

GEOCHRONOLOGY AND MAGNETOSTRATIGRAPHY OF PALEOGENE NORTH AMERICAN LAND MAMMAL "AGES": AN UPDATE

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ABSTRACT: Laser-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ dating and magnetostratigraphy have significantly changed our conception of the temporal duration and correlation of Paleogene North American land mammal "ages." The Wood Committee (1941) originally divided the Paleocene Epoch into five land mammal "ages." Current age estimates of their time spans are: Puercan, 65–63.8 Ma; Torrejonian (including the "Dragonian"), 63.8–61 Ma; Tiffanian, 61–56 Ma; and Clarkforkian, 56–55.2 Ma. The Paleocene/Eocene boundary, long placed in the Clarkforkian, occurs in the earliest Wasatchian, based on correlations using mammals, pollen, and terrestrial carbon isotopes.

The Wood Committee (1941) divided the North American Eocene Epoch into four land mammal "ages": Wasatchian (originally thought to be early Eocene), Bridgerian (thought to be middle Eocene), and Uintan and Duchesnean (both once thought to be late Eocene). The earliest Wasatchian is now considered Paleocene age, and the Wasatchian/Bridgerian boundary is about 50.4 Ma in age. The Bridgerian, Uintan and Duchesnean land mammal "ages" are all middle Eocene age. The Bridgerian/Uintan boundary occurs in magnetic Chron C21n, about 47 Ma. The Uintan/Duchesnean boundary occurs within Chron C18n, and lies above an ash dated at about 40 Ma. The Duchesnean/Chadronian boundary lies within Chron C16n, about 37 Ma.

Finally, the Wood Committee (1941) divided their concept of North American Oligocene sequence into three land mammal "ages": the Chadronian, Orellan and Whitneyan (supposedly early, middle, and late Oligocene). The Chadronian/Orellan transition occurs just above a date of 33.9 Ma, late in Chron C13r; it is slightly younger than the Eocene/Oligocene boundary, and this makes the Chadronian mostly late Eocene, not early Oligocene age. The Orellan/Whitneyan boundary occurs in the middle of Chron C12r, just below a date of 31.8 Ma. The Whitneyan/Arkareean boundary occurs within Chron C11n, above a date of 30.0 Ma. Consequently, the Orellan and Whitneyan are both early Oligocene, and most of the Arkareean (long considered early Miocene) is late Oligocene age. These new age estimates and correlations differ greatly from the time scales published as recently as 1987.

INTRODUCTION

In North America, the only practical method of correlation and dating of most Cenozoic terrestrial deposits has been with land mammals. At the turn of the century, William Diller Matthew and Henry Fairfield Osborn (Matthew, 1899; Osborn and Matthew, 1909; Osborn, 1907, 1910, 1929) attempted to create biostratigraphic zonations of the North American terrestrial sequence, based on principles followed by European stratigraphers at the time (see review by Tedford, 1970). But the good beginning established by Osborn and Matthew was lost, since the next generation of vertebrate paleontologists virtually ignored their pioneering work.

Unlike most marine invertebrates, fossil mammals typically occur in localized fossiliferous horizons, or in isolated pockets or quarries without stratigraphic superposition. As a result, traditional biostratigraphic methods developed by European invertebrate paleontologists (based on detailed stratigraphic ranges of fossils in measured sections) were not widely followed by North American vertebrate paleontologists (nor are they followed by European vertebrate paleontologists, then or now). In 1937 the Vertebrate Paleontology Section of the Paleontological Society appointed a committee to clarify the confusion over correlation, and adopt a terminology that could be widely used. Known as the Wood Committee (Wood and others, 1941), it was chaired by Horace E. Wood II, and included four other vertebrate paleontologists (Edwin H. Colbert, John Clark, Glenn L. Jepsen, and Chester Stock), plus paleobotanist Ralph Chaney, and invertebrate paleontologist J. B. Reeside.

The Wood Committee's "Provincial Ages" were a complex hybrid of local rock units and time units delineated by index taxa, characteristic taxa, and first and last occurrences of mammalian genera. As Tedford (1970) and Woodburne (1977, 1987) have pointed out, these units were not true geochronological ages, which must be based on biostratigraphic zones and stages (according to western stratigraphic codes, such as the 1983 North American Code of Stratigraphic Nomenclature). Since

they were not standard stratigraphic ages, the North American land mammal "ages" should properly be put in quotes in most publications. Instead, the Wood Committee's methods resemble a system called "biochronology," first proposed by H. S. Williams (1901), which attempts to reconstruct the sequence of occurrences of taxa without documenting every event in a local stratigraphic section. Demonstration of stratigraphic superposition was noted when available, but detailed biostratigraphic work in the tradition of European invertebrate paleontologists was not considered essential to their "provisional" system.

In spite of their loose characterization, the land mammal "ages" of the Wood Committee worked quite well for over forty years, mostly because mammals do evolve and disperse very rapidly (Savage, 1977). However, problems eventually arose. For example, the Chadronian land mammal "age" was originally defined both on the co-occurrence of the horse *Mesohippus* and brontotheres, and also on the limits of the Chadron Formation. At the time, the last occurrence of brontotheres was thought to coincide with the top of the Chadron Formation, so there was no conflict. When Morris Skinner discovered brontothere specimens in rocks correlative with the overlying Orellan Member of the Brule Formation (which typified the Orellan), the difficulty with defining the Chadronian both biochronologically and lithostratigraphically became apparent (Emry and others, 1987; Prothero, 1982; Evanoff and others, 1992). Yet many of Skinner's contemporaries could not accept this evidence, since the misconception that rock units could be treated as time units was widespread among paleontologists of that generation.

