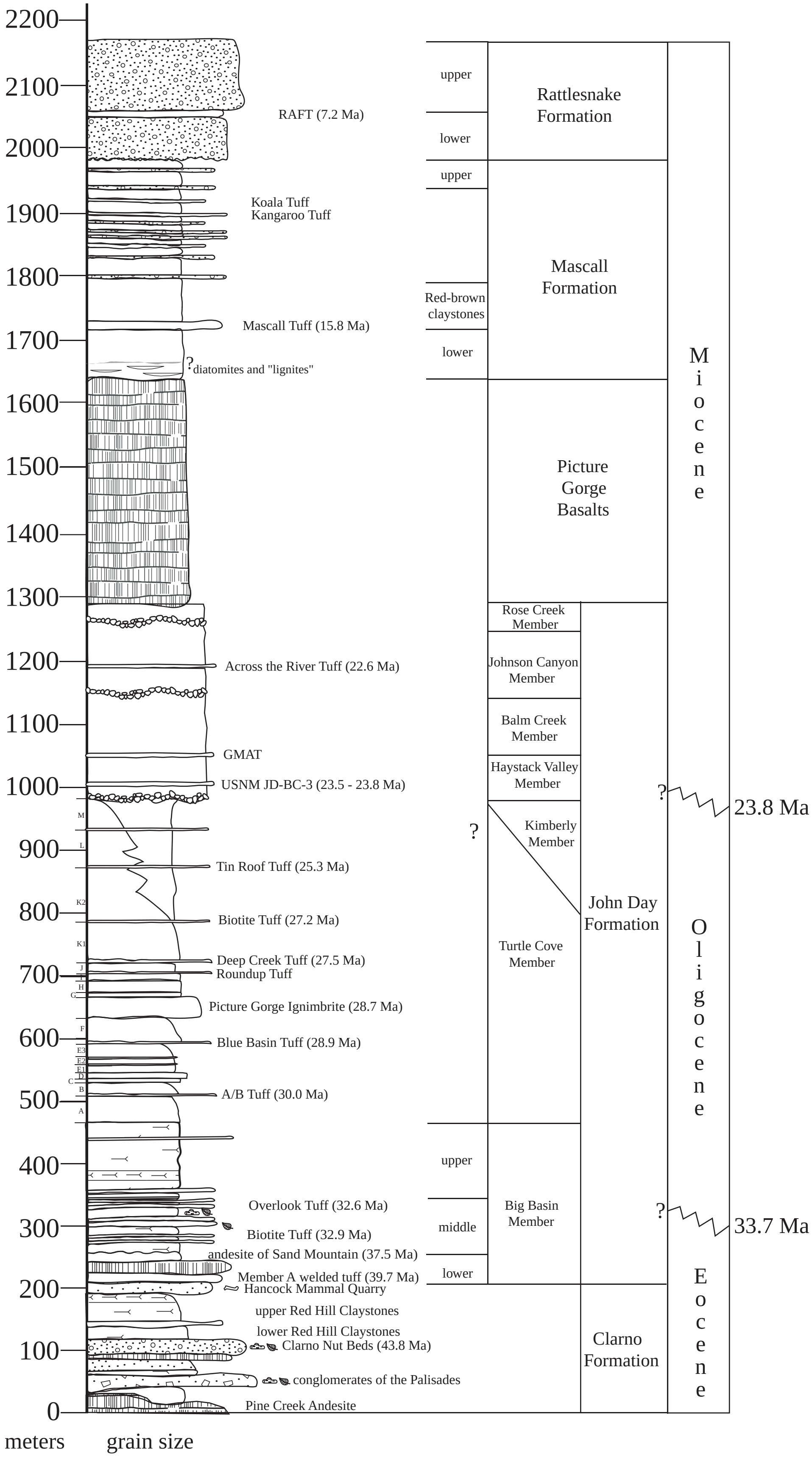

Figure 3. Composite stratigraphic section of Cenozoic rocks in the John Day Basin. Geologic columns adapted from Retallack et al. (2000), Fremd et al. (1994), and Bestland and Forbes (2003).

spaced stratocones on a near sea-level coastal plain. Some may have stood offshore. Formation of the Cascades arc built the Oregon coast westward leaving the John Day Basin well interior to the coast. However, it is important to note that the Western Cascades did not produce a significant regional rainshadow until the Cascades block was tilted up in the east during the Late Miocene (Priest, 1990).

The topographically irregular and chaotic landscape of the Clarno arc was gradually replaced by gentler hills separated by broad lake basins. The absence of significant sediment sources resulted in formation of repetitive paleosols that characterize much of the upper Clarno and John Day formations. Voluminous ash falls from the new Western Cascades contributed the bulk of sediment to the region after ca. 32 Ma (Robinson et al., 1984).

Breakoff of the "flat slab" also produced renewed regional extension, now in the backarc of the Western Cascades (e.g., Lipman et al., 1972; Noble, 1972). Intense crustal heating accompanied extension as the asthenosphere came into contact with thinned continental crust. Volcanism resulting from the melting of continental lithosphere produced highly silicic caldera eruptions of the "ignimbrite storm." The "ignimbrite storm" followed detachment of the "flat slab" as it tore from north to south, from ca. 53 Ma in the north (southern British Columbia and Washington State) to ca. 18 Ma in the south near Las Vegas. Silicic caldera volcanism reached the John Day Basin ca. 40 Ma, and produced rhyolite tuffs including Ignimbrite A, which forms the base of the John Day Formation at 39.7 Ma.

The John Day Formation spans the timeframe from 39.7 Ma until 18.2 Ma. From a paleobotanical perspective, the main focus is on the lower John Day Formation, which contains the Bridge Creek flora. The Big Basin Member is the basal member of the John Day Formation formalized by Fisher and Rensberger (1972). Radiometric dating indicates that it ranges from ca. 40 to 30 Ma (Bestland et al., 1994, 1997; Retallack et al., 2000). The type area for the member is near Picture Gorge, but 260 m of section are exposed at Painted Hills (Bestland et al., 1994). It consists mostly of fine- to coarse-grained rhyodacitic material that was deposited in a back-arc setting and represents a distal record of early Cascade volcanism (Robinson et al., 1984). The highly oxidized tuffaceous mudstones and claystones that are red, orange and yellow in color are highly distinctive among the members of the John Day Formation, although they are similar in appearance to tuffaceous units of the upper Clarno Formation.

The multiple-colored strata of the Big Basin Member are interpreted as fossil soils. Numerous papers by G.J. Retallack and E.A. Bestland describe the composition, geometry, weathering rates and many other aspects of the paleosol record of the Big Basin Member (e.g., Bestland et al., 1994, 1997; Bestland, 1997; Retallack et al., 2000; Retallack, 2008d). The Big Basin Member was probably deposited in a floodplain environment surrounded by moderate topography (Bestland, 1997). Fossil leaves of the Bridge Creek flora are found in tuffaceous siltstones representing lacustrine environments within those floodplains. Refer to Figure 6 for detailed stratigraphy of the Painted Hills.

Floral assemblages at the Painted Hills occur in the Middle Big Basin Member and are bound by tuffs that have been dated radiometrically. Leaf-bearing strata are underlain by the Biotite Tuff dated as 32.99 ± 0.11 Ma and overlain by the Overlook Tuff dated as 32.66 ± 0.03 Ma (Retallack et al., 2000).

About 16.5 Ma, lava flows of the Picture Gorge Basalt erupted from fissures in the Blue Mountains Anticline, producing the Kimberly Dike Swarm. The feeder dikes can be seen along the John Day River near Kimberly. The Picture Gorge Basalt is a southern extension of the Grand Ronde Series of Columbia River Flood Basalts, and caps the John Day Formation. The Picture Gorge Basalts have been dated using both radiometric and paleomagnetic methods at 16.5–16.3 Ma (Bestland et al., 2008). These lava flows, with caps of baked paleosols, are best seen in Picture Gorge, near the Thomas Condon Center.

Cessation of the Picture Gorge Basalt eruptions was followed by deposition of the Middle Miocene Mascall Formation. The Mascall Formation conformably overlies the Dayville Basalt Formation of the Picture Gorge Basalt Subgroup, with a tuff bed near the base of the formation dated at 16.2 ± 1.4 Ma. In its type area, the Mascall Formation consists of a series of sedimentary sequences with a total thickness of at least 350 m. The interpretation of Bestland et al. (2008) is that the Mascall basin was an alluvial system in a tectonically quiet area of low relief on the southern margin of the Columbia River Plateau. Columbia River Basalt eruptions continued to the north and east of the Mascall basin for the next several million years, but these did not directly impact Mascall. The sediments are dominated by paleosols laid down in a floodplain depositional environment. Radiometric dates have not been obtained to constrain the upper age of the Mascall Formation, but it is estimated at ca. 12 Ma based on the time it would take for the observed paleosol sequences to develop (Bestland and Forbes, 2003; Prothero et al. 2006; Bestland et al., 2008).

Most fossil plant bearing horizons in the Mascall Formation are located near the base of the sequence and represent alluvial and lacustrine sedimentary environments. The dominant lithology for the lacustrine deposits is silty diatomite. Diatoms that have been identified include *Anlacosira ambigua* (dominant), *A. granulata, Melosira teres*, and pennate diatoms of *Gomphonema, Cymbella, Fragilaria, Synedra,* and *Navicula*. Although rare, the presence of *Tetracyclus ellipticus* is consistent with a Miocene age for the deposit. Most of these diatoms are still extant, and are typically found in comparatively shallow eutrophic freshwater lakes (Kuiper, 1988).

The Late Miocene Rattlesnake Formation overlies the Mascall Formation with an angular unconformity of 7–8° (Bestland et al., 2008), and is the last major depositional sequence in the region. It contains ~120 m of conglomerates, paleosols and tuff, including the prominent Rattlesnake Ash Flow Tuff (RAFT) which has been radiometrically dated at 7.2 Ma (Bestland and Forbes, 2003). While the Rattlesnake is an important source for Late Miocene mammals, it is not known to contain any important paleobotanical deposits, although Chaney (1948b) does reference one fossil plant bearing site in sediments below the RAFT.

Vegetation and Climate History Recorded in the John Day Basin

The Clarno, John Day and Mascall Formations contain abundant and well-preserved macro and microfloras that record the floristic, vegetational, climatic, and ecosystem evolution of the region and correlate closely with broader Northern Hemisphere and global biotic and environmental transitions (e.g., Fig. 4; Wolfe, 1992, 1994b; Myers, 2003). Vegetation and climate inferences from fossil plant data are supported, in part, by interpretation of climatic and environmental change from abundant associated paleosols, which form a nearly continuous record in the John Day Basin (e.g., Retallack, 2004b, 2007, 2008; Sheldon et al., 2002).

During the Middle Eocene multi-tiered paratropical broadleaved evergreen "boreotropical" forest covered the North American west coast to Alaska (Wolfe, 1977; Manchester, 1994b; Graham, 1999). The Clarno Formation contains nearly a dozen well-preserved assemblages of Middle Eocene age, including lake delta and floodplain assemblages from the Clarno Nut Beds (e.g., Manchester, 1994b; Wheeler and Manchester, 2002) and Ochoco Summit, as well as lacustrine impression floras from

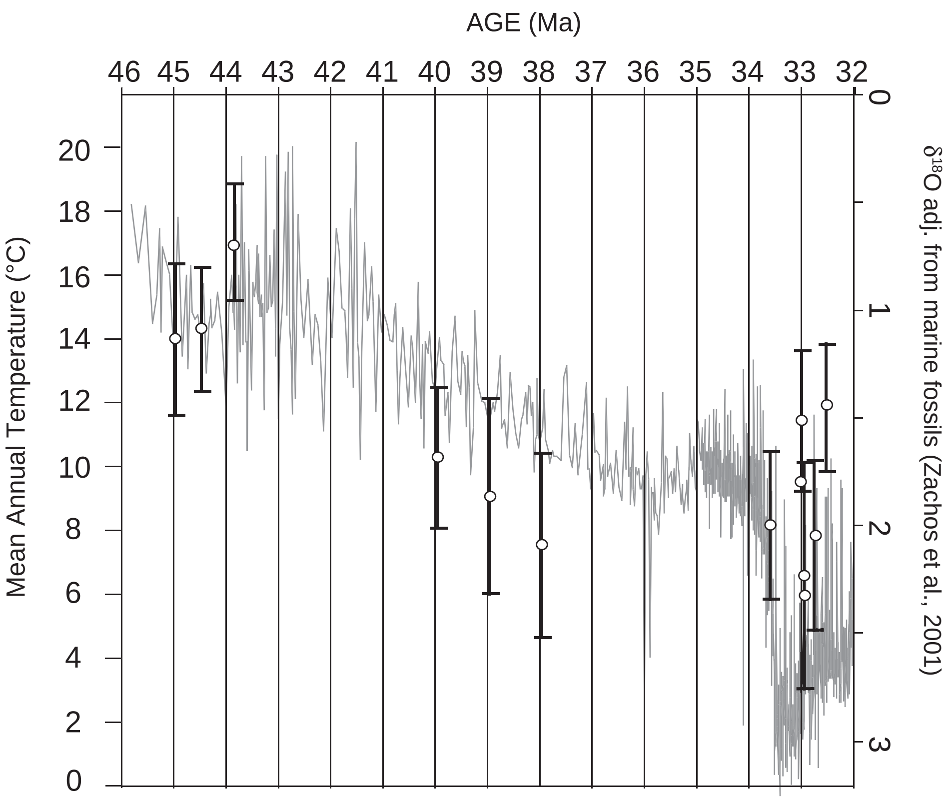

Figure 4. Comparison of the Cenozoic marine $\delta^{18}O$ isotopic record (Zachos et al. 2001) and changes in mean annual temperature (MAT) established from CLAMP (Climate-Leaf Analysis Multivariate Program) and leaf margin analyses of paleofloras from the John Day Basin. MAT estimates from Manchester (2000), Meyer and Manchester (1997), and Smith et al. (1998).

Locality	Age (Ma)	MAT (°C)	MAT Error(°C)	# Dicot Leaves
West Branch Creek	45	13.99	2.35	41
White Cliffs	44.5	14.29	1.94	61
Clarno Nut Beds	44	17.05	1.84	69
John Day Gulch	40	10.32	2.20	40
Kings Gap	39	15.50	3.18	19
White Cap Knoll	39	9.09	3.07	19
Sumner Spring	38	7.56	2.86	19
Slanting Leaf Beds	33.62	8.18	2.31	31
Nichols Spring	33	6.60	3.26	11
Canal Flora	33	6.00	3.55	10
Cove Creek	33	9.40	2.40	26
Lost Creek	33	10.62	2.83	18
Crooked River	33	8.48	1.81	41
Painted Hills	32.7	7.87	2.14	37
Fossil High School	32.58	11.85	1.93	53

West Branch Creek, Alex Canyon, White Cliffs, Cherry Creek, Red Gap, John Day Gulch, Horse Heaven Mine, Dry Hollow, and other localities. While some of these assemblages are well-dated, including the Clarno Nut Beds at 43.8 Ma (Retallack et al., 2000) and White Cliffs at 44.23 Ma (Manchester, 1990), the precise age of others remains unknown, and considerable disagreement surrounds the exact stratigraphic placement of several assemblages.

The Clarno flora is characterized by abundant thermophilic taxa, including *Ensete* (banana), large-leaved monocotyledons, cycads and palms that for physiological reasons cannot tolerate frost (Manchester, 1995). These taxa define climatic minima under which the flora could have grown. Crocodilians found in the Clarno Formation similarly point to frost-free conditions (Fremd et al. 1994). Although dominated by thermophiles, virtually all Clarno assemblages include a significant proportion of taxa that today achieve their maximum diversity in temperate regions, including *Mahonia*, Betulaceae, Pinaceae, Platanaceae, Juglandaceae, Ulmaceae, and others. In some assemblages, including the John Day Gulch assemblage, these plants dominate the flora. This reflects, in part that the majority of Clarno assemblages grew in or near disturbed settings where temperate lineages grow regardless of climate (so-called azonal vegetation).

Analyses of leaf physiognomy (CLAMP: Climate-Leaf Analysis Multivariate Program) and leaf margins (LMA: Leaf Margin Analysis) of Clarno assemblages suggest a mean annual temperature (MAT) of 14–21 °C (Wolfe, 1992; Wiemann et al., 1998; Manchester, 2000; Myers, 2003) and a relatively high mean annual precipitation (MAP) of up to 3000 mm of relatively non-seasonal rainfall. It is critical to note that the cold month mean temperature recorded in all Clarno assemblages is well above freezing. This may account for the presence of true thermophiles in an otherwise more temperate flora. In general the analysis of wood structure yields similar climatic results (Wiemann, et al., 1998; Wheeler and Manchester, 2002)

It is possible that the region became seasonally drier and cooler near 40 Ma. A sparse flora from the ca. 40 Ma Hancock Quarry locality appears to lack the characteristic thermophiles of the Nut Beds flora (McKee, 1970), and the paleosol sequence spanning this interval suggests a seasonally drier environment (Bestland et al., 1997). A drier, more open habitat is also indicated by Hancock Quarry mammals (Pratt, 1988; Retallack et al., 1996).

