PALEOCENE–EOCENE BOUNDARY IN CONTINENTAL NORTH AMERICA: BIOSTRATIGRAPHY AND GEOCHRONOLOGY, NORTHERN BIGHORN BASIN, WYOMING

GREGG F. GUNNELL[1], WILLIAM S. BARTELS[2] and PHILIP D. GINGERICH[1]

[1]Museum of Paleontology, University of Michigan, Ann Arbor, Michigan 48109-1079; [2]Department of Geological Sciences, Albion College, Albion, Michigan 49224

Abstract—The Clarkforkian–Wasatchian boundary in continental sediments of the Western Interior of North America is marked by the simultaneous appearance of three important orders of mammals: Artiodactyla, Perissodactyla, and Primates; this boundary is also marked by the disappearance of choristoderan reptiles (champsosaurs). The northern Bighorn Basin in northwestern Wyoming contains a continuous sedimentary record representing the late Tiffanian, Clarkforkian and Wasatchian land-mammal "ages." Densely concentrated fossil localities have been examined through this sequence, and the resultant faunal record represents the most complete documentation of vertebrate evolution across the Paleocene–Eocene boundary in the world. The northern Bighorn Basin mammalian faunal sequence is an ideal continental reference section for the Paleocene–Eocene transition. We propose that the boundary between these two epochs continues to be placed at the Clarkforkian–Wasatchian boundary because of the dramatic reorganization of mammalian faunas that occurs there.

Correlation of biostratigraphic units is an issue separate from recognition. Independent geochronologic evidence is required to assure synchronous comparisons of geographically diverse faunas. Geochronologic evidence from the northern Bighorn Basin and elsewhere suggests that reorganization of vertebrate faunas at the Clarkforkian–Wasatchian boundary may have occurred in response to a global restructuring of ecosystems across the Paleocene–Eocene boundary.

INTRODUCTION

The Paleocene Epoch was originally defined by Schimper (1874), based on fossil floras from the Paris and London basins. Schimper's definition of the Paleocene included the Thanetian marine stage and, at least, a portion of the Ypresian marine stage (Schorn, 1971; Gingerich, 1975). From the point of view of vertebrate paleontology, the Paleocene in Europe can be recognized by its distinctive mammalian fauna (Russell, 1964; Pomerol, 1969; Schmidt-Kittler, 1987).

Matthew (1914, 1920) was one of the first to characterize the North American Paleocene, including the Puerco and Torrejon mammalian faunas of New Mexico, in an interval distinct from Wasatch faunas. Matthew (1914) noted the presence of many archaic mammalian taxa (multituberculates, insectivores, "edentates") in the Paleocene of North America, and distinguished Eocene mammalian faunas by the presence of more modern groups such as perissodactyls, artiodactyls, primates and rodents. Matthew (1914) equated the Torrejon fauna with that of the Thanetian in Europe. He felt that the Sparnacian was equivalent to the early Wasatchian faunas of North America, and that the Ypresian (=Cuisian) may have been equivalent to late Wasatchian faunas.

For the past 18 years, University of Michigan field parties have been working in the northern Bighorn Basin (Clarks Fork Basin and adjacent areas) in northwestern Wyoming (Fig. 1). A major portion of this work has concentrated on a thick, essentially continuous, basin-fill sequence represented by the Fort Union and Willwood formations. This lithologic sequence spans the Puercan land-mammal "age" (earliest Paleocene) through the Wasatchian land-mammal "age" (early Eocene). Nearly 800 fossil vertebrate localities have been sampled through this sequence, all from precisely controlled stratigraphic levels (Gingerich, 1974, 1976a, b, 1980, 1982, 1983; Gingerich and Gunnell, 1979; Gingerich and Simons, 1977).

The following contribution summarizes lithologic and biotic information gathered over the past two decades pertinent to recognition of the Paleocene–Eocene boundary in the North American Western Interior. We find compelling evidence, based on mammalian and reptilian faunas, to maintain the Paleocene–Eocene boundary at the boundary between the Clarkforkian and Wasatchian land-mammal "ages." We propose that the northern Bighorn Basin is the ideal reference section for documenting the transition from the Paleocene to the Eocene in continental sediments.

GEOLOGIC SETTING

The localities discussed in this paper are located in the northern part of the Bighorn Basin, a structural and topographic basin in northwestern

Wyoming. The basin is bounded by the Laramide uplifts of the Bighorn Mountains to the east, the Pryor Mountains to the northeast, the Beartooth Mountains (and Absaroka volcanic field) to the west and the Owl Creek and Southern Bighorn Mountains to the south. The basin opens into the Crazy Mountain Basin to the north. The Beartooth and Bighorn Mountains were the source areas for the local basin-fill sequences deposited during the Late Cretaceous and Early Tertiary (Bown, 1979, 1980). This lithologic sequence includes the Paleocene Fort Union Formation and the Paleocene and Eocene Willwood Formation (Van Houten, 1944; Neasham and Vondra, 1972).

The Fort Union Formation is underlain by the Lance Formation and overlain by the Willwood Formation. It is generally about 1000 m thick, but reaches a maximum thickness of over 3000 m in the Beartooth foredeep along the western edge of the Bighorn Basin (Moore, 1961). It is composed of drab conglomerates, sandstones, siltstones, mudstones, argillaceous limestones, lignites and coals, with sandstones,
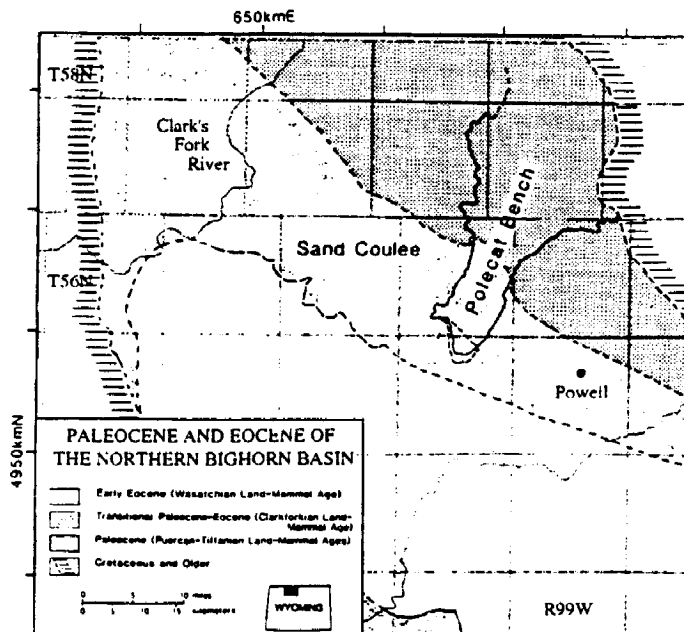

