BIOSTRATIGRAPHY OF THE CONTINENTAL PALEOCENE-EOCENE BOUNDARY INTERVAL ON POLECAT BENCH IN THE NORTHERN BIGHORN BASIN

PHILIP D. GINGERICH

Department of Geological Sciences and Museum of Paleontology, The University of Michigan, Ann Arbor, Michigan 48109-1079

Abstract.— The Paleocene-Eocene boundary interval in land-mammal evolution is best documented at the south end of Polecat Bench, in the northern Bighorn Basin of Wyoming. Faunas of the late Paleocene Tiffanian and Clarkforkian land-mammal ages and the succeeding early Eocene Wasatchian land-mammal age are all well represented here. Strata on Polecat Bench and in the contiguous Sand Coulee area of the Clarks Fork Basin include type sections of thirteen successive mammalian zones, abbreviated Ti-4 to Ti-6, Cf-1 to Cf-3, Wa-0?, and Wa-0 to Wa-4 (with Wa-3 subdivided) that together span much of the upper Paleocene and lower Eocene. University of Michigan locality SC-67 at the south end of Polecat Bench has yielded the largest and most diverse fauna of earliest Wasatchian age (Wa-0), but facies changes, channel scouring-and-filling, faulting, and topography have long combined to make a clear understanding of physical stratigraphy difficult. This has been clarified now by detailed differential GPS mapping of a critical area covering several square kilometers. In the western part of the study area the early Eocene Wa-0 mammalian faunal interval is composed of unusually mature red and purple stage-3 and stage-4 cumulative paleosols, underlain and overlain by sheet-like 'boundary' channel sandstone complexes. However, from SC-67 eastward there are no bounding channel sandstones. A ribbon sandstone near the base of SC-67 has been mistaken for a lower boundary sandstone in the past, and a major scour-and-fill sequence just east of SC-67 has been mistaken for an upper boundary sandstone.

The Wa-0 faunal zone is about 25 m thick, and the transition from underlying to overlying zones appears to be virtually continuous in fine-grained mudstones. A ca. 4-5 m thick interval of brown paleosols below Wa-0, in what were previously thought to be Clarkforkian strata, is now included in the lower Wasatchian as a new zone. The new zone, abbreviated Wa-0?, has yielded numerous endocarps of the elm-related dicot *Celtis* (hackberry) and a dentary of the mammalian condylarth *Meniscotherium* (but no other Wasatchian mammals). Early appearance of the *Celtis-Meniscotherium* association and an average rate of sediment accumulation of 470 to 475 m/m.y. suggest that Wasatchian floral and faunal change started some 9-10 k.y. earlier than previously recognized. The thickness of the Wa-0 zone proper indicates that it probably represents only about 50 k.y. of geological time.

INTRODUCTION

Polecat Bench is a northeast-to-southwest-trending Pleistocene river terrace in the northern Bighorn Basin, north and west of the town of Powell, Wyoming (Fig. 1). It stands some 150 m above the surrounding 'flats' or plains, forming a watershed that separates the Clarks Fork Basin to the northwest from the northern part of the Bighorn Basin to the southeast. The surface of Polecat Bench slopes downward at a low gradient toward the northeast, falling from an elevation of 1580 m to an elevation of 1460 m in a distance of twenty kilometers.

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Alignment with the Shoshone River canyon west of Cody, Wyoming, indicates that the river that formed Polecat Bench was a precursor of the present-day Shoshone River and part of the greater Bighorn River drainage excavating the Bighorn Basin.

Polecat Bench is important geologically because its resistant gravel surface supports a virtually continuous sequence of finer-grained, softer, and older continental sedimentary rocks spanning the uppermost Cretaceous through lower Eocene. Cretaceous and Paleogene strata form a southwesterly-dipping monocline well exposed in badlands along the west and southeast sides of the bench (Figs. 2-3). The Paleocene part of the sequence is some 1500 m thick (Fig. 3), making it one of the thickest and most continuous records of continental Paleocene strata known anywhere. Most of this thickness is upper Paleocene, with localities yielding mammalian fossils of the Tiffanian and Clarkforkian land-mammal ages (open diamonds and open circles, respectively, in Fig. 1). In addition, there is a 100 m thick wedge of lower Eocene strata at the south end of Polecat Bench with localities that yield Wasatchian land mammals (open squares and solid squares in Fig. 1).

