

30. Summary

DONALD R. PROTHERO AND ROBERT J. EMRY

CHRONOSTRATIGRAPHY

The chronostratigraphic age assignments of the major late middle Eocene through early Oligocene terrestrial deposits in western North America are shown in Figures 1-5. Although not all areas are dated and correlated with equal precision, we feel that these correlations are considerably more accurate and highly resolved than those presented by Prothero (1985), Emry et al. (1987), and Krishtalka et al. (1987). These major improvements in geochronology are due primarily to the development of $^{40}\text{Ar}/^{39}\text{Ar}$ dating, providing both new dates, and the correction and rejection of certain K-Ar dates. In addition, magnetic stratigraphy provides even finer-scale correlation of localities whose general age is already known from biostratigraphy or radiometric dating.

Uintan

When Prothero and Swisher (1992) summarized the chronostratigraphic controls on the Uintan known at that time, there were relatively few constraining data points, and few grounds for controversy. The primary data base consisted of Flynn's (1986) magnetic stratigraphy of selected Bridgerian-Uintan sections, plus recently obtained $^{40}\text{Ar}/^{39}\text{Ar}$ dates and the magnetic polarity pattern of the Uinta Formation in the Uinta Basin (this volume, Chapter 1). Based on the evidence available at the time, Prothero and Swisher (1992) suggested that the Bridgerian/Uintan boundary occurred early in Chron C20r (based largely on Flynn's data), and that the early/late Uintan boundary (Uinta B2/C boundary in the Uinta Basin) occurred in Chron C20n. They also discussed another possibility—that the early/late Uintan boundary occurred in Chron C19n—but rejected that alternative as less likely for the reasons discussed below.

Since that time, the interpretation of Prothero and Swisher (1992) has been challenged, and new data have emerged. McCarroll et al. (1993) moved the early/late Uintan boundary to C19n, based on previously unpublished data from the Washakie Basin of Wyoming. This interpretation was followed in several early drafts of Prothero's chapters in this volume until new data from

the San Diego section (this volume, Chapters 4, 5, and 6) forced yet another re-examination of the evidence (compare Chapters 2 and 4 of this volume). Rather than repeat all the intricate arguments detailed in those chapters, we will summarize the chronostratigraphic constraints on the problem, and assess the reliability of the various sources of data.

Geochronological constraints

Despite many attempts, there are few reliable radioisotopic dates. Prothero and Swisher (1992) gave reasons for rejecting much of the old K-Ar data base in favor of the new $^{40}\text{Ar}/^{39}\text{Ar}$ dates, and this argument is still valid. We will mention K-Ar dates as appropriate below, but many are discordant with all other sources of data. We feel that the most reliable dates are the following:

—an $^{40}\text{Ar}/^{39}\text{Ar}$ date by Carl Swisher of 47.3 ± 0.05 Ma on the Henry's Fork tuff, high in the upper Bridgerian Bridger C (E. Evanoff, personal communication). This suggests that the late Bridgerian is at least as young as 47.3 Ma, which would place it early in Chron C21n (Berggren et al., 1995).

—an $^{40}\text{Ar}/^{39}\text{Ar}$ date by Chris Henry of 46.29 ± 0.05 Ma on a tuff just below the Alamo Creek basalt in the lower member of the Devil's Graveyard Formation of Trans-Pecos Texas (Henry, personal communication; see this volume, Chapter 9). This date is just below the early Uintan Whistler's Squat l.f. (in rocks of reversed polarity—Walton, 1992) and just above the late Bridgerian Junction and 0.6 local faunas, which suggests that the Bridgerian/Uintan boundary occurs in late Chron C21n.

—an $^{40}\text{Ar}/^{39}\text{Ar}$ date by John Obradovich of 42.83 ± 0.24 Ma from the late Uintan Mission Valley Formation (Berry, 1991; Prothero, 1991; Obradovich and Walsh, in prep; this volume, Chapters 4 and 6). On the Berggren et al. (1995) time scale, this date falls within Chron C20n, and the date comes from rocks of normal magnetic polarity.

—an $^{40}\text{Ar}/^{39}\text{Ar}$ date by Carl Swisher of 39.74 ± 0.07 Ma on the Lapoint Tuff at the base of the late Duches-

nean Lapoint Member of the Duchesne River Formation, Uinta Basin, Utah (Prothero and Swisher, 1992). This date seems to place the early Duchesnean in Chron C18n, and relegates the latest Uintan Brennan Basin and Dry Gulch Creek members of the Duchesne River Formation (Andersen and Picard, 1972) to early Chron C18n or earlier time.

In addition to the $^{40}\text{Ar}/^{39}\text{Ar}$ dates, there are several K-Ar dates of varying reliability:

—a K-Ar date of 46.9 ± 1.1 Ma on the Quarry Tuff, in rocks of reversed magnetic polarity just below the early Uintan Whistler Squat l.f. of West Texas (McDowell, 1979; Walton, 1992). Given the large error estimates, this seems to place early Uintan faunas early in Chron C20r.

—a K-Ar date of 43.9 ± 0.9 Ma on a tuff just above the early Uintan Whistler Squat l.f. of West Texas in rocks of both normal and reversed polarity (McDowell, 1979; Walton, 1992). This seems to place early Uintan mammals late in Chron C20r, based on the Berggren et al. (1995) time scale.

—a K-Ar date of 42.7 ± 1.6 Ma on the Skyline tuff in rocks of normal magnetic polarity above the late Uintan Serendipity l.f., and just below the early Duchesnean Skyline Channels l.f. of West Texas (Stevens et al., 1984; Walton, 1992; see this volume, Chapter 9). This date has been widely regarded as anomalous, because it has large error bars and seems to conflict with other data. It was based on a few tiny crystals of biotite (M. Stevens, personal communication). It seems to place the late Uintan Serendipity and Purple Bench l.f. in Chron C20r if taken at face value. Given the large error estimates, however, these faunas could also be placed in Chron C19r.

—a series of K-Ar dates averaging 42.2 Ma associated with NP16 calcareous nannofossils and late Uintan mammals from the Casa Blanca l.f. of the Texas Gulf Coastal Plain (Westgate, 1988). Although NP16 spans late Chron C20n to early Chron C18n (Berggren et al., 1995), the date would tend to support the correlation of the late Uintan with Chrons C20n-C19r.

As discussed by Prothero and Swisher (1992), all the K-Ar dates given by Mauger (1977) for the Uinta Basin have been rejected; none seem to be consistent with the framework of dates outlined above. Mauger's date of 43.1 ± 1.3 Ma on rocks of normal polarity correlative with Uinta A seems much too young, given that those rocks seem to be associated with Chron C20r elsewhere.

The date of 42.8 ± 1.0 Ma in rocks of reversed polarity (placing them in Chron C20n or at best C19r) laterally correlative with the Uinta-Duchesne River contact is much too old, given its apparent correlation with Chron C18r. In addition, there are three long magnetic polarity zones in the Indian Canyon section between the 43.1 and 42.8 dates spaced only 0.3 million years apart (Prothero and Swisher, 1992; this volume, Chapter 1). Likewise, many of the old K-Ar dates from Wyoming used by Flynn (1986) were rejected by Swisher, as he

been the K-Ar date of 42.3 Ma from Duchesnean Badwater locality 20 (Prothero and Swisher, 1992).

Marine biostratigraphic constraints

The San Diego section is the only place where well-dated strata with Bridgerian and Uintan mammals interfinger with marine strata bearing planktonic microfossils. The most important datum is the occurrence of coccolith subzones CP12b, CP13a, and CP13b, and planktonic foraminiferan Zone P10 (Flynn, 1986; Walsh et al., this volume, Chapter 6) in the Ardath Shale. Based on these microfossil zones, all authors (Flynn, 1986; Botzjer et al., 1991; Walsh et al., this volume, Chapter 6) agree that the normal magnetozone that encompasses the Ardath, Scripps, and lower Friars formations correlates with Chron C21n (46.3-48.0 Ma in the Berggren et al., 1995, time scale). Bridgerian faunas occur beneath this level in rocks of reversed polarity (= Chron C21r) in the upper part of the Delmar Formation (Swami's Point l.f.; see Walsh, this volume, Chapter 5). Bridgerian or early Uintan mammals occur above the Ardath Shale in rocks of normal magnetic polarity (= C21n) in the lower part of the Scripps Formation ("Horizon A" of Flynn, 1986, fig. 9; Black's Beach l.f. of Walsh, this volume, Chapter 5). Undoubted early Uintan faunas occur in rocks of normal magnetic polarity (= C21n) at the base of the Friars Formation. As discussed by Walsh (this volume, Chapters 4 and 6), these data would place the Bridgerian/Uintan boundary in Chron C21n.

The Mission Valley Formation in San Diego produces a late Uintan mammalian fauna in rocks of variable magnetic polarity. Steineck et al. (1972) also reported planktonic foraminifera correlative with Zone P13, which would imply a correlation of these strata with Chron C18n (Berggren et al., 1995). However, this age assignment is based on only two poorly preserved taxa, *Globorotaloides suteri* and *Truncorotaloides collacteus*, and there are problems with the quality of these identifications, and with the supposed restriction of these taxa to Zones P13-P14 (McWilliams, 1972; Philips, 1972; Flynn, 1986, p. 350; W. A. Berggren, personal communication). However, the $^{40}\text{Ar}/^{39}\text{Ar}$ date of 42.8 Ma mentioned above rules out correlation with Chrons C18n or C19n for the late Uintan strata of normal magnetic polarity in the Mission Valley Formation. Correlation with Chron C20n is the only reasonable alternative.