FIGURE 1. Sketch map of the northern Bighorn Basin (Clarks Fork Basin) in northwestern Wyoming.

siltstones, mudstones and lignites predominating. Red beds are absent, and extensive claystones and clayey mudstones are virtually absent. The lower part of the formation can be locally dominated by either channel or floodplain deposits. The upper part contains a predominance of overbank deposits that include highly carbonaceous shales (rather than lignites), occasional clayey mudstones, and highly mottled beds that are often reddish in color. Paludal and lacustrine facies are present also in the Fort Union, exposed primarily near the Montana border (Hickey, 1980; Yuretich et al., 1984). In the northern Bighorn Basin, the Fort Union ranges in age from Puercan (earliest Paleocene) to, at least, the early Clarkforkian (late Paleocene).

The Willwood Formation overlies the Fort Union Formation conformably near the basin center, but along some margins of the basin the Willwood contacts the Fort Union and underlying Cretaceous formations along an angular unconformity (Van Houten, 1944). The Willwood Formation is truncated by Cenozoic erosion surfaces throughout most of the Bighorn Basin, but is overlain conformably by Absarokan tuffaceous sediments of the fluvio-lacustrine Tatman and fluvial Aycross formations in the western part of the basin (Bown, 1982; Torres, 1985). The preserved thickness of the Willwood is generally about 800 m in the northern Bighorn Basin (Rose, 1981). The deposits are dominated by clay-rich overbank mudstones. These mudstones have been overprinted by paleosols of varying maturity (Bown and Kraus, 1981; Winkler, 1983) and are highly variegated. Channel and sheet sandstones are typically thin and isolated, local impure limestones are rare (Gingerich, 1987), conglomerates are restricted to certain basin margins (Van Houten, 1944; Bown, 1980) and lignites are locally absent. The age of the Willwood ranges from middle Clarkforkian (latest Paleocene) to late Wasatchian (early Eocene) in the basin proper, and to early Bridgerian (middle Eocene) along the western basin margin (Torres and Gingerich, 1983; Gunnell et al., 1992).

BIOSTRATIGRAPHY

Three land-mammal "ages" are recognized at and around the Paleocene–Eocene boundary in the northern Bighorn Basin: the late Paleocene Tiffanian, the transitional Paleocene–Eocene Clarkforkian (here regarded as latest Paleocene), and the early Eocene Wasatchian.

Late Tiffanian vertebrate assemblages are dominated by typically archaic Paleocene elements. Among reptiles, baenid and trionychid turtles are beginning to give way to emydid turtles (which show up locally in the middle Tiffanian). The common lizards are primitive glyptosaurine anguids (*Odaxosaurus* and *Proxestops*) and a variety of small insectivorous forms such as *Restes*, "*Haplodontosaurus*" and a varanoid (Estes, 1975; Bartels, 1987). The champsosaurs *Champsosaurus* and *Simoedosaurus* are present (Sigogneau-Russell and Baird, 1978) along with at least one species of the crocodilid *Leidyosuchus* and two species of the alligator *Allognathosuchus* (Bartels, 1987).

Late Tiffanian mammalian assemblages consist of exclusively archaic elements. Multituberculates (*Prochetodon* and *Ectypodus*), proprimates (*Plesiadapis*, *Phenacolemur* and *Carpolestes*) and condylarths (*Ectocion*, arctocyonids) are the most common mammalian taxa. Other archaic orders (Carnivora, Proteutheria, Lipotyphla, Pantodonta) are represented by moderately diverse radiations.

The Clarkforkian land-mammal "age" has been defined based on fossil mammals recovered from the northern Bighorn Basin (Granger, 1914; Rose, 1981). Clarkforkian deposits are central to understanding the transition from archaic Paleocene vertebrate faunas to Eocene assemblages of modern aspect. Clarkforkian reptile assemblages are a mixture of Tiffanian and new elements. Trionychids, champsosaurs, crocodilids and the Tiffanian lizards are still present, but the assemblage is now dominated by emydid turtles, alligators (including *Ceratosuchus*) and the derived glyptosaurine lizard *Melanosaurus* (Bartels, 1983, 1984).

Clarkforkian mammal assemblages are still dominated by archaic groups, but some new elements are present also. Condylarths (especially *Phenacodus* and *Ectocion*) are very common, as are proprimates (*Plesiadapis*). Rodents (*Paramys*) and tillodonts (*Azygonyx*) represent new mammalian groups present in Clarkforkian faunas. Overall, mammalian diversity remains relatively consistent, although common elements seem to dominate Clarkforkian faunas more than in the Tiffanian.

The Wasatchian land-mammal "age" is characterized by a classic early Eocene fauna (Matthew and Granger, 1915, 1918). The reptile assemblage continues to be dominated by small alligators, emydid turtles and glyptosaurine lizards (which undergo additional diversification), while champsosaurs and *Ceratosuchus* are extinct. Later Wasatchian faunas include a more diverse aquatic and terrestrial turtle component (Hutchison, 1980). Modern orders of mammals such as Artiodactyla (*Diacodexis*), Perissodactyla (*Hyracotherium*) and Primates (*Cantius*, *Teilhardina*) are present and become the dominant groups through the Wasatchian. Archaic mammalian groups remain relatively common (especially the hyopsodontid condylarths *Hyopsodus* and *Haplomylus*) in the early part of the Wasatchian.