Biozones reflecting faunal change through the middle-late Paleocene and early Eocene in northwestern Wyoming are summarized in Table 1. Zones and subzones can be recognized where strata of suitable age are exposed throughout the Bighorn–Clarks Fork–Crazy Mountain region of Wyoming and Montana, and some zones undoubtedly have broader geographic extent. Stages and ages of higher rank are recognized by the biozones (zones and subzones) included within them: the Clarkforkian land-mammal stage/age, named for the Clarks Fork Basin on the west side of Polecat Bench (Granger, 1914; Wood et al., 1941) includes the Rodentia interval zone, the *Plesiadapis cookei* taxon range zone, and the *Phenacodus-Ectocion* acme zone. Wa-3 as a whole includes both the *Homogalax protapirinus* and *Hyracotherium aemulor* interval subzones. The Sandcouleean substage/age of Granger (1914) and Wood et al. (1941) includes Wa-0 through Wa-2. The Graybullian substage/age of Granger (1914) and Wood et al. (1941) includes Wa-3 through Wa-5. The zones described here differ conceptually from the ages and 'zones' (biochrons) of Archibald et al. (1988) in being explicitly based on type sections, providing a tangible stratigraphic basis for recognition of corresponding ages and biochrons. Some or all biozones will undoubtedly require modification as new fossils are found, but superpositional relationships will not change and the utility of such a system of biozones for studying the Paleocene-Eocene transition in the Bighorn-Clarks Fork-Crazy Mountain region is amply demonstrated. Each biozone is distinctive as a faunal assemblage, and the index taxa listed in Table 1 are those perceived to be most useful for recognizing broader faunal changes.

The Clarkforkian-Wasatchian transition at the south end of Polecat Bench has proven particularly interesting and important in recent years because of its distinctive basal Wasatchian or Wa-0 mammalian fauna (Gingerich, 1989, 2000; Clyde and Gingerich, 1998; open squares in Fig. 1). The Wa-0 fauna includes the first North American representatives of colonizing Perissodactyla, Artiodactyla, Primates, and hyaenodontid Creodonta that mark the beginning of the Eocene on northern continents, and it includes many seemingly-dwarfed taxa smaller than those that preceded and/or succeeded them. Such distinctive faunas deserve special attention because they may presage, as Wa-0 has done, unusual conditions of great interest for understanding environmental change.

The Wa-0 fauna at the south end of Polecat Bench is associated with unusually mature paleosols for the northern Bighorn and Clarks Fork basins (Kraus, 1987), a large negative carbon isotope excursion (decrease in the ratio of δ^{13}C to δ^{12}C) that can be correlated worldwide (Koch et al., 1992, 1995; Bains et al., submitted; Bowen et al., this volume), and coincides with benthic marine extinctions and global climatic warming thought to result from melting of hydrated methane on continental shelves (Kennett and Stott, 1991; Zachos et al, 1994; Dickens et al., 1995; Bains et al., 1999; Norris and Röhl, 1999).

The importance of the south end of Polecat Bench is now well established, both for studying the Clarkforkian-Wasatchian transition locally, and for understanding the impact of global Paleocene-Eocene environmental change on continental climates and biotas more generally. Diverse investigations are being carried out by scholars from different institutions, and this will continue in the future. To be comparable, independent studies must be carried out and reported in a common reference frame, which prompted a new effort in 2000 to map the south end of Polecat Bench and clarify its stratigraphy. The map and stratigraphic sections that follow will help in providing a better understanding of the Clarkforkian-Wasatchian transition and its relationship to Paleocene-Eocene environmental change.