Since the 1950s, a newer generation of paleontologists (see Savage, 1955, 1962, 1977; Tedford, 1970; Woodburne, 1977, 1987) has tried to bring vertebrate paleontology back to more rigorous classical biostratigraphic methods. Trained in modern stratigraphic thinking, vertebrate biostratigraphers now appreciate the possibility that rock units can be time-transgressive over distance (Shaw, 1964; Prothero, 1990), and so they rarely confuse rock units with time units. In addition, we have come

to realize that detailed stratigraphic zonations of mammal fossils provides much higher resolution of time than collections whose only stratigraphic information is the formation they came from. As discussed by Woodburne (1977), such detailed zonation could potentially subdivide the Cenozoic Era into increments of time of 300,000 years or less. In recent years, portions of the North American continental Tertiary have been formally subdivided by proper biostratigraphic methods. However, the zonation of the entire Cenozoic Era is still in progress, and biochronological methods are still widely used.

Although mammalian paleontologists are increasingly moving toward classical biostratigraphic procedures, there are still problems. For example, biostratigraphic "zonations" proposed by Gingerich (1980, 1983), Sloan (1987), and Gunnell (1989) do not meet all the criteria established by the North American Code of Stratigraphic Nomenclature. Typically, these "zones" do not have formally proposed type sections (required in Article 54e), and in some cases the actual local stratigraphic ranges of key taxa are not clearly indicated. Consequently, they are still "biochrons" based on the abstract first and last occurrences of taxa, not true biostratigraphic zones and stages, which must be based on local ranges of fossils in specific sections.

Even the review of the Paleocene land mammal chronology by Archibald and others (1987), which attempted to rigorously define a number of different biostratigraphic zones, did not tie these to specific levels in a local biostratigraphic zonation. Instead, these authors relied on the Wood Committee's practice of referring a number of different localities to a specific "zone" and listing taxa of biochronological importance. Rather than follow the stricter criteria of the North American Stratigraphic Code, they adopted lineage-zones and interval-zones in the looser sense of the International Stratigraphic Guide (Hedberg, 1976), which were not tied to local biostratigraphic zonations. Archibald and others (1987, p. 25) acknowledge that "these ages (and zones) are based on faunal content that in many instances cannot be defined with precision in type sections . . . for the most part these units cannot be regarded as stages. This is, of course, one of the goals for the future."

In addition to higher-resolution biostratigraphy, other techniques have come along to improve terrestrial correlation. The original application of K-Ar dating by Evernden and others (1964) to the North American terrestrial record provided an independent test of the Wood Committee sequence and showed it to be substantially correct. For over 25 years, K-Ar methods continued to refine the chronology, and provided numerical estimates of the age for most of the sequence (Savage, 1977; Savage and Russell, 1983; Woodburne, 1987). However, in the last five years, the development of high-precision single-crystal $^{40}\text{Ar}/^{39}\text{Ar}$ dating (McDougall and Harrison, 1988; Swisher, this volume) showed that many of the classical K-Ar dates must be recalibrated. In some cases, they have significantly changed the chronology that was accepted for decades (Swisher and Prothero, 1990; Prothero and Swisher, 1992; Berggren and others, this volume).

Another breakthrough came from the application of magnetic stratigraphy to terrestrial sections. Unlike any other method of correlation, magnetic stratigraphy can supply many globally synchronous, numerically dated time horizons to terrestrial sections (Lindsay and others, 1987; Prothero, 1988, 1990; Opdyke, 1990). The combination of both magnetic stratigraphy and $^{40}\text{Ar}/$

^{39}Ar dating has provided much higher temporal resolution and precision than was thought possible just 20 years ago. More importantly, magnetic stratigraphy is the only technique that allows direct correlation with the global polarity record and thus with the marine time scale. This in turn allows us to make direct comparison between global climatic changes, diversity fluctuations, and mass extinctions and the North American terrestrial record for the first time.

THE NORTH AMERICAN TERRESTRIAL PALEOGENE "AGES"

Paleocene Epoch

In 1941, the Wood Committee created five land mammal "ages" for an interval they considered approximately equivalent to the Paleocene Epoch (Fig. 1). The first two, the Puercan and Torrejonian, were based on faunas from the San Juan Basin in