By ca. 38 Ma, climate had cooled significantly, and the Whitecap Knoll flora of the lower Big Basin Member of the John Day Formation yields LMA estimates of MAT in the range of ~8 °C (Manchester, 2000). Although small, the flora is overwhelmingly temperate in composition, but still includes a few evergreen broadleaved taxa that indicate that cold month temperature must have remained no lower than slightly above freezing. Other floras from this period are rare, and include a Late Eocene fruit and seed assemblage from near Post (Manchester and McIntosh, 2007), as well as assemblages from Gray Butte, to the west (Smith et al., 1998). The warm, wet, latest Eocene (ca. 34 Ma) “Goshen-type” interval (Wolfe, 1981) does not appear to be recorded in paleofloras or paleosols from the John Day Basin, although this interval is well documented elsewhere in the Northwest (Wolfe, 1968, 1992, 1994a; Myers, 2003).

The transition to the Oligocene marks a distinct departure from warmer climates in Oregon. Although humid, paratropical latest Eocene “Goshen-type” paleofloras have not been recovered from central Oregon, some of the best known of these floras occur to the west in the Willamette Valley, including the Goshen flora itself. Ar^{40}/Ar^{39} dates from the Bond Creek Tuff, which underlies the Goshen flora, indicate a maximum age of 34–34.8 Ma for the flora (Myers et al., 2002; Retallack, 2004b; Retallack et al., 2004a). The oldest dated Bridge Creek assemblage, the Iron Mountain assemblage (Slanting Leaf Beds), yields an Ar^{40}/Ar^{39} age of 33.62 Ma. Dramatic climate change of the Eocene-Oligocene “Boundary Event” thus occurred between ca. 34 and 33.6 Ma in Oregon, or near the Eocene-Oligocene boundary at 33.9 Ma. Comparisons of pre and post cooling paleofloras from western Oregon suggest a decrease in MAT of between 3 °C (Myers, 2003) and 6 °C (Wolfe, 1993). In spite of large statistical uncertainties, CLAMP data also suggest that precipitation became markedly more seasonal during the event, and cold month mean temperature dropped below freezing throughout much of the Far West. These changes may have had a far more important impact on plant communities than the temperature decline alone, because seasonal drying and increasingly cold winters may have exceeded threshold tolerances for many lineages that were common during the late Eocene (Myers, 1998, 2003). Indeed, the Bridge Creek flora retains few lineages incapable of withstanding freezing winter temperature or seasonal drought.

The diverse Bridge Creek flora includes at least seven major assemblages from throughout the John Day Basin (Meyer and Manchester, 1997). Bridge Creek vegetation most closely resembles modern temperate hardwood deciduous forest of Southeast Asia, and contains many species belonging to genera or families that achieve their maximum diversity and abundance in these Southeast Asian forests. The Bridge Creek flora marks the appearance of *Metasequoia* in Oregon; and this taxon is a dominant member of all Bridge Creek assemblages, along with a number of other conifer genera (Chaney, 1952; Meyer and Manchester, 1997). Important angiosperm families in the flora include most of the characteristic Arcto-Tertiary groups: Hamamelidaceae, Platanaceae, Ulmaceae, Fagaceae, Betulaceae, Juglandaceae, Tiliaceae, Rosaceae, Sapindaceae, and Rhamnaceae. Many of these families are diverse, including Rosaceae (8 species), Juglandaceae (7 species), Betulaceae (at least 6 species), and the genus *Acer* (at least 10 species). Conspicuously absent is the tremendous diversity of evergreen dicotyledons found in the Clarno flora; and these groups appear to have been extirpated from central Oregon by Bridge Creek time. A few do make it into the early Oligocene Willamette flora of western Oregon, however, including *Meliosma*, *Magnolia*, and several evergreen laurels. These cold intolerant plants appear to have remained along the coast through ca. 10–12 Ma.

The Eocene-Oligocene “Boundary Event” is thought to form part of the major global cooling event near the Eocene-Oligocene boundary, manifested as an ~+1.5‰ change in oxygen isotopic ($\delta^{18}O$) values of benthic foraminifera in a short time period (~300,000 years) (e.g., Coxall et al., 2005). Proposed mechanisms for this event include a global drop in CO_2 (Deconto and Pollard, 2003; Liu et al., 2009), altered oceanic circulation leading to thermal isolation and ice buildup in Antarctica (Kennett, 1977), and changes in Earth's obliquity causing cooler summers (Coxall et al., 2005). MAT estimates from floras of the John Day area show gradual cooling beginning in the Middle-Late Eocene (Meyer and Manchester, 1997; Manchester, 2000), as do paleosol data (Sheldon et al., 2002; Retallack, 2007, 2008). The coolest temperatures of the interval are recorded in the earliest Oligocene floras, but the lack of latest Eocene leaf fossils precludes direct observation of biotic perturbation during the "Boundary Event" itself (Meyer and Manchester, 1997; Manchester, 2000).

There are few floras from the Late Oligocene and Early Miocene of the John Day Basin or elsewhere in Oregon. The Late Oligocene or Early Miocene Yaquina flora from western Oregon reflects a coastal rainforest under humid to mesic conditions, with a MAT of 15.5 °C (Wolfe, 1993; Graham, 1999). In contrast, paleosol chemistry indicates development of cool, dry conditions in central Oregon during the Late Oligocene (Sheldon et al., 2002; Retallack 2004b, 2007, 2008). The Early Miocene Alvord flora (ca. 24 Ma) of southeastern Oregon is considered an upland coniferous-hardwood forest (Axelrod, 1944; Schorn et al., 2007), but vegetational data from central and western Oregon are scarce (Graham, 1999). Reconstructions of climate in central and eastern Oregon based on paleosols suggest a dip in both MAT (from ~10 °C to 5 °C) and mean annual precipitation (MAP) (from ~750 mm to 550 mm) at the Oligocene-Miocene boundary, followed by a more or less gradual increase in both MAT and MAP toward the Middle Miocene (Retallack, 2008).

A warming trend in the Early Miocene culminated in the Middle Miocene Climatic Optimum (MMCO; ca. 17–15 Ma), marking the highest global temperatures since the Late Eocene. Although the exact cause of this warming remains controversial, this phase of warmer climates has recently been correlated with increased atmospheric CO_2 levels, potentially caused by massive Columbia River Basalt and Central European volcanism (Hodell and Woodruff, 1994; Kürschner et al., 2008). It is evident in paleofloras of the Mascall Formation (ca. 16 Ma) of the John Day Basin. The Mascall Formation preserves important records of the MMCO in the Pacific Northwest, including representative plant assemblages as well as a diverse mammalian fauna. It is one of a series of roughly coeval deposits that formed in the northwest during the Miocene, including the Latah Formation of northeastern Washington and northern Idaho, the Vantage wood flora in the Columbia River Basalts of central Washington, and the Succor Creek flora of southeastern Oregon and southwestern Idaho (Chaney and Axelrod, 1959; Graham, 1999). Together these sites preserve plants and animals that indicate a regional humid, temperate climate with relatively high diversity.

The macrofossil flora of the Mascall Formation includes representatives of 28 families, 46 genera, and 68 species (Chaney, 1959; Chaney and Axelrod, 1959). The 15 most common taxa in Table 1 each comprise over 1% of the total assemblage, and together they account for 92% of the total megafossils in the Mascall flora.

TABLE 1. FIFTEEN MOST COMMON SPECIES OF THE MASCALL FLORA

Taxon	% of total
Taxodium dubium	34.25
Quercus pseudolyrata	15.98
Carya bendirei	10.61
Quercus dayana	8.14
Platanus dissecta	3.52
Quercus merriami	2.53
Acer bolanderi	2.30
Metasequoia occidentalis	2.28
Ginkgo adiantoides	2.25
Ulmus speciosa	2.05
Acer minor	2.04
Cedrela trainii	1.99
Ulmus paucidentata	1.42
Betula thor	1.40
Acer scottiae	1.24

Based on comparisons with nearest living relatives of the Mascall taxa Chaney and Axelrod (Chaney, 1959; Chaney and Axelrod, 1959) concluded that the flora represented both upland and lowland wooded environments indicating a regional landscape with some geographical relief with lakes and swamps in the valleys. They interpreted the assemblage as consisting of a swamp cypress and deciduous forest in the lowlands and slopes, with coniferous forests in the uplands, and identified several taxa with affinities to modern temperate forests in eastern Asia and eastern North America, with an element related to the Mississippi Valley cypress swamps. Based on a comparison with the flora of Blytheville, Arkansas, which has a MAT of ~17 °C and a MAP of ~1270 mm, climate for the lowland association was interpreted as warm temperate with summer wet conditions (Chaney, 1959). The Succor Creek flora (ca. 16–14.8 Ma) similarly suggests mesophytic deciduous forests in the lowlands and coniferous forests in the upland, with a mixed coniferous coniferous-hardwood transition (Fields 1996, Graham, 1999). More recent interpretations of the paleosol and paleobotanical records of the Mascall Formation (Retallack, 2007, 2008; Bestland et al., 2008) point to an overall humid, but seasonal temperate climate with dry, warm summers and cool to cold winters. These paleosol studies indicate that the climate was more Mediterranean in aspect than the humid, continental climate that the paleobotanical studies alone would show.

The Evolution of Grasslands in Oregon

Fossil floras, documenting mainly the evolution of forest elements during the Eocene-Middle Miocene, reveal little about the evolutionary history of grasses in the Pacific Northwest. Instead, knowledge of this important change in vegetation types has come from interpretations of fossil soils supplemented by faunal information in the John Day Basin. Based on paleosol data, Retallack (2004a, 2004b, 2007, 2008) has proposed that North American grassland ecosystems evolved in three distinct phases. The earliest grass-dominated habitats, in the form of bunch grasslands, are thought to have expanded in Oregon during the Early Oligocene (27–30 Ma), somewhat later than in the Great Plains and northern Rocky Mountains (Retallack, 2007; Retallack et al., 2000). This expansion apparently occurred in parallel with the spread of sagebrush steppe and at the expense of forest, woodland, and swamp vegetation (Retallack, 2007, 2008). The second phase of grassland ecosystem evolution consisted of the appearance of short sod grasslands in the Early Miocene (19–16 Ma), briefly interrupted by the return of forests and woodlands during the climatically milder Middle Miocene (Retallack, 2004b, 2007). The presence of herbivorous mammals with presumed adaptations to grazing in the Middle Miocene Mascall Formation supports the notion of grass-dominated habitats (Downs, 1956; Fremd et al., 1994; Janis et al., 1998). Although the existence of these grasslands is not represented in the plant megafossil record, Jane Gray did identify grass pollen among the Mascall microfossils (Chaney, 1959). During the Late Miocene, short sod grasslands spread again alongside sagebrush steppe. Paleosols indicative of tall sod grasslands, dominated by C_4 grasses, appear at 7–6 Ma, marking the final phase of grassland expansion in North America (Retallack, 2007; Retallack et al., 2002). The periods during which grasses gained ecological dominance in parts of the Oregon landscape are interpreted as warm-wet spikes, leading Retallack (2007) to suggest that cooling and drying was not the main driver of the spread of grassland ecosystems but instead the coevolution between grasses and grass-eating herbivores.

In the Great Plains, a similar scenario for vegetation change has been developed based on paleosols (Retallack, 1997, 2001, 2007), and was supported by preliminary study of plant silica (phytolith) assemblages from this region (Strömberg, 2002). However, more detailed phytolith work lead to a different inference with regards to vegetation change in the Great Plains (Strömberg, 2004, 2005, 2006). Accordingly, relatively closed forests with palms and, in the Central Great Plains, herbaceous or woody bamboos in the understory dominated in the Late Eocene–Early Oligocene; by the Late Oligocene or earliest Miocene, this vegetation type was replaced by grass-dominated habitats (savannas-open woodlands) with a carpet of predominantly C_3 open-habitat grasses (Strömberg, 2005). Phytolith data point to a somewhat more homogenous Eocene-Miocene landscape than reported by Retallack (2007), who described a mosaic of vegetation types (woodland to sagebrush steppe) at each stratigraphic level. Phytoliths also suggest overall less arid environments in the Great Plains, indicated by the persistence of palms and gingers into the Middle-Late Miocene (Strömberg 2004, 2005), as compared to paleosols. Phytolith assemblage data currently being gathered from John Day Basin sediments (Dunn and Strömberg, unpublished data) will provide a record of grass dominance that can be compared to paleosol-based hypotheses for grassland evolution in the Pacific Northwest.

Biogeographic Connections

The clear taxonomic similarities between the Eocene floras in the John Day Basin and modern Asian forests were initially recognized by Chaney (e.g., 1951). His work and later studies have made clear the importance of vicariance and dispersal among and across continents for understanding the formation of Cenozoic floras in Oregon. The significant migration routes for Pacific Northwest plant taxa discussed here are Beringia, the North Atlantic, and across the Rocky Mountains.

Distribution data on marine invertebrates and mammals indicate that a physical connection between eastern Asia and North America across today's Bering Strait (the Bering Land Bridge) existed throughout most of the Cenozoic (Tiffney and Manchester, 2001). During the early Cenozoic, deciduous angiosperms and conifers are thought to have crossed this land bridge, which may have been situated as far north as 80°N, pointing to a possible limitation of dispersal in the form of winter daylight. It has been suggested that paratropical taxa, many with Asian affinities (e.g., palm, *Myristica*, Lauraceae taxa) in Paleocene–Middle Eocene floras on the southern margin of Alaska, imply migration of evergreens across the Bering Land Bridge (Wolfe, 1994a). However, the possibility that these floras grew at lower latitudes on terranes that were later, after the fossilization of the floras, displaced along the western margin of the North American plate to the current geographic position cannot be ruled out (Tiffney and Manchester, 2001). A connection between North America and Europe was also present in the Paleocene and Early Eocene, as evidenced by taxonomic overlap in mammalian faunas and floras. The more southern location of this land bridge allowed for dispersal of tropical or subtropical plant taxa. As global climates cooled during the later Paleogene and Neogene, the plants that were able to traverse the Beringian and North Atlantic routes became restricted to more cool-tolerant, deciduous and eventually boreal species (Tiffney and Manchester, 2001).

Fossil floras attest to the relative floral continuity across North America of thermophilic, moisture-loving, evergreen taxa at mid-latitudes during the Paleocene and Early Eocene (Wing, 1998; Graham, 1999) The development of a rain shadow associated with the uplift of the Rocky Mountains starting in the Late Eocene is thought to have promoted the development of arid plant communities such as conifer-shrub woodlands in the Rocky Mountain region (Leopold and MacGinitie, 1972). These regional climate changes seem to also have limited migration of subtropical evergreens across North America during the later Eocene, but may have permitted plants adapted to seasonal climates to spread from coast to coast also in the Neogene (Leopold et al., 1992; Wing, 1998; Tiffney and Manchester, 2001).

DAY 1. THE CLARNO AND LOWER JOHN DAY FORMATION NEAR HANCOCK FIELD STATION (FIG. 5)

Thomas Bones and Lon Hancock began collecting fossils in Hancock Canyon in the late 1930s. The Oregon Museum of Science and Industry (OMSI) took an interest in the site in the 1950s and acquired the property that now includes Hancock Field Station to operate a summer science camp. Generations of Oregonians fondly recall their visits to Camp Hancock, which now supports OMSI national and international programs in astronomy, archaeology, and biosciences, as well as paleontology. Construction of Berry Hall in the early 1950s was the first step in the establishment of the facility.

The Pacific Northwest supports a large and active community of amateur and professional paleontologists. Since the 1940s, paleontologists of all ages have joined Tom Bones and Lon Hancock to collect in the Clarno and John Day formations. The ongoing legacy of Hancock and Bones led to establishment of the National Science Foundation–funded OMSI Young Scholars summer paleontology program in the 1980s. Since that time High School age Young Scholars have discovered, relocated, and systematically collected from localities in the Clarno and John Day formations, including seminal collections from the Nut Beds, Whitecap Knoll, and Dugout Gulch, which we will visit today. Many well-known West Coast paleobotanists, including Jack Wolfe, Steven Manchester, and Herb Meyer, participated in OMSI paleontology programs as high school students, and many more—including all but one of this field trip's leaders—led teams of OMSI Young Scholars during the past several decades. These efforts have produced large collections now housed at the Florida Museum of Natural History, University of California Museum of Paleontology, and Oregon Museum of Science and Industry.

Our hike today will begin northwest of the camp and will follow a 5 km loop through the Clarno Formation into the Big Basin Member of the John Day Formation, and return through Clarno lahar deposits in Hancock Canyon to the northeast (Fig. 5).