Faunal Boundaries

Two major faunal reorganizations are recorded within the northern Bighorn Basin sequence, one between the Tiffanian and Clarkforkian (Rose, 1981) and the other between the Clarkforkian and Wasatchian (Gingerich, 1989). Both are recognized by first and last occurrences and changes in relative abundance and diversity of vertebrate assemblages. The horned alligator *Ceratosuchus*, an emydid box turtle and, perhaps, the derived glyptosaurine lizard *Melanosaurus* appear for the first time at the Tiffanian–Clarkforkian boundary (Bartels, 1983). The first appearance of the mammalian orders Rodentia and Tillodontia (Rose, 1981; Krause and Maas, 1990) also occurs at this horizon. Among mammalian families, coryphodontid pantodonts appear at the beginning of the Clarkforkian.

Clarkforkian–Wasatchian changes in the reptilian assemblage are more dramatic than those at the beginning of the Clarkforkian. *Ceratosuchus*, a large chelydrid turtle, the emydid box turtle and champsosaurs become extinct (Bartels, 1983; Hutchison, pers. comm., 1982). There is additional diversification within the emydids (including the first appearance of *Echmatemys*) and the initial appearance of glyptosaurinid lizards (Bartels, 1983) and kinosternid turtles (Hutchison, 1980). Modern rhineurid amphisbaenians and the problematical crocodilian *Orthogenysuchus* (Mook, 1924) also make their first appearance at this datum, but they are of questionable utility due to small sample sizes. Other typical early Eocene elements, such as the lizard *Xestops*, a robust species of *Allognathosuchus* and dermatemydid and testudinid turtles make their initial appearances later in the Wasatchian (Hutchison, 1980; Bartels, 1987).

The Clarkforkian–Wasatchian transition can be recognized by the first occurrences of the mammalian orders Artiodactyla, Perissodactyla and Primates, and the last occurrence of Notoungulata (Rose, 1981; Gingerich, 1989). At the familial level, ptilodontid multituberculates, arctostylopid notoungulates, cyriacotheriid pantodonts and carpolestid and plesiadapid proprimates disappear at the end of the Clarkforkian. There is, however, one enigmatic published record of a single *Plesiadapis* specimen from the middle Wasatchian (Rose and Bown, 1982). Dichobunid artiodactyls, hyaenodontid creodonts, equid perissodactyls and adapid and omomyid primates first appear in the earliest Wasatchian. A principal component analysis of mammalian faunas across the Clarkforkian–Wasatchian boundary (Fig. 2) shows a marked contrast between the composition of Clarkforkian and Wasatchian mammalian assemblages (Gingerich, 1989).

The faunal break at end of the Clarkforkian is by far the most striking one recorded in the entire northern Bighorn Basin sequence. Closer examination of certain mammalian taxa reveals other, less dramatic, but nonetheless important changes in composition across the Clarkforkian–Wasatchian boundary. Figure 3 summarizes within order compositional changes at the family level based on relative frequencies of genera and total numbers of specimens. Within "Condylarthra" (Fig. 3A), several changes occur. Arctocyonid condylarths become increasingly less frequent from Cf3 through Wa1. Hyopsodontids are more abundant than phenacodontids in the late Clarkforkian based on relative frequency of genera, but are much less common in actual numbers of specimens (hyopsodontids—7%, phenacodontids—92%).

In the earliest Wasatchian (Wa0), hyopsodontids are less abundant than phenacodontids based on percentages of genera, but have become relatively more common based on numbers of specimens (hyopsodon-
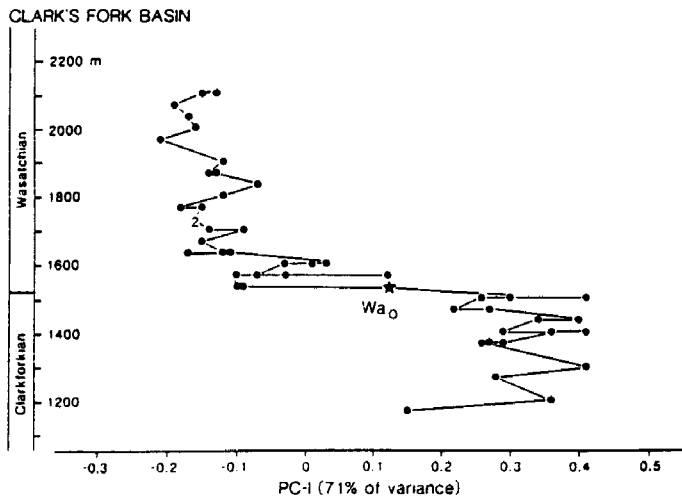
CLARK'S FORK BASIN

FIGURE 2. Plot of first principal-component scores (PC-I) of mammalian faunal composition versus stratigraphic level from the Clarks Fork Basin, Wyoming. PC-I component loadings contrast Clarkforkian faunas (on right) dominated by archaic mammalian groups (phenacodontid condylarths, proprimates) with Wasatchian faunas (on left) dominated by more modern mammalian groups (artiodactyls, perissodactyls, primates). The fauna from Wasatchian biostratigraphic zone Wa0 (star) is intermediate in composition between Clarkforkian and Wasatchian faunas (from Gingerich, 1989).

tids—33%, phenacodontids—61%). In Wasatchian zone Wa1, hyopsodontids and phenacodontids are equally abundant generically, while hyopsodontids (64%) have now become more common based on numbers of specimens compared to phenacodontids (31%).

Compositional changes take place within other orders across the Clarkforkian–Wasatchian boundary as well. Within Proprimates (Fig. 3B), paromomyids and microsyopids become more frequent both in terms of genera and specimen numbers. Among true carnivores (Fig. 3C), viverravids dominate both in percent genera and in specimen numbers in the late Clarkforkian and earliest Wasatchian (Wa0). By Wa1, miacids and viverravids are equally diverse, but viverravids still remain more common based on total numbers of specimens. In Cf3, all creodonts are oxyaenids (Fig. 3D). Hyaenodontids suddenly appear in the earliest Wasatchian and immediately are the dominant creodont family.