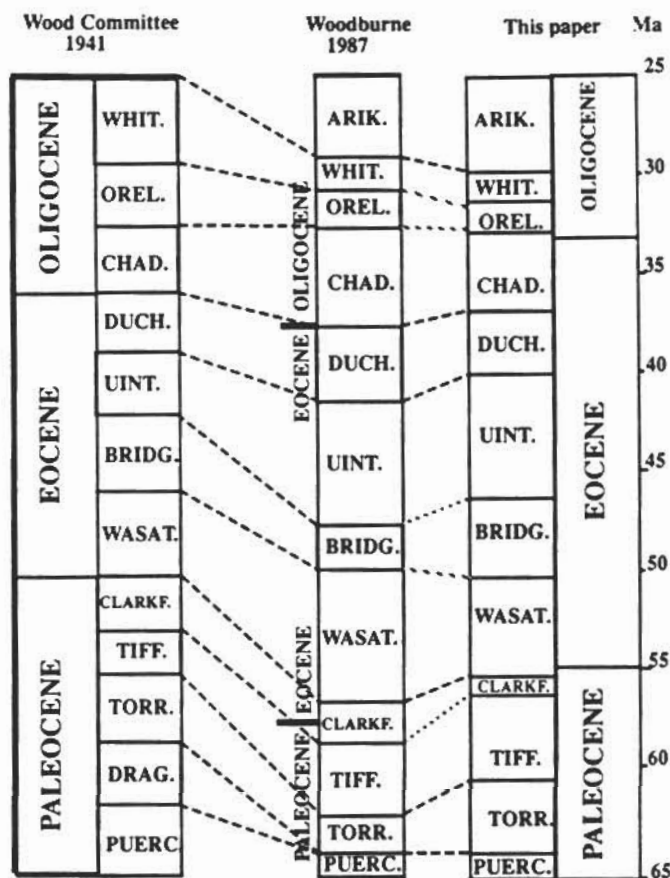


FIG. 1.—Comparison of the correlation of Paleogene North American land mammal "ages" from their original formulation by the Wood Committee (1941) to the present. K-Ar dating was unavailable in 1941, so the Wood Committee had no means of estimating numerical ages. Note that the Arikareean had become mostly late Oligocene age by the time of Woodburne (1987), and the Dragonian had been abandoned. The most important recent changes (besides the new numerical age estimates) is the shifting of the Chadronian from the early Oligocene to the late Eocene age, and the placement of the Paleocene/Eocene boundary in the early Wasatchian, rather than the Clarkforkian. Abbreviations are as follows: ARIK. = Arikareean; BRIDG. = Bridgerian; CHAD. = Chadronian; CLARKF. = Clarkforkian; DRAG. = Dragonian; DUCH. = Duchesnean; OREL. = Orellan; PUERC. = Puercan; TIFF. = Tiffanian; TORR. = Torrejonian; UINT. = Uintan; WASAT. = Wasatchian; WHIT. = Whitneyan.

New Mexico. The controversial Dragonian "age" was based on the limited Dragon Canyon local fauna from the North Horn Formation of central Utah. Although correlative faunas were later found in New Mexico (Tomida, 1981), most paleontologists now consider the Dragonian to be the beginning of the Torrejonian (Tomida and Butler, 1980; Tomida, 1981; Sloan, 1987; Archibald and others, 1987). The Tiffanian was originally based on faunas from the San Juan Basin in Colorado, but since then the Tiffanian has become much better known from faunas in Montana and Wyoming. The Clarkforkian land mammal "age" was originally based on faunas from the Clark's Fork Basin on the Montana-Wyoming border. Originally considered latest Paleocene age by the Wood Committee (1941), in recent years it was thought to span the Paleocene/Eocene boundary based on correlations of plesiadapids from Europe and North America (Gingerich, 1976; Gingerich and Rose, 1977; Rose, 1981). As we shall see in the next section, the Paleocene/Eocene boundary is now thought to occur in the earliest Wasatchian, so not only the Clarkforkian but also the earliest Wasatchian are now considered Paleocene age.

North American Paleocene chronology was most recently summarized by Archibald and others (1987). Most of the Paleocene Epoch has now been subdivided into a series of biostratigraphic "zones," abbreviated "Pu1, Pu2, Pu3, To1" ("Puercan 1, 2, 3, Torrejonian 1") and so on (Fig. 2). This scheme was originally introduced by Gingerich (1976, 1980, 1983) based on a local zonation of adapid primates and plesiadapids from Tiffanian and Clarkforkian of the northern Bighorn Basin of Wyoming, and expanded to the Puercan and Torrejonian strata by Archibald and others (1987) and by Sloan (1987).

Archibald and Lofgren (1990) added an additional "interval-zone," Pu0, for the earliest Paleocene beds above the K/T boundary in eastern Montana (called the "Bugcreekian" by Sloan and others, 1986). As noted above, these "zones" do not meet the criteria of the North American Code of Stratigraphic Nomenclature since they lack type sections. Although there are some difficulties with this zonation (see Schankler, 1980, 1981), the scheme has been modified with additional mammalian groups and has been widely adopted (Archibald and others, 1987). There are four Puercan "zones," three Torrejonian "zones," six Tiffanian "zones," and three Clarkforkian "zones" (plus Wasatchian 0, which is also latest Paleocene).

Relatively few Paleocene radiometric dates are available. The most recent dates on the Cretaceous/Tertiary boundary place its age at 65 Ma (Berggren and others, this volume). Revisions to the dating of the magnetic polarity time scale and new dates on the Eocene (Berggren and others, this volume) place the Paleocene/Eocene boundary at about 55 Ma. Magnetic polarity stratigraphy (Fig. 2) has been studied in the key sections of the Bighorn Basin of Wyoming and Montana (Butler and others, 1980, 1984, 1987; Clyde and others, 1994; Tauxe and others, 1995), the Crazy Mountain Basin in Montana (Butler and others, 1987), the San Juan Basin in New Mexico and Colorado (Butler and others, 1977; Lindsay and others, 1978, 1981; Taylor and Butler, 1980; Butler and Lindsay, 1985; Butler and others, 1987), Dragon Canyon in Utah (Tomida and Butler, 1980), and the Big Bend region in Texas (Rapp and others, 1983).

Based on magnetic stratigraphy from the San Juan and Crazy Mountain Basins, Butler and Lindsay (1985) and Butler and others (1987) squeezed the Puercan into Chron C29n and latest C29r (64–65 Ma), so Puercan "zones" Pu0–Pu3 are each about 250,000 years in duration. In the San Juan and Crazy Mountain Basins, Torrejonian "zone" To1 occurs in Chron C28n (62.5–63.5 Ma), To2 in C27r (61.3–62.5 Ma), and To3 in Chron C27n (61.0–61.3 Ma), so the three Torrejonian "zones" To1–To3 range from 0.3–1.2 million years in duration. The Torrejonian/Tiffanian boundary occurs early in Chron C26r, about 60.5 Ma. Based on magnetic stratigraphy from the northern Bighorn Basin, Butler and others (1980, 1984) showed that Ti2 occurs early in Chron C26r (about 59–60 Ma), and Ti3 in late Chron C26r and C26n (57.5–58.5 Ma). Ti4 occurs in earliest Chron C25r (57.0–57.3 Ma), and Ti5 in early Chron C25n (56.1–56.3 Ma). The Tiffanian/Clarkforkian boundary occurs in Chron C25n, about 56.2 Ma, so the five Tiffanian "zones" range from 0.2–1.0 million years in duration. The Clarkforkian/Wasatchian boundary occurs in the middle of Chron C24r, about 55.5 Ma, so the three Clarkforkian "zones" are each about 200,000 years in duration.