Stop A. Clarno Overlook

From this location one may see a fairly complete sequence of the Clarno Formation (Fig. 7). A large andesitic stratovolcano to the east of Camp Hancock generated voluminous basaltic andesite flows and laharic breccias that form the majority of Clarno rocks in the Camp Hancock area. According to White and Robinson (1992) these deposits form the inner medial ring plain facies of a large stratovolcano located to the east.

The mountains to the south of us form the Blue Mountains Anticline which strikes northeast-southwest from the Blue Mountains to just north of Prineville. This major structural feature apparently began forming during the Oligocene or Miocene, and separates the John Day Basin into a northern and southern "facies" (Robinson, et al., 1984). A thick sequence of Clarno andesitic lahar deposits and lava flows forms the cliffs south of Pine Creek. The thickest of these, the Andesite of Pine Creek, is not exposed at our location, nor are the thick sequences of laharic breccias of the Conglomerate of Hancock Canyon and Conglomerate of the Palisades, which form the prominent cliffs to the east.

Where we are standing the thick andesite flows and laharic breccias, and the sequence containing the Clarno Nut Beds flora,

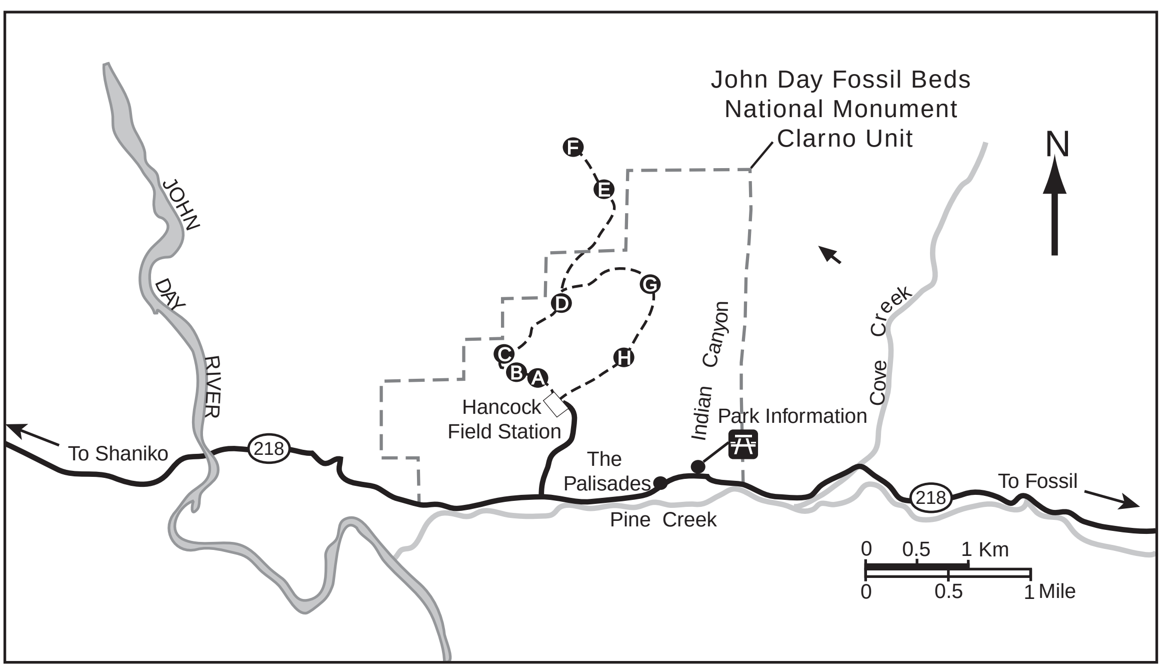

Figure 5. Day 1 route map.

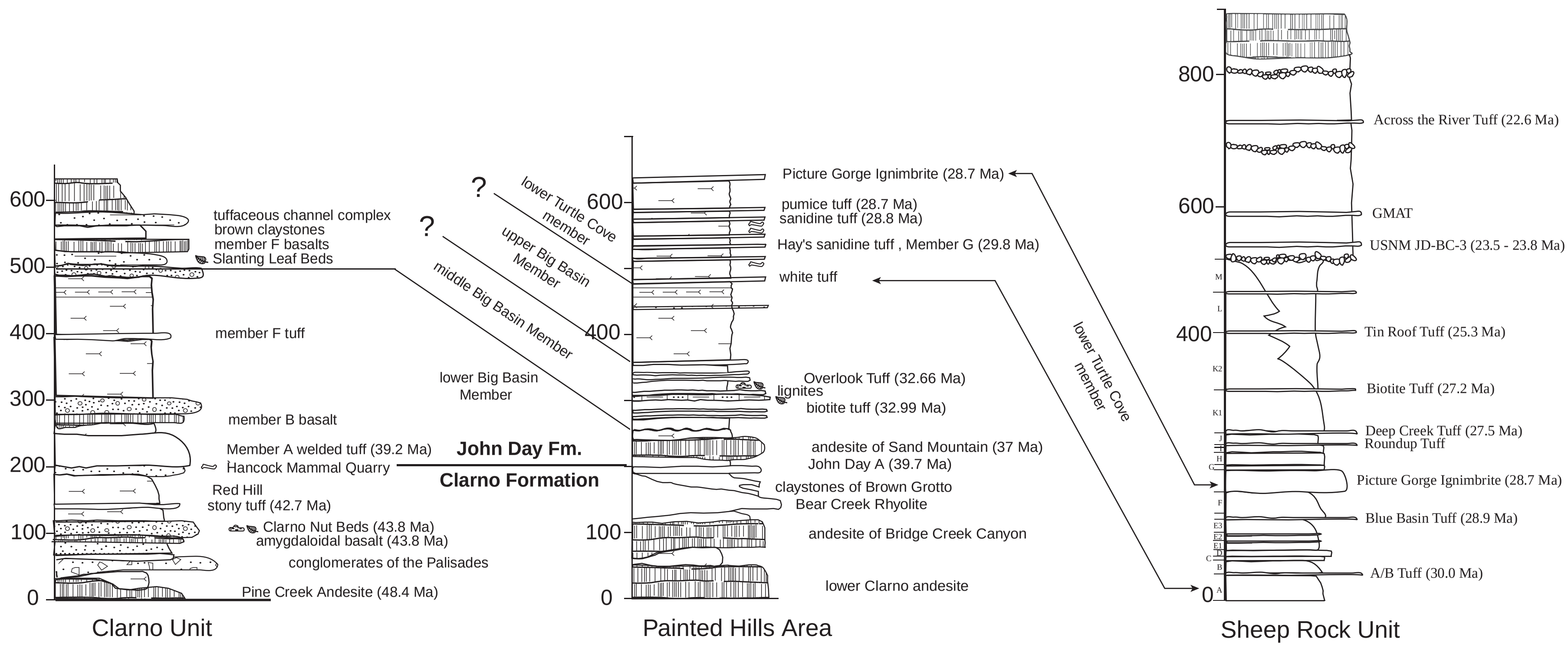

Figure 6. Fence diagram of the Cenozoic sequence extending from Painted Hills, south of the Blue Mountains Anticline to Hancock Field Station. Painted Hills and Clarno sections adapted from Retallack et al. (2000); Sheep Rock section adapted from Fremd et al. (1994). Correlation lines adapted from Bestland et al. (1999).

lap against a 53.6 Ma dacite dome, composed of the light tan rocks visible immediately to the north of us.

Stop B. The Clarno Nut Beds (Fig. 7)

The Clarno Nut Beds are composed of an upper and a lower sequence. Basal rocks of the sequence unconformably overlie the Camp Hancock dacite dome, and, further west, overlie laharic breccia of the Hancock Canyon sequence. This basal sequence is composed of claystone, siltstone, and fine-grained to medium-grained sandstone in 1–5 cm thick thinly laminated intervals that fine upward from sand to mud. Convoluted laminae and flame structures indicate deposition in a wet environment. Abundant *Equisetum* in growth position at the bottom of the section grew upon the surface immediately underlying the Nut Beds. The reeds stand perfectly erect to a height of up to a meter, and are now enclosed by laminated siltstone derived, most likely, from fine silicic volcanic ash. Retallack et al. (1996) suggested that some of the deformed mudstone may be footprint impressions. Taken together, sedimentological and fossil evidence point to deposition in a shallow channel within a lake-margin delta or meandering river floodplain.

Years of hard work by OMSI Young Scholars under the direction of Dr. Steven Manchester recovered impressions of leaves from the lower sequence, which are now housed at the Florida Museum of Natural History, the Condon Museum, and OMSI. Posts and quarries lining the outcrop hark back to this work. Because rock of the lower Nut Beds is highly fractured and difficult to quarry, each leaf represents many hours of painstaking work. When we return to Hancock Field Station, have a look at the photograph in Berry Hall of Lon Hancock and his crew dynamiting large blocks of the Nut Beds. These blocks still lie below us in the wash.

The upper Nut Beds sequence consists of a massive bed of red-tan poorly sorted, clast supported subangular pebble breccia. Crystals extracted from the deposit produced an age of 43.8 Ma for this part of the sequence (Manchester, 1994), although Hanson (1995) reports an older age ca 47–48 Ma, based on mammal correlations and an unpublished radiometric date from C. Swisher. Permineralized fruits and seeds are abundant in the breccia, preserved as three-dimensional compactions, along with rounded pieces of permineralized wood. It is likely that plant detritus was concentrated on the gravel bar of a meandering river, then picked up en masse by a flood and redeposited over the lake margin delta or flood plain sequence upon the lower Nut Beds sequence.

Initially collected on a large scale by Tom Bones, the Nut Beds fruits and seeds were thoroughly described by Manchester (1994b), who recognized 173 species of plants. Fossils are preserved anatomically in three dimensions. Sectioning reveals internal features that permit comparison with modern fruits and seeds. The Nut Beds flora is among the most important fossil assemblages known, and has been seminal for understanding northern hemisphere biota of the Eocene (Scott, 1954; Wolfe, 1972; Tiffney, 1985a, 1985b; Manchester 1994a, 1999). The Bones collection and subsequent systematic collections are now housed at the Florida Museum of Natural History, National Museum of Natural History, Smithsonian Institution, John Day Fossil Beds National Monument, OMSI, and Condon Museum, University of Oregon.

Figure 7. The Clarno Nut Beds.

Plants represented in the Nut Beds belonged largely to families and genera that now grow in moist or humid tropical and near tropical environments. These include Menispermaceae, Icacinaceae, Vitaceae, Musaceae, Burseraceae, Actinidiaceae, Annonaceae, Sapotaceae, Symplocaceae, and many other taxa. Perhaps most interesting, fully 40% of Nut Beds genera are shared with the Eocene of Europe, strongly supporting the concept of a mid-latitude Northern Hemisphere circum-global "boreotropical" forest and the presence of migratory corridors across the northern Atlantic and Pacific during the Paleogene (see above). Figures 8 and 9 show examples of specimens from the Nut Beds.

While the European Paleogene is rich in three-dimensionally preserved reproductive structures, almost all Paleogene assemblages in North America contain impression assemblages. The three-dimensionally preserved permineralized reproductive structures of the Nut Beds are a notable exception, and provided the basis for direct comparisons with Eocene floras of Europe.

Fully 43% of Nut Bed species for which growth habit can be inferred grew as lianas or scrambling climbers. This unusually large percentage in part reflects that lianas are particularly prevalent in tropical vegetation, but also suggests that plants represented in the Nut Beds grew in disturbed habitats in which vines commonly grow in abundance today.

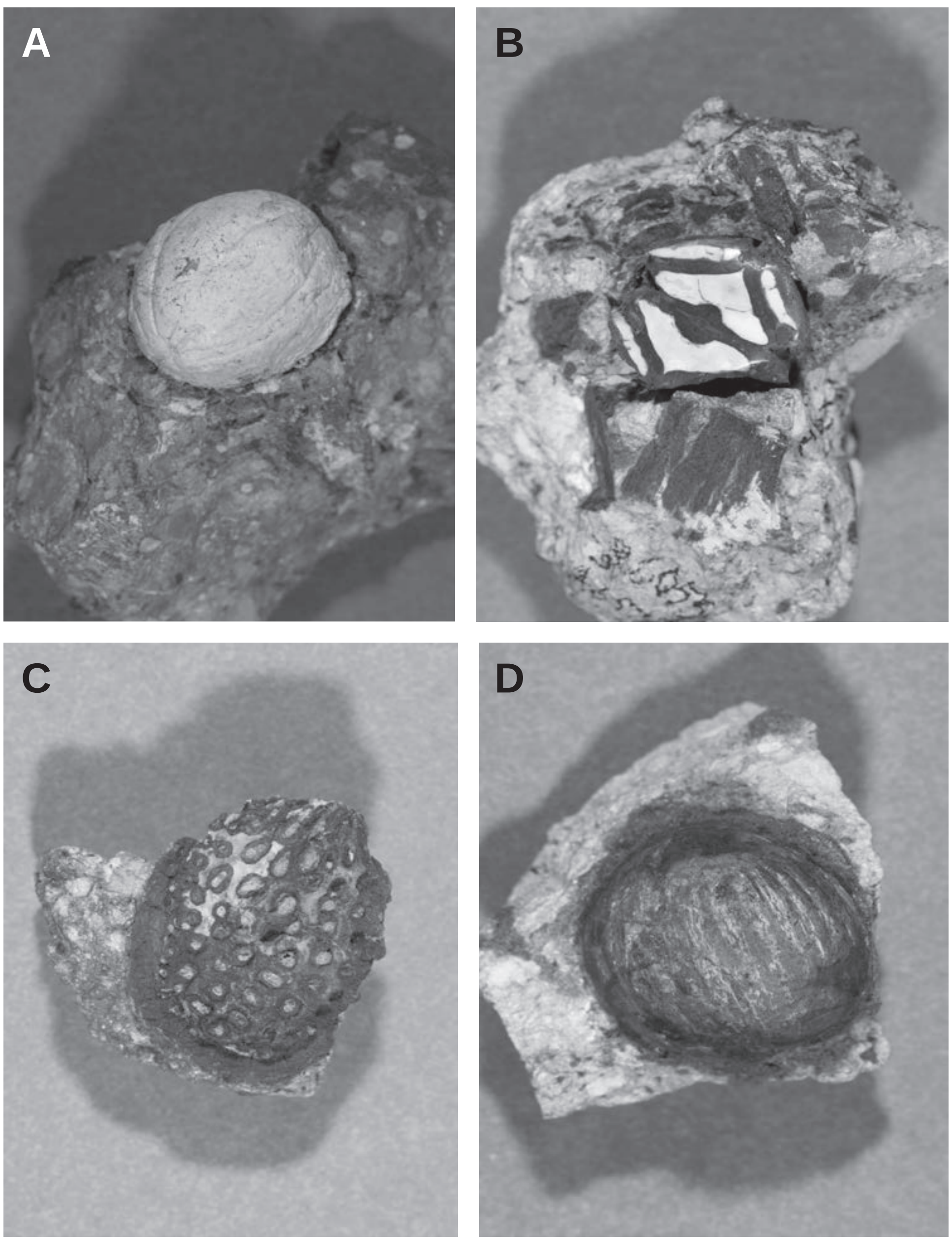

Figure 8. Common fruit species of the Clarno Nut Beds. (A and B) *Juglans clarnoensis*. (C) *Paleophytocrene pseudopersica*. (D) *Coryloides hancockii*.

Abundant permineralized wood from the upper Nut Beds was thoroughly described by Wheeler and Manchester (2002), who recognized 66 genera and 77 wood taxa. Nineteen families co-occur as wood and reproductive structures, while 14 families are known from reproductive structures but not wood. Both Cercidiphyllaceae and Ginkgoaceae occur as wood, but not as reproductive structures. Only 5% of Nut Beds woods possess structures characteristic of lianas, which is not surprising given the much smaller likelihood that the xylem-poor stems of lianas will be preserved in the fossil record when compared to the wood of trees.

Vertebrate fossils from the Nut Beds, most of which are housed at the University of California Museum of Paleontology (UCMP), include tortoise, a crocodilian, titanothere, four-toed horse, rhino such as perissodactyl, and the lion-like *Patrofelis* (Hanson, 1995; Retallack et al., 1996).