European Comparisons

A reorganization of vertebrate faunas occurs across the Thanetian–Ypresian (Sparnacian) boundary in Europe, with modern orders (Primates, Artiodactyla, Perissodactyla) appearing for the first time. Figure 4 compares this compositional change with that of the Clarkforkian–Wasatchian boundary.

There are discrepancies between the two records as well. For example, in North America rodents and tillodonts appear before (at the Tiffanian–Clarkforkian boundary) primates, artiodactyls and perissodactyls. In Europe all of these orders appear at the same time (Thanetian–
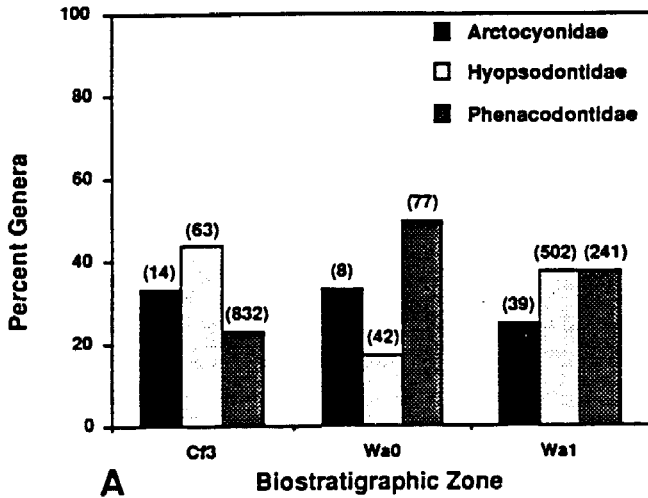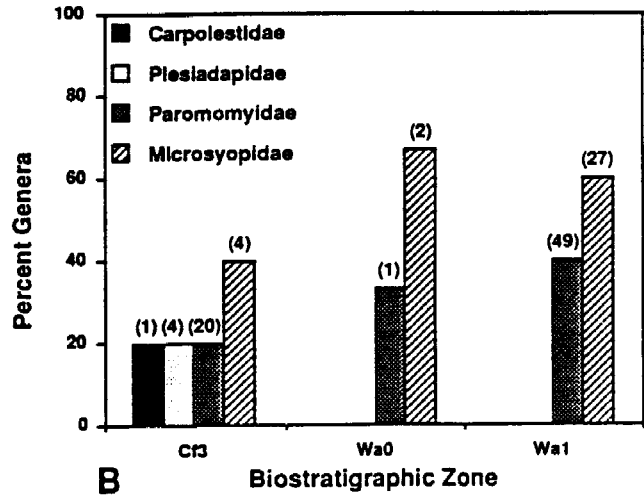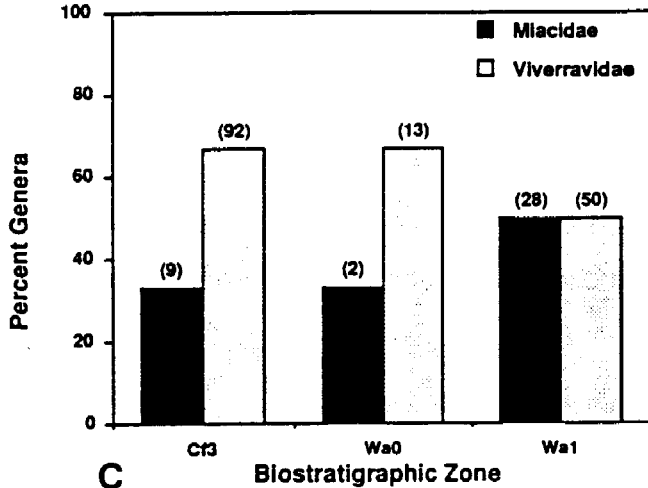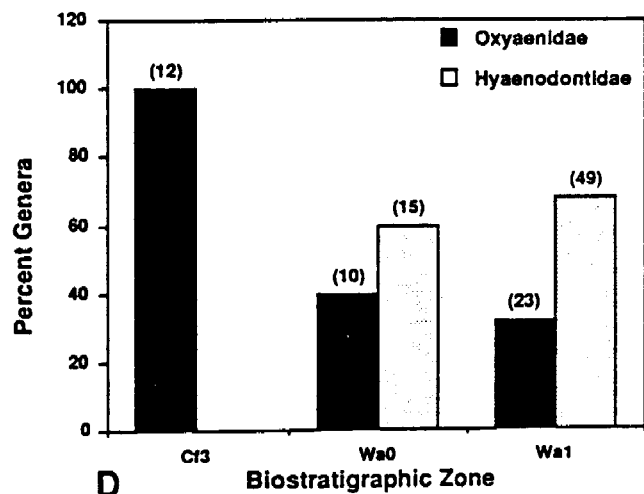

FIGURE 3. Histograms showing percentage of genera representing families of four mammalian orders from biostratigraphic zones Cf3 through Wa1 in the Clarks Fork Basin. A, "Condylarthra." B, Proprimates. C, Carnivora. D, Creodonta. Numbers in parentheses indicate total numbers of specimens representing each family.

EUROPE

THANETIAN	YPRESIAN
	CHIROPTERA
	PRIMATES
	RODENTIA
	CREODONTA
	CARNIVORA
	ARTIODACTYLA
	PERISSODACTYLA
	TILLODONTIA
Cimolodontidae	
Meniscotheriidae	
Tricuspiodontidae	
Champsosaurs	

NORTH AMERICA

LATE TIFFANIAN	CLARKFORKIAN	EARLY WASATCHIAN
		ARTIODACTYLA
		PERISSODACTYLA
		PRIMATES
		Hyaenodontidae
	TILLODONTIA	
	RODENTIA	
	Coryphodontidae	
	NOTOUNGULATA	
	Ptilodontidae	
	Carpolestidae	
	Cyriacotheriidae	
	Champsosaurs	

FIGURE 4. Summary of appearances and disappearances among important mammalian orders and families and of champsosaurs in Europe and North America. Shading indicates mammalian orders that first appear at the beginning of the Ypresian and Wasatchian.