Magnetic Stratigraphy and Mammalian Biostratigraphy

Given the constraints outlined above, we can now examine the numerous magnetic polarity stratigraphies for Bridgerian-Uintan-Duchesnean strata that have been reported and see if we can make sense of the pattern (Fig. 1). Three primary constraints seem to limit our range of possible interpretations:

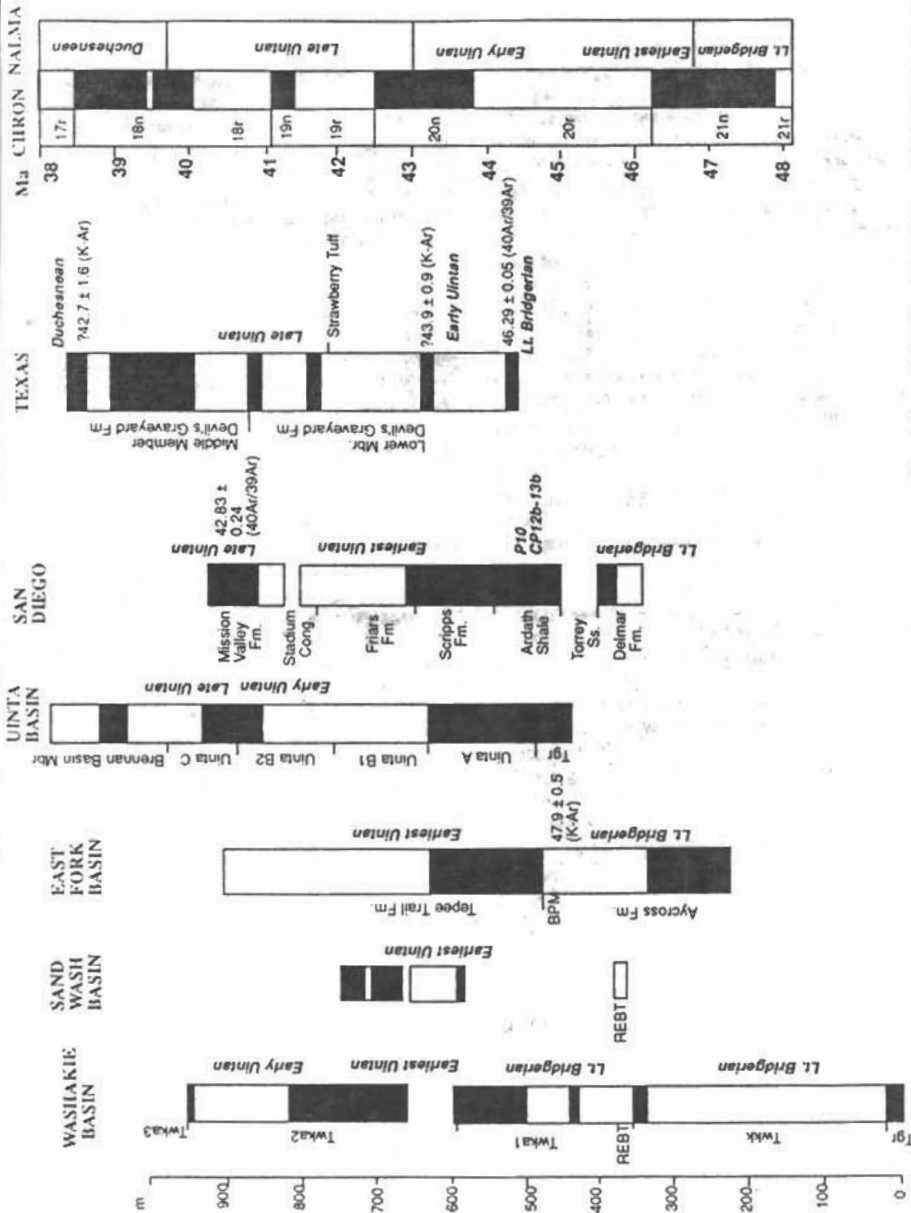


Figure 1. Chronostratigraphic correlations of Uintan sections discussed in text. Abbreviations: BPM, Blue Point Marker; REBT, Robin's Egg Blue Tuff; Tgr, Green River Formation; Twk, Kinney Rim Member, Washakie Formation; Twk1, Twk2, Twk3, units 1, 2, and 3, Adobe Town Member, Washakie Formation.

1. The San Diego magnetic and marine microfossil data seem to place the Bridgerian/Uintan boundary in Chron C21n. Only in San Diego is there a superposed sequence of Bridgerian mammals (Delmar Formation, Swami's Point l.f.) underlying planktonic microfossils of Zones P10 and CP12b-CP13b (Ardath Shale), which are in turn overlain by early Uintan mammals (lower Friars Formation); the Ardath, Scripps, and lower Friars formations are apparently all within the same zone of normal magnetic polarity. This interpretation is also consistent with the ⁴⁰Ar/³⁹Ar dates of 47.3 Ma for the late Bridgerian in the Bridger Basin, and 46.29 Ma for the Bridgerian/Uintan transition in Trans-Pecos Texas.

2. The ⁴⁰Ar/³⁹Ar date of 42.83 on the late Uintan Mission Valley Formation places the early/late Uintan boundary in Chron C20n, and does not allow it to be as young as C19n.

3. The ⁴⁰Ar/³⁹Ar date of 39.74 Ma on the Lapoint Tuff places the Dry Gulch Creek and Lapoint Members of the Duchesne River Formation in middle Chron C18n in the time scale of Berggren et al. (1995). Any interpretation which forces the Uintan/Duchesnean boundary younger than this would be contradicted by this date (and also by other dates on the Duchesnean discussed below).

Uinta Basin, Utah: Prothero and Swisher (1992) and Prothero (this volume, Chapter 1) reported the results of magnetostratigraphic analysis in the Uinta Basin of Utah, the "type areas" for the Uintan and Duchesnean land mammal "ages." Unfossiliferous Uinta A is of normal polarity. Upper B2 and lower Uinta C are of reversed polarity. Upper Uinta C and the lower Brennan Basin Member of the Duchesne River Formation are in a zone of reversed polarity. Another zone of normal and then of reversed polarity is found in the lower Brennan Basin Member. Sampling was discontinued above this level because of problems with diagenetic hematite, and because the rocks were either too hard or too crumbly for sampling.

Prothero and Swisher (1992) and Prothero (this volume, Chapter 1) correlated the Uinta A normal magnetozone with Chron C21n, the upper B2-lower C normal magnetozone with Chron C20n, and the lower Duchesne River normal magnetozone with Chron C19n. McCarroll et al. (1993) suggested that this entire sequence should be shifted up one magnetic chron, placing Uinta A in Chron C20n, Uinta B2-C in Chron C19n, and the lower Brennan Basin Member in Chrons C18n and C17r. However, this interpretation conflicts with several of the data constraints outlined above. In particular, it contradicts the 42.83 Ma date on the late Uintan in San Diego, and it would force the Lapoint Tuff into Chron C17n or younger, which is inconsistent with its ⁴⁰Ar/³⁹Ar date of 39.74 Ma.

Thus, the Uinta Basin section is best correlated with Chrons C21n-C18r, which places the early/late Uintan boundary in Chron C20n, and the Bridgerian/Uintan

boundary at some time earlier than mid-Chron C20r.

Washakie Basin, Wyoming: This section was originally reported by Flynn (1986), and has since been modified by McCarroll et al. (1993; this volume, Chapter 2). The late Bridgerian Kinney Rim Member (Twkk) was mostly of reversed polarity except for a few sites below the unconformity at the top. The lower half of unit 1 of the Adobe Town Member (Twk1) was of reversed polarity, with a short (2-site) zone of normal polarity; the upper third was of normal polarity. There is a 90-m (300-foot) sampling gap in the basal part of member 2 (Twk2); the middle third of this unit was of normal polarity, and produces earliest Uintan ("Shoshonian") and early Uintan faunas. The upper third of Twk2 was of reversed polarity except for a single normal site at the top. Unit 3 (Twk3) has not yet been sampled magnetically.

Flynn (1986, fig. 9) originally correlated the reversed magnetozone in the late Bridgerian Kinney Rim Member to Chron C21r, and the upper part of the Kinney Rim Member to Chron C21n. The reversed magnetozone spanning the lower half of Twk1 was correlated to Chron C20r, and the long normal magnetozone (C+ of Flynn, 1986) spanning upper Twk1 and lower Twk2 was correlated with Chron C20n. The upper part of Twk2 was correlated with Chron C19r. McCarroll et al. (1993) also preferred this correlation, although McCarroll et al. (this volume, Chapter 2) were equivocal. However, it presents several problems. It places late Bridgerian faunas in Chron C20r; that conflicts with the marine planktonic evidence which places early Uintan mammals within Chron C21n. It also forces the early/late Uintan boundary up into Chron C19n, contradicting the 42.83 Ma date on the late Uintan in San Diego. This also implies that the Brennan Basin Member of the Duchesne River Formation correlates with Chron C18n and C17r (McCarroll et al., this volume, Fig. 5). This interpretation conflicts with the ⁴⁰Ar/³⁹Ar date of 39.74 Ma on the Lapoint Tuff, as discussed above.

An alternative correlation, as suggested by Prothero and Swisher (1992), places the late Bridgerian faunas of Twkk and lower Twk1 in Chron C21n-C21r and earlier (how much earlier depends on how one interprets the many short zones of normal polarity in this interval). "Shoshonian" and early Uintan faunas of Twk2 are then correlated with Chron C21n and C20r, which is consistent with all the known data.

Sand Wash Basin, Colorado: Stucky et al. (this volume, Chapter 3) outline the magnetic stratigraphy and biostratigraphy of the Washakie Formation in the Sand Wash Basin of Colorado, just to the south of the Washakie Basin of Wyoming. Certain key beds, such as the "Robin's Egg Blue Tuff," allow correlation of these two sections across the state line. Given these constraints, Stucky et al. (this volume, Chapter 3) found that the most reasonable correlation matched the lower (earliest Uintan, or "Shoshonian") reversed

magnetozone with the 300-foot (90-m) with either the reversed rock of middle Twka1 (which may have Bridgerian small mammals, but lacks the key large mammal taxa), or with the sampling gap within magnetozone C+ in the lower part of Twka2. This latter interpretation is consistent with the level from which McCarroll et al. (this volume, Chapter 2, Fig. 3) report earliest Uintan faunas in Twka2. The upper half of the Sand Wash section is of normal polarity, and probably correlates with the rest of magnetozone C+ in Twka2. If magnetozone C+ is correlated with Chron C21n (as suggested above), these correlations would place "Shoshonian" and early Uintan faunas in Chron C21n or possibly C21r.

East Fork Basin, Wyoming: Flynn (1986, fig. 6) reported magnetostratigraphic results from the East Fork Basin of the Absaroka Mountains of northwest Wyoming. The Aycross Formation is characterized by a basal normal magnetozone (containing an early Bridgerian fauna, "Horizon A" of Flynn, 1986, fig. 9), a long reversed interval (containing the late Bridgerian "Horizon B" of Flynn, 1986, fig. 9), followed by an upper normal magnetozone that continued into the basal Tepee Trail Formation. The rest of the Tepee Trail Formation is of reversed polarity, and includes 7 early Uintan "Horizon C" of Flynn (1986, fig. 9) and Bone Bed A of McKenna (1980; "Horizon D" of Flynn, 1986), a definite early Uintan assemblage. Flynn (1986, Fig. 9) interpreted this sequence as Chrons C22n-C20r, placing the Bridgerian/Uintan boundary at the base of C20r (although the evidence could also place the boundary in Chron C21n). These results are consistent with the interpretations advocated above and with those of Prothero and Swisher (1992), but not with the interpretation of McCarroll et al. (1993), which would place the Bridgerian/Uintan boundary in Chron C20n.

As Sundell et al. (1984) point out, however, Flynn (1986) apparently missed some polarity zones in the Absaroka sequence. They agreed with Flynn that the normal magnetozone at the base of the Tepee Trail Formation is Chron C21n, but showed that Flynn missed a 300-m interval in the upper Aycross and lower Tepee Trail Formations. Thus, the normal magnetozone at the top of the Aycross Formation is Chron C22n, not C21n.