Stop C. Red Hill

The steep purple to red-ochre slope above the Nut Beds consists of a 59-m-thick sequence of Ultisol to Alfisol-like paleosols

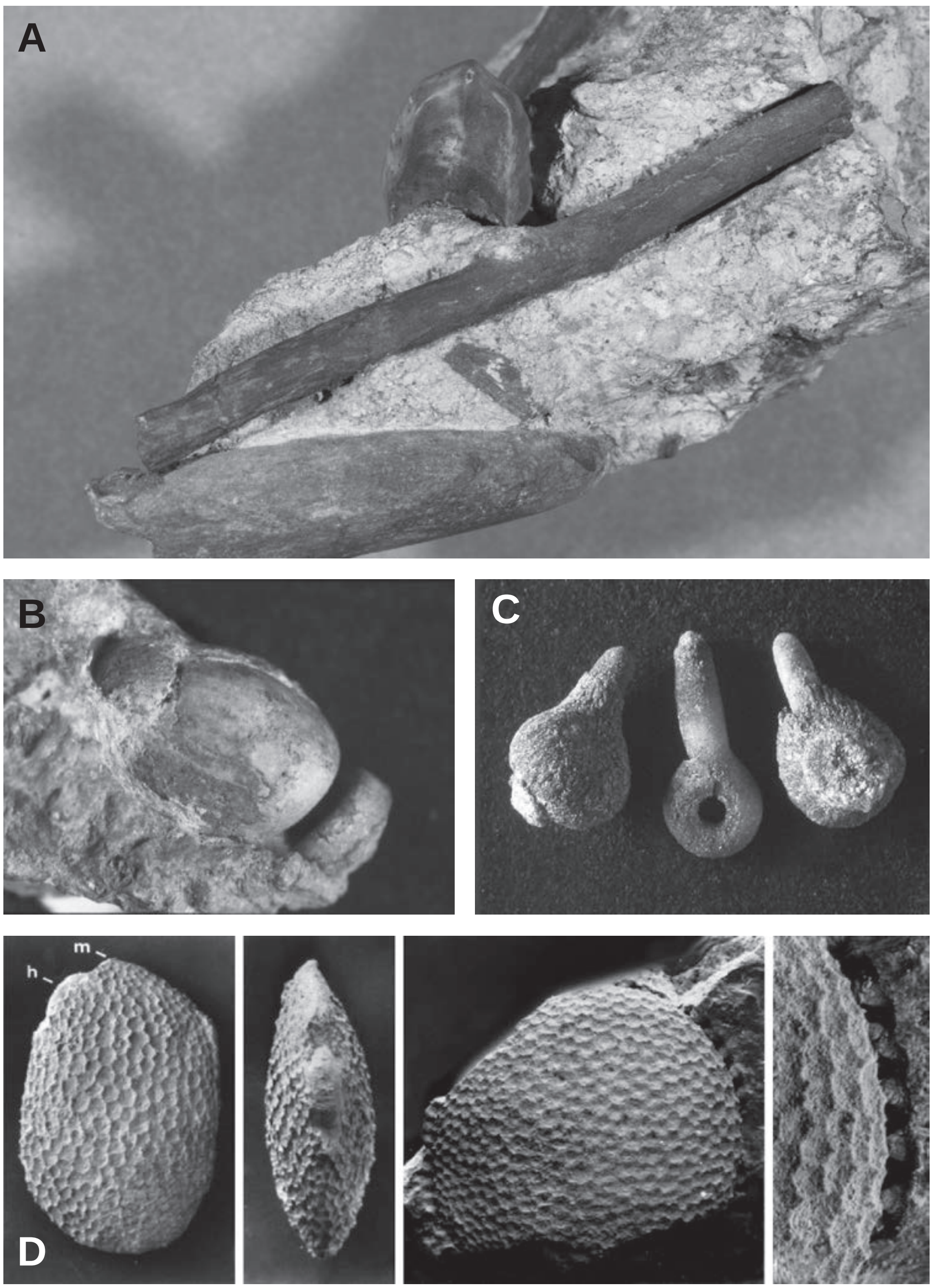

Figure 9. Extinct genera and tropical elements from the Clarno Nut Beds. (A) *Chandlera lacunose*. (B) *Ensete oregonense* (banana). (C) *Microphallus perplexus*. (D) *Actinidia oregonense* (kiwi). B, C, and D provided by Steven R. Manchester.

spanning ~2–3 million years, from ca. 43 to 40 Ma. During this time the Clarno volcanic arc became locally inactive after the "flat slab" subducted beneath far western North America during the Late Cretaceous to late Middle Eocene detached (see above).

In spite of its great thickness, the Red Hill paleosols extend laterally only a short distance, becoming a saprolite horizon overlying the Conglomerate of Hancock Canyon. Even this thick paleosol sequence locally includes cobble-filled channels re-eroded from the slopes immediately surrounding the soil-forming basin. The Red Hill sequence includes two intervals separated by the 42.7 Ma "Stony Tuff" (Bestland et al., 1999). Lower Red Hill deposits are composed of Ultisol-like paleosols formed in a near-tropical, humid environment, while the Alfisol-like paleosols of the Upper Red Hill sequence formed under less weathering subtropical conditions (Bestland et al., 1997; Retallack, et al, 2000). This transition marks the first of several episodes of Late Eocene and Oligocene cooling and seasonal drying interpreted from fossils and paleosols in the Clarno–John Day sequence.

Stop D. The Hancock Mammal Quarry and John Day Ignimbrite A

The Hancock Mammal Quarry directly overlies the Red Hill sequence, at the top of the Clarno Formation. Although not directly dated, the mammal locality directly underlies John Day Ignimbrite A at 39.7 Ma, and is hence thought to be ca. 40 Ma. Disarticulated skeletons are extremely abundant in the Mammal Quarry bed, probably having been concentrated on the point bar of a meandering river channel (Pratt, 1988).

Hancock Quarry mammals include nimravid cats, oreodonts, rhinoceroses, tapirs, and three-toed horses (Retallack et al., 1996). The assemblage differs profoundly from that of the Nut Beds, and reflects a more open habitat than the multi-tiered rainforest of the Middle Eocene, a possible consequence of cooling climate and seasonal drying. A small diversity of fruits and seeds occurs in Mammal Quarry deposits (McKee, 1970), including the Clarno Nut Beds taxa *Odontocaryoidea* and *Diploclisia* (Menispermaceae), *Juglans clarnensis* (Juglandaceae), *Vitis* (Vitaceae), and *Palaeophytocrene* (Icacinaceae), among others. An updated list is provided by Manchester (1994, p. 13).

Ignimbrite A (Fig. 10), well exposed at the top of the hill above us, marks the base of the John Day Formation north of the Blue Mountain Anticline, and yields a radiometric age of 39.7 Ma. The highly silicic Ignimbrite A crossed nearly 100 km from a caldera eruption near Madras, mantling a largely flat topography. Flattened, stretched pumice fiamme form the conspicuous vugs in the rock. At one time it was thought that Ignimbrite A encountered the Blue Mountains Anticline and, hence, did not extend to the southern facies of the John Day Basin. More recently the ignimbrite has been recognized in the Painted Hills sequence, which suggests that the anticline did not form a significant topographic barrier at the time.

The lowermost John Day Big Basin Member exposed above Ignimbrite A consists of varicolored paleosols interrupted by basalt lava flows, ignimbrite runouts, and ash fall deposits, with local lacustrine lenses. The dramatic change in lithology from the underlying Nut Beds sequence attests to the abandonment of the "flat slab" volcanic arc and transformation of the region into a tectonically quiescent backarc basin with a gentle topography.

Stop E. Whitecap Knoll

One of the few paleofloras known from the lower Big Basin Member of the John Day Formation occurs in ashy lacustrine

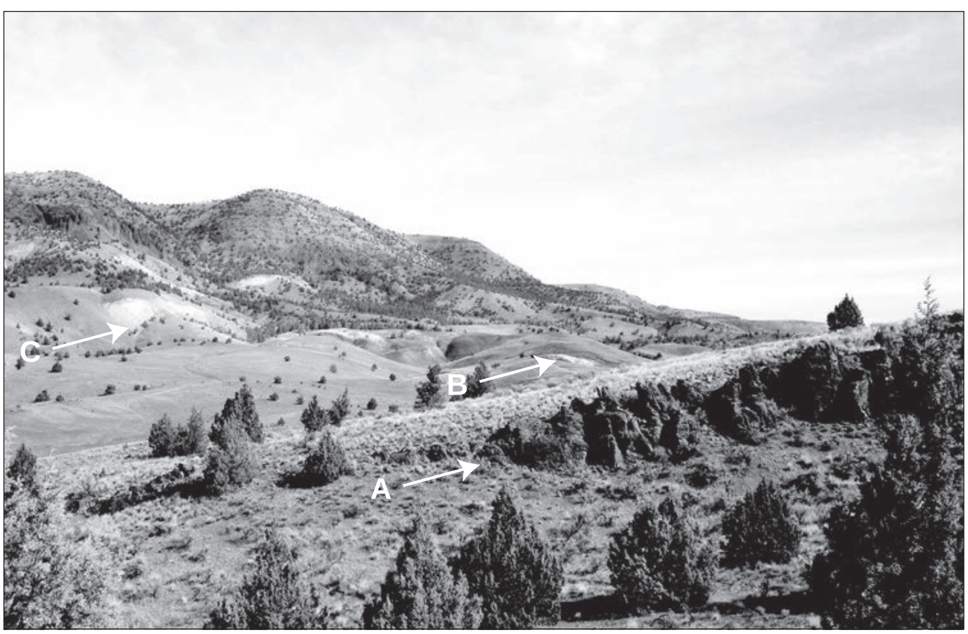

Figure 10. John Day Formation Lower Big Basin Member showing John Day Ignimbrite A (A) at the base of the photo, the location of the Whitecap Knoll flora (B) and the Bridge Creek flora Iron Mountain assemblage (C).

beds stratigraphically below the Whitecap Knoll Tuff (Fig. 10), dated as 38.2 ± 0.06 Ma (Retallack et al., 2000), The leaf locality is inferred to be ca. 38.8 Ma (Manchester, 2000). Although relatively sparse, the flora provides a critical datum point between paleofloras of the upper Clarno Formation and the lowermost of the classic Bridge Creek assemblages up section. The Whitecap Knoll fossil beds consist of tan-white siltstone with very little coarser clastic sediment. This, combined with the presence of unoxidized, coaly plant material and an abundance of fish scales and bones, suggests that deposition took place in a mid-lake setting, far from shore, and below the aerobic mixed surface waters. The flora includes a significant aquatic component, including *Nelumbo* and *Decodon* (Manchester, 2000). A representative collection from Whitecap Knoll by Steve Manchester with the help of OMSI Young Scholars, the Dillhoffs, and Myers, has been painstakingly recovered from the paper shale, and is now housed at the Florida Museum of Natural History.

Sparse plant material recovered from the Whitecap Knoll beds includes a number of temperate plants, including maple, alder, rose, various Juglandaceae, and oaks as both leaves and reproductive structures. The very small size of leaves and preponderance of winged fruits is typical of mid-lake assemblages, which are dominated by blown in plant debris. Leaf margin analysis suggests that the growth environment experienced significantly cooler temperature than the underlying Clarno floras, and the frost intolerant plants which dominate the Nut Beds flora have not been recovered here, with the exception of a leaf of an evergreen laurel. The presence of *Eucommia* and other mesophytes suggests a mesic or humid climate.

Stop F. The "Slanting Leaf Beds"

The prominent white cliff on the face of Iron Mountain to the north of us (Fig. 10) contains the oldest dated Bridge Creek assemblage at 33.62 Ma, the age established from a fallout tuff within the fossil-bearing sequence. Variously referred to as Dugout Gulch and the Slanting Leaf Beds, the fossil plant assemblage contained in the white lacustrine paper shales is now formally referred to as the Iron Mountain Assemblage (Meyer and Manchester, 1997). The white tuffaceous siltstone contains abundant fish bones and scales along with caddis fly larval cases typical of lacustrine deposits.

Paleobotanically, the Iron Mountain assemblage is interesting because it is the only Bridge Creek assemblage to include *Zingiberopsis*, which indicates that cold season temperature remained above freezing at the time the Iron Mountain assemblage grew. The assemblage also includes *Keteleeria*, which today is restricted to warm temperate Asia. Leaf margin analysis provides an estimate of mean annual temperature near 10 °C, which is more typical of cooler temperate environments than those in which these genera would be expected. The occurrence of thermophilic plants in the assemblage strongly suggests that cold season temperature could not have been much cooler than the mean annual temperature, and well above freezing.

Stop G. The Hancock Tree (Fig. 11)

Descending Hancock Canyon, we cross back into the Clarno Formation. Conglomerate and breccia of the Conglomerate of Hancock Canyon lines the walls along the trail in massive beds as thick as 3–4 m, deposited by lahars from a vent complex to the east of Hancock Canyon. Thin paleosols separate the massive deposits, and include a low diversity flora of untransported forest floor plant litter. *Macginitiea*, *Joffrea* (Cercidiphyllaceae), and *Alnus* dominate the assemblage, which records disturbed habitat vegetation. Rounding a corner in the canyon, above us and to the left, stands the remarkable Hancock Tree. The vertically erect trunk belonged to the family Cercidiphyllaceae. Because the junction between the trunk and the ground from which it grew is not exposed, it remains unclear whether this tree was transported vertically or remains in growth position. In either case, a forest floor litter can be seen at the level of the presumed tree base. The regularly spaced axe-like fractures in the tree trunk have been interpreted in various ways, none of them entirely satisfactory. The top two sections remained in place until a few decades ago.

Stop H. The Clarno Fern Quarry

Proceeding down Hancock Canyon, note the quarry high to the left. This locality, referred to as the Clarno Fern Quarry, lies within laharic breccias of the Conglomerate of the Palisades, which underlies the Conglomerate of Hancock Canyon. Plants are preserved as impressions in siltstone, much like the basal siliceous siltstone of the Nut Beds sequence. Although specimens examined by Arnold (1952) were recovered from a different locality, species of the ferns *Lygodium* and *Acrostichum* described by Arnold also occur here. Some of the large blocks lying on the canyon floor contain fossils of ferns and angiosperms. Today both of these ferns occupy very wet habitats in the tropics and near tropics, often lining estuaries, bays and floodplains.

Continue down Hancock Canyon to Hancock Field Station, where we will spend the night.

DAY 2. THE MASCALL FORMATION NEAR DAYVILLE. (FIG. 12)

Leaving the Hancock Field Station road, turn left on Oregon 218. At this point, reset your trip odometer to 0 in order to identify relevant landmarks.

Road Log. Hancock Field Station to John Day, Oregon

Cumulative mileage	*Description*
0	Turn east on Highway 218 toward town of Fossil.
0.7	On left side of road are The Palisades of the John Day Fossil Beds National Monument. The cliffs here consist of Conglomerates of the Palisades lahar

deposits of the Clarno Formation. In the middle of these flows are fossilized tree trunks, and leaf impressions of *Macginitea* can be found on fallen blocks at the base of the cliffs. Thirteen lahar flows can be counted here.

3.0 To the north is Cove Creek where several Bridge Creek floral localities are located including Pentecost Ranch, Cove Creek, and Knox Ranch.

4.9 On the north side of the road are hoodoos of lahar deposits that are correlative to the upper flows of Hancock Canyon.

12.2 Descending this small pass are strata of the Clarno Formation including breccia deposits and andesite intrusions.

17.8 Turn right (south) on Highway 19 in the town of Fossil. Fossil possesses one of the critical localities of the Bridge Creek flora, the 32.58 Ma "Wheeler High School" or "Fossil" locality (Meyer and Manchester, 1997; McIntosh et al., 1997). The locality is exposed next to the high school sports field. In the past, a visit to Fossil would include a view of, at times, several dozen fossil collectors digging on this slope. More recently the site has been regulated by the county government and private non-profit collaborative of the Oregon Paleo Lands Institute, which is attempting to preserve what remains of the locality. This site is open to the public for collecting for a small fee, of which proceeds go to support the school system. The richly fossiliferous Wheeler High School locality consists of tan to brown lake margin deposits containing salamanders and abundant fish bones. Much of the plant detritus was washed into the lake from the surrounding landscape. The sequence also includes widely spaced gray or light tan volcanic siltstone intervals recording lake high stands. The fossil sequence is capped by a coarser lake infilling interval.