HISTORY OF STUDY

Recognition of Wa-0 as a distinctive faunal interval has taken a long time. The first Wa-0 mammals, *Dipsalidictis platypus* and *Ectocion parvus*, were collected by Princeton University professor William J. Sinclair on August 12 and 13, 1911, from red-banded beds in the bluff three miles north of Ralston, Wyoming [i.e., Polecat Bench], while working with an American Museum of Natural History field party. *Meniscotherium priscum* was collected in the same area at the same time. These were part of a fauna from the Clarks Fork Basin first described as being Clarkforkian in age (Sinclair and Granger, 1912, p. 59; Granger, 1914, p. 204). A few additional specimens were collected over the years by Princeton University field parties but these were not considered interesting enough to warrant publication at the time.

University of Michigan research on the Paleocene-Eocene transition started in 1975, when the existence of a Clarkforkian land-mammal age was in doubt because the Clarkforkian fauna was considered artificial, possibly resulting from inadvertent mixing of Tiffanian and Wasatchian fossils (Wood, 1967). In our first summer of field work, 64 localities (SC-1 through SC-64) were established in the Sand Coulee area of the Clarks Fork

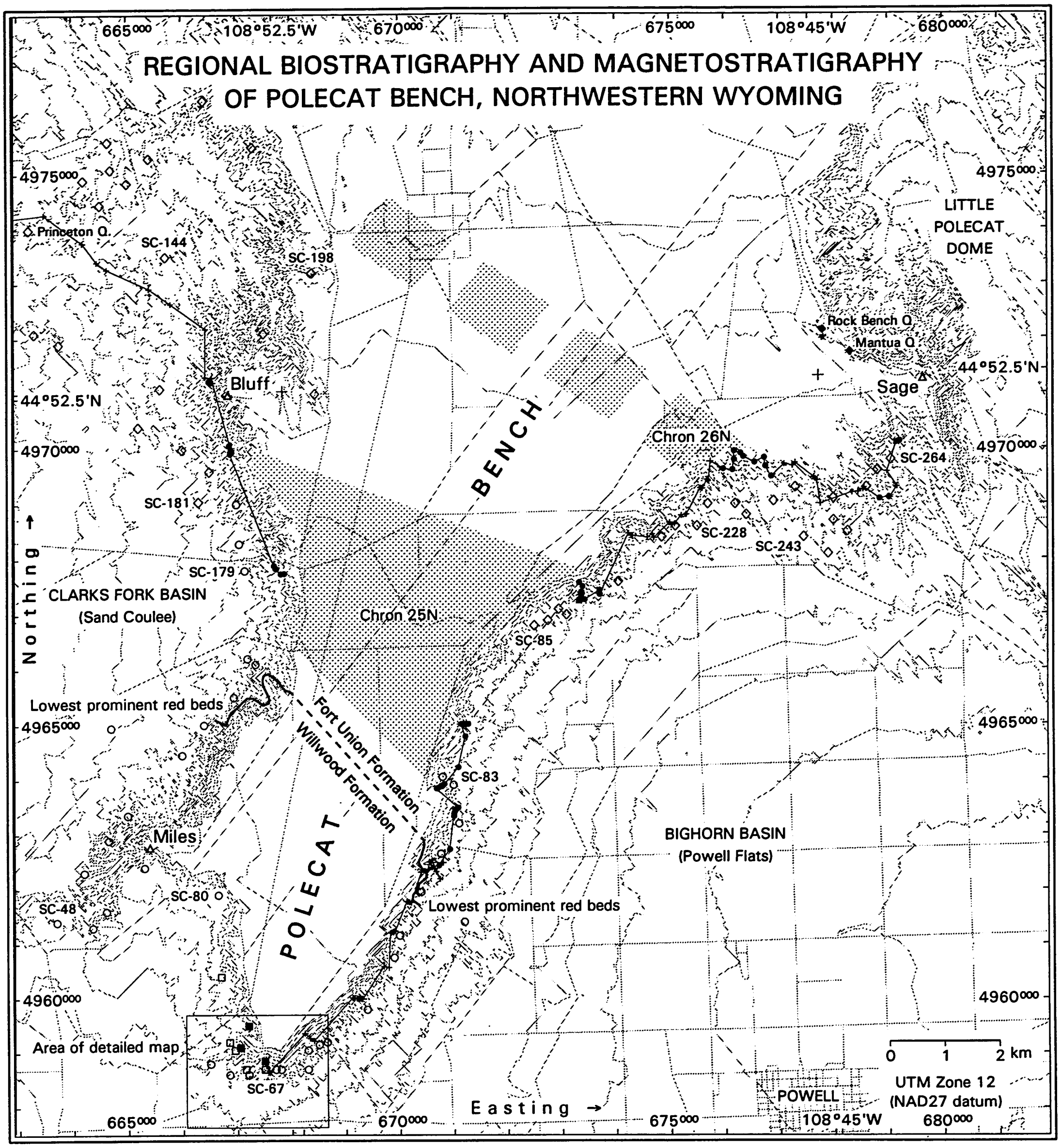