Trans-Pecos Texas: Walton (1992) described the magnetostratigraphy of the lower and middle members of the Devil's Graveyard Formation in Trans-Pecos Texas (Stevens et al., 1984; Wilson, 1984, 1986). Walton (1992, fig. 3.8) correlated the Bridgerian 0.6 l.f. and Junction l.f. with Chron C21n and correlated the early Uintan Whistler Squat l.f. with C20r (consistent with our preferred correlations discussed above, and with all the available dates). However, she also placed the late Uintan Serendipity l.f. in Chron C20r, which conflicts with the data discussed above. As discussed in Chapter 9 of this volume, the normal magnetozone immediately above the Strawberry Tuff is probably

Chron C20n, placing these late Uintan faunas in C20n, C19r, and C19n, and making them consistent with the rest of the available data. The long normal magnetozone in the middle member of the Devil's Graveyard Formation probably correlates with Chron C18n (this volume, Chapter 9), as it is overlain by the early Duchesnean Skyline and Cotter Channels faunas (see discussion below).

Summary

Despite the apparently conflicting mass of data and interpretations discussed by McCarroll et al. (this volume, Chapter 2) and Walsh (this volume, Chapter 4), there does seem to be a solution to this problem that conforms to the constraints of all the reliable data. Several sections (primarily San Diego, but also the Washakie Basin, East Fork Basin, and Trans-Pecos Texas) are consistent with the interpretation that the Bridgerian/Uintan boundary occurs in Chron C21n (and not in C20n, as suggested by McCarroll et al., 1993). The Uinta Basin section, and the date of 42.83 Ma on the late Uintan Mission Valley Formation in San Diego, establishes that the early/late Uintan transition occurs within Chron C20n (and not C19n, as suggested by McCarroll et al., 1993). The magnetostratigraphy of the Uinta Basin section, the date on the Lapoint Tuff, and the pattern of other late Uintan-Duchesnean sections (such as the Sespe Formation; see this volume, Chapter 8) place the Uintan/Duchesnean boundary in Chron C18n (and not in Chron C17r or younger, as suggested by McCarroll et al., 1993).

Of course, this interpretation is subject to further testing and falsification. It predicts, for example, that the 90-m sampling gap in the lower part of unit 2 of the Adobe Town Member between the Adobe Town and Skull Creek sections of Flynn (McCarroll et al., this volume, Chapter 3, Fig. 3) will be found to have reversed polarity, as is the Shoshonian lower half of the Sand Wash Basin section (this volume, Chapter 4). It also predicts that all of Bridger C and at least the lower part of Bridger D will be of normal polarity, corresponding to Chron C21n. Because Bridger E may be early Uintan (Evanoff et al., 1994), the Chron C21n-C20r transition will probably occur in either upper Bridger D or in Bridger E. Flynn and McCarroll (personal communication) have resampled the Bridger Formation, so it will soon be possible to test this prediction.

Duchesnean

Emry (1981), Wilson (1978, 1984, 1986), Krishtalka et al. (1987), Kelly (1990), and Lucas (1992) have discussed the basis for the Duchesnean. The main problem is that the "type area" for this land mammal "age," part of the Duchesne River Formation, is very sparsely fossiliferous, and most of the rare "type" Duchesnean fossils from the formation come from unknown levels within the Lapoint Member. The lowest two members (Brennan Basin and Dry Gulch

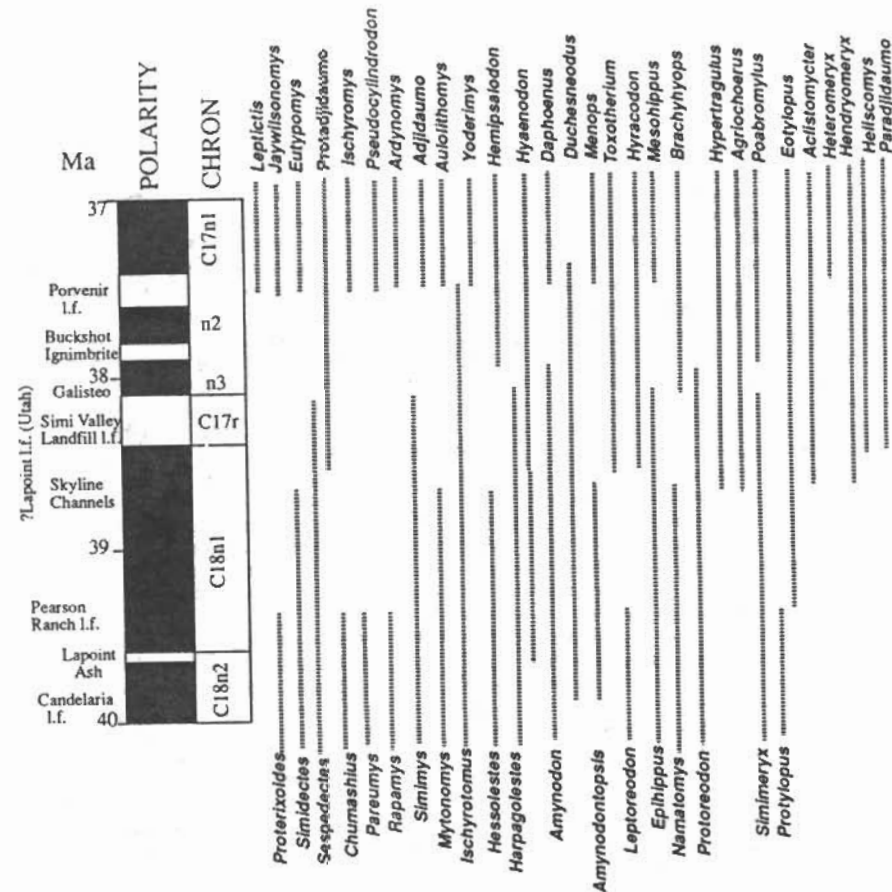


Figure 2. Ranges of key taxa and chronostratigraphy of Duchesnean localities discussed in text.

Creek Members of Andersen and Picard, 1972) are apparently late Uintan. The "type Duchesnean fauna" from the Lapoint Member has been considered so depauperate, and so similar to the faunas of the Chadronian, that Emry (1981) and Wilson (1984, 1986) considered the Duchesnean a "subage" of the Chadronian. Kelly (1990; Kelly, 1992; Kelly et al., 1991; Kelly and Whistler, 1994), however, further documented the Duchesnean faunas of California, and Storer (1987, 1990, 1993, this volume, Chapter 12) described Duchesnean faunas from Saskatchewan. Lucas (1992) summarized the Duchesnean localities from throughout western North America, and argued that there was more to the interval than just the faunas of the Lapoint Member. Since these studies, the validity of the Duchesnean as a discrete land mammal "age" has regained popularity.

The advent of $^{40}\text{Ar}/^{39}\text{Ar}$ dating and magnetic stratigra-

phy have improved the chronostratigraphy of key Duchesnean sections. Although most of the type Duchesne River Formation proved intractable to magnetostratigraphy (this volume, Chapter 1), Prothero and Swisher (1992) demonstrated that the lower part of the Brennan Basin Member was correlative with parts of Chrons C19r-C18r. In addition, Swisher obtained a $^{40}\text{Ar}/^{39}\text{Ar}$ date of 39.74 ± 0.07 Ma from the Lapoint Ash, at the base of the Lapoint Member, about 50 m (150 feet) below the Carnegie Museum "Teleodus" (= *Duchesneodus*) Quarry, the principal Duchesnean locality in the Lapoint Member. This information suggests that at least some part of the Duchesnean correlates with the long Chron C18n. Combining this fact with the magnetic stratigraphy of the late Uintan and early Duchesnean (Pearson Ranch l.f.) faunas in the Sespe Formation of California (this volume, Chapter 8), it appears that the Uintan/Duchesnean boundary

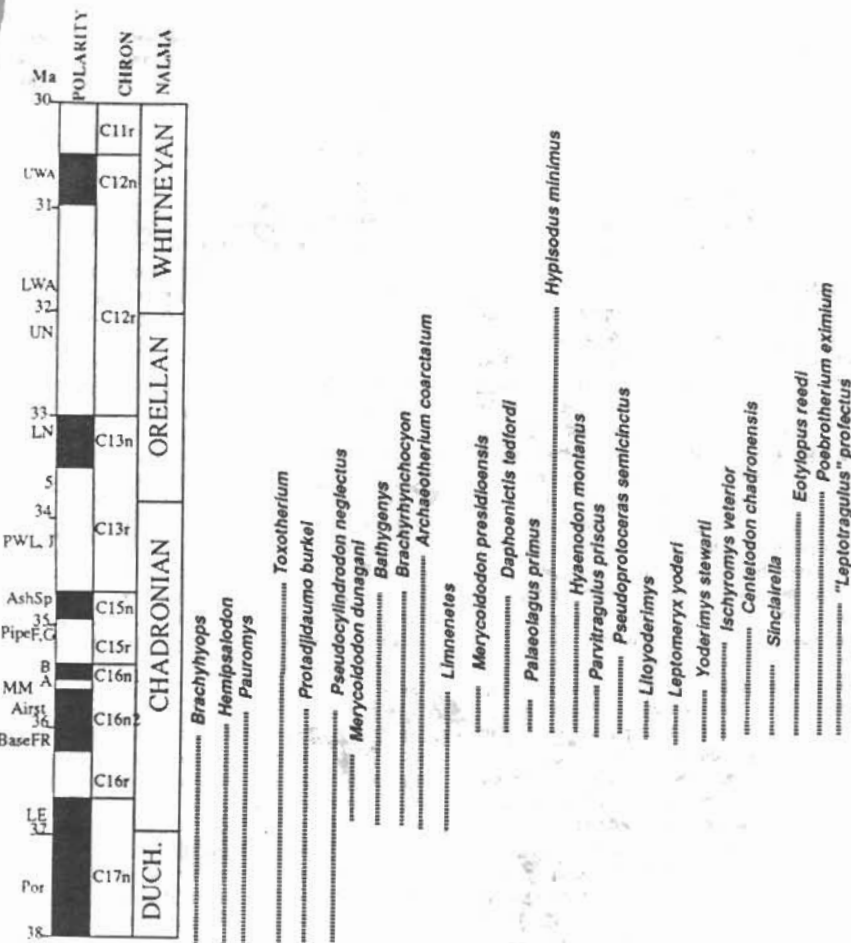


Figure 3. Chronostratigraphy of key early Chadronian localities and taxa discussed in text. Abbreviations: NALMA = North American land mammal "age"; l.f. = local fauna; LE = Little Egypt l.f.; BaseFR = Base of Flagstaff Rim section; Airst. = Airstrip l.f.; Pipe = Pipestone Springs l.f.; AshSp = Ash Springs l.f.; PWL = Persistent White Layer; A, B, G, J = Marker ashes at Flagstaff Rim; LN = lower nodular zone in the Big Badlands; UN = upper nodular zone; LWA = Lower Whitney Ash; UWA = Upper Whitney Ash. Time scale after Berggren et al. (1995).

occurs early in Chron C18n, and that early Duchesnean faunas are correlative with Chron C18n (38.3–40.1 Ma). The slightly younger Duchesnean Simi Valley Landfill l.f. of Kelly et al. (1991) is correlative with C17r (38.1–38.3 Ma).