Eocene Epoch

The major difficulty in establishing the correlation of the North American terrestrial chronology with the marine-based global time scale is the lack of direct interfingering of mammal-bearing terrestrial deposits with marine sequences. Fortunately, the type areas of many of the European marine stages interfinger with mammal-bearing beds in both the Paris and London Basins (Savage and Russell, 1983). This allows direct correlation of the European Eocene mammalian chronology with the global time scale. During intervals of faunal interchange with North

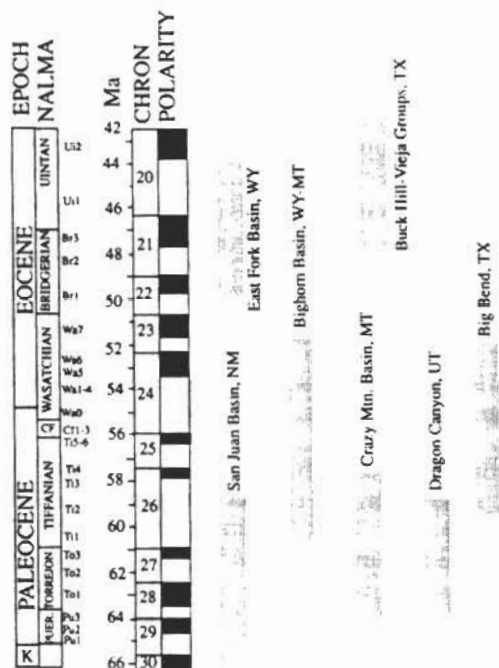


FIG. 2.—Calibration of early Paleogene North American land mammal "ages" with the revised magnetic polarity time scale of Berggren and others (this volume). Subdivisions of the "ages" (i.e., Pu1, Pu2, and so on) are discussed in the text. On the right, the temporal span (based on magnetostratigraphy) of some important Paleocene and early Eocene sections is shown.

America (such as in the early Eocene, but not the middle or late Eocene), we can correlate the North American sequence with the epoch stratotype sequences based in Europe. We also have magnetic stratigraphy and a large number of radiometric dates for many areas in the North American Eocene sequence. New radiometric dates, however, have greatly changed our notions of the temporal correlation of the North American sequences of middle and late Eocene age (Swisher and Prothero, 1990; Prothero and Swisher, 1992).

The Wood Committee recognized four land mammal "ages" in North America (Figs. 1–3), which they thought were approximately correlative with the European Eocene sequence. The Wasatchian land mammal "age" was named for the Wasatch Formation in basins of southern Wyoming. The Bridgerian land mammal "age" got its name from the faunas of the Bridger Formation in southwest Wyoming, and the Uintan and Duchesnean land mammal "ages" were named for the Uinta and Duchesne River Formations in the Uinta Basin of northeast Utah. The Wood Committee thought that the Wasatchian was early Eocene, the Bridgerian middle Eocene, and the Uintan and Duchesnean were late Eocene age. The next "age," the Chadronian (named after the Chadron Formation in the High Plains, especially Nebraska and South Dakota), was considered early Oligocene age.

As mentioned in the previous section, the Wood Committee and most subsequent authors placed the Paleocene/Eocene boundary within or at the end of the Clarkforkian in North America (Gingerich, 1976; Gingerich and Rose, 1977; Rose, 1981; Gunnell, 1989). However, a number of recent lines of

evidence suggest that the boundary actually falls within the earliest Wasatchian. The original correlations of Gingerich and Rose were based primarily on the interpretation of adapid primates and plesiadapids. Other taxa, such as pantodonts (Lucas, 1984, 1989, 1993; Rea and others, 1990) and omomyid primates (Beard and Tabrum, 1991) suggested that the boundary occurs in the earliest Wasatchian. Another datum is the first appearance of *Platycarya* pollen in the earliest Wasatchian of the northern Bighorn Basin (Wing, 1984; Wing and others, 1991). This palynological datum occurs at the NP9/NP10 nanofossil zone boundary in the Gulf Coast (Frederiksen, 1980), which is 300,000 years older than the Paleocene/Eocene boundary (Berggren, 1993). These correlations were borne out by the recent detection of the striking carbon isotopic event near the Paleocene/Eocene boundary (Rea and others, 1990; Kennett and Stott, 1991) in earliest Wasatchian terrestrial carbon isotopes extracted from paleosols and mammalian teeth and bones (Koch and others, 1992).

Yet some mammalian paleontologists (Gingerich, 1989; Gunnell and others, 1993) continue to place the Paleocene/Eocene boundary at the Clarkforkian/Wasatchian boundary. The key to the entire controversy lies in the interpretation of the Sparnacian mammalian faunas of Europe. In the past, European mammalian paleontologists had considered the Sparnacian the beginning of the Eocene Epoch, because its mammals were more similar to later Eocene faunas, and differed radically from the underlying upper Paleocene Thanetian faunas (Savage and Russell, 1983). The discovery of a new earliest Wasatchian fauna (Wa0) in North America with strong similarities to the Sparnacian in Europe supported that correlation (Gingerich, 1989, p. 83–87). Gunnell and others (1993) argued that the beginning of the Clarkforkian/Wasatchian transition was the time of greatest faunal turnover, and therefore it seemed to be the best place to mark the boundary.