Ypresian boundary). Several possibilities exist to explain this discrepancy. Rodents and tillodonts may well have arrived in North America from Asia, before reaching Europe. Alternatively, the appearance of rodents and tillodonts at the Thanetian–Ypresian boundary in Europe may indicate that this reorganization corresponds to the North American Tiffanian–Clarkforkian boundary and that primates, artiodactyls and perissodactyls occurred in Europe before reaching North America. A third alternative is that the Clarkforkian land-mammal "age" is not represented in Europe (Dashzeveg, 1982, 1988). A fourth possibility (perhaps the most likely) is that the appearance and disappearance of reptilian and mammalian taxa on a global scale is time-transgressive. These discrepancies do not represent difficulties with the recognition of Paleocene and Eocene epochs, but do present difficulties concerning the correlation of epoch boundaries on a global scale based on biotic appearance and disappearance evidence alone.

GEOCHRONOLOGY

Geochronologic evidence can provide information on the absolute timing of biotic events. While Paleocene and Eocene faunas can be distinguished from one another, the diachronous biotic reaction to geologic events, and the intra- and intercontinental time-transgressive nature of biotic reorganization make such biotic events unreliable indicators of temporal compatibility among geographically diverse samples. Recent efforts in the Bighorn and Clarks Fork basins have produced several geochronologically useful pieces of evidence, based on magnetic-polarity stratigraphy, carbon isotopes, radiometric dating and paleosols.

Butler et al. (1981) reported on the paleomagnetic stratigraphy of the Clarks Fork Basin lithologic sequence. The Tiffanian–Clarkforkian

boundary falls within magnetic anomaly 25. The Clarkforkian–Wasatchian boundary occurs between anomalies 25 and 24 (within chron 24R). Butler et al. (1987) confirmed the magnetostratigraphic position of these boundaries.

Koch et al. (1992) reported on changes in $\delta^{13}C$ through the Tiffanian–Wasatchian sequence in the Clarks Fork Basin. Samples analyzed from teeth (enamel apatite of the herbivorous mammal *Phenacodus*) and paleosol carbonate nodules revealed decreases in $\delta^{13}C$ of 4 to 6% at the Clarkforkian–Wasatchian boundary. Koch et al. (1992) suggested that the $\delta^{13}C$ excursion recorded from North American continental sediments is isochronous with a similar excursion recorded from ODP hole 690B (Weddell Sea, Antarctica) at approximately 57.3 Ma (Stott et al., 1990).

Wing et al. (1991) provided a radiometric date for the upper portion of the Willwood Formation in the central Bighorn Basin. A date of 52.8 Ma (± 0.16) was obtained from a crystal-rich "bentonite" near the top of the local Willwood section using $^{40}Ar/^{39}Ar$ dating. Recognizing the first occurrence of *Platycarya* pollen in the Willwood Formation as isochronous with the NP9/10 boundary (Wing, 1984) and using available dates for NP10 (Obradovich, 1988), Wing et al. (1991) suggested an interpolated date of approximately 55.7 Ma for the *Platycarya* FAD (35 m below the Willwood contact with the underlying Fort Union Formation).

Bown and Kraus (1993) discuss a method for addressing depositional gaps (hiatuses) in the lithologic record based on relative maturity of paleosol horizons recorded in the Willwood Formation of the central Bighorn Basin. The presence of an extremely mature paleosol horizon at the beginning of the Wasatchian (biostratigraphic zone Wa0; Gingerich, 1989) suggests that a substantial period of non-deposition occurred in the Bighorn Basin at the Clarkforkian–Wasatchian boundary. Bown and Kraus (1993) indicate that such periods of non-deposition may be correlated with regional tectonic events (pulses).

A change in depositional regime at the end of the Clarkforkian is also indicated by an extensive sheet sandstone complex deposited by laterally migrating channels during an interval of low sediment accumulation (Kraus, 1980).

Correlations

Correlation of biostratigraphic and geochronologic events within the Bighorn and Clarks Fork basins indicates relative compatibility, if not congruence (Fig. 5). The *Platycarya* FAD and the appearance of artiodactyls, primates and perissodactyls are almost coincident near the Clarkforkian–Wasatchian boundary, although Wing et al. (1991) suggest the *Platycarya* FAD is slightly earlier than Wa0; however, no mammalian specimens are available from relevant sections that would confirm this. The restructuring of plant and animal communities suggests that substantial ecosystem reorganization was occurring across this boundary.

Isotopic evidence also suggests some regional perturbation of ecosystems at the Clarkforkian–Wasatchian boundary, as evidenced by the substantial $\delta^{13}C$ excursion occurring there. Koch et al. (1992) equate this carbon-isotopic excursion with an abrupt climatic warming event at the Paleocene–Eocene boundary (Rea et al., 1990). The extremely mature, non-hydromorphic nature of Wa0 paleosols indicates a period of non-deposition that may have been correlated with regional tectonism and climatic warming occurring at or near the Clarkforkian–Wasatchian boundary (Bown and Kraus, 1993).

Available radiometric dates from Bighorn and Clarks Fork basin sections do not seem to be compatible at first glance. Wing et al. (1991) report a date of approximately 55.7 Ma for the *Platycarya* FAD in the central Bighorn Basin. Koch et al. (1992) report a date of 57.3 Ma for the isotope excursion coincident with the Clarkforkian–Wasatchian boundary (assuming synchrony with a similar marine isotopic excursion). However, Koch et al. (1992) note that this date will be shifted approximately 2 million years younger by impending revisions (Koch et al., 1992, fig. 1). Therefore the date for the Clarkforkian–Wasatchian boundary and the *Platycarya* FAD are essentially identical.