The other constraint on the Duchesnean comes from the Trans-Pecos Texas region (this volume, Chapter 9). The late Duchesnean Porvenir l.f. occurs just above the Buckshot Ignimbrite, which has been $^{40}\text{Ar}/^{39}\text{Ar}$ dated at 37.8 ± 0.15 Ma (Prothero and Swisher, 1992). Within the Chambers Tuff in the Capote Creek drainage, the

Porvenir l.f. occurs below the Chadronian Little Egypt l.f. This fauna, in turn, is overlain by the Bracks Rhyolite, which has been $^{40}\text{Ar}/^{39}\text{Ar}$ dated at 36.7 ± 0.07 Ma. Combining the magnetic stratigraphy with the stratigraphic position (this volume, Chapter 9) suggests that the Porvenir l.f. is about 37.5 Ma in age (Chron C17n2). Similarly, the Duchesnean Skyline and Cotter channels of the Agua Fria area (Stevens et al., 1984; Wilson, 1986) appear to correlate with Chron C18n–C17r (this volume, Chapter 9). Based on magnetostratigraphy and faunal similarities, the Duchesnean

faunas of the Galisteo Formation of New Mexico are correlated with C17n3–C17r (this volume, Chapter 10).

Although this does not provide precise chronostratigraphy of all Duchesnean faunas, a framework for subdividing the Duchesnean can be developed (Fig. 2). The Pearson Ranch l.f. is early Duchesnean (C18n2, 39–40 Ma), and the Simi Valley Landfill l.f. and Skyline-Cotter Channels l.f. are "middle" Duchesnean (C17r–C18n1, 38.2–38.6 Ma). The Povenir l.f. is late Duchesnean, because it overlies a date of 37.8 Ma and is overlain by a Chadronian fauna constrained by a date of 36.7 Ma. The Galisteo fauna also appears to be late Duchesnean (38.0–38.3 Ma). The chronostratigraphic position of the Lapoint fauna is not well constrained, but based on faunal evidence, it is most likely late Duchesnean (Wilson, 1984, 1986; Kelly, 1990; Lucas, 1992). Lucas (1992) discussed the possible correlation of other Duchesnean localities, but presently none of these has $^{40}\text{Ar}/^{39}\text{Ar}$ dates or magnetic stratigraphy to date them more precisely.

Chadronian

The Duchesnean/Chadronian boundary is best constrained in Trans-Pecos Texas, where the late Duchesnean Porvenir l.f. and early Chadronian Little Egypt l.f. are bracketed by $^{40}\text{Ar}/^{39}\text{Ar}$ dates of 37.8 ± 0.15 and 36.7 ± 0.07 Ma (Prothero and Swisher, 1992; this volume, Chapter 9). Based on the magnetic stratigraphy and the stratigraphic position of the faunas, the Reeves Bonebed (part of the Little Egypt l.f.) probably correlates with part of Chron C17n1. This would place the Duchesnean/Chadronian boundary at about 37.0 Ma.

The best chronostratigraphic data for the remainder of the Chadronian come from the Flagstaff Rim section in Wyoming. $^{40}\text{Ar}/^{39}\text{Ar}$ dating and magnetic stratigraphy (Prothero and Swisher, 1992) shows that the sampled part of the section spans Chrons C16n to C13r (Fig. 3). However, the lowest part of the section (from the base to about 60 feet on the composite section of Emry, 1973, 1992) was not sampled paleomagnetically. As indicated by Emry (1992), this section may be much older than Chron C16n because at the very base Duchesnean taxa such as *Brachyhyops* and *Hemipsalodon* are associated with earliest Chadronian taxa similar to those found in the Yoder l.f. of Wyoming. Following Emry (1992, fig. 5.3), we correlate the base of the Flagstaff Rim section with the earliest Chadronian (36.0–36.5 Ma). This suggests that the lower 60 feet of the section spans Chrons C16r and C16n2, with either very low sedimentation rates, or else significant hiatuses through this interval.

Emry et al. (1987, p. 136) gave evidence that the Airstrip l.f. of Trans-Pecos Texas was early Chadronian, correlative with that part of the section below Ash B at Flagstaff Rim. Ash B has been $^{40}\text{Ar}/^{39}\text{Ar}$ dated at 35.9 ± 0.2 Ma (Prothero and Swisher, 1992) and 35.41 ± 0.14 Ma (Obradovich et al., 1995). Either date places Ash B

within Chron C16n of the Berggren et al. (1995) time scale. The normal magnetic polarity of the main Airstrip section also suggests a correlation with Chron C16n (this volume, Chapter 9). Similarly, the McCarty's Mountain l.f. of Montana is early Chadronian (Emry et al., 1987; Tabrum et al., this volume, Chapter 14), and its magnetostratigraphy (this volume, Chapter 14) suggests a correlation with Chrons C16n1 to C16r.

Typically middle Chadronian faunas occur between Ash B and Ashes F and G at Flagstaff Rim (Emry et al., 1987; Ostrander, 1985). Based on the magnetic stratigraphy (Prothero and Swisher, 1992), the middle Chadronian spans Chron C16n1 and early Chron C15r (35.0–35.5 Ma). The faunas and magnetic stratigraphy of the Pipestone Springs area (this volume, Chapter 14) also suggest a correlation with Chron C13r–C15r. The magnetic stratigraphy of the middle Chadronian Raben Ranch l.f. of Nebraska (this volume, Chapter 13) is consistent with this correlation.

Emry et al. (1987, p. 136) suggested that the Ash Springs l.f. of Trans-Pecos Texas was also middle Chadronian, based on the presence of *Toxotherium* and the stage of evolution of *Meliakronomys*. However, Stevens and Stevens (this volume, Chapter 25) argue that Ash Springs is slightly younger than other middle Chadronian localities based on the oreodonts. The Ash Springs l.f. contains *Merycoidodon culbertsoni* rather than *Merycoidodon presidioensis* or *Miniochoerus forsythae*, and lacks *Bathygenys* and other characteristic middle Chadronian taxa. Unfortunately, there are no magnetostratigraphic or $^{40}\text{Ar}/^{39}\text{Ar}$ data to resolve this question, but we place the Ash Springs l.f. slightly later than Ash G to reflect this interpretation (Fig. 3).

Above Ash G (440 feet on the composite section of Emry, 1973), fossils become very scarce at Flagstaff Rim. A few taxa are known from the upper part of the section that might characterize the late Chadronian (Emry, 1992), but a better record of this time interval comes from the base of the Pine Ridge escarpment in Wyoming and Nebraska. Recent tephrochronology (Larson and Evanoff, personal communication) has shown that the widespread marker ash known as the "Persistent White Layer," "Purple-White Layer," or "PWL" in Niobrara County, Wyoming, and Sioux County, Nebraska, is not the same as the "100 foot white layer" or "5 tuff" of the Douglas area, Converse County, Wyoming (Evanoff et al., 1992), as has long been assumed. Instead, the PWL appears to correlate geochemically with Ash J at Flagstaff Rim, which has been $^{40}\text{Ar}/^{39}\text{Ar}$ dated at 34.7 ± 0.04 Ma (Prothero and Swisher, 1992) or 34.36 ± 0.11 Ma (Obradovich et al., 1995). According to Larson and Evanoff (personal communication), the PWL and Ash J also appear to correlate with the "4 tuff" at Douglas (Evanoff et al., 1992), rather than the "5 tuff", which has been $^{40}\text{Ar}/^{39}\text{Ar}$ dated at 33.91 ± 0.06 Ma (Prothero and Swisher, 1992). Ash J at Flagstaff Rim and the 4 and 5 tuffs at Douglas

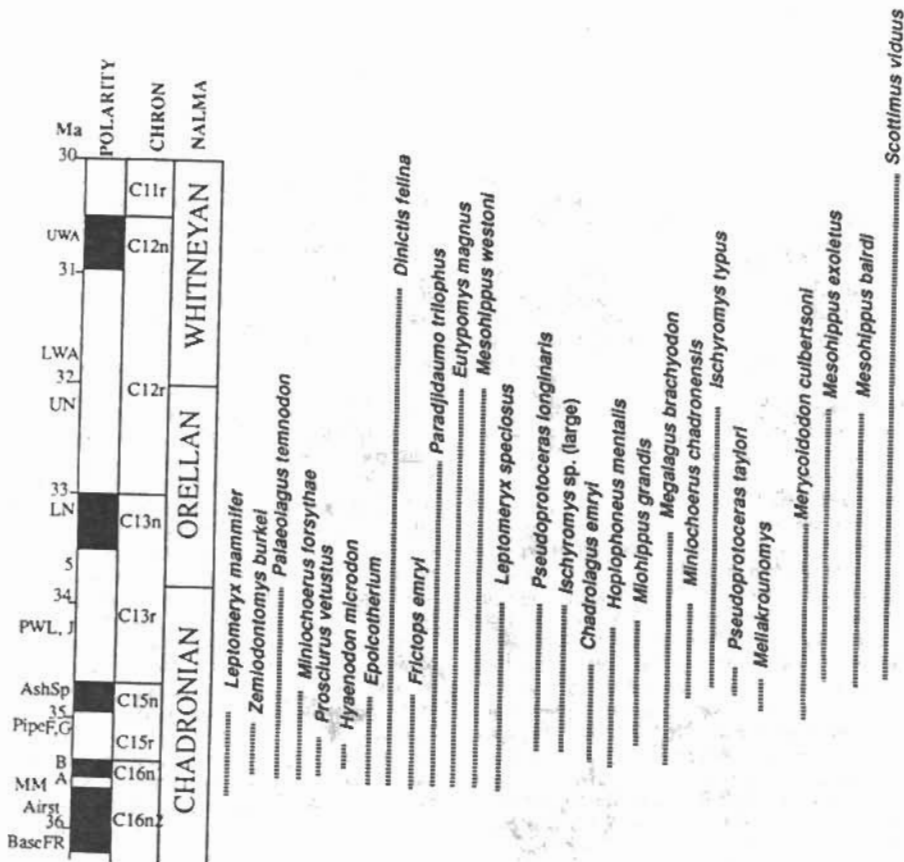


Figure 4. Chronostratigraphy and ranges of key middle-late Chadronian taxa. Abbreviations as in Figure 3.

all occur in Chron C13r (Prothero and Swisher, 1992; Evanoff et al., 1992).

These new data require some slight adjustments in the correlations within Wyoming (this volume, Chapter 13). More important, they provide the first direct tie between the upper Flagstaff Rim section and the slightly more fossiliferous sections below the PWL in Niobrara County, Wyoming. For this reason, we will use the sections in the Lusk area to characterize the biostratigraphy of the late Chadronian.