FIGURE 1 — Regional biostratigraphy and magnetostratigraphy of Polecat Bench in northwestern Wyoming. Fossil localities yielding mammals of successive land-mammal ages are coded by age, using the following symbols: Torrejonian (solid diamonds), Tiffanian (open diamonds), Clarkforkian (open circles), earliest Wasatchian Wa-0 (open squares), and later early Wasatchian (solid squares). Some of the more important localities are labeled (SC-67, etc.). National Geodetic Survey stations Bluff, Miles, and Sage are shown as open trianges. Paleomagnetic traverses of Butler et al. (1981) are shown as connected lines on both the west and southeast sides of Polecat Bench, where plus signs mark sites of reversed polarity and solid circles mark sites of normal polarity: stippled bands show inferred traces of magnetozones across Polecat Bench. Stratigraphic sections on the west and southeast sides of Polecat Bench are illustrated in Figs. 2 and 3, respectively; these sections are tied together at the top by a prominent purple mudstone (Purple-4) that can be traced from a point above SC-67 to a point stratigraphically above SC-80. A detailed map of upper Clarkforkian and lower Wasatchian strata at the south end of Polecat Bench is illustrated in Fig. 6.

Basin, and we were able to draw a line on a map separating localities yielding the archaic proprimate *Plesiadapis* from those yielding the dawn horse *Hyracotherium* and other characteristic Wasatchian mammals.

In 1976 we devoted special attention first to Polecat Bench, and then to identification of the line of separation of Clarkforkian and Wasatchian faunas in Clarks Fork Basin. The line on our initial map proved to coincide with a sheet-like