But the Paleocene/Eocene boundary is defined on the basis of marine taxa in European type sections, not on the basis of North American or European mammalian faunas. Where the Clarkforkian/Wasatchian boundary in North America (or the Thanetian/Sparnacian boundary in Europe) falls in relation to marine stratotypes must be demonstrated, not asserted. One cannot assume the coincidence of mammalian faunal turnover and European epoch boundaries. For instance, the "Grande Coupure" in Europe was long thought to represent the Eocene/Oligocene boundary because of the great faunal turnover, but recent work (Hooker, 1992) has demonstrated that it actually occurred in the early Oligocene, about 1 my after the Eocene/Oligocene boundary.

Marine stratigraphers have long ago shown that the European Sparnacian correlates with late Paleocene nannoplankton zone NP9 (Costa and Downie, 1976; Costa and others, 1978; Berggren and others, 1985, this volume; Aubry and others, 1988). It is at least one or two sequences lower (and about 1 million years older) than the Paleocene/Eocene boundary as denoted by the base of the London Clay or the Argile d'Ypres (Berggren, 1993), long recognized as the base of the Ypresian and therefore the base of the Eocene Epoch (Berggren and others, 1985; Aubry and others, 1988).

Tauxe and others (1995) described the magnetic stratigraphy of the Willwood Formation in the southern Bighorn Basin of Wyoming, and also argued that the Paleocene/Eocene boundary

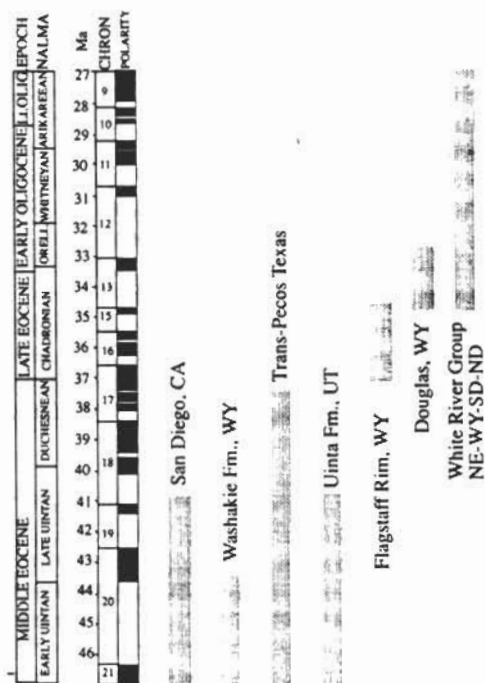


FIG. 3.—Calibration of late Paleogene North American land mammal "ages" with the revised magnetic polarity time scale of Berggren and others (this volume). On the right, the temporal span (based on magnetostratigraphy) of some important middle-late Eocene and Oligocene sections is shown. Abbreviations as in Figure 1.

might correlate with the Clarkforkian/Wasatchian boundary. The only direct evidence to support their argument is that the *Platycarya* datum apparently occurs 35 meters below the first occurrence of a Wa0 fauna in the southern Bighorn Basin, although it occurs 160 meters above the Wa0 mammals in the northern Bighorn Basin. Thus, Tauxe and others (1995) suggest that the range of *Platycarya* (and thus the Paleocene/Eocene boundary) has been extended downward. However, as we saw above, the *Platycarya* datum and the NP9/NP 10 boundary are not at the Paleocene/Eocene boundary, but about 300,000 years older (Berggren, 1993).

The most recent summary of most of the Eocene North American land mammal "ages" (Krishtalka and others, 1987) did not attempt to formally divide the entire interval into biostratigraphic stages. However, biostratigraphic zonations for the Wasatchian and Bridgerian have been proposed by Savage (1977), Gingerich (1976, 1980, 1983), Gingerich and Simons (1977), Schankler (1980), Stucky (1984), and Gunnell (1989). Some of these biostratigraphic schemes (especially those of Savage, 1977, Schankler, 1980, and Stucky, 1984) follow the 1983 North American Stratigraphic Code in specifying type sections, but others do not. Currently, the Wasatchian is divided into eight "zones," labeled Wa0 to Wa7 (Gingerich, 1983, 1989). Clyde and others (1994) found that Wa0 to lower Wa5 occurred in Chron C24r (53.5–55 Ma) in the northern Bighorn Basin, and that upper Wa5 and Wa6 correlated with C24n (52.3–53.4 Ma). Wa7 occurred in C23r (51.6–52.3 Ma). These ages are in good agreement with a new $^{40}\text{Ar}/^{39}\text{Ar}$ date on Wa6-7 of 52.8 ± 0.3 Ma (Woodburne and Swisher, this volume).

No magnetic stratigraphy for the Wasatchian-Bridgerian transition has ever been published. Good sections are available in the Wind River, Green River, and Huerfano Basins (see Krishtalka and others, 1987, p. 86–87), so eventually it should be possible to tie these areas to the magnetic polarity time scale. Based on K-Ar dates of 50.5 Ma on the latest Wasatchian and 50.3 Ma on the earliest Bridgerian in the Wind River Formation (Evernden and others, 1964; Krishtalka and others, 1987, p. 93, dates T and U), the boundary probably occurs around 50.4 Ma, or within Chron C22r (Woodburne, this volume). Recently, Clyde and others (1995) reported on the magnetic stratigraphy of the Wasatchian-Bridgerian transition in the Green River Basin, Wyoming. They found this transition in Chron C22r and suggested that it occurs between 49.7 Ma and 50.7 Ma.