Orellan-Whitneyan

Prothero and Swisher (1992) and Prothero (this volume, Chapter 13) outlined the new $^{40}\text{Ar}/^{39}\text{Ar}$ dates and magnetics within the White River Group, which places chronostratigraphic controls on the Orellan and

Whitneyan (Figs. 3-5). The Chadronian/Orellan boundary (see Prothero and Whittlesey, in press) lies within Chron C13r and just above the "5 tuff" at Douglas (Evanoff et al., 1992), which has been $^{40}\text{Ar}/^{39}\text{Ar}$ dated at 33.91 ± 0.06 Ma (Prothero and Swisher, 1992) or 33.59 ± 0.02 Ma (Obradovich et al., 1995). Earliest Orellan faunas occur in the latest part of Chron C13r, and late early Orellan faunas are found in strata correlative with Chron C13n. Late Orellan mammals occur throughout the early part of Chron C12r. The Orellan/Whitneyan boundary occurs in the middle of Chron C12r, just below the Lower Whitney Ash, which has been $^{40}\text{Ar}/^{39}\text{Ar}$ dated at 31.8 ± 0.15 Ma (Prothero and Swisher, 1992). This places the Orellan/Whitneyan boundary at about 32.0 Ma. Late Whitneyan faunas first appear in the later part of Chron C12r.

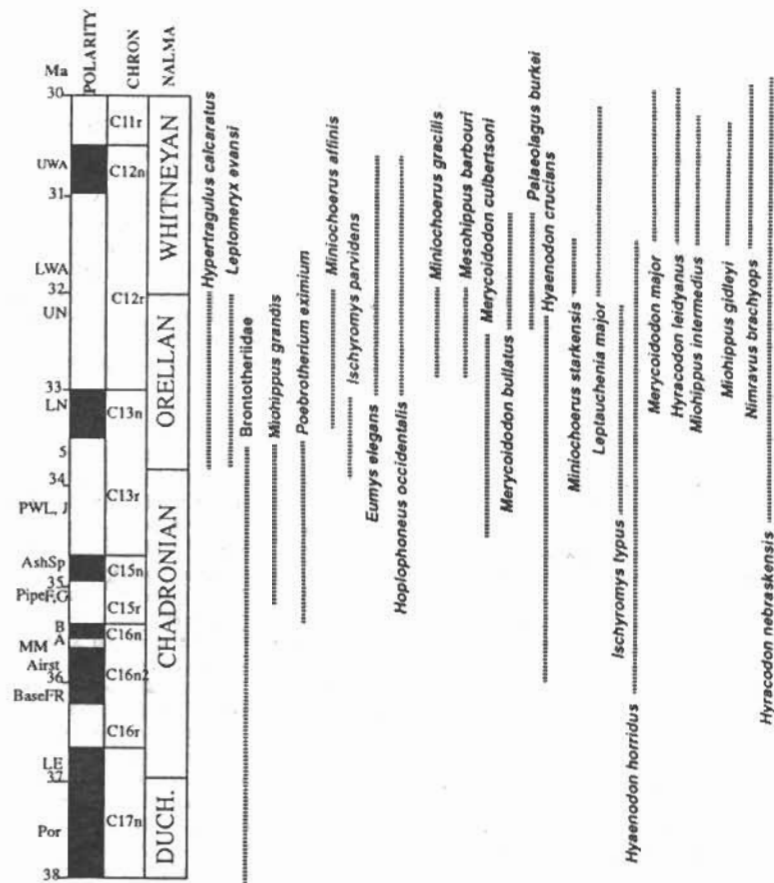


Figure 5. Chronostratigraphy and temporal ranges of key Orellan and Whitneyan taxa. Abbreviations as in Figure 3.

The Whitneyan/Arikarean transition is discussed by Tedford et al. (1985, 1987; this volume, Chapter 15). Characteristic Arikarean taxa occur in the base of the Sharps Formation in South Dakota, and in the brown siltstone beds of the Brule Formation in Nebraska in early Chron C11n (30.0 Ma). Because the Berggren et al. (1995) time scale places the early-late Oligocene boundary at 28.5 Ma, this makes the Orellan, Whitneyan, and earliest Arikarean (including the Sharps and Gering formations) early Oligocene.

BIOCHRONOLOGY AND BIOSTRATIGRAPHY

In the past, mammalian paleontologists rarely attempted to resolve the age of assemblages more closely than to a single North American land mammal "age." In many cases, this was because few of the specimens had precise enough biostratigraphic data to

determine where they came from within a given rock unit. As discussed by Emry et al. (1987), some paleontologists used lithostratigraphic units as biostratigraphic units (e.g., Schultz and Falkenbach, 1968). In recent years, however, a number of authors have begun to emphasize the exact stratigraphic position of their fossils within lithostratigraphic units. It is now possible to subdivide the Uintan through Whitneyan North American land mammal "ages" into smaller units, and ultimately into biostratigraphic zones based on measured sections in the field.

In this regard, the Uintan through Whitneyan have lagged behind the rest of the mammalian time scale. For example, Archibald et al. (1987) suggested biostratigraphic "zones" for much of the Paleocene, and Gingerich (1983) and Gunnell (1989) have erected biostratigraphic "zones" for part of the Paleocene and Eocene. However,

in both of these instances, these are not true biostratigraphic zones in the sense of the 1983 North American Code of Stratigraphic Nomenclature, because they lack type sections and other features specified by the Code (see Prothero, 1995). Tedford et al. (1987) proposed biochronological criteria for subdividing the late Oligocene-Miocene land mammal "ages," but did not attempt to create a range-zone biostratigraphy for the entire interval.

The detailed biostratigraphic data for the Uintan through early Arikarean interval has progressed considerably since the reports of Krishtalka et al. (1987) and Emry et al. (1987). Yet because key parts of the data base are still incomplete as this volume goes to press, we will not propose formal biostratigraphic range zones at this time. Instead, we will indicate the criteria that we would recommend for such a zonation, and likely areas that might serve as zonal stratotypes for each unit.

Uintan

Biostratigraphic zonation of the Uintan is complicated by several factors. The conflicts over chronostratigraphy are the foremost problem. Assuming that the correlation shown in Figure 1 is approximately correct, there is also a problem with the biostratigraphic data base itself. Until the summary by McCarroll et al. (this volume, Chapter 2), there was no detailed biostratigraphic information for the Washakie Basin. The biostratigraphic summary of the Uinta Basin (this volume, Chapter 1) was the first in over 30 years (since Black and Dawson, 1966), and the first to tie the specimens to specific levels within Uinta B or C. A third problem is the high degree of endemism of Uintan faunas (Lillegraven, 1979; Walsh, this volume, Chapter 5). In particular, the smaller mammals of the Rocky Mountain region are less well studied, and their distribution in the Uinta Basin is restricted to a few well sampled levels (such as White River and Myton Pockets). Consequently, the Rocky Mountain zonation is dominated by larger mammals. By contrast, the Uintan localities in California produce mostly small mammals, and only a few of the large mammal taxa represented in the Rocky Mountains are also present in the San Diego or Sespe sections.

The Uintan was originally based on the faunas of the Uinta Formation in Utah, so this is the obvious place to begin. The available biostratigraphic data for the collections of the Uinta Basin were summarized in Chapter 1 of this volume. Combining this information with the biostratigraphy of the Washakie Basin (this volume, Chapter 2) and the faunal list of the Sand Wash Basin (this volume, Chapter 3), it is possible to suggest a biostratigraphy for the Rocky Mountains.

Early Uintan

Flynn (1986, p. 380) defined the beginning of the Uintan (and the beginning of his "Shoshonian Subage")

on the first appearance of *Amyndodon*, and characterized it by the first appearances of *Leptoreodon*, *Protoreodon*, *Protylopus*, *Epihippus* and *Achaenodon*. Krishtalka et al. (1987, p. 89) gave a similar list: *Amyndodon*, *Protoreodon*, *Triplopus*, *Forstercooperia*, *Metarhinus*, *Dolichorhinus* (= *Sphenocoelus*, according to Mader, 1989), *Epihippus*, and *Achaenodon*. Stucky et al. (1989, p. 38) gave a slightly longer list, with many of the same taxa: *Amyndodon*, *Oligoryctes*, *Eobasileus*, *Protoreodon*, *Achaenodon*, *Macrotrarsius*, *Protylopus*, *Ourayia*, *Forstercooperia*, *Triplopus*, *Epihippus*, and *Isectolopus*.

If the fauna from the middle Adobe Town Member (unit 2, or Twka2) of the Washakie Formation in the Washakie Basin, and from the "Locality 1—Turtle Hill" collections in the Sand Wash Basin, are taken as typical of the earliest Uintan, then not all the taxa listed above define the beginning of the Uintan. *Amyndodon*, *Protylopus*, *Eobasileus*, *Metarhinus*, *Sphenocoelus*, *Triplopus*, *Forstercooperia*, *Achaenodon*, and *Protylopus* first occur in Twka2 in the Washakie Basin; *Epihippus* first occurs in Twka3 (McCarroll et al., this volume, Chapter 2, Table 1). In the Sand Wash Basin, *Amyndodon*, *Eobasileus*, *Protoreodon*, *Epihippus*, *Metarhinus*, and *Triplopus* are recorded from the Turtle Hill-Locality 1 levels (Stucky et al., this volume, Chapter 3). Combining the common elements of these lists, only *Protoreodon*, *Eobasileus*, *Metarhinus*, and *Triplopus* are consistently recorded at the beginning of the Uintan in more than one location. *Amyndodon*, *Ourayia*, *Macrotrarsius*, *Epihippus*, *Protoreodon*, *Leptoreodon*, and *Protylopus* make their first appearance in Texas in the earliest Uintan Whistler's Squat l.f. (Wilson, 1986). *Amyndodon*, *Leptoreodon* and *Protoreodon* also occur in the earliest Uintan part of the Friars Formation in San Diego (Walsh, this volume, Chapter 5), so these seem to be the only elements that can be used across North America. Apparently, Flynn's (1986) recommendation of *Amyndodon* as the defining taxon of the beginning of the Uintan still works.

Although the large number of first occurrences makes the Bridgerian/Uintan distinction fairly easy to make, there is some controversy over whether the early Uintan can be further subdivided. Flynn (1986) proposed a "Shoshonian Subage" for the earliest Uintan, and this has been followed by a number of authors. The Shoshonian was defined on the overlapping first occurrences of the early Uintan taxa listed above, and the last occurrence of Bridgerian holdover taxa, such as *Uintasorex*, *Notharctus robustior*, *Trogolemur myodes*, *Microsypops annectens*, and *Hemiacodon*. *Notharctus robustior*, *Microsypops annectens*, and *Hemiacodon* also occur in the Sand Wash Basin faunas. However, as Walsh (this volume, Chapter 4) points out, *Uintasorex* and *Microsypops* are now known from the late Uintan, and *Uintasorex* even ranges into the late Duchesnean (Storer, personal communication), leaving only three taxa which last appear in the earliest Uintan. To that

list could be added *Hyopsodus paulus* and *Dilophodon minusculus*. So far, none of these taxa are known from Uinta B, although this may not be very significant, since the existing collections from Uinta B are almost entirely large mammals (except for those from White River Pocket, at the very top of Uinta B2).