26.6 Butte Creek Pass (elevation 3788 ft), Clarno andesites visible in road cuts.

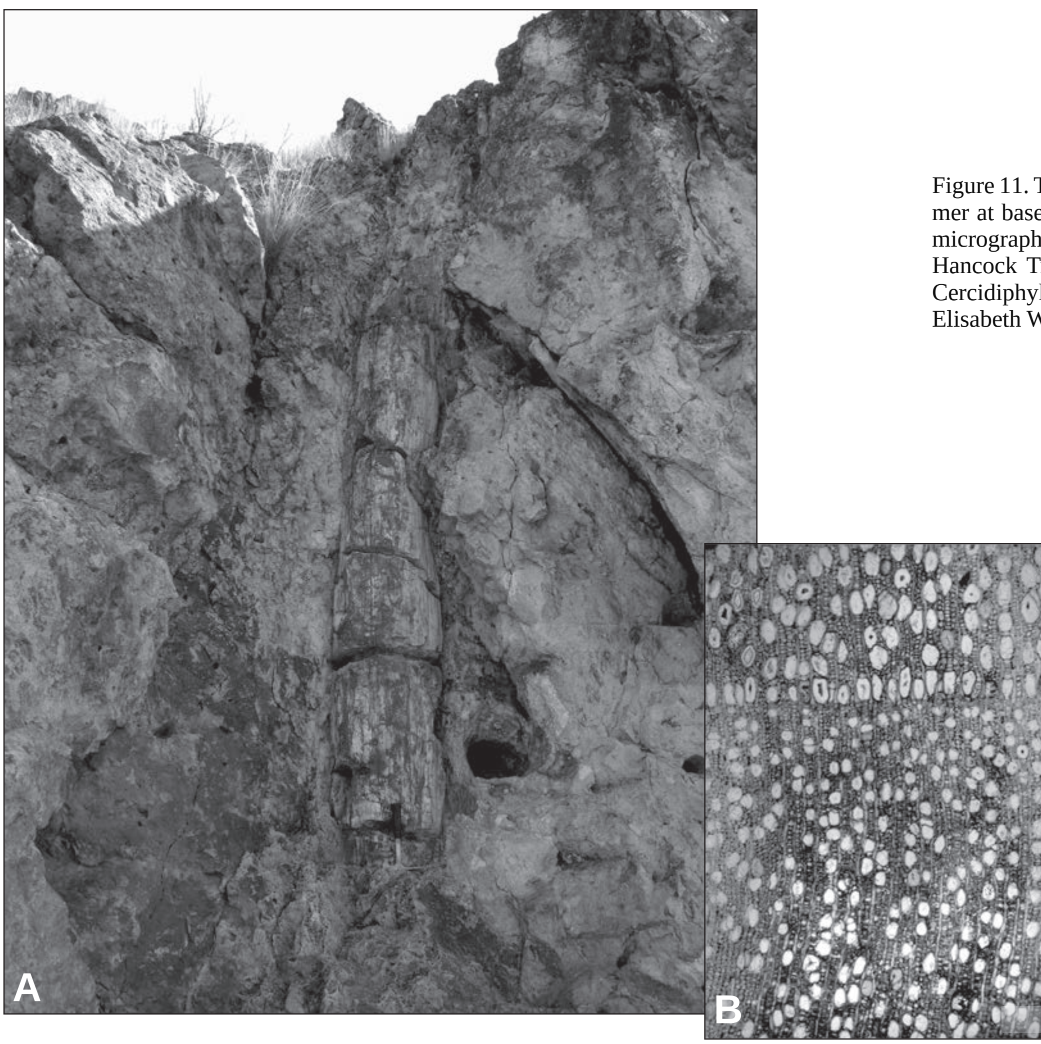

Figure 11. The Hancock Tree (note hammer at base for scale) with inset photomicrograph of wood sectioned from the Hancock Tree, attributed to the family Cercidiphyllaceae. Photomicrograph by Elisabeth Wheeler.

27.3 Road to Twickenham veers off to the right (west). Chaney described Oligocene Bridge Creek floras from this site. This road continues to Painted Hills.

27.6 Rancheria Rock, a Clarno andesite plug is visible to the west. It has multiple radio towers on its summit.

31.1 Clarno Formation visible in stream bank to the west.

36.3 Service Creek Outpost.

36.6 Highway 207 veers off to the right (west) and Highway 19 parallels the John Day River.

48.7 Exposures of the Haystack Valley Member of the upper John Day Formation are visible to the east (left side of road).

49.2 Town of Spray.

51.1 Road crosses Haystack Creek. To the north is the Haystack Valley, namesake of the Haystack Valley Member.

57.6 Along this section are exposures of Kimberly Member that are rich in vertebrate fossils. These are UCMP localities Junction 2 and 3.

61.3 Town of Kimberly, Oregon.

61.6 Cross the North Fork of the John Day River.

62.5 Exposures of upper John Day Formation members are on the right (west) side of road.

66.7 Round Up Flat is an exposure of the Turtle Cove Member. A prominent tuff in the bottom third of the exposure is the Deep Creek Tuff dated as 27.5 Ma .

69.5 Foree Unit of the John Day Fossil Beds National Monument. Foree contains strata of the Turtle Cove Member and is very rich in vertebrate fossils, especially in units below the Picture Gorge Ignimbrite.

70.1 Big Basin and Turtle Cove transitional contact visible on east side of road.

71.7 Cathedral Rock, Turtle Cove Member topped with Picture Gorge Ignimbrite.

73.3 Metamorphosed Jurassic and Triassic marine basement rock.

73.7 Dick Creek Road on left (east) leads to type area of the Big Basin Member (~0.5 miles east of Highway 26).

74.2 Blue Basin, John Day Fossil Beds National Monument. This is the area originally referred to as Turtle Cove by Thomas Condon.

75.6 Cant's Ranch leaf locality, a Bridge Creek floral site excavated by Chaney is less than a mile west of here.

75.9 Goose Rock. This rock is from the Aptian-aged Gable Creek Formation. Mantling this rock are claystones of the Big Basin Member.

78.2 **Stop A.** Arrive at Thomas Condon Paleontology Center.

This center, opened in 2005 serves as a collections facility and interpretive center. Housed within the collections are over 50,000 paleontological specimens from the John Day basin. The facility contains a fully equipped preparation lab, small library, and museum exhibits with over 400 fossils on display. We will tour the museum, lab, and collections at this stop.

Return to Highway 19, and turn south (right).

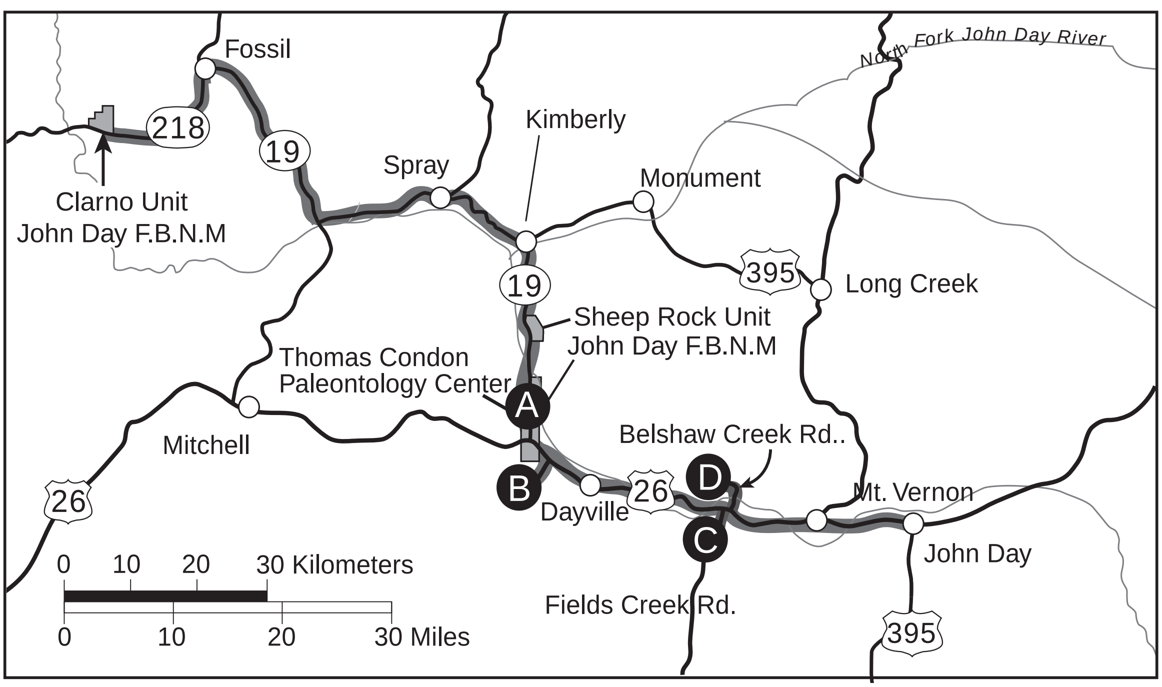

Figure 12. Day 2 route map.

79.2 Interbasalt tuffaceous lacustrine unit in roadcut on right (west) side of road. This tuff has been dated as 16.0 Ma.

79.3 Junction of Highways 19 and 26, turn left (east) onto Highway 26 into Picture Gorge.

80.9 Road crosses Rattlesnake Creek, namesake for the Late Miocene Rattlesnake Formation.

81.1 Day Creek Road; turn right.

81.5 **Stop B.** Mascall Overlook stop. At this site we will see the type exposures of the Mascall and Rattlesnake Formations (Figs. 13 and 14). The Mascall overlies the Picture Gorge Basalts which can be seen in Picture Gorge, the deeply incised canyon to the northeast. Above the basalts are ~350 m of exposed Mascall sediments, which are in turn capped by the nearly horizontal beds of the Rattlesnake Formation. While the majority of Mascall plant fossil localities are in the basal part of the formation, most mammal sites are further up in section, associated with the 15 Ma Mascall tuff (Prothero, et al., 2006)

The Late Miocene Rattlesnake Formation lies unconformably on top of the Mascall and spans the time from ca. 8–6 Ma. The formation contains ~120 m of siltstones, conglomerates and tuffs. The most prominent feature is the Rattlesnake Ash Flow Tuff (7.2 Ma), which is the welded tuff seen at the top of the ridge to the west. From a paleontological standpoint, the Rattlesnake is an important source for Hemphillian mammals, but is generally lacking in fossil plants (Retallack, et al., 2000). The majority of the mammal fossils have been found in conglomerates below the ignimbrite.

Return to Highway 26; turn right (east).

85.3 Town of Dayville.

88 Mascall exposures on the north side of road.

90.6 Directly to the south, the Picture Gorge Basalts have been rotated 90° along the trend of the John Day Fault. South of the basalts are deposits of the Clarno Formation yielding fossil wood that has long been collected by local rockhounds.

92.3 Mascall Formation blanketing Picture Gorge Basalts on south side of river.

97 Mascall roadcut on left. This is a diatomaceous lacustrine bed that contains fossils of leaves, snails and occasionally fish.

98.4 **Stop C (Optional).** Fields Creek Road. Turn right (north), proceed to parking area on right ~0.25 miles. A road cut here exposes diatomaceous beds of the Mascall Formation deformed by the John Day Fault. Across the river to the north, exposures of these same beds on the riverbank compose one of Knowlton's (1902) original collecting sites. This site is on U.S. Forest Service land and contains leaf fossils of the Mascall Formation. To the northeast, you can see the Belshaw's Ranch–White Hills locality where we will be going next. We will spend a short time at this site to allow anyone interested to do some excavation. Typical Mascall leaf fossils can be found here as well as specimens of the gastropod *Lymnaea* cf. *stearnsi* and the small percid fish, *Plioplarchus septemspinosus* (Fremd et al., 1994).

Return to Highway 26, continue east.

Figure 13. View of the type section for the Mascall Formation from the overlook site. The Rattlesnake Ignimbrite caps the ridges seen in the upper right of the photo. Photograph by Sue Anderson.

100.6 **Stop D.** PRIVATE PROPERTY—no collecting or access without permission. Turn left on Belshaw Creek Road (north). Cross bridge continue 0.25 miles, turn left on gravel road, continue 0.5 miles and park on right. This is the Belshaw's Ranch–White Hill locality (Fig. 15). We will spend time here to allow participants to collect typical Mascall fossils. We will be collecting on private land with the kind permission of the landowners, so please be respectful of the property. This site is one of the classic Mascall fossil plant localities that has been collected since the late 1800s, and has been used in the most important studies of the formation (e.g., Knowlton, 1902; Chaney and Axelrod 1959). It is a lacustrine deposit with a diatomaceous matrix. This deposit is stratigraphically near the base of the Mascall Formation, and is estimated to be 15.5–16 million years old. A list of the most common taxa of the Mascall flora is provided in Table 1, and photographs of Mascall specimens are shown in Figs. 16 and 17.

Return to Highway 26, continue east.

109 Town of Mount Vernon.

109.8 The Rattlesnake Ashflow Tuff (RAFT) is exposed to the north and continues east through the John Day Valley.

110.5 Clyde Holliday Sate Park on right (south), Clarno lahars and interbedded tuffaceous paleosols on left (north).

114.2 Ophiolites and serpentine of Canyon Mountain Complex. These rocks were mined extensively for gold beginning in 1862.

116.5 Town of John Day.

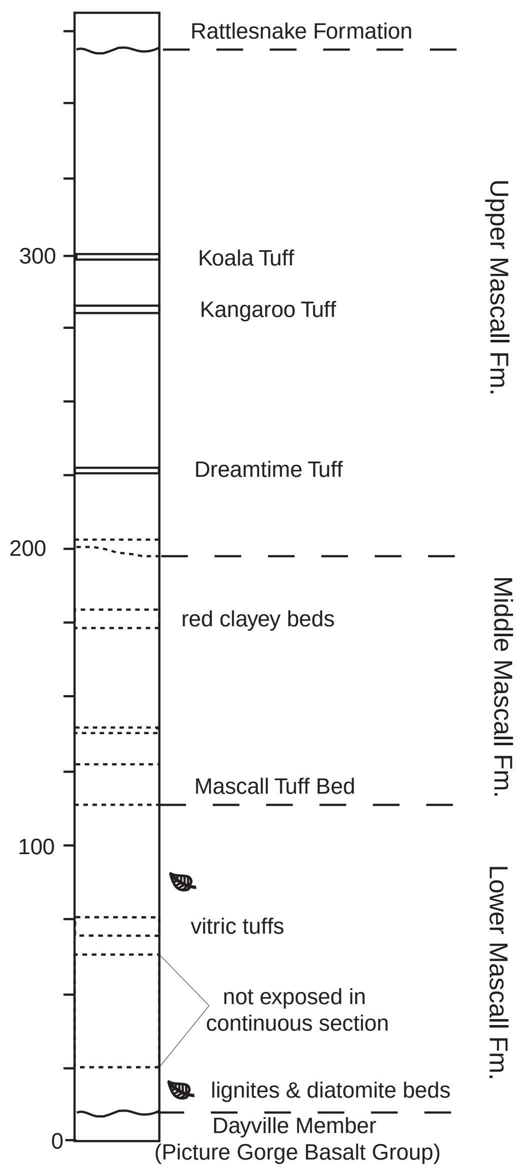

Figure 14. Simplified stratigraphy of the Mascall Formation in the type section (from Bestland et al., 2008).

DAY 3. THE JOHN DAY FORMATION AT THE PAINTED HILLS UNIT OF THE JOHN DAY FOSSIL BEDS NATIONAL MONUMENT (FIG. 18)

Travel back on same route as Day 2 to junction of Highways 19 and 26 and continue west on Highway 26 toward Mitchell and Painted Hills.

Reset odometers to 0 at the junction of Highways 26 and 19.

Cumulative mileage	*Description*
2	Rock Creek roadcut (Mascall Formation). At the base of the light-resistant layer in this road cut occasional fossil leaves can be found. Species recovered here include a lobate *Quercus* sp.
3.2	South of the road are exposures of Mascall Formation that have yielded mammalian fossils.
7.6	Resistant Clarno lahar deposits are exposed here.
16.4	Antone Road.
20	RAFT exposure where an Ar^{40}/Ar^{39} date yielded an age of 7.2 Ma
23	Westernmost exposure of the RAFT.
24.5	Keyes Summit (elevation 4389 feet).
27.9	Andesites and altered volcaniclastics can be seen here in road cuts along the flanks of Keyes Mountain, a Clarno aged volcano. In the distance toward the west are two conical peaks, White and Black Buttes, which are likely andesite plugs intruded into Cretaceous marine strata.
30.8	Town of Mitchell.
33.2	Gable Creek Formation, 9000-ft-thick sequence of submarine turbidites (Little, 1987) of Albian and

possibly Cenomanian age (Housey and Dorsey, 2005; Dorsey and Lenegan, 2007).

34.1 Intersection with Burnt Ranch Road, turn right (north), Clarno-Cretaceous contact along highway 50 m to east of junction.

36.7 East of road (right side) is Ruby Basin, a sequence of Clarno and John Day paleosols onlapping the andesite of Bridge Creek canyon.

36.9 Exposures of paleosols of the middle and upper Big Basin Members.

37.7 West side of road is exposures of Sand Mountain andesite.

Turn left (southwest) at intersection of Bear Creek and Burnt Ranch Road into Painted Hills Unit of the John Day Fossil Beds National Monument.

Stop A. Painted Hills Unit Picnic Area

The Painted Hills have long been an attraction in eastern Oregon because of their stunning scenery of brightly colored outcrops against a typical high desert backdrop of basalt, junipers, grass, and sage. Early Oligocene plant fossils found in the lacustrine shales in the John Day and Crooked River basins are collectively known as the Bridge Creek flora. First coined by R.W. Chaney in 1925, the assemblage was named for its type locality near Bridge Creek, a tributary of the John Day River that flows north through the Painted Hills. More formally, Meyer and Manchester (1997) refer to the Bridge Creek flora as fossil plant assemblages of the lower John Day Formation that follow the Eocene-Oligocene cooling and are dominated by deciduous species. Sites other than Painted Hills that are considered within the Bridge Creek floral assemblage are Fossil High School, Cove Creek, Iron Mountain in the western facies of the John Day Formation, and Crooked River and Lost Creek in the southern facies of the John Day Formation. However, specimens collected in the vicinity of the Painted Hills were among the first to be studied by paleontologists working in the John Day region.