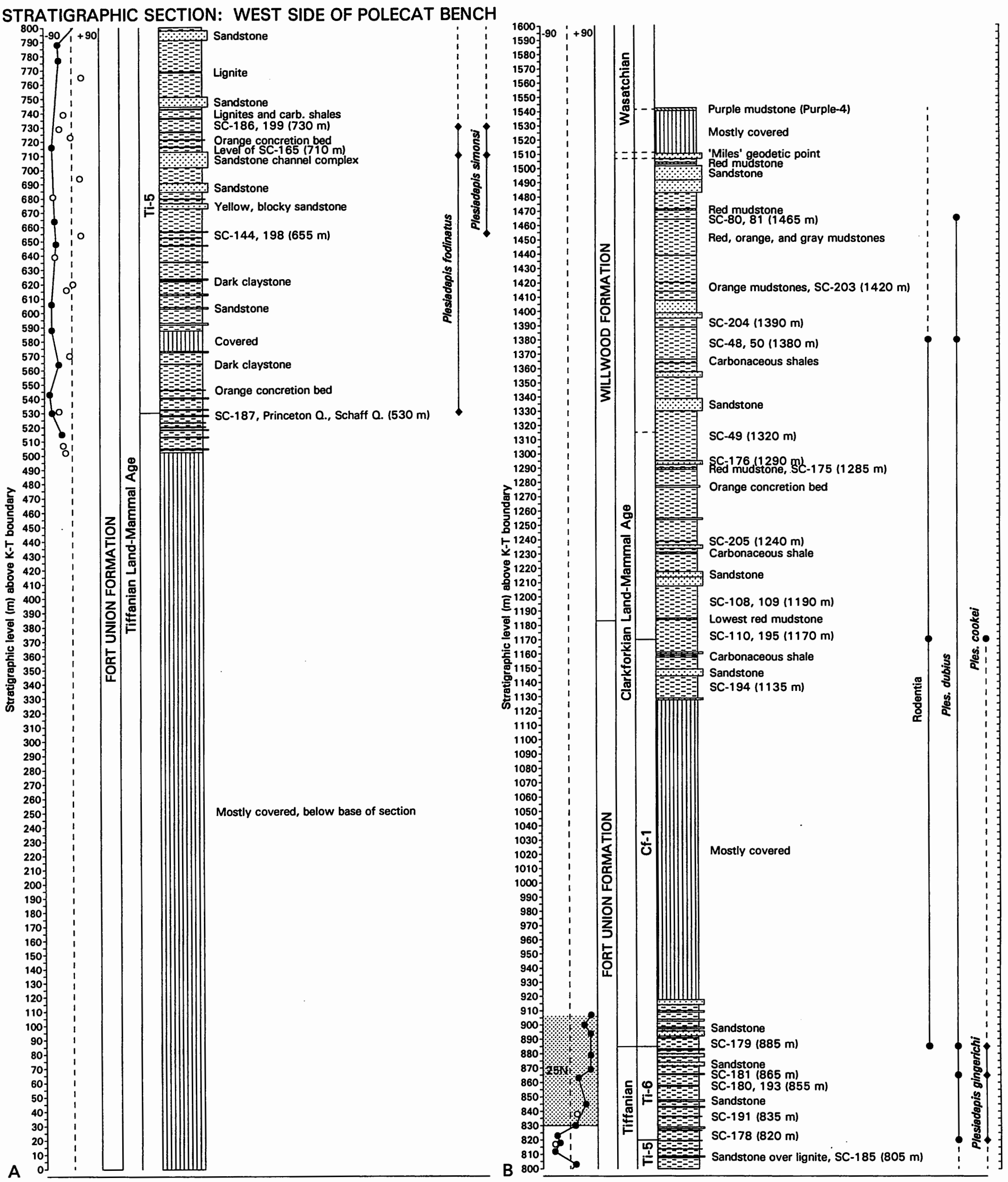

FIGURE 2 — Stratigraphic section of Tiffanian, Clarkforkian, and lower Wasatchian strata in the Fort Union and Willwood formations on the west side of Polecat Bench. Lithologies for the lower part of the section (column A and lower part of B) were recorded by E. H. Lindsay in connection with paleomagnetic sampling (Butler et al., 1981). Lithologies for the upper part of the section (upper part of column B) were recorded by the author and D. W. Krause. Stratigraphic ranges of index taxa are shown to the right of both columns, where solid figures indicate occurrences in this section: diamonds mark type sections for zones (see Table 1). Correlation to the southeast side of Polecat Bench (Fig. 3) is based on: (1) the base of magnetochron 25N; (2) the level of the lowest prominent red mudstone marking the base of the Willwood Formation; and (3) the level of the Purple-4 mudstone, which can be traced from the south end of the bench above SC-67 to a level above SC-80. Meter levels correspond to those in Fig. 3.