Correlation of geochronologic events recorded in the Clarks Fork and Bighorn basins with continental records from Europe is not com-

Figure chart labels:

			CHRON	CFB	Wing et al., 1991	Koch et al., 1992	Bown & Kraus, 1993

Koch et al., 1992: Paleosol Carbonate; axis δ¹³C from -14 to -6; 55.3 Ma
Bown & Kraus, 1993: Paleosol Maturity Index; Mature ← → Immature

EOCENE — WASATCHIAN — Wa1, 24R, Wa0
PALEOCENE — CLARKFORKIAN — Cf3, Cf2, Cf1; 25N
TIFFANIAN — Ti6, 25R, Ti5

CFB: Willwood Fm.; Artiodactyla / Perissodactyla; Primates / Hyaenodontidae; Fort Union Fm.
Wing et al., 1991: Willwood Fm.; Platycarya; NP10; 55.7 Ma; NP9; Fort Union Fm.
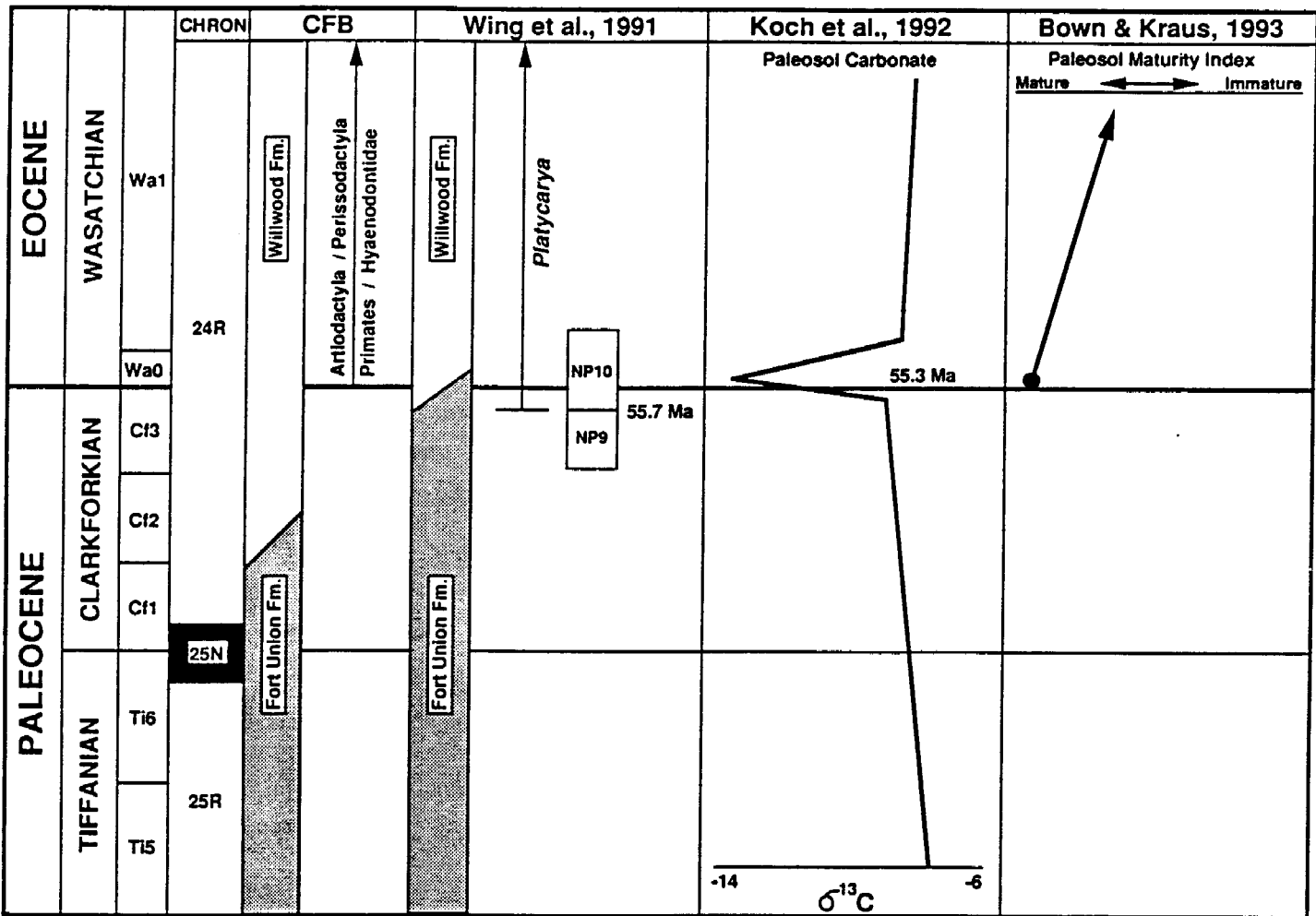
FIGURE 5. Summary of geochronologic and biostratigraphic information for the Bighorn Basin in northwestern Wyoming. Paleomagnetic chrons are taken from Butler et al., 1981. CFB indicates duration of Fort Union and Willwood deposition in the Clarks Fork Basin (from Rose, 1981) and the appearance of new mammals at the Clarkforkian–Wasatchian boundary. Information from Wing et al. (1991) indicates the duration of Fort Union and Willwood deposition in the central Bighorn Basin. the position of the *Platycarya* FAD. its correlation with nannoplankton zones 9 and 10 and an interpolated date for the FAD. Data from Koch et al. (1992) indicate the occurrence of a substantial ¹³C excursion at the Clarkforkian–Wasatchian boundary in the Clarks Fork Basin. Information from Bown and Kraus (1993; also see Gingerich. 1989) indicates the presence of an extremely mature. non-hydromorphic paleosol at the Clarkforkian–Wasatchian boundary suggesting a relatively long period of non-deposition marking the onset of the Wasatchian.