Established as a state park in 1947, this 14,000-acre unit known as Painted Hills became part of the John Day Fossil Beds National Monument, administered by the National Park Service (NPS) in 1975. **Important Note**: No collecting is allowed within the boundaries of the National Monument without a permit. Bridge Creek runs along the east side of the picnic area. The NPS maintains a small arboretum in the picnic area that features some living relatives of the Bridge Creek flora.

Follow the driveway back out towards the north and turn left at the intersection. Drive 0.9 miles and turn left at Overlook Trail Parking Area.

Stop B. Painted Hills Overlook

Turn into the parking lot and view the scenic Painted Hills. Looking eastward, the colorfully banded hills of the upper Big Basin Member are exposed. These red, yellow, and black claystones represent a succession of paleosols on a floodplain (Bestland et al., 1994; Retallack, et al., 2000). To the north is Carroll Rim, a cuesta composed of paleosols and tuffs of the Turtle Cove Member that is capped by the Picture Gorge Ignimbrite (28.7 ± 0.06 Ma). Visible in the distance to the east and northeast is Sutton Mountain, a massif capped by Picture Gorge Basalts. Below the basalts, the Turtle Cove, Kimberly, and Haystack Valley members are visible. These beds contain abundant vertebrate fossils of Oligocene and Miocene age including oreodonts, agriochoeres, nimravids, equids, entelodonts and early canids. Immediately to the west, slightly lower in elevation to where we are standing is a thick white tuff unit; this is the Overlook Tuff that caps the leaf-bearing sequences in the Painted Hills.

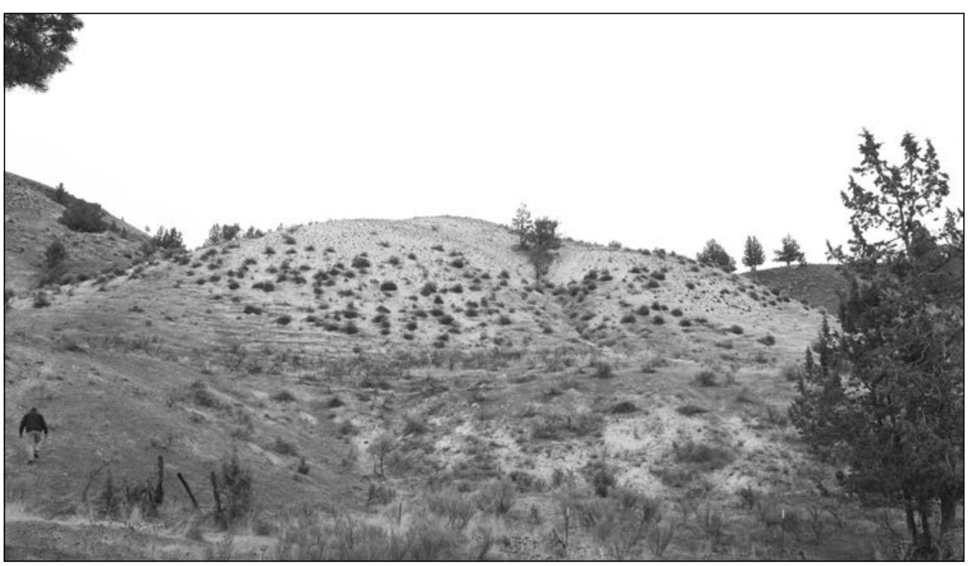

Figure 15. The Belshaw Ranch/White Hill locality.

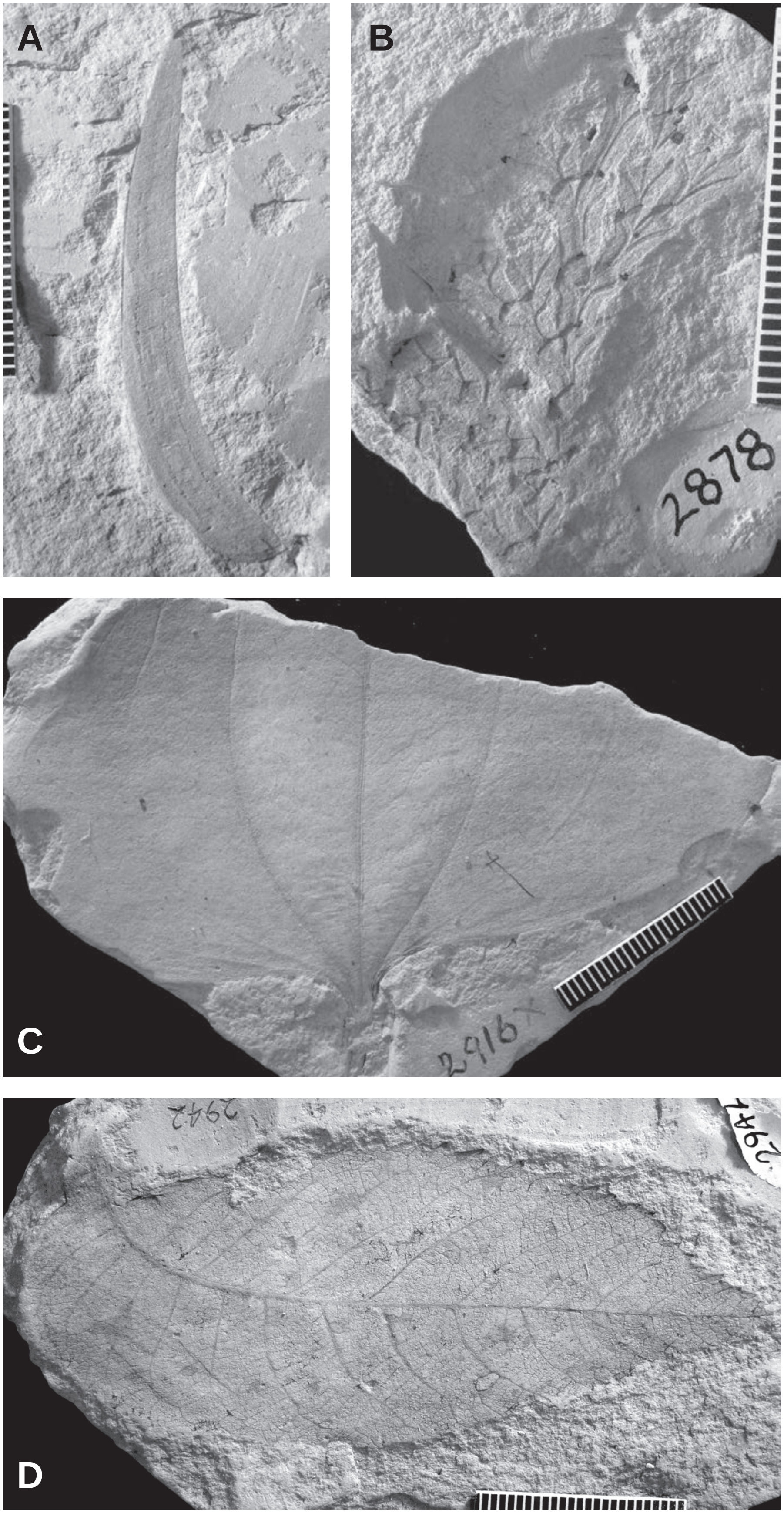

Figure 16. Some common and rare leaves/foliage types found in the Mascall flora (Chaney and Axelrod, 1959). (A) *Cephalotaxus californica* (hypotype, UCMP 2824). (B) *Thuja dimorpha* (hypotype, UCMP 2878). (C) *Smilax magna* (hypotype, UCMP 2916). (D) *Carya bendirei* (hypotype, UCMP 2942). Scale in mm. Specimens photographed by D.M. Erwin, courtesy of the UCMP.

Drive ~0.2 miles west from Overlook and park in the small pull out on the south side of the road.

Stop C. "Rainbow Hill" and Berwick Adit Hike

We will walk (~0.4 miles) along the gully here following an unmarked trail to an abandoned coal mine. The middle Big Basin Member is exposed in the surrounding hills. As we walk across an unvegetated exposed slope and enter another drainage, traces of fossilized wood should begin to appear. These are likely from large, compressed trunks of *Metasequoia* that lie in the carbonaceous beds ahead. This section of weakly developed lignites lies above the "pumice-charcoal tuff" that caps the leaf-bearing lakebeds. Lignites are otherwise very rare in the John Day Basin, and occur elsewhere in the Big Basin Member near Twickenham (north of here) and in the basal Mascall Formation between Dayville and Mount Vernon.

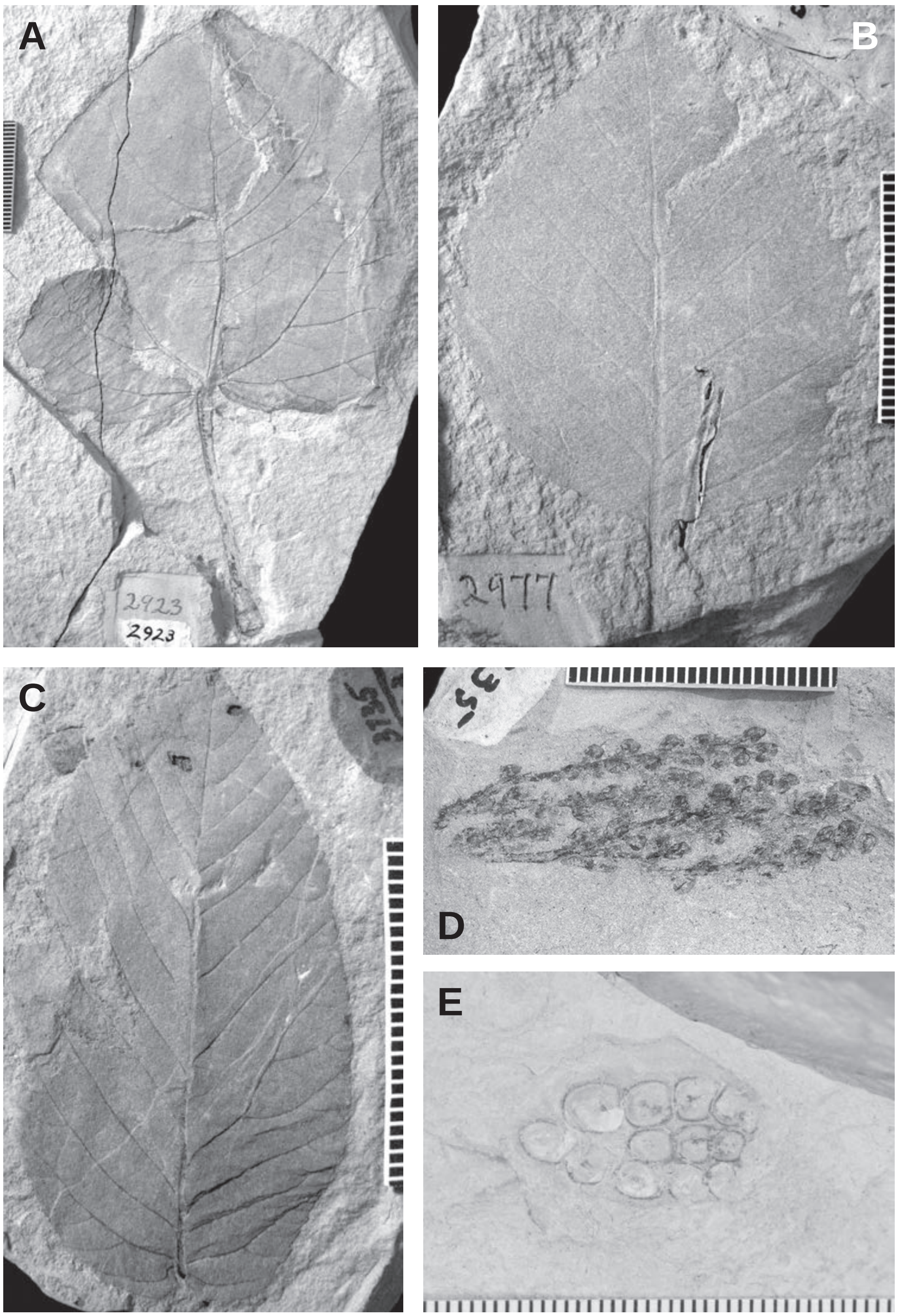

Figure 17. Leaves (A–C) and reproductive structures (D–E) found in the Mascall flora (Chaney and Axelrod, 1959). (A) *Populus lindgreni* (hypotype, UCMP 2923). (B) *Betula thor* (hypotype, UCMP 2977). (C) *Ostrya oregoniana* (hypotype, UCMP 2984). (D) *Taxodium dubium*, shoot with staminate cones (hypotype, UCMP 2905). (E) Nymphaceae fruit. Scale in mm. Specimens in A–D photographed by D.M. Erwin, courtesy of the UCMP.

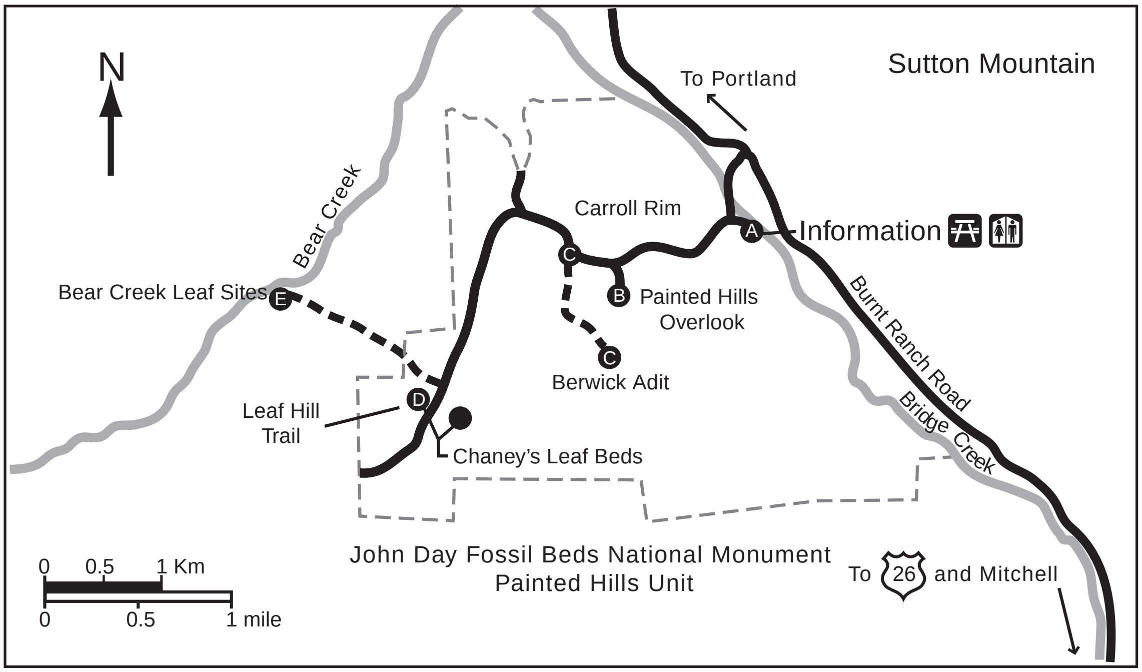

Figure 18. Day 3 route map.

Drive 0.4 miles and turn left, drive another 1.1 miles and park in Leaf Hill Trail parking area.

Stop D. Chaney's Leaf Hill, "Leaf Hill Trail," Type Locality for the Bridge Creek Flora

Exposed here in two hummocks, "leaf hill" to the west and a white-topped hill to the east of the road are the type localities of the Bridge Creek flora. Leaf Hill is the site of the first quantitative census study to be performed in the field of paleobotany. Chaney's (1924) quantitative studies of the flora involved quarrying three pits at different stratigraphic levels. A total of 98 cubic feet of rock was removed and resulted in the identification of over 20,000 specimens of leaves, cones and seeds that were assigned to 31 different taxa. The assemblage as a whole was dominated by *Alnus*, *Metasequoia*, and *Quercus* but also contained *Ulmus*,

Figure 19. Shale exposures in the Bear Creek Rim area.

Acer, *Platanus* and *Pinus* to name a few (Chaney, 1924; Meyer and Manchester, 1997). Unique to the Painted Hills assemblages are *Cunninghamina*, *Menispermum*, *Liquidambar*, *Betula*, *Dipteronia* and *Micropodium ovatum* and conspicuously absent is *Paracarpinus* which is common at other sites containing the Bridge Creek flora (Meyer and Manchester, 1997). Meyer and Manchester report the occurrence of 38 species from all of the lakebeds at Painted Hills.

Walk back to the parking area and back along the gravel road to the north ~0.1 miles. Turn left on a NPS service road and continue walking ~0.2 miles to a locked gate. Proceed through the locked gate on foot; this is now Bureau of Land Management managed land.