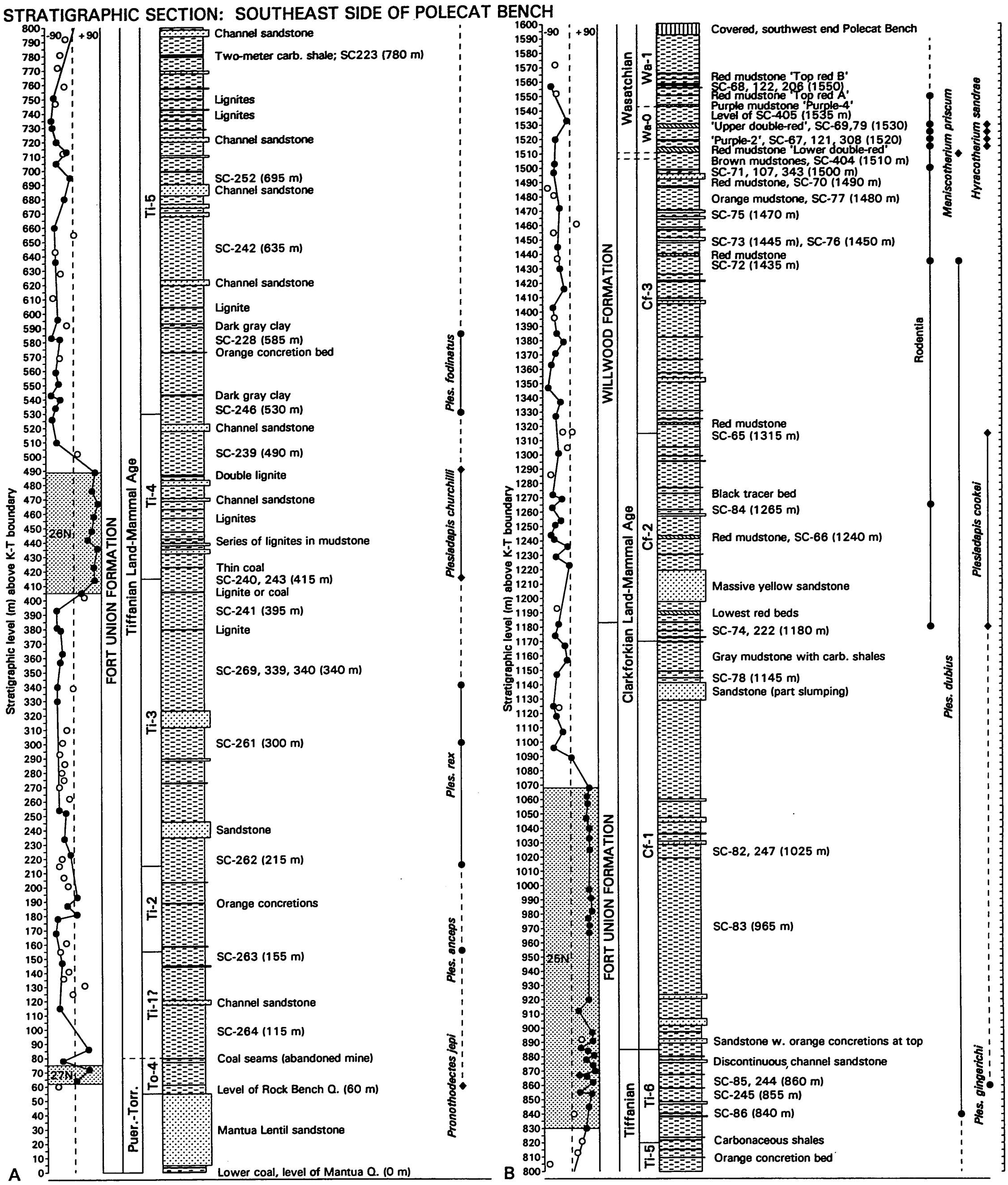

FIGURE 3 — Stratigraphic section of Puercan, Torrejonian, Tiffanian, Clarkforkian, and lower Wasatchian strata in the Fort Union and Willwood formations on the southeast side of Polecat Bench. Lithologies in both columns (A and B) were recorded by E. H. Lindsay and Y. Tomida in connection with paleomagnetic sampling (Butler et al., 1981). Stratigraphic ranges of index taxa are shown to the right of both columns, where solid figures indicate occurrences in this section: diamonds mark type sections for zones (see Table 1). Meter levels are measured above the Cretaceous-Tertiary (K-T) boundary. Thickness of the Fort Union part of the section here was measured by the author (Gingerich, 1968, 1976). Thickness of the Willwood part of the section was measured by the author and K. D. Rose.

TABLE 1 — Formal stratigraphic nomenclature of mammalian biozones spanning the Paleocene-Eocene boundary in northwestern Wyoming (following NACSN, 1983). Abbreviations: *LRD*, lowest range datum (equivalent to first appearance datum or FAD in type section); *HRD*, highest range datum (equivalent to last appearance datum or LAD in type section). Beginnings and ends of zones are defined by LRDs unless otherwise noted. Some ranges reported here differ slightly from those of Gingerich (2000) due to newly improved correlation across Polecat Bench.