A better way to subdivide the early Uintan would be based on first occurrences which separate the Twka2-Sand Wash faunas from Uinta B. Stucky et al. (1989) listed the first appearances of *Hessolestes*, *Auxontodon*, *Bunomeryx*, *Diplobunops*, and *Leptotragulus* as defining the late early Uintan (although *Hessolestes* is known from the earliest Uintan Whistler's Squat l.f. of Texas). Unfortunately, the remaining list of artiodactyls (plus many other taxa restricted to White River Pocket—see this volume, Chapter 1, Fig. 8) are not known from any early Uintan localities outside the Rocky Mountains. As Walsh (this volume, Chapter 4) points out, these taxa are unknown from San Diego, the only place where a possible "late early Uintan" assemblage (Murray Canyon l.f.) overlies a presumed "Shoshonian" fauna (Poway assemblage). The Badwater area of central Wyoming produces several superposed early Uintan localities (Krishtalka et al., 1987), but so far it is not clear whether they represent both "Shoshonian" and "Uinta B" equivalents, because a comprehensive biostratigraphy of the Wagonbed Formation has never been published.

Thus, there is no direct evidence from superposed assemblages for a faunal distinction between "Shoshonian" and "late early Uintan." Instead, the evidence must come from faunal differences and the chronostratigraphic correlations shown in Figure 1, which are controversial, as we have seen. Nevertheless, the fact that the Twka2 faunas are in a zone of normal polarity, and Uinta B is almost entirely of reversed polarity, shows that they are different in age, no matter how one juggles the correlations.

Late Uintan

The distinction between early and late Uintan is easy to make in the Uinta Basin, since there are a large number of taxa which last appear in Uinta B2, and many more which first appear in Uinta C (this volume, Chapter 1, Fig. 8). Krishtalka et al. (1987, p. 89) list *Protylopus*, *Metarhinus*, *Telmatherium*, taeniodonts, and uinatheres as last appearing in Uinta B, and eomyids, *Domnina*, *Thylacaelurus*, *Colodon*, *Poebrodon*, *Prodaphoenus*, *Simidectes*, *Procyonictis*, and *Epiptilopus* as first occurring in the late Uintan. *Telmatherium*, as now defined (Mader, 1989), is restricted to the Bridgerian, but the rest of the last occurrences are still valid. *Simidectes* (Whistler's Squat l.f.) and *Poebrodon* (Twka2) are now known from the early Uintan, and *Epiptilopus* first occurs in the latest Uintan Randlett horizon of the lower Duchesne River Formation, but the rest of the list of late Uintan first appearances remains valid. Stucky et al. (1989, p. 38)

gave a slightly different list of taxa defining the late Uintan: *Domnina*, *Thylacaelurus*, *Chumashius*, *Mytonius*, *Tapocyon*, *Colodon*, *Simimeryx*, *Mytonolagus*, and *Pseudocylindrodon*. Again, this list works for the Uinta Basin and possibly Badwater, but not for San Diego or the Sespe Formation. *Tapocyon* occurs in the early Uintan Friars Formation (this volume, Chapter 5) but in the late Uintan in the Sespe Formation. *Simimeryx* first appears in the late Uintan in the Sespe Formation (Mason, 1988). *Domnina*, *Thylacaelurus*, *Mytonius*, *Prodaphoenus*, *Colodon*, and *Pseudocylindrodon* are unknown from the San Diego area, and all but *Pseudocylindrodon* is unknown from the Sespe Formation as well.

The chronostratigraphic controversies, faunal endemism, and lack of superposed faunas in more than one region have created problems for any biostratigraphic zonation of the Uintan. Since the San Diego region (this volume, Chapter 5) has more superposed Uintan faunas than any other, it may eventually provide the standard on which a Uintan biostratigraphy could be based. In the Rocky Mountain region, the faunal evidence is insufficient to subdivide the Uintan beyond "Shoshonian," "Uinta B," and "Uinta C," since in no place do all three "subages" occur in superposition.

Duchesnean

Lucas (1992) summarized the faunal lists for most Duchesnean localities, and that information is presented graphically in Figure 2. Wilson (1984, 1986) and Kelly (1990) suggested that distinctions could be made between early and late Duchesnean faunas, but Lucas (1992) questioned whether we have enough information to make that assessment. However, with the new chronostratigraphic data outlined above, both the relative and numerical ages of Duchesnean faunas are becoming better known.

Between the Pearson Ranch and Porvenir local faunas, the distinction between early and late Duchesnean is apparent (Fig. 2). Indeed, as Wilson (1978, 1984, 1986) and Emry (1981) noted, the Pearson Ranch l.f. has much more in common with the late Uintan, and the Porvenir l.f. with the Chadronian, than either share with each other as parts of the Duchesnean. Only the brontothere *Duchesneodus* unites the various Duchesnean faunas (Lucas, 1992). Early Duchesnean local faunas (primarily Pearson Ranch and Skyline-Cotter Channels) are dominated by Uintan holdovers, including the genera *Proterixoides*, *Simidectes*, *Sespedectes*, *Chumashius*, *Pareumys*, *Rapamys*, *Simimys*, *Mytonomys*, *Ischyrotomus*, *Hessolestes*, *Harpagolestes*, *Amyndodon*, *Leptoreodon*, *Epihippus*, *Protoreodon*, *Simimeryx*, and *Protylopus*. Some of the species of these genera, however, are unique to the Duchesnean. Only a few genera, such as *Amyndodontopsis* and *Mahgarita*, are restricted to the early Duchesnean.

Similarly, late Duchesnean local faunas (primarily Porvenir, Simi Valley Landfill, Galisteo, and possibly

Lapointe) are dominated by genera which continue into the Chadronian. These include *Leptictis*, *Jaywilsonomys*, *Eutypomys*, *Ischyromys*, *Pseudocylindrodon*, *Ardynomys*, *Protadajidamo*, *Adjidamo*, *Aulolithomys*, *Yoderimys*, *Hyaenodon*, *Daphoenus*, *Menops*, *Toxotherium*, *Hyracodon*, *Mesohippus*, *Agriohippus*, *Poabromylus*, *Eotylopus*, *Aclistomycter*, *Heteromeryx*, and *Hendryomeryx*. *Hemipsalodon* and *Brachyhyops* continue into the Chadronian in a number of places. The genera *Rooneyia*, *Ischognathus*, and *Haplohyops*, and some of the species of the genera listed above, are restricted to the late Duchesnean.

From these data, a subdivision and biostratigraphic zonation of the Duchesnean is within reach. Since the exposures of the "type" Duchesnean in the Uinta Basin are so poorly fossiliferous, they are inadequate as a basis for biostratigraphic zonation. Instead, we would recommend that the early Duchesnean be based on the exposures of the middle member of the Sespe Formation in western Simi Valley, which produce the Pearson Ranch l.f. Unfortunately, the exposures are located in Simi Valley Landfill, and they are vanishing as the landfill is modified and filled in. *Amyndontopsis* would probably be the best candidate for a zonal indicator of the early Duchesnean. The best candidate for a late Duchesnean type section would be the exposures of the Chambers Tuff, such as Big Cliff (Wilson, 1978, Fig. 7), that produce the Porvenir l.f. The zonal name-bearers might be *Hemipsalodon*, or possibly *Brachyhyops*, since they are very distinctive and virtually restricted to this interval, although many of the genera that carry over into the Chadronian are much more common.

Storer (1987; this volume, Chapter 12) described the Duchesnean Lac Pelletier Lower Fauna of Saskatchewan. Storer was unsure whether it was early or late Duchesnean, although he thought it was older than the Porvenir l.f. This uncertainty is due to the high endemism of the fauna, with only 51% of the genera shared with other Duchesnean faunas. The fact that Lac Pelletier has many taxa in common with the Chadronian, and few in common with the Pearson Ranch l.f., suggests that it is later Duchesnean. In fact, the most distinctive feature is the large number of taxa which do not appear until the Chadronian or later in the White River Group. They include *Sinclairiella*, *Hesperocyon*, *Heptacodon*, *Pseudoprotoceras*, "*Leptotragulus*" (= *Trigenicus*) *projectus*, *Adjidamo*, and *Heliscomyx*. *Hesperocyon* and *Adjidamo* (known from the Porvenir l.f.) and *Heptacodon* (known from the Duchesnean of the Gulf Coast), however, do occur in the Duchesnean outside the White River Group.

Chadronian

Earliest Chadronian (36.5-37.0 Ma)

Based on the chronostratigraphic data discussed above, the earliest Chadronian (Chron C16r) may be incompletely represented at Flagstaff Rim. The only early

Chadronian fauna that clearly falls within the interval between 36.5 and 37.0 Ma is the Little Egypt l.f. of Texas, which lies below a date of 36.7 ± 0.07 Ma (the Rancho Gaitan l.f. of Chihuahua, Mexico, may be a correlative). Thus, the taxa that define the beginning of the Chadronian and the earliest Chadronian time interval (C16r-C17n1, 36.5-37 Ma) are known mainly from Texas (Fig. 3). They include the first appearance of *Bathygenys*, *Merycoidodon dunagani*, *Brachyrhynchocyon* (formerly *Daphoenocyon*) *dodgei*, and *Archaeotherium* (if the upper Porvenir entelodont is *Brachyhyops*, rather than *Archaeotherium*, as suggested by Storer in Emry, 1992, p. 114). On this basis, the Duchesnean/Chadronian boundary could be indicated by the first appearance of *Bathygenys*, *Merycoidodon*, *Brachyrhynchocyon*, and *Archaeotherium*. This list is less extensive than the early Chadronian indicators suggested by Lucas (1992, p. 98), but these are the only taxa that can be clearly shown to first occur immediately above the Duchesnean/Chadronian boundary. Most of the rest have not been documented until strata correlative with Chron C16n (36.0 Ma).

Of these taxa, we suggest *Bathygenys* as the best candidate for zonal indicator of the beginning of the Chadronian, since it is extremely distinctive and abundant in the earliest Chadronian. The sections of Chambers Tuff that include the Reeves Bonebed (the main locality in the Little Egypt l.f.) might serve to typify the Duchesnean/Chadronian boundary and the earliest Chadronian.

Late early Chadronian (35.7-36.5 Ma)

Strata which are correlative with Chron C16n2 (35.7-36.5 Ma) are much better known, and might be considered late early Chadronian. They include the interval from 60-120 feet above base of the section (to 50 feet below Ash B) at Flagstaff Rim, as well as the Airstrip l.f. of Texas and the McCarty's Mountain l.f. of Montana. They may also include the Yoder l.f. of Wyoming (Kihm, 1987), although there are no radiometric dates or magnetics to test this correlation.