Stop E. Lacustrine Shales of Bear Creek Rim

In the Bear Creek drainage (a tributary to Bridge Creek) are excellent exposures of the Big Basin Member leaf-bearing shales (Fig. 19). These outcrops are an extension of Leaf Hill, but are located beyond the boundary of the National Monument,

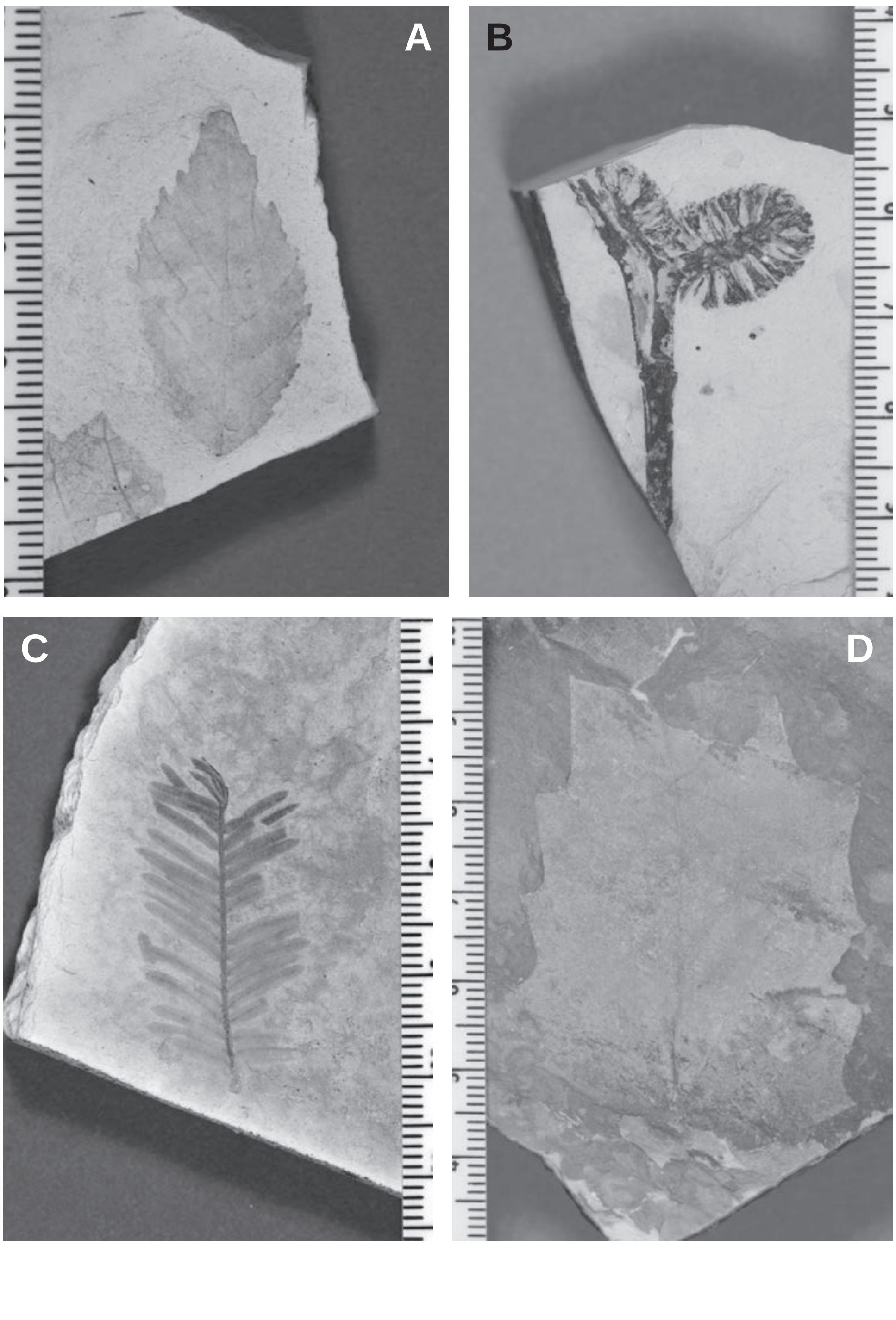

Figure 20. Common Bridge Creek flora species. (A) *Alnus heterodonta* (Painted Hills). (B) *Alnus* sp. (Iron Mountain). (C) *Metasequoia* sp. (Painted Hills). (D) *Mahonia simplex* (Iron Mountain). Scale in mm.

so collecting is allowed here. Figures 20 and 21 show examples of plant fossils found in the Bridge Creek flora. Return to the vehicles and exit Painted Hills, turn right on Bridge Creek Road and proceed to Highway 26. Turn right on Highway 26 toward the west and proceed up Ochoco Summit to Prineville and return to Portland.

CONCLUSIONS

The John Day Basin holds a geological section that is world renowned for its completeness, well-established geochronology, animal and plant fossils, and paleosols. This field trip has visited some of the key localities in the basin, and attempted to synthesize

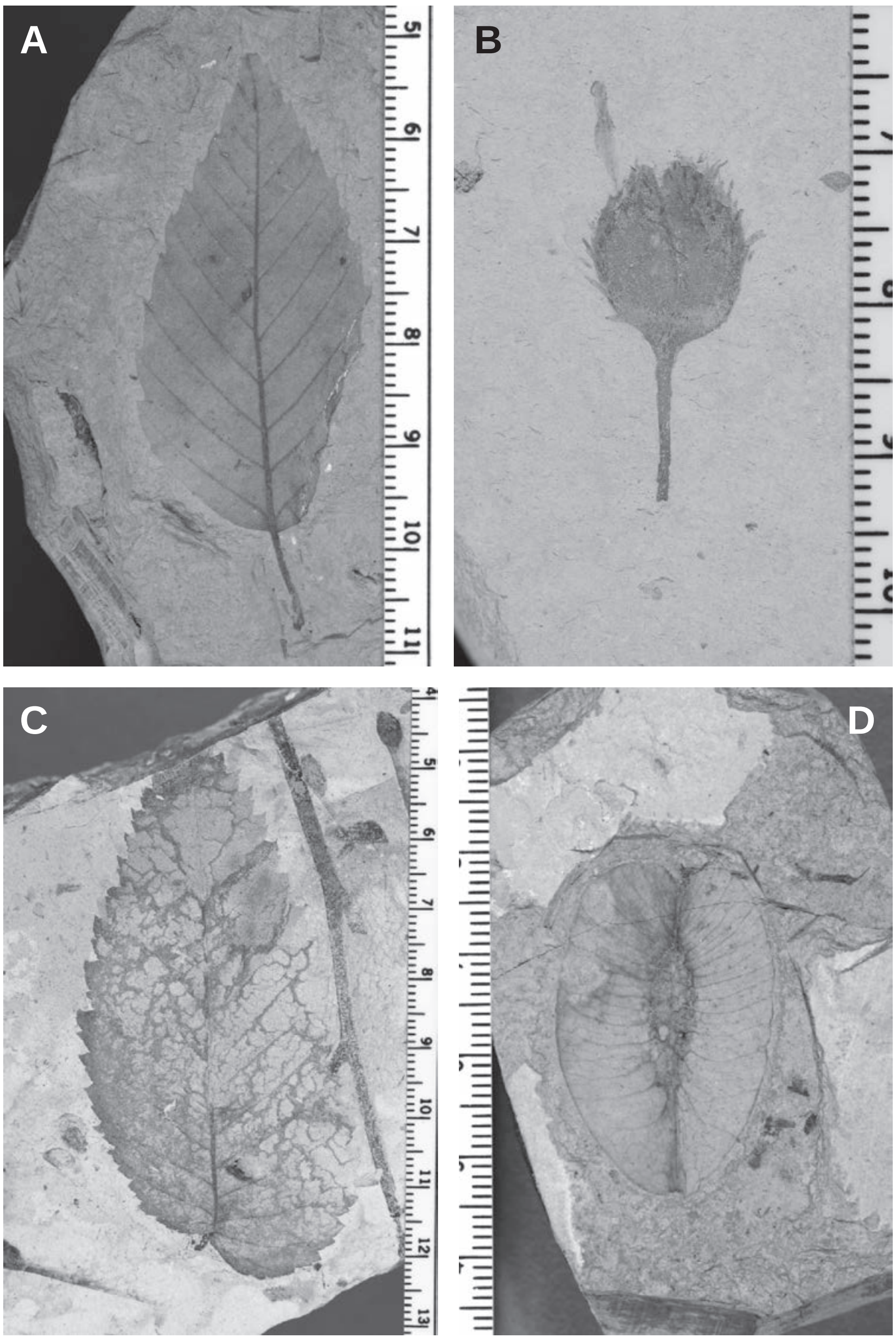

Figure 21. Bridge Creek flora leaves and reproductive structures from Wheeler High School, Fossil, Oregon. (A) *Fagus pacifica*. (B) *Fagus pacifica* cupule. (C) *Ulmus speciosa*. (D) *Craigia oregonensis*. Scale in mm.

information from a variety of disciplines and sources to provide a thorough and up to date general overview of the sequence and its recent and historical scientific study. The John Day Basin is very much an area of active research. Each year brings to light new discoveries and interpretations with immense relevance for understanding regional and global biotic and climatological trends.

ACKNOWLEDGMENTS

This field trip would not have been possible without the generous assistance of the National Park Service staff at the Thomas Condon Paleontology Center, Oregon Museum of Science staff at Camp Hancock and many individuals. Special thanks to Theodore Fremd and Christopher Schierup for arranging access to localities and specimens, Natascha Cronin, our host at Camp Hancock and Dr. Diane M. Erwin for providing photos of Mascall flora type material housed at the University of California Museum of Paleontology. Steven R Manchester, Greg Retallack, and Rebecca Dorsey provided helpful comments to this manuscript. Thank you to Anthony Tirico and Mary Maurer for allowing us to collect on their property.

REFERENCES CITED

Arnold, C.A., 1952, Fossil Osmundaceae from the Eocene of Oregon: Palaeontographica, v. 92B, p. 63–78.

Axelrod, D.I., 1944, The Alvord Creek flora: Carnegie Institute of Washington Contributions to Paleontology, v. 553, p. 225–262.

Bestland, E.A., 1997, Alluvial terraces and paleosols as indicators of early Oligocene climate change (John Day Formation, Oregon): Journal of Sedimentary Research, v. 67, p. 840-855

Bestland, E.A., and Forbes, M.S., 2003, Stratigraphy and geochemistry of the Mid-Miocene Mascall Formation (upper part) in its type area: Report for John Day Fossil Beds National Monument, 49 p.

Bestland, E.A., Retallack, G.J., and Fremd, T., 1994, Sequence stratigraphy of the Eocene-Oligocene transition: examples from the non-marine volcanically influenced John Day Basin, *in* Swanson, D.A., and Haugerud, R.A., eds., Geologic Field Trips in the Pacific Northwest: University of Washington, Department of Geological Sciences, p. A1–A19.

Bestland, E.A., Retallack, G.G., and Swisher, C.C., III, 1997, Stepwise climate change recorded in Eocene-Oligocene paleosol sequences from central Oregon: The Journal of Geology, v. 105, p. 153–172.

Bestland, E.A., Hammond, P.E., Blackwell, L.D.S., Kays, M.A., and Retallack, J.G., 1999, Geological framework of the Clarno Unit, John Day Fossil Beds National Monument, central Oregon: Oregon Geology, v. 61, p. 3–19.

Bestland, E.A., Forbes, M.S., Krull, E.S., Retallack, G.J., and Fremd, T., 2008, Stratigraphy, paleopedology, and geochemistry of the middle Miocene Mascall Formation (type area, central Oregon, USA): PaleoBios, v. 28, no. 2, p. 41–61.

Brown, R.W., 1959, A bat and some plants from the upper Oligocene of Oregon: Journal of Paleontology, v. 33, p. 125–129.

Chaney, R.W., 1920, The flora of the Eagle Creek Formation: Chicago, University of Chicago Press, Contributions from Walker Museum, v. II (5), p. 1–181.

Chaney, R.W., 1924, Quantitative studies of the Bridge Creek flora: American Journal of Science, v. 8, p. 127–144.

Chaney, R.W., 1925a, A comparative study of the Bridge Creek flora and the modern redwood forest: Carnegie Institute of Washington Publications, v. 349, p. 1–22.

Chaney, R.W., 1925b, The Mascall flora—Its distribution and climatic relation: Carnegie Institute of Washington Publication, v. 349, p. 23–48.

Chaney, R.W., 1927, Geology and paleontology of the Crooked River Basin, with special reference to the Bridge Creek flora: Carnegie Institute of Washington Publications, v. 346, p. 45–138.

Chaney, R.W., 1948a, The bearing of the living *Metasequoia* on problems of Tertiary paleobotany: Proceedings of the National Academy of Sciences of the United States of America, v. 34, p. 503–515, doi: 10.1073/pnas.34.11.503.

Chaney, R.W., 1948b, The ancient forests of Oregon: Condon Lectures, Oregon State System of Higher Education, Eugene, Oregon, 56 p.

Chaney, R.W., 1951, A revision of fossil *Sequoia* and *Taxodium* in western North America based on the recent discovery of *Metasequoia*: Transactions of the American Philosophical Society, v. 40, p. 171–263, doi: 10.2307/1005641.

Chaney, R.W., 1952, Conifer dominants in the middle Tertiary of the John Day basin, Oregon: The Paleobotanist, v. 1, p. 105–113.

Chaney, R.W., 1959, Miocene floras of the Columbia Plateau. Part I. Composition and interpretation: Carnegie Institute of Washington Contributions to Paleontology, v. 617, p. 1–134.

Chaney, R.W., and Axelrod, D.I., 1959, Miocene floras of the Columbia Plateau. Part II. Systematic considerations: Carnegie Institute of Washington Contributions to Paleontology, v. 617, no. 135–237.

Clark, R.D., 1989, The odyssey of Thomas Condon: Oregon Historical Society, Portland, 569 p.

Coxall, H.K., Wilson, P.A., Pälike, H., Lear, C.H., and Backman, J., 2005, Rapid stepwise onset of Antarctic glaciation and deeper calcite compensation in the Pacific Ocean: Nature, v. 433, p. 53–57, doi: 10.1038/nature03135.

D'Allura, J., and Hopt, B., 2009, Compositional variation in clasts in volcanic debris flows, Oligocene Colestin and Roxy formations, southwestern Oregon: Proceedings of the Oregon Academy of Science, v. 68, p. 25.

Deconto, R.M., and Pollard, D., 2003, Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2: Nature, v. 421, p. 245–249, doi: 10.1038/nature01290.

Dorsey, R.J., and Lenegan, R.J., 2007, Structural controls on Middle Cretaceous sedimentation in the Toney Butte area of the Mitchell inlier, Ochoco basin, central Oregon, *in* Cloos, M., Carlson, W.D., Gilbert, M.C., Liou, J.G., and Sorenson, S.S., eds. Convergent margin terranes and associated regions: A tribute to W.G. Ernst: Geological Society of America Special Paper 419, p. 97–115.

Downs, T., 1956, The Mascall fauna from the Miocene of Oregon: University of California Publications in Geological Sciences, v. 31, no. 5, p. 199–354.

Graham, A., 1999, Late Cretaceous and Cenozoic History of North American Vegetation: Oxford University Press, New York.

Fields, P.F., 1996, The Succor Creek flora of the Middle Miocene Sucker Formation, southwestern Idaho and eastern Oregon; systematic and paleoecology [Ph.D. dissertation]: East Lansing, Michigan, Michigan State University.

Fisher, R.V., and Rensberger, J.M., 1972, Physical stratigraphy of the John Day Formation, central Oregon: University of California Publications in Geological Sciences, v. 101, p. 1–33.

Fremd, T., Bestland, E.A., and Retallack, G.J., 1994, John Day Basin paleontology field trip guide and road log: 1994 Society of Vertebrate Paleontology Annual Meeting: Seattle, Washington, Northwest Interpretive Association, in cooperation with John Day Fossil Beds National Monument, Kimberly, Oregon.

Hanson, C.B., 1995, Stratigraphy and vertebrate faunas of the Bridgerian-Dichesnian Clarno Formation, north-central Oregon, *in* Prothero, D.R., and Emry, R.J., eds., The Terrestrial Eocene-Oligocene Transition in North America: Cambridge, Cambridge University Press, p. 206–239.

Hodell, D.A., and Woodruff, F., 1994, Variations in the strontium isotopic ratio of seawater during the Miocene: stratigraphic and geochemical implications: Paleoceanography, v. 9, no. 3, p. 405–426, doi: 10.1029/94PA00292.

Housen, B.A., and Dorsey, R.J., 2005, Paleomagnetism and tectonic significance of Albian and Cenomanian turbidites, Ochoco Basin, Mitchell inlier, central Oregon: Journal of Geophysical Research, v. 110, B7, 22 p.

Janis, C.M., Scott, K.M., and Jacobs, L.L., 1998, Evolution of Tertiary Mammals in North America. 1. Terrestrial Carnivores, Ungulates and Ungulatelike Mammals: Cambridge, Cambridge University Press.