Biozone Stratotype section	Author	LRD marking beginning of zone	LRD marking end of zone	Abbr.
Wasatchian land-mammal age (in part)				
Bunophorus etsagicus interval zone 380-530 m interval in Elk Creek section of Schankler, central Bighorn Basin [see Schankler, 1980, p. 103; *B. etsagicus* is present at the 2240 m level (locality SC-295) in South Rim section of Gingerich (1982a; for map see Gingerich and Klitz, 1985)]	Schankler (1980)	*Bunophorus etsagicus*	*Heptodon calciculus*	Wa-5
Hyracotherium pernix interval zone 2020-ca. 2200 m interval (localities SC-112, 113, 148, 255, 297, 253, 256, 265, 299, and 303) in South Rim section of Gingerich (1982a; for map see Gingerich and Klitz, 1985)	Gingerich (1983a, 1991)	*Hyracotherium pernix*	*Bunophorus etsagicus*	Wa-4
Hyracotherium aemulor interval subzone 1780-2020 m interval (localities SC-32, 224, 290, 33, 225, 236, 34, 314, 35, 36, 232, 63, 114, 3, 64, 111, and 254) in South Rim section of Gingerich (1982a; for map see Gingerich and Klitz, 1985)	Gingerich (1991)	*Hyracotherium aemulor*	*Hyracotherium pernix*	Wa-3b
Homogalax protapirinus interval subzone 1750-1780 m interval (localities SC-5, 309, 310, 87, 213,and 221) in Sand Coulee Divide section of Gingerich (1982a; for map see Gingerich and Klitz, 1985); also present (locality SC-133) in South Rim section of Gingerich (1982a; for map see Gingerich and Klitz, 1985)	Gingerich (1991)	*Homogalax protapirinus*	*Hyracotherium aemulor*	Wa-3a
Arfia shoshoniensis interval zone 1645-1750 m interval (localities SC-210, 54, 2, and 12) in Sand Coulee Divide section of Gingerich (1982a; for map see Gingerich and Klitz, 1985); also present (localities SC-47 and 46) in South Rim section of Gingerich (1982a; for map see Gingerich and Klitz, 1985)	Gingerich (1991)	*Arfia shoshoniensis*	*Homogalax protapirinus*	Wa-2
Cardiolophus radinskyi interval zone 1543-1645 m interval (localities SC-40, 142, 44, 17, 18, 16, and 37) in Sand Coulee Divide section of Gingerich (1982a; for map see Gingerich and Klitz, 1985); also present (localities SC-6, 4, and 129) in South Rim section of Gingerich (1982a; for map see Gingerich and Klitz, 1985)	Gingerich (1991)	*Cardiolophus radinskyi*	*Arfia shoshoniensis*	Wa-1
Hyracotherium sandrae interval zone 5-35 m interval in South Polecat Bench SC-67 section of this paper (ca. 1510-1543 m interval in Fig. 10; for map see Fig. 6)	Gingerich (1991)	*Hyracotherium sandrae*	*Cardiolophus radinskyi*	Wa-0
Meniscotherium priscum interval zone 6-10 m interval in South Polecat Bench SC-343 section of this paper (ca. 1506-1510 m interval in Fig. 9; for map see Fig. 6)	New	*Meniscotherium priscum*	*Hyracotherium sandrae*	Wa-0?
Clarkforkian land-mammal stage/age				
Phenacodus-Ectocion acme zone 1315-1506 m interval (localities SC-72, 73, 76, 75, 77, 70, 71, 107, 343) in Figure 3 (for maps Fig. 1 and Gingerich and Klitz, 1985)	Rose (1981)	*Plesiadapis cookei* (HRD)	*Meniscotherium priscum*	Cf-3
Plesiadapis cookei taxon range zone 1180-1315 m interval (localities SC-74, 65) in Figure 3 (for maps see Fig. 1 and Gingerich and Klitz, 1985)	Gingerich (1975, 1983a)	*Plesiadapis cookei*	*Plesiadapis cookei* (HRD)	Cf-2
Rodentia interval zone 885-1180 m interval (locality SC-179) in Figure 2 (for maps see Fig. 1 and Gingerich and Klitz, 1985)	Rose (1981)	Rodentia	*Plesiadapis cookei*	Cf-1