pletely satisfactory. Based on paleomagnetic stratigraphy, Pomerol (1989) placed the Thanetian–Ypresian stage boundary (the European Paleocene–Eocene boundary based on mammalian biostratigraphy) at or slightly below chron 25N. which would loosely correlate with the North American Clarkforkian–Wasatchian boundary. Berggren et al. (1985) and Aubry et al. (1988) place the Thanetian–Ypresian boundary in chron 24R. well above chron 25N. This would correspond more closely with the Clarkforkian–Wasatchian boundary in North America. However, Berggren et al. (1985) included the Sparnacian stratotype section within the Thanetian stage and equated the early Eocene with the Cuisian (= Ypresian). not the Sparnacian. Pomerol (1989) points out that the Sparnacian stratotype section (at Epernay) is. in fact. early Cuisian (Sables de Laon) in age (above Paris Basin hiatus 5). not Thanetian (but older than the classic "Sables de Cuise"). Hooker (1991), citing Knox (1990). argued that the unconformity at the base of the London Clay equates with the P6a/b boundary and. as such. early Sparnacian faunas (Suffolk Pebble Beds. Dormaal. MP reference level 7) should be latest Paleocene in age. Pomerol (1989) equated the London Clay unconformity to Paris Basin hiatus 5 (HP5). suggesting that early Sparnacian faunas are early Eocene based on their position above hiatus 4. Hooker (1991) correlated MP7 faunas with Wa0 faunas from North America (also see Gingerich. 1989). If this is the case. it lends evidence

in support of Pomerol's (1989) interpretation that early Sparnacian faunas should be recognized as Eocene.

If the *Platycarya* FAD of Wing et al. (1991) corresponds to the NP9/10 boundary, the base of the Willwood Formation in the central Bighorn Basin approximately corresponds to the beginning of the Ypresian in the Paris Basin (at the P6a/b boundary, Berggren et al.. 1985; in NP10. Aubry et al. 1988) and to mammalian reference level MP7 in the London and Belgian basins (Hooker, 1991). The base of the Willwood Formation in the central Bighorn Basin correlates temporally with Wa0 in the northern Bighorn and Clarks Fork basins (Gingerich, 1989). Willwood deposition in the northern Bighorn Basin began by the middle Clarkforkian, and the Fort Union–Willwood contact is clearly time-transgressive, making the use of this lithostratigraphic boundary for broad temporal correlations inappropriate. The proposed 55.7 Ma age of the NP9/10 boundary and the *Platycarya* FAD (Wing et al., 1991) is comparable with the age given by Pomerol (1989) for the NP9/10 boundary. but is about 2 million years younger (as noted by Wing et al.; also see Koch et al. 1992) than that reported by Berggren et al. (1985) and Aubry et al. (1988).

Pomerol (1989) discusses a series of depositional hiatuses in the Paris Basin (also see Dashzeveg, 1982, 1988). If a date of approximately 55 Ma is correct for both the Clarkforkian–Wasatchian boundary and the

Thanetian–Ypresian boundary, then Pomerol's hiatus zone 4 (HP4) may correspond to a similar non-depositional period represented by the mature paleosol horizon of Wa0 (Bown and Kraus, 1993). If hiatuses in the Paris Basin are also the result of tectonic pulses as suggested for the Bighorn Basin, this may argue for a global tectonic event occurring at that time. Rea et al. (1990) hypothesize that such global tectonism did in fact occur at the Paleocene–Eocene boundary.

CONCLUSIONS

Two separate issues are involved in addressing biostratigraphic units and the boundaries between them: recognition and correlation. Recognition is related to unique biotic events that give biostratigraphic units identity. These unique biotic events often serve to delimit the boundaries of adjacent biostratigraphic units. By necessity, biotic events are limited to those sets of evidence sampled by any particular lithologic system. It is useless, for example, to attempt to delimit biostratigraphic units within continental sediments based on a strictly marine biota (the opposite also holds true). Therefore, recognition of Paleocene and Eocene epochs will always hinge on the kinds of biotic evidence and types of sediments being sampled.

The northern Bighorn Basin in northwestern Wyoming offers the most complete and best sampled record of vertebrate evolution from the late Paleocene through the early Eocene in the world. We propose that the boundary between the Paleocene and Eocene in continental sediments be based on the most dramatic and obvious evidence of biotic reorganization. It is clear that this reorganization occurs at the Clarkforkian–Wasatchian boundary when there is a dramatic restructuring of mammalian communities and synchronous changes among reptiles.

The Clarks Fork Basin sequence, because of its complete section and because it has been so well sampled and studied, is the ideal continental reference section for recognizing the Paleocene–Eocene boundary.

Correlation of biostratigraphic units is an issue separate from recognition. The time-transgressive nature of biotic reorganization on a global or even regional scale is such that correlation of one event with the same or a similar event in a separate geographic area does not, in and of itself, offer substantial support for synchrony of the two events. Relating biostratigraphic units to an independent geochronologic time scale is the only method of assuring synchronous comparisons. Evidence from carbon isotopes, the boundary sandstones and paleosols indicates that some perturbations of the local environment were occurring at the Clarkforkian–Wasatchian boundary in the Clarks Fork Basin, perhaps concurrent with similar perturbations from other areas of the globe. Absolute dating and paleomagnetic stratigraphy constrain these events in time and indicate that the worldwide ecosystem reorganizations that are known to have occurred around 55 Ma *may* have been synchronous events in response to global tectonism at or near the Paleocene–Eocene boundary.

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ROAD LOG, NORTHERN BIGHORN BASIN PALEOCENE–EOCENE BOUNDARY

This road log begins and ends in Cody, situated in the northwestern portion of Wyoming at the eastern edge of the Yellowstone Plateau. The entire tour totals 153 km (95 miles) and will probably take the better part of a day to complete. It is recommended that vehicles with low ground clearance not attempt this trip.