Based primarily on the lower Flagstaff Rim section, a large number of taxa make their first appearance in the late early Chadronian, and are more or less restricted to that interval (Fig. 3). These include *Palaeolagus primus*, *Merycoidodon presidioensis*, *Parvitrugulus priscus*, *Pseudoprotoceras semicinctus*, *Litoyoderimys lustrorum*, *Yoderimys stewarti*, and *Leptomeryx yoderi*. In addition, a number of taxa first appear in the late early Chadronian and range into the middle Chadronian. These include *Daphoenictis tedfordi*, *Hyaenodon montanus*, *Ischyromys veterior*, *Centetodon chadronensis*, "*Leptotragulus*" (= *Trigenicus*) *projectus*, and *Sinclairiella dakotensis*. As noted above, however, the Duchesnean Lac Pelletier Lower Fauna of Saskatchewan includes a number of taxa that are otherwise known from strata no earlier than the late early Chadronian in the White River Group, Montana, or Texas. These

include *Sinclairiella*, *Pseudoprotoceras*, "*Leptotragulus*" (= *Trigenicus*) *projectus*, and *Heliscomyx*. This shortens the list of late early Chadronian first appearances somewhat, although it remains valid south of the Canadian border.

A number of Duchesnean taxa last appear in the late early Chadronian, including *Ardynomys* and *Protadajidamo*. The oreodont *Limnnetes* appears to be restricted to this interval.

Of these taxa, *Leptomeryx yoderi* might be used as the defining taxon of the late early Chadronian, since it is common, distinctive, and found not only at Flagstaff Rim, but also at many other late early Chadronian localities. The type section for this interval should also be established at Flagstaff Rim, which has the most complete section in terms of both fossils and chronostratigraphy.

Middle Chadronian (34.7-35.7 Ma)

As discussed above, the middle Chadronian is typified by the strata from about 50 feet below Ash B to Ash G at Flagstaff Rim (120-440 feet on the zonation section of Emry, 1973). The principal correlatives are the Pipestone Springs l.f. and Little Pipestone Creek l.f. of Montana (this volume, Chapter 14), the Raben Ranch l.f. of Nebraska (Ostrander, 1985; this volume, Chapter 13), and fauna of the Crazy Johnson Member of the Chadron Formation in South Dakota (Fig. 4). These strata all appear to correlate with Chron C15n-C15r (34.7-35.7 Ma).

A large number of taxa first appear in this interval, and are more or less restricted to it. They include *Leptomeryx mammifer*, *Zemiodontomys burkei*, *Miniochoerus forsythae*, *Prosciurus vetustus*, *Hyaenodon microdon*, *Chadrolagus emryi*, and *Frictops emryi*. Many other taxa first appear at this level and range into younger strata, including *Palaeolagus temnodon*, *Dinictis felina*, *Eutypomys magnus*, *Mesohippus westoni*, *Leptomeryx speciosus*, *Pseudoprotoceras longinaris*, large *Ischyromys* (see Heaton and Emry, this volume, Chapter 27), *Hoplophonus mentalis*, *Miohippus grandis*, and *Megalagus brachyodon*. Of the taxa listed above, Emry et al. (1987) recommended *Leptomeryx mammifer* as the best indicator of the middle Chadronian. The best candidate for a type section would be Flagstaff Rim from about 50 feet below Ash B to Ash G.

Late Chadronian (34.7-33.7 Ma)

As discussed above, the Flagstaff Rim section above Ash G is too poorly fossiliferous to characterize the late Chadronian, so the section below the PWL (= Ash J at Flagstaff Rim, 4 tuff at Douglas) in the Seaman Hills, north of Lusk, Niobrara County, Wyoming, better typifies the late Chadronian. The Ash Springs l.f. in Texas might also correlate with these strata, as might the Douglas section below the 4 tuff (Evanoff et al., 1992), the late Chadronian strata in western Nebraska

(Ostrander, 1985; Gustafson, 1986; this volume, Chapter 13), and the Peanut Peak Member of the Chadron Formation in South Dakota. All of these strata appear to correlate with late Chron C13r-C15n (33.7-34.7 Ma).

A few taxa, such as *Meliakrounomys* and *Pseudoprotoceras taylori*, are restricted to the higher levels at Flagstaff Rim (Emry, 1992). Other late Chadronian sections, however, produce the first occurrences of *Merycoidodon culbertsoni*, *Poebrotherium franki* (both found at Ash Springs), *Miniochoerus chadronensis*, *Ischyromys typus*, *Mesohippus exoletus*, *Mesohippus bairdi*, and *Scottimus viduus*, among many others (Fig. 4). *Pseudocylindrodon* and *Toxotherium* are among the Duchesnean taxa that last appear at this level in the Ash Springs l.f. *Palaeolagus temnodon*, *Hoplophonus mentalis*, *Miohippus grandis*, *Mesohippus westoni*, *Eotylopus reedi*, *Poebrotherium eximium*, and *Archaeotherium coarctatum* are among the taxa that last occur in the late Chadronian (most terminate near the Chadronian/Orellan boundary).

Of these taxa, *Miniochoerus chadronensis* might be the best candidate for a zonal indicator, since it is abundant, distinctive, and restricted to this interval. An appropriate type section could be designated in the Seaman Hills, Niobrara County, Wyoming.

Orellan

Prothero and Whittlesey (in press) reviewed the biostratigraphy of the Orellan and Whiteyan strata in the White River Group (Fig. 5). The key points are summarized below.

The Chadronian/Orellan boundary occurs late in Chron C13r, above the 5 tuff at Douglas, which has been $^{40}\text{Ar}/^{39}\text{Ar}$ dated at 33.91 ± 0.06 Ma (Prothero and Swisher, 1992) and at 33.59 ± 0.02 Ma (Obradovich et al., 1995). As discussed by Prothero and Whittlesey (in press), there are at least four separate occurrences of brontotheres in strata correlative with the Brule Formation, so this creates problems for the Wood Committee's (1941) definitions of the Chadronian based on the last appearance of brontotheres and the top of the Chadron Formation. Prothero and Whittlesey (in press) recommended that the first appearance of the ruminant *Hypertragulus caicarus* be used to recognize the beginning of the Orellan, because it is distinctive, abundant, and appears suddenly at the beginning of the Orellan. There are no Chadronian species of *Hypertragulus* in the White River Group with which it might be confused. *Hypertragulus heikeni* from the early Chadronian Rancho Gaitan l.f. of Mexico is very different, both in time and morphology, and may not be *Hypertragulus* at all.

Korth (1989) called the Orella A strata in Toadstool Park, Nebraska, the "*Palaeolagus hemirhizis* zone." As discussed by Prothero and Whittlesey (in press), this zone is difficult to use because *P. hemirhizis* may be a taxonomic composite of specimens of *P. temnodon* and

P. haydeni, and also because *P. hemirhizis*, if valid, may also occur in the Chadronian of Saskatchewan. In addition, the zone was based on a lithostratigraphic unit, and not on detailed biostratigraphic data within Orella A, so it unacceptably mixes lithostratigraphy and biostratigraphy. Finally, Korth (1989) designated no type section for this or any other zone in his scheme.

The earliest Orellan can also be recognized by the first appearance of *Leptomeryx evansi*, although as shown by Heaton and Emry (this volume, Chapter 27), the transformation from *L. speciosus* to *L. evansi* is subtle and hard to recognize. The earliest Orellan is also marked by the first appearance of *Palaeolagus intermedius* and *Paratylopus labiatus*, and by the last appearance of *Poebrotherium eximium*, *Miohippus grandis*, and *brontotheres*. At this level, there is also a small species of *Miniochoerus* (mean M^{1-3} length = 42 mm; observed range = 39–45 mm) between *M. chadronensis* and *M. affinis* in size. It was originally called *M. "douglasensis"* by Stevens (MS), but is now referred to *M. chadronensis* (Stevens and Stevens, this volume, Chapter 26). This oreodont is also a good indicator of the earliest Orellan, along with the overlapping ranges of *H. calcaratus*, *L. evansi*, *M. grandis* and *brontotheres*. On this basis, Prothero and Whittlesey (in press) recognized the earliest Orellan *Hypertragulus calcaratus* Interval Zone. Its type section is the Reno Ranch East section at Douglas, Wyoming, 20–50 feet above the 5 tuff (Evanoff et al., 1992).

Several different biostratigraphic events mark the late early Orellan (Fig. 5), which appears to span most of Chron C13n (33.0–33.5 Ma). Specimens referable to *Miniochoerus affinis* (mean M^{1-3} length = 38 mm; observed range = 36–41 mm) first appear at the beginning of Chron C13n, as well as *Eumys elegans*, *Pelycomys brulani*, *Adjidaumo minutus*, *Cedromus wardi*, and *Hoplophoneus occidentalis*. Korth (1989) named the Orella B strata at Toadstool Park the "Eumys elegans zone," but we hesitate to use this taxon as name-bearer. Although it first appears at this level in the White River Group, *Eumys* may appear earlier in Montana and Saskatchewan (this volume, Chapters 12 and 14). The late early Orellan would be better defined by the overlapping ranges of *Miniochoerus affinis* and *Ischyromys parvidens*, taxa which are much more abundant and easy to recognize. Prothero and Whittlesey (in press) named the *Miniochoerus affinis* Interval Zone for the late early Orellan. This zone is typified by the strata between 50–80 feet above the PWL in Boner Ranch section in the Seaman Hills, north of Lusk, Niobrara County, Wyoming.

Early late Orellan strata are correlative with the earliest part of Chron C12r (32.5–33.0 Ma), and are marked by slightly fewer distinctive biostratigraphic events. However, the first appearance of the dwarfed oreodont *Miniochoerus gracilis* (mean M^{1-3} length = 34 mm; observed range = 31–37 mm) and the advanced horse *Mesohippus barbouri* are both unique to this

interval. *Ischyromys parvidens* last appears at this level as well (see this volume, Chapter 18). Korth (1989) showed that *Agnostocaster readingi*, *Paradjidaumo validus*, *Eutyomys thomsoni*, and *Eumys parvidens* are restricted to the early late Orellan (Orella C). Prothero and Whittlesey (in press) named this interval the *Miniochoerus gracilis* Interval Zone, and designated its type section as the strata from 80–150 feet above the PWL in the Boner Ranch section of the Seaman Hills.

Latest Orellan strata (early Chron C12r, 32.0–32.5 Ma) are marked by many distinctive taxa. The most useful is the appearance of *Merycoiododon* with large auditory bullae, now referred to *Merycoiododon bullatus* by Stevens and Stevens (this volume, Chapter 26). The advanced rabbit *Palaeolagus burkei* first appears at this level, as does the last of the miniochoeres, *Miniochoerus starkensis*, along with many other taxa listed by Prothero and Whittlesey (in press). Korth (1989) named a late Orellan zone based on Orella D in Toadstool Park, Nebraska, after the rare rodent *Diplolophus insolens*. Although this taxon is apparently unique to the latest Orellan, it is so rare that it would not be a very useful range-zone indicator. In addition, Korth (1989) did not designate a type section for this zone. Prothero and Whittlesey (in press) named the *Merycoiododon bullatus* Interval Zone for the latest Orellan. The "Upper Nodular zone" of the Big Badlands of South Dakota in the Cottonwood Pass-Sheep Mountain Table area was chosen as the stratotype.