After the Wasatchian, North America was separated from direct faunal interchange with Europe, and the correlations become more indirect. As a result, the most effective technique has been radiometrically-dated magnetic stratigraphy. The magnetic stratigraphy of the type Bridgerian in the Bridger Basin of Wyoming has been studied, but not published (Jerskey, pers. commun., 1981), and is now being restudied (Flynn, pers. commun., 1994). The magnetic stratigraphy of the classic Uintan and Duchesnean sections in the Uinta Basin of Utah was described by Prothero and Swisher (1992) and Prothero (1995a). Bridgerian and Uintan beds have been studied in California and Wyoming by Flynn (1986) and by McCarroll and others (1993), and in Texas by Walton (1992) and Prothero (1995b). Uintan-Duchesnean beds in the Sand Wash Basin of Colorado (Stucky and others, 1995), the Sespe Formation of Ventura County, California (Prothero and others, 1995), the Poway Group in San Diego County, California (Walsh and others, 1995), the Galisteo Formation in central New Mexico (Prothero and Lucas, 1995) and several units in western Montana (Tabrum and others, 1995) have also been sampled.

According to Flynn (1986), the Bridgerian-Uintan transition occurs early in Chron C20r, about 46 Ma. However, recent studies of the critical sections in San Diego suggest that the transition might lie within Chron C21n, about 47 Ma (Walsh, 1995; Walsh et al., 1995). The Uintan-Duchesnean transition occurs within Chron C18n, about 40 Ma (Prothero and Swisher, 1992; Prothero, 1995a, 1995b; Prothero and others, 1995). The latest stratigraphic correlations of the middle Eocene Bartonian and late Eocene Priabonian stages in Europe (Berggren and others, 1985; Aubry and others, 1988) place the Priabonian/Bartonian boundary in Chron C17n1 (Berggren and others, this volume), so that the middle Eocene includes not only the Bridgerian, but also the Uintan and Duchesnean (Figs. 1, 3).

Gunnell (1989) named two "zones" (Ui1, the *Epihippus* assemblage "zone," and Ui2, the camelid-canid appearance "zone") for the early and late Uintan. However, unlike earlier Eocene zones, these are not based on recent detailed biostratigraphic work, but simply formalize the distinction between the faunas of Uinta Formation Member "B" (upper part of the Wagonhound Member of Wood, 1934) and Member "C" (Myton Member of Wood, 1934). More detailed biostratigraphic work to subdivide the seven million years of the Uintan would be valuable, but the stratigraphic data on the existing collections from the Uinta Basin are too imprecise, and the area is too poorly fossiliferous to make significant new collections with good stratigraphic data (Prothero and Swisher, 1992; Prothero, 1995a). The biostratigraphy of existing Uinta Formation collections was summarized by Prothero (1995a). Ultimately, it would be better to subdivide the Uintan by precisely dating stratigraphically superposed faunas in Texas (from the Vieja and Buck Hill Groups in the Big Bend region), Colorado (the Sand Wash Basin), Wyoming (the Washakie Basin), and California (the Sespe and San Diego sections). However, this effort is also hampered by the high degree of endemism of Uintan faunas, making true first and last occurrences difficult to distinguish from local geographic effects (Lillegraven, 1979; Flynn, 1986; Krishtalka and others, 1987).

The Duchesnean has always been the most controversial land mammal "age" of the Eocene Epoch (Fig. 1). Originally considered the last of the Eocene ages by Wood and others (1941), opinions have fluctuated from placing it in the early Oligocene (Scott, 1945) or back in the late Eocene (Simpson, 1946), and back and forth several times since then. Gazin (1955, 1956, 1959) assigned the faunas from the lower Duchesne River Formation (Randlett and Halfway faunas) to the late Uintan. The poor quality of the overlying Lapoint fauna (the "classic" Duchesnean) and its similarity to some Chadronian faunas led several workers to reduce the Duchesnean to a subage of the Chadronian, or drop it altogether (Wilson, 1978, 1984, 1986; Emry 1981). In recent years, opinion has swung back toward recognizing a distinct Duchesnean, with important correlatives in Saskatchewan, South Dakota, Wyoming, Montana, Texas, New Mexico, Oregon, and California (Krishtalka and others, 1987; Kelly, 1990; Lucas, 1992).

Even though the Duchesnean spans almost three million years, efforts to subdivide it into biostratigraphic zones have been controversial since the faunas are so sparse and often endemic to the many scattered localities (Lucas, 1992). Several authors have attempted to recognize an early and late Duchesnean in Texas (Wilson, 1984, 1986) and California (Kelly,

1990). Further radiometric dating and magnetic stratigraphy will probably provide the best test of the age of these faunas, and may eventually help establish a biostratigraphic zonation for the Duchesnean.

The most surprising conclusion of recent dating, however, concerns the Chadronian land mammal "age." Considered early Oligocene age by the Wood Committee, it was K-Ar dated by Evernden and others (1964) at between 32 and 36 Ma. Since the Eocene/Oligocene boundary was generally placed around 36.5 Ma (Berggren and others, 1985), the correlation of the Chadronian with the early Oligocene seemed secure. However, the European Eocene/Oligocene boundary has been recently redated at 33.5 Ma (Berggren and others, this volume). At the same time, redating of K-Ar-dated ashes by $^{40}\text{Ar}/^{39}\text{Ar}$ methods have shown that the Chadronian spans an interval from 33–37 Ma (Swisher and Prothero, 1990; Prothero and Swisher, 1992). This places the Chadronian in the late Eocene, and the Eocene/Oligocene boundary appears to fall just below the Chadronian/Orellan boundary, not at the Duchesnean/Chadronian boundary, as long thought.