From Cody, proceed northeast on Wyoming Highway 14A towards Powell (38 km, 23 miles). Eight kilometers (5 miles) east of Cody the highway crosses the Shoshone River. This crossing is near the boundary between the drab Fort Union Formation (below) and the red-banded Willwood Formation (above). As you continue, Heart Mountain rises some 1220 m in isolation on the left side of the highway. The lower portion of Heart Mountain consists of brightly colored Wasatchian Eocene beds of the Willwood Formation overlain by a massive detachment block of Mississippian Madison Limestone. The Willwood Formation is more impressively exposed in the McCullough Peaks on the right side of the highway. McCullough Peak itself is also capped by a Heart Mountain detachment block.

Upon reaching Powell, turn north (left) on Wyoming Highway 295. Directly ahead against the skyline is a long, flat-topped terrace known as Polecat Bench. Polecat Bench is a Plio-Pleistocene pediment consisting of a thin veneer of gravel capping a nearly continuous sequence of latest Cretaceous (north end) through earliest Eocene (south end) formations exposed along the flanks.

Proceed north on Highway 295 for 13 km (8.5 miles), climbing the southeast flank of Polecat Bench near the Powell Airport. The drab interbedded sandstones, mudstones and lignites of the Fort Union Formation are exposed on either side of the highway to the top of Polecat Bench. Along the road the beds are Tiffanian in age, but progressively younger strata are exposed to the west (right) where variegated Clarkforkian beds of the overlying Willwood Formation can be seen dipping to the southwest.

STOP 1—Turn right on the first graded dirt road on top of Polecat Bench and proceed 2.5 km (1.5 miles) to fence line. Turn left along fence line and follow track for 1.6 km (1 mile); turn right and proceed to edge of Polecat Bench (a few hundred feet). From this vantage point the Little Polecat oil field and the Late Cretaceous Lance Formation can be seen. Directly to the right and below is an isolated hill topped by a sandstone block. Rock Bench quarry (Torrejonian, middle Paleocene) is located in the clay-clast conglomerate at the base of this sandstone. Mantua quarry (Puercan, early Paleocene) is located out of view approximately 0.8 km (0.5 miles) southeast of Rock Bench, also in a clay-clast conglomerate below a large channel sandstone. Both quarries are in the lower portion of the Fort Union Formation.

STOP 2—Return to Highway 295 and turn north (right) for 3.8 km (2.4 miles). Turn left on an improved road and proceed 5 km (3.1 miles) to the west edge of Polecat Bench. Just before the road turns to the right, turn south (left) onto a grassy track and proceed 0.8 km (0.5 miles). Directly to the right are exposures of the Fort Union Formation in a locality known as Fossil Hollow (Tiffanian, late Paleocene). From the edge of the bench at Fossil Hollow to the west and northwest are extensive exposures of Tiffanian sediments. Princeton

quarry, a rich Tiffanian locality, is situated approximately 4.3 km (2.6 miles) west of Fossil Hollow.

STOP 3—Continue south along the western edge of Polecat Bench 12 km (7.5 miles). As you drive up section to the south, sediments of the Fort Union Formation and overlying Willwood Formation are continuously exposed along the western flank of the bench. These sediments span the Tiffanian through Clarkforkian land-mammal "ages." Turn west (right) and proceed for 0.8 km (0.5 miles) to the edge of Polecat Bench. From this vantage point the whole of the Clarks Fork Basin can be viewed spreading westward. Directly beneath your feet is a sheet sandstone unit referred to as the "boundary sandstone." This sandstone separates the underlying Clarkforkian (Paleocene) from the overlying Wasatchian (Eocene) land-mammal "ages." This sandstone unit can be traced laterally for several miles. It often appears as a multi-storied sheet sand, but may also encompass a package of finer-grained mudstone units within it. This can be observed at the next stop.

STOP 4—Continue south to the southern tip of Polecat Bench (4.8 km, 3 miles). From the top of the bench, the brightly colored red, yellow and purple beds of University of Michigan locality SC-67 can be seen. These sediments (Wasatchian, earliest Eocene) are enveloped in the boundary sandstone unit. The mammalian fauna from this locality is distinctive (Wasatchian biostratigraphic zone Wa0) and represents the earliest known record of Eocene mammals in North America. The first appearances of such typical Eocene orders as Artiodactyla, Perissodactyla and Primates are recorded here.

Return north for 0.8 km (0.5 miles) and then turn left onto the old Billings to Meeteetse stagecoach road and descend the southern tip of Polecat Bench.

(If conditions are very wet, backtrack to Powell and take Lane 9 west to the Badger Basin Highway). Follow this road for 3.1 km (1.9 miles) to the south until you reach Lane 9 (paved road). Turn west (right) and proceed 1.8 km (1.1 miles) to the T-intersection with the Badger Basin Highway. Turn north (right) and proceed 10 km (6.2 miles). During this leg of the trip you will cross over the south rim of the Sand Coulee drainage basin and descend into the head of Big Sand Coulee. Exposures on either side of the highway are of Clarkforkian age. Turn west (left) onto the Little Sand Coulee Road. (If conditions are very wet, continue straight to Wyoming Highway 120 and turn left).

STOP 5—Proceed 7.3 km (4.5 miles), crossing a small rise in the road. At this point the Clarkforkian–Wasatchian boundary sandstone is directly beneath your feet. To the north is Saddle Mountain (1.3 km, 0.8 miles). The boundary sand unit runs through the saddle so that the Wasatchian is exposed above and the Clarkforkian below. Directly ahead (to the west) are Wasatchian exposures of the Willwood Formation. Large collections of early Eocene fossils have been amassed from these exposures. Proceed west for 11.2 km (7 miles) through the Sand Coulee badlands and onto Chapman Bench, a Pleistocene terrace. At the T-intersection with Wyoming Highway 20 turn south (left). Pause to view Beartooth Range features such as Bald Ridge (straight ahead), Clark's Fork Canyon (just to the north) and Pat O'Hara Mountain (to the south, opposite Heart Mountain). Cody and the end of this tour lie 32 km (20 miles) ahead. As you drive to Cody, note the variegated Willwood Formation sitting unconformably on the drab Upper Cretaceous Mesa Verde and Meeteetse formations and close-up views of Heart Mountain on the left (east).