Many taxa disappear at or near the Orellan/Whitneyan boundary, including *Ischyromys*, *Mesohippus*, *Subhyracodon*, *Prosciurus*, *Pelycomys*, *Protosciurus*, *Oligospermophilus*, *Eutyomys*, *Adjidaumo*, *Heliospermus*, *Wilsoniomyx*, *Eoemyx*, *Tenuodmys*, *Pipestoneomys*, *Megalagus*, *Palaeolagus intermedius*, *Leptictis haydeni*, and *Hyaenodon crucians*.

Whitneyan

Unlike the detailed biostratigraphic records for the Orellan, few collections have very detailed records for the Whitneyan. Even in the Frick Collection, specimens are only recorded as "upper Orodont beds," "Leptauchenia beds" or "Protoceras channels" with little indication of exactly how many feet they occurred above or below a given horizon. In the University of Nebraska State Museum collections, specimens are only recorded as derived from "Whitney A," "Whitney B," or "Whitney C." Because the primary data base is so low in resolution, the Whitneyan cannot be so finely subdivided as the Chadronian or Orellan at the present time (Fig. 5).

A number of distinctive biostratigraphic events mark the Orellan/Whitneyan boundary (mid-Chron C12r, about 32.0 Ma), although their apparent coincidence may be an artifact of the coarse resolution of the biostratigraphic data. The earliest Whitneyan is marked by abundant *Leptauchenia decora* and the first appearance of *Leptauchenia* (formerly *Cyclopidius*) *major*, and by

the first appearances of *Hyracodon leidyianus*, *Paratylopus primaevus*, *Paralabis cedrensis*, *Diceratherium tridactylum*, *Protapirus obliquidens*, *Ectopocynus antiquus*, *Oxetocyon cuspidatus*, *Cynodesmus thooides*, *Agnostocaster praetereadens*, and *Oropycitis pediasius*. This zone also yields the last *Miniochoerus* and *Hyaenodon horridus*. Prothero and Whittlesey (in press) named this the *Leptauchenia major* interval zone, with a stratotype in the "upper Orodont beds" on the south side of Sheep Mountain Table in the Big Badlands. It correlates with mid-Chron C12r (32.0–31.4 Ma).

The late Whitneyan (late Chron C12r–early-C11n, 31.4 Ma–30.0 Ma) can also be distinguished by a number of distinctive taxa. They include the first appearance of the large oreodont *Merycoiododon major*, the tylopod *Protoceras celer*, the horses *Miohippus intermedius*, *Miohippus equinanus*, *Miohippus annexens*, and *Miohippus gidleyi*, the nimravids *Hoplophoneus dakotensis*, *Eusmilus cerebialis*, and *Nimravus brachyops*, the rodents *Eumys brachyodus* and *Scottimus lophatus*, and the creodont *Hyaenodon brevirostris*. Prothero and Whittlesey (in press) designated the late Whitneyan as the *Merycoiododon major* Interval Zone, with its stratotype in the "Leptauchenia-Protoceras beds" in the Sheep Mountain Table area of the Big Badlands.

Tedford et al. (1985, 1987; this volume, Chapter 15) noted a number of taxa that mark the Whitneyan/Arikareean boundary. According to their definition, this boundary occurs in early Chron C11n (about 30.0 Ma), very near the Rockyford Ash at the base of the Sharps Formation in South Dakota, and near Nonpareil Ash 2 in the brown siltstone beds in Nebraska. Earliest Arikareean first occurrences include the rabbits *Palaeolagus hypsodus* and *P. philoi*, the beaver *Palaeocastor nebrascensis*, the canid *Shunkehetanka geringensis*, the ruminant *Nanotragulus loomisii*, and the oreodonts *Sespia nitida* and ?*Mesoreodon minor*. In addition, the rhinos *Diceratherium armatum* and *D. annexens*, and the rodents *Leidyomys blacki*, *Sanctimus stuartae*, *Geringia mcgregori*, *Tenuodmys*, *Plesiosminthus*, and several other taxa first occur in the earliest Arikareean as now defined. Of these taxa, *Sespia* would make the most distinctive and abundant biostratigraphic indicator, especially since it also marks the early Arikareean in areas outside the High Plains, such as California. The best candidate for a type section might be the Sharps Formation above the Rockyford Ash in either the Cedar Pass or Wolff Table-Warblee areas of the Big Badlands of South Dakota, since these produce the richest faunas. In addition, many taxa last occur in the late Whitneyan and are currently unknown from Arikareean strata, including *Leptomeryx*, *Merycoiododon*, *Paratylopus*, *Paralabis*, *Perchoerus*, *Heptaecodon*, *Leptochoerus*, *Hyracodon*, *Colodon*, *Protapirus*, *Hesperocyon*, *Osbornodon*, *Dinictis*, *Paradjidaumo*, *Eumys*, and *Scottimus*.

Tedford et al. (1987; this volume, Chapter 15) also

note that the late early Arikareean (early Chron C9n, 27.8 Ma) is marked by the "enrichment phase" of Arikareean faunas, including the addition of such taxa as *Pacliculus*, *Gregorymys*, *Pseudoheteridomys*, *Archaeolagus*, and *Ethydrocyon crassidens*. These taxa are all first reported from the "Monroe Creek Formation" and equivalents. This zone falls very near the early/late Oligocene boundary as currently defined (Berggren et al., 1995), and concludes our discussion of the early Oligocene zonation of the North American terrestrial record.

Although much work remains to be done, we have made considerable progress in our understanding of the chronostratigraphy and biostratigraphy of the Uintan through Arikareean interval since the last summaries were published in 1987. For the Orellan and Whitneyan, range zone biostratigraphy has already been proposed. In the Uintan, Duchesnean, and Chadronian, much needs to be resolved before formal biostratigraphic zones can be proposed, and they may not be applicable beyond their local area. Nevertheless, we hope this discussion has laid the foundation for future work, and before yet another decade has passed, we may have a standardized, well-dated chronostratigraphy and biostratigraphy for the entire middle Eocene through early Oligocene.

THE EOCENE-OLIGOCENE CLIMATIC TRANSITION

Berggren and Prothero (1992) and Prothero (1994a, 1994b) reviewed the evidence of global climatic changes that accompanied the Eocene-Oligocene transition. Although most of the conclusions presented in those papers are still valid, it is worthwhile to re-examine them in the light of the correlations discussed above.

According to Stucky (1990, 1992), North American land mammal faunas reached a peak of diversity in the late Uintan, and began to decline in overall diversity through the Duchesnean and Chadronian. Wolfe (1978; 1994, fig. 3) also reported a drop in mean annual temperatures of 10°C as indicated by floras from mid-latitudes of North America at about 40 Ma (the Uintan/Duchesnean boundary). According to Boersma et al. (1987) and Aubry (1992), the Uintan/Duchesnean boundary (early Chron C18n, early Bartonian, planktonic foraminiferan Zone P13/P14 boundary, nanoplankton Zone NP16/NP17 boundary) apparently corresponds to a number of global climatic events and oceanographic changes (cooling of bottom waters, which become decoupled from surface waters; increased thermal isolation of Antarctica; increased oxygenation of surface waters; cooling in mid-latitudes and extinction of their warm-water plankton).

The most dramatic change in global faunas occurred at the end of the middle Eocene (about 37–38 Ma, according to Berggren et al., 1995), when mass extinctions decimated the marine invertebrates and plankton. Tropical taxa and warm-adapted organisms were the most hard-hit, suggesting that this extinction

was caused by global cooling. Based on the dating outlined above, this event probably corresponds to the middle Duchesnean transition, when the typically Uintan-early Duchesnean faunas (such as the Pearson Ranch l.f.) were replaced by elements of the White River Chronofauna (such as the Porvenir l.f.). Although total mammalian diversity did not change between the early and late Duchesnean (Stucky, 1990, 1992), there was a much higher rate of turnover during this interval.

The Eocene-Oligocene boundary itself was not a major extinction horizon in the global marine record (Berggren and Prothero, 1992; Prothero, 1994a), nor was it a major event on the land. Based on the chronostratigraphy outlined above, the Eocene/Oligocene boundary (late Chron C13r, 33.7 Ma) falls very near the Chadronian/Orellan boundary, which saw the disappearance of a few archaic groups (especially brontotheres, oromyids, and cylindrodonts), but relatively little in the way of extinction in the remaining taxa (Stucky, 1992, fig. 24.4; Prothero and Heaton, in press).

Based on many climatic indicators, the most dramatic event of all should have occurred in the earliest Oligocene (about 33 Ma, middle Chron C13n). This was when the first major ice sheets appeared in Antarctica, global temperatures dropped 5-6°C (as indicated by oxygen isotopes), and many marine invertebrates suffered another episode of mass extinction. In Europe, a major change took place in land faunas, as the archaic Eocene endemic mammals were replaced by Eurasian immigrants in an event known as the "Grande Coupure" (Hooker, 1992).

In North America, the climatic signals are even more dramatic. Wolfe (1978) reported a 13°C drop in mean annual temperatures based on land floras, with a great increase in seasonality during what he then called the "Terminal Eocene Event" (now dated as earliest Oligocene). Paratropical floras now found in central America were replaced by broadleaved deciduous forests or northern hardwood forests, now found in New England. His more recent estimates based on more sophisticated methods (Wolfe, 1994, fig. 3) are consistent with this interpretation. According to Retallack (1983, 1992), the paleosols in the Big Badlands show a transformation from dry woodland to wooded grassland in the earliest Orellan. In places such as Douglas, Wyoming, late Chadronian floodplain deposits are replaced by early Orellan eolian deposits in mid Chron C13n (Evanoff et al., 1992). Land snails from these same beds are consistent with this interpretation. Late Chadronian land snails are large-shelled, tropical forms typical of the modern southern Rocky Mountains or central Mexican Plateau, and indicate a mean annual temperature of 16.5°C and a mean annual precipitation of 450 mm (Evanoff et al., 1992). During Chron C13n, these snails were replaced by small-shelled, drought-tolerant taxa indicative of an open woodlands habitat with a pronounced dry season, such

as are found today in Baja California. In addition, aquatic reptiles and amphibians (especially salamanders, crocodilians, and pond turtles) disappear by the early Orellan, replaced by land tortoises (Hutchinson, 1982, 1992).

Given all this striking climatic evidence, the response by the mammalian fauna was remarkably mild. As reviewed by Prothero and Heaton (in press), the vast majority of mammalian lineages (62 out of 70) found in the earliest Orellan continued into the late early Orellan with no observable morphological change worthy of species distinction. The few extinctions and originations that did occur were remarkably minor, and about the only noticeable change was the dwarfing in the oreodont *Miniochoerus*, which was already underway in the late Chadronian. The implications of this discordance between the climatic evidence and mammalian faunal data is analyzed in Prothero and Heaton (in press), so it will not be discussed further here.

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