At the time of the Wood Committee report, the biostratigraphy of the Chadronian was very poorly understood. Many of the taxa (especially brontotheres and oreodonts) were badly oversplit taxonomically, and the stratigraphic data on the fossils from the classic collections in the Chadron Formation were inadequate (Emry and others, 1987). Attempts to divide the Chadronian based on lithostratigraphy of the Chadron Formation in Nebraska (Schultz and Stout, 1955) or South Dakota (Clark, 1937, 1954; Clark and others, 1967) were unsuccessful (Emry, 1973; Emry and others, 1987). Since that time, however, Emry (1973, 1992) has carefully documented the mammalian biostratigraphy in the thickest and most fossiliferous Chadronian sequence at Flagstaff Rim, Wyoming. Based on this work, Emry (1992; Emry and others, 1987) suggested criteria for recognizing early, middle, and late Chadronian, but no formal biostratigraphic zonation was proposed. Such a zonation is now in progress (Prothero and Emry, 1995).

Oligocene Epoch

The geochronology of the Eocene/Oligocene boundary has long been controversial. For decades, the dates produced by K-Ar methods on volcanics and by various isotopes in marine glauconites produced highly contradictory estimates ranging from 32 to 38 Ma (Hardenbol and Berggren, 1978; Berggren and others, 1985; Berggren, 1986; Aubry and others, 1988; Obradovich, 1988; Odin, 1978, 1982; Curry and Odin, 1982; Odin and Curry, 1985; Glass and Crosbie, 1982; Glass and others, 1986; summarized in Prothero, 1990, 1994b, and Berggren and others, 1992). However, recent $^{40}\text{Ar}/^{39}\text{Ar}$ dating of volcanic ashes in the deep marine sections in Gubbio and Massignano, Italy, directly tied to marine microfossils and magnetic stratigraphy (Montanari, 1988, 1990; Montanari and others, 1985, 1988; Odin and others, 1988, 1991) and of terrestrial volcanic ashes in North America (Swisher and Prothero, 1990; Prothero and Swisher, 1992) have resolved the controversy by eliminating many erroneous age estimates. The emerging consensus places the Eocene/Oligocene boundary at about 33.5 Ma (Berggren and others, this volume).

In addition to recalibrating the Eocene/Oligocene boundary, new $^{40}\text{Ar}/^{39}\text{Ar}$ methods provided radiometric dates on much of

the rest of the North American Oligocene land mammal sequence for the first time. The Wood Committee (Wood and others, 1941) named three land mammal "ages" which they thought were approximately Oligocene in age (Fig. 1): the Chadronian, the Orellan (based on the Orella Member of the Brule Formation in Nebraska), and the Whitneyan (based on the Whitney Member of the Brule Formation in Nebraska). They informally considered the Chadronian land mammal "age" to be early Oligocene, the Orellan to be middle Oligocene, and the Whitneyan to be late Oligocene age. The Arikareean (based on the Arikaree Group in Nebraska) was thought to be early Miocene. As we have seen above, the Chadronian is now considered late Eocene age. The Orellan/Whitneyan boundary occurs at about 32 Ma, within Chron C12r, and the Whitneyan/Arikareean boundary within Chron C11n, about 30 Ma (Swisher and Prothero, 1990; Prothero and Swisher, 1992). This makes both the Orellan and Whitneyan early Oligocene, and most of the Arikareean becomes late Oligocene age (since the European type Oligocene has only two stages, the Rupelian and Chattian, there is no "middle" Oligocene). Magnetic stratigraphy has now been completed on virtually all the important Orellan, Whitneyan and early Arikareean outcrops from the White River and Arikaree Groups (Prothero, 1982; Prothero and others, 1983, Prothero, 1985a, 1985b; Prothero and Swisher, 1992; Evanoff and others, 1992; Prothero, 1995c; Tedford and others, 1995), as well as important localities in Montana (Prothero, 1984; Tabrum and others, 1995) and California (Prothero, 1991; Prothero and others, 1995).

The Oligocene/Miocene boundary is less well constrained than the boundaries discussed above. When the Wood Committee considered the Arikareean to be early Miocene, their concept of the Arikareean was based on the Agate Springs fauna, which is latest Arikareean; it does have taxa in common with the early Miocene in Europe. However, all of the underlying units in the Arikaree Group have a very different fauna, and the entire Arikareean appears to span an interval from 30 Ma to 21 Ma, almost nine million years—by far the longest land mammal "age" (Tedford and others, 1987, 1995). In addition, the definition of the Oligocene/Miocene boundary in Europe has fluctuated over the years but now seems stabilized around 23–24 Ma (Berggren and others, 1985, this volume). Recent $^{40}\text{Ar}/^{39}\text{Ar}$ dating now places the early Arikareean Gering Fauna between 28 and 30 Ma (Tedford and others, 1995), and most of the Monroe Creek Fauna also appears to be late Oligocene age (Tedford and others, 1987, 1995). The late Arikareean Harrison Fauna and the overlying latest Arikareean Agate Springs Quarry (in the Upper Harrison Formation of Peterson, 1909) may be earliest Miocene.