Kennett, J.P., 1977, Cenozoic evolution of Antarctic glaciation, the circum-Antarctic Ocean, and their impact on global paleoceanography: Journal of Geophysical Research, v. 82, p. 3843–3860, doi: 10.1029/JC082i027p03843.

Knowlton, F.H., 1902, Fossil flora of the John Day Basin, Oregon: U.S. Geological Survey Bulletin No. 204.

Kuiper, J.L., 1988, Stratigraphy and sedimentary petrology of the Mascall Formation, eastern Oregon [unpublished MS thesis]: Oregon State University.

Kürschner, W.M., Kvaček, Z., and Dilcher, D.L., 2008, The impact of Miocene atmospheric carbon dioxide fluctuations on climate and the evolution of terrestrial ecosystems: Proceedings of the National Academy of Sciences of the United States of America, v. 105, no. 2, p. 449–453, doi: 10.1073/pnas.0708588105.

Leopold, E.B., and MacGinitie, H.D., 1972, Development and affinities of Tertiary floras in the Rocky Mountains, *in* Graham, A., ed., Floristics and paleofloristics of Asia and eastern North America, p. 147–200.

Leopold, E.B., Liu, G., and Clay-Poole, S., 1992, Low-biomass vegetation in the Oligocene? *in* Prothero, D.R., and Berggren, W.A., eds., Eocene-Oligocene Climatic and Biotic Evolution: Princeton University Press, Princeton, New Jersey, p. 399–420.

Lesquereux, L., 1878, Report on the fossil plants of the auriferous gravels of the Sierra Nevada: Memoirs of the Harvard Museum of Comparative Zoölogy, v. 6, no. 2, p. 1–62.

Lesquereux, L., 1888, Recent determinations of fossil plants from Kentucky, Louisiana, Oregon, California, Alaska, Greenland, etc., with descriptions of new species: Proceedings of the U.S. National Museum, vol. 11, p. 11–38.

Lipman, P.W., Prostka, H.J., and Christiansen, R. L., 1972, Cenozoic volcanism and plate tectonic evolution of the Western United States I: Early and middle Cenozoic: Royal Society (London), Philosophical Transactions, Series A, v. 271, p. 217-248.

Little, S.W., 1987, Stratigraphy, petrology and provenance of the Cretaceous Gable Creek Formation, Wheeler County, Oregon [M.S. thesis]: Department of Geology, Oregon State University. 133 p.

Liu, Z., Pagani, M., Zinniker, D., DeConto, R., Huber, M., Brinkhuis, H., Shah, S.R., Leckie, R.M., and Pearson, A., 2009, Global cooling during the Eocene-Oligocene climate transition: Science, v. 323, p. 1187–1190, doi: 10.1126/science.1166368.

Manchester, S.R., 1987a, The fossil history of Juglandaceae: Monographs of Systematic Botany: Missouri Botanical Garden, v. 21, p. 1–137.

Manchester, S.R., 1987b, Extinct Ulmaceous fruits from the Tertiary of Europe and western North America: Review of Palaeobotany and Palynology, v. 52, p. 119–129, doi: 10.1016/0034-6667(87)90049-2.

Manchester, S.R., 1990, Eocene to Oligocene floristic changes recorder in the Clarno and John Day formations, Oregon, USA, *in* Knobloch, E., and Kvaček, Z., eds., Symposium proceedings, paleofloristic and paleoclimatic changes in the Cretaceous and Tertiary: Geological Survey Press, Prague Czechoslovakia, p. 183–187.

Manchester, S.R., 1992, Flowers, fruits, and pollen of Florissantia, an extinct Malvalean genus from the Eocene and Oligocene of western North America: American Journal of Botany, v. 79, p. 996–1008, doi: 10.2307/2444909.

Manchester, S.R., 1994a, Inflorescence bracts of fossil and extant *Tilia* in North America, Europe, and Asia: Patterns of morphologic divergence and biogeographic history: American Journal of Botany, v. 81, p. 1176–1185, doi: 10.2307/2445480.

Manchester, S.R., 1994b, Fruits and seeds of the Middle Eocene Nut Beds flora, Clarno Formation, Oregon: Palaeontographica Americana, v. 58, no. 1–205.

Manchester, S.R., 1995, Yes, we had bananas: Oregon Geology, v. 57, p. 41–43.

Manchester, S.R., 1999, Biogeographic relationships of North American Tertiary floras: Annals of the Missouri Botanical Garden, v. 86, p. 472–522, doi: 10.2307/2666183.

Manchester, S.R., 2000, Late Eocene fossil plants of the John Day Formation, Wheeler County, Oregon: Oregon Geology, v. 62, p. 51–63.

Manchester, S.R., and Crane, P.R., 1987, A new genus of Betulaceae from the Oligocene of western North America: Botanical Gazette (Chicago, Ill.), v. 148, p. 263–273, doi: 10.1086/337654.

Manchester, S.R., and McIntosh, W.C., 2007, Late Eocene silicified fruits and seeds from the John Day Formation near Post, Oregon: PaleoBios, v. 27, no. 1, p. 7–17.

Mason, H.L., 1927, Fossil records of some west American conifers: Carnegie Institution of Washington Publication, v. 346, p. 139–158.

Mason, H.L., 1947, Origin and development of natural floristic areas with special reference to North America—Evolution of certain floristic associations in western North America: Ecological Monographs, v. 17, no. 2, p. 201–210, doi: 10.2307/1943264.

McIntosh, W.C., Manchester, S.R., and Meyer, H.W., 1997, Age of the plant-bearing tuffs of the John Day Formation at Fossil, Oregon, based on $^{40}Ar/^{39}Ar$ single crystal dating: Oregon Geology, v. 59, p. 3–30.

McKee, T.M., 1970, Preliminary report on the fossil fruits and seeds from the mammal quarry of the Clarno Formation: The Ore Bin, v. 32, p. 117–132.

Merriam, J.C., 1901, A contribution to the geology of the John Day Basin: University of California Bulletin, Department of Geology, v. II, no. 9, p. 269–314.

Meyer, H.W., and Manchester, S.R., 1997, The Oligocene Bridge Creek Flora of the John Day Formation, Oregon: University of California Publications Geological Sciences, v. 141, p. 1–195, 75 plates.

Myers, J.A., 1998, Paleovegetational heterogeneity and the record of Eocene-Oligocene climate change in the interior Pacific Northwest [Ph.D. dissertation]: Santa Barbara, California, University of California, 502 p.

Myers, J.A., 2003, Terrestrial Eocene-Oligocene vegetation and climate in the Pacific Northwest, *in* Prothero, D.R., Ivany, L.C., and Nesbitt, E.A., eds., From Greenhouse to Icehouse; the Marine Eocene-Oligocene Transition: Columbia University Press, New York, p. 171–185.

Myers, J.A., Kester, P.R., and Retallack, G.J., 2002, Paleobotanical record of Eocene-Oligocene climate and vegetational change near Eugene, Oregon, *in* Moore, G.W., ed., Field Guide to Geological Processes in Cascadia, p. 145–154.

Newberry, J.S., 1883, Brief descriptions of fossil plants, chiefly Tertiary, from western North America: U.S. National Museum: Proceedings, v. 5, p. 502–514.

Newberry, J.S., 1898, The later extinct floras of North America: U.S. Geological Survey Monograph, v. 35, p. 1–295.

Noble, D.C., 1972, Some observations on the Cenozoic volcano-tectonic evolution of the Great Basin, western United States: Earth and Planetary Science Letters, v. 17 (1), p. 142-150.

Pratt, J.A., 1988, Paleoenvironment of the Eocene/Oligocene Hancock Mammal Quarry, upper Clarno Formation, Oregon [M.S. thesis]: Eugene, Oregon Department of Geological Sciences, University of Oregon, 104 p.

Priest, G.R., 1990, Volcanic and tectonic evolution of the Cascade volcanic arc, central Oregon: Journal of Geophysical Research, v. 95, no. B12, p. 19,583–19,599, doi: 10.1029/JB095iB12p19583.

Prothero, D.R., Draus, E., and Foss, S.E., 2006, Magnetic stratigraphy of the lower portion of the middle Miocene Mascall Formation, central Oregon: PaleoBios, v. 26, p. 37–42.

Retallack, G.J., 1997, Neogene expansion of the North American prairie: Palaios, v. 12, no. 4, p. 380–390, doi: 10.2307/3515337.

Retallack, G.J., 2001, Cenozoic expansion of grasslands and climatic cooling: The Journal of Geology, v. 109, p. 407–426, doi: 10.1086/320791.

Retallack, G.J., 2004a, Late Miocene climate and life on land in Oregon within a context of Neogene global change: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 214, p. 97–123.

Retallack, G.J., 2004b, Late Oligocene bunch grasslands and early Miocene sod grasslands from central Oregon: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 207, p. 203–237, doi: 10.1016/S0031-0182(04)00042-2.

Retallack, G.J. 2004c, Ecological polarities of Cenozoic fossil soil, plants and animals from central Oregon: Paleobiology, v. 30, p. 561–588.

Retallack, G.J., 2007, Cenozoic paleoclimate on land in North America: The Journal of Geology, v. 115, p. 271–294, doi: 10.1086/512753.

Retallack, G.J., 2008, Cenozoic cooling and grassland expansion in Oregon and Washington: PaleoBios, v. 28, no. 3, p. 89–113.

Retallack, G.J., Bestland, E.A., and Fremd, T.J., 1996, Reconstructions of Eocene and Oligocene plants and animals of central Oregon: Oregon Geology, v. 58, no. 3, p. 51–68.

Retallack, G.J., Bestland, E.A., and Fremd, T.J., 2000, Eocene and Oligocene paleosols of central Oregon: Geological Society of America Special Paper 344, 192 p.

Retallack, G.J., Tanaka, S., and Tate, T., 2002, Late Miocene advent of tall grassland paleosols in central Oregon: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 183, p. 329–354, doi: 10.1016/S0031-0182(02)00250-X.

Robinson, P.T., Brem, G.F., and McKee, E.H., 1984, John Day Formation of Oregon: A distal record of early Cascade volcanism: Geology, v. 12, no. 4, p. 229–232, doi: 10.1130/0091-7613(1984)12<229:JDFOOA>2.0.CO;2.

Schorn, H.E., 1966, Revision of the fossil species of Mahonia from North America [master's thesis]: University of California, Berkeley, 150 p.

Schorn, H.E., Myers, J.A., and Erwin, D.M., 2007, Navigating the Neogene: Updating the paleobotanical record of the later Cenozoic in the Far West, *in* Jarzen, D., and Retallack, G.J., eds., Festschrift Volume in Honor of the 70th Birthdays of Jack A. Wolfe and David R. Dilcher: Senckenberg Museum Publication, Frankfurt, Germany, v. 258, p. 139–146.

Scott, R.A., 1954, Fossil fruits and seeds from the Eocene Clarno Formation of Oregon: Palaeontographica, v. B96, p. 66–97.

Sheldon, N.D., Retallack, G.J., and Tanaka, S., 2002, Geochemical climofunctions from North American soils and application to paleosols across the Eocene-Oligocene boundary in Oregon: The Journal of Geology, v. 110, p. 687–696, doi: 10.1086/342865.

Smiley, C.J., and Rember, W.C., 1985, Composition of the Miocene Clarkia Flora, *in* Smiley, C.J., Leviton, A.E., and Berson, M., eds., Late Cenozoic History of the Pacific Northwest: American Association for the Advancement of Science, p. 95–112.

Smith, G.A., Manchester, S.R., Ashwill, M., McIntosh, W.C., and Conrey, R., 1998, Eocene-Oligocene tectonics, volcanism and floral change near Gray Butte, central Oregon: Geological Society of America Bulletin, v. 110, p. 759–778, doi: 10.1130/0016-7606(1998)110<0759:LEEOTV>2.3.CO;2.

Strömberg, C. A. E. 2002. The origin and spread of grass-dominated ecosystems in the Late Tertiary of North America: Preliminary results concerning the evolution of hypsodonty: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 177, no. 1-2, p. 59–75.

Strömberg, C.A.E., 2004, Using phytolith assemblages to reconstruct the origin and spread of grass-dominated habitats in the Great Plains during the late Eocene to early Miocene: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 207, no. 3-4, p. 239–275, doi: 10.1016/S0031-0182(04)00043-4.

Strömberg, C.A.E., 2005, Decoupled taxonomic radiation and ecological expansion of open-habitat grasses in the Cenozoic of North America: Proceedings of the National Academy of Sciences of the United States of America, v. 102, no. 34, p. 11,980–11,984, doi: 10.1073/pnas.0505700102.

Strömberg, C.A.E., 2006, The evolution of hypsodonty in equids: testing a hypothesis of adaptation: Paleobiology, v. 32, no. 2, p. 236–258, doi: 10.1666/0094-8373(2006)32[236:EOHIET]2.0.CO;2.

Tanai, T., and Wolfe, J.A., 1977, Revisions of *Ulmus* and *Zelkova* in the middle and late Tertiary of western North America: U.S. Geological Survey Professional Paper 1026, p. 1–14.

Tiffney, B.H., 1985a, Perspectives on the origin of the floristic similarity between eastern Asia and eastern North America: Journal of the Arnold Arboretum, v. 66, p. 73–94.

Tiffney, B.H., 1985b, The Eocene North Atlantic land bridge: Its importance in Tertiary and modern phytogeography of the Northern Hemisphere: Journal of the Arnold Arboretum, v. 66, p. 243–273.

Tiffney, B.H., and Manchester, S.R., 2001, The use of geological and paleontological evidence in evaluating plant phylogeographic hypotheses in the northern hemisphere Tertiary: International Journal of Plant Sciences, v. 162, no. 6, Supplement, p. S3–S17, doi: 10.1086/323880.

Wheeler, E.A., and Manchester, S.R., 2002, Woods of the Eocene Nut Beds flora, Clarno Formation, Oregon, USA: International Association of Wood Anatomists Journal Supplement 3.

White, J.D.L., and Robinson, P.T., 1992, Intra-arc sedimentation in a low-lying marginal arc, Eocene Clarno Formation, central Oregon: Sedimentary Geology, v. 80, p. 89–114, doi: 10.1016/0037-0738(92)90034-O.

Wiemann, M.C., Manchester, S.R., Dilcher, D.L., Hinojosa, L.F., and Wheeler, E.A., 1998, Estimation of temperature and precipitation from morphological characters of dicotyledonous leaves: American Journal of Botany, v. 85, no. 12, p. 1796–1802, doi: 10.2307/2446514.

Wing, S.L., 1998, Tertiary vegetation of North America as a context for mammalian evolution, *in* Janis, C.M., Scott, K.M., and Jacobs, L.L., eds., Evolution of Tertiary Mammals in North America. 1. Terrestrial Carnivores, Ungulates and Ungulatelike Mammals: Cambridge University Press, Cambridge, p. 37–65.

Wolfe, J.A., 1968, Paleogene biostratigraphy of nonmarine rocks in King County, Washington: Geological Survey Professional Paper, v. 571, p. 1–33.

Wolfe, J.A., 1972, An interpretation of Alaskan Tertiary floras, *in* Graham, A., ed., Floristics and Paleofloristics of Asia and Eastern North America: Amsterdam, Elsevier, p. 201–231.

Wolfe, J.A., 1977: Paleogene floras from the Gulf of Alaska region: U.S. Geological Survey Professional Paper 997, p. 1–108.

Wolfe, J.A., 1981, A chronologic framework for Cenozoic megafossil floras of northwestern North America and its relation to marine geochronology, *in* Armentrout, J.A., ed., Pacific Northwest Cenozoic biostratigraphy: Geological Society of America Special Paper 184, p. 39–47.

Wolfe, J.A., 1992, Climatic, floristic, and vegetational change near the Eocene/Oligocene boundary in North America, *in* Prothero, D.R., and Berggren, W.A., eds., Eocene-Oligocene Climatic and Biotic Evolution: Princeton University Press, Princeton, New Jersey, p. 421–436.

Wolfe, J.A., 1993, A method of obtaining climatic parameters from leaf assemblages. U.S. Geological Survey Bulletin 2040:1–70.

Wolfe, J.A., 1994a, Alaskan Paleogene climates as inferred from the CLAMP database, *in* Boulter, M.C., and Fisher, H.V., eds., Cenozoic Plants and Climates of the Arctic: Springer, Berlin, p. 223–237.

Wolfe, J.A., 1994b, Tertiary climatic changes at middle latitudes of western North America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 108, no. 3-4, p. 195–205, doi: 10.1016/0031-0182(94)90233-X.

Wolfe, J.A., and Tanai, T., 1987, Systematics, phylogeny, and distribution of *Acer* (maples) in the Cenozoic of western North America: Journal of the Faculty of Science Hokkaido University series IV, v. 22, p. 1–246.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001, Trends, rhythms, and aberrations in global climate 65 Ma to present: Science, v. 292, no. 5517, p. 686–693, doi: 10.1126/science.1059412.

Manuscript Accepted by the Society 24 June 2009

Printed in the USA