Unlike the detailed biostratigraphic "zonation" now in place for most of the Paleocene and parts of the Eocene (Gingerich, 1983; Gunnell, 1989; Archibald and others, 1987; Krishtalka and others, 1987), a detailed Oligocene biostratigraphy is just now being published. For decades, it was impossible to subdivide the Orellan or Whitneyan land mammal "ages," since most of the early collections had very poor stratigraphic data. The stratigraphic scheme of Schultz and Stout (1955, 1961) was actually based on lithostratigraphic units, and did not have biostratigraphic resolution within the units. Outlines of the biostratigraphic potential of the North American Oligocene sequences were presented by Emry and others (1987), but no

detailed zonation was proposed. Thanks to decades of work by Morris Skinner, Bob Emry, and collectors of the Frick Laboratory, however, there are now large collections of White River mammals with stratigraphic data zoned to the nearest foot from volcanic ashes. These collections allowed Prothero (1982) to propose a preliminary biostratigraphy which divided the Orellan into four zones, and recognize one zone for the early Whiteneyan. Korth (1989) also proposed a biostratigraphic zonation for the Orellan, but it is based on University of Nebraska collections which do not have the resolution to subdivide the lithostratigraphic units. Hence, Korth's (1989) "faunal zones" are really based on lithostratigraphic boundaries.

A finely resolved biostratigraphy for the Orellan and Whiteneyan has long been in preparation, but its publication has been delayed by the lack of up-to-date systematic revisions of many of the key taxa, especially oreodonts, leptomyricids, and ischymyrod rodents. Such revisions are now in press (various papers in Prothero and Emry, 1995), and that volume suggests a formal biostratigraphic zonation for the Chadronian through early Arikareean (Prothero and Emry, 1995).

Rensberger (1971, 1973, 1983; Fisher and Rensberger, 1972) proposed a formal biostratigraphic zonation of rodents from the late Oligocene-early Miocene John Day Formation of central Oregon. The magnetostratigraphy of these beds has also been published (Prothero and Rensberger, 1985), although it may need further revision when new $^{40}\text{Ar}/^{39}\text{Ar}$ dates are analyzed by Carl Swisher. Unfortunately, some of the key rodent taxa used in Rensberger's zonation do not occur in the classic Arikareean faunas in the High Plains, so his biostratigraphic zones have proven useful only in Oregon, Montana, and South Dakota (Tedford and others, 1987). When the magnetic stratigraphy of the sequences containing the "type" Arikareean fauna in Nebraska is published (Hunt and MacFadden, pers. commun.), it will be possible to overcome these difficulties, and establish biostratigraphic zones for the Arikareean throughout the western United States.

CONCLUSION

Despite its limitations, correlation by fossil mammals is still the only practical method of dating most Cenozoic terrestrial deposits. In retrospect, the pioneering work of the Wood Committee (1941) was remarkably accurate in most of its correlations. However, new technologies not available until the last decade have significantly changed some of the important correlations. In particular, the Paleocene/Eocene boundary has moved up from the middle of the Clarkforkian into the early part of the Wasatchian, and the Eocene/Oligocene boundary shifted from the base to the top of the Chadronian. The Oligocene/Miocene boundary has moved up to include most of the Arikareean. Although these changes may seem minor to the non-specialist, they require major adjustments in the thinking of several generations of paleontologists who were trained to equate Chadronian with early Oligocene, Arikareean with early Miocene, and so on. Those who have long talked about huge "Oligocene" brontotheres must now get used to the fact that there are probably no Oligocene brontotheres at all (not even in Asia, see Berggren and Prothero, 1992). As uncomfortable as that may be, it is required by the data that have now emerged. More importantly, such major shifts in the time scale strongly

affect all studies of evolutionary patterns, rates of sedimentation, climatic changes, and other geologic processes that depend upon a particular correlation scheme or version of the time scale (e.g., Berggren and Prothero, 1992; Prothero, 1994a).

In the past, some vertebrate paleontologists have tried to salvage their outmoded concepts by referring to the Duchesnean as the "North American late Eocene," or the Arikareean as "North American early Miocene," or similar evasions. This is indefensible, since the Lyellian epochs are strictly a European marine concept, and the global time scale is based on European, not North American, chronostratigraphy. The duration of the epochs in North America is only known by correlation to an independent North American chronology, and not by redefining the European epochs in North American terms to rescue obsolete notions. Indeed, the strength of the original North American land mammal chronology lies in its independence. The relative sequence of land mammal "ages" remains the same, regardless of where the European epoch boundaries fall, as the Wood Committee (1941) realized.

Although North American vertebrate paleontologists are making encouraging attempts to construct formal biostratigraphies consistent with standard biostratigraphic methods, some problems remain. Considering all the detailed work done by some paleontologists to construct their "zonations," it is rather surprising that they did not finish the job and propose their "zones" in compliance with the North American Stratigraphic Code. These same paleontologists would be appalled if someone did not follow the International Code of Zoological Nomenclature and proposed taxa that had no type specimen and became *nomina nuda*, yet they have done something analogous with their "biostratigraphic zonations." In some places where the fossils occur in isolated quarries without much vertical biostratigraphic ranges, the reason for this non-compliance with the North American Stratigraphic Code is potentially excusable. However, Gingerich (1976; Gingerich and Rose, 1977), Sloan (1987), and Archibald and others (1987) abundantly document much of the stratigraphic detail necessary for formal type sections, yet do not take this final step.

With the detailed documentation now available, we should soon be able to replace the informal biochronological schemes used by Archibald and others (1987), Krishtalka and others (1987), and Emry and others (1987) with formal range-zone biostratigraphy. When a formal biostratigraphic basis for all the North American land mammal "ages" is established, they will become true stratigraphic stages. At that point, we will no longer need to apologize for our system with the ubiquitous quotes around the word "age." More importantly, tying the informal biochronology to specific sections will make our task of locating magnetic polarity zones and radiometric dates much easier. Half a century of ignoring standard biostratigraphic practice is enough!

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