multistory sandstone interval, soon called the 'boundary sandstone,' that could be traced across much of the Clarks Fork Basin. The boundary sandstone was studied in detail by Kraus (1979, 1980), who found it to be 12-31 m thick and deposited by a meandering stream system, with paleocurrent directions indicating that the stream system flowed nearly due north. Kraus interpreted the boundary sandstone as indicating extensive reworking and selective preservation of coarser sediments, due to decreased basin subsidence and decreased rates of sediment accumulation at the end of the Clarkforkian and beginning of Wasatchian time.

Locality SC-67 was established in 1976, and the initial SC-67 collection included a specimen of *Hyracotherium* that showed the locality to be Wasatchian, but the species represented, *H. sandrae*, was not recognized as distinctive until later when a larger sample was available. The fauna at SC-67 was first recognized to be unusual because of the relative abundance of *Ectocion parvus*, a small species named by Granger (1915). Another species named by Granger, *Meniscotherium priscum*, was considered to be part of this fauna as well (Gingerich, 1982b). However, it was not until later, after the Wasatchian had been subdivided into zones Wa-1 through Wa-7 (Gingerich, 1983a), that the distinctiveness and importance of the SC-67 fauna were recognized (Gingerich, 1989). This required addition of a zone at the beginning of the Wasatchian sequence: hence the designation Wa-0.

TABLE 1 (cont.) — Formal stratigraphic nomenclature of mammalian biozones spanning the Paleocene-Eocene boundary in northwestern Wyoming (following NACSN, 1983). Abbreviations: *LRD*, lowest range datum (equivalent to first appearance datum or FAD in type section); *HRD*, highest range datum (equivalent to last appearance datum or LAD in type section). Beginnings and ends of zones are defined by LRDs unless otherwise noted. Some ranges reported here differ slightly from those of Gingerich (2000) due to newly improved correlation across Polecat Bench.

Biozone Stratotype section	Author	LRD marking beginning of zone	LRD marking end of zone	Abbr.
Tiffanian land-mammal stage/age				
Plesiadapis gingerichi interval zone 820-885 m interval (localities SC-178 and 181) in Figure 2 (for maps see Fig. 1 and Gingerich and Klitz, 1985)	Rose (1981)	*Plesiadapis gingerichi*	Rodentia	Ti-6
Plesiadapis simonsi lineage zone 655-820 m interval (localities SC-198, 165, 186) in Figure 2 (for maps see Fig. 1 and Gingerich and Klitz, 1985)	Gingerich (1975)	*Plesiadapis simonsi*	*Plesiadapis gingerichi*	
Plesiadapis fodinatus lineage zone 530-820 m interval (localities SC-187, 165, 186, 198) in Figure 2 (for maps see Fig. 1 and Gingerich and Klitz, 1985)	New	*Plesiadapis fodinatus*	*Plesiadapis dubius*	Ti-5
Plesiadapis churchilli lineage zone 415-530 m interval (localities SC-240, 243, 239) in Figure 3 (for maps see Fig. 1 and Gingerich and Klitz, 1985)	Gingerich (1975)	*Plesiadapis churchilli*	*Plesiadapis fodinatus*	Ti-4
Plesiadapis rex lineage zone Ca. 1500 m interval (locality GGS-13) of Hartman and Krause (1993): table 2 (for map see fig. 1, loc. cit.). Reference section: 215-415 m interval (localities SC-262, 261, 339) in Figure 3 (for maps see Fig. 1 and Gingerich and Klitz, 1985)	Gingerich (1975)	*Plesiadapis rex*	*Plesiadapis churchilli*	Ti-3
Plesiadapis anceps lineage zone Ca. 1170-1500 m interval (Scarritt Quarry) of Hartman and Krause (1993): table 2 (for map see fig. 1, loc. cit.). Reference section: 155-215 m interval (locality SC-263) in Figure 3 (for maps see Fig. 1 and Gingerich and Klitz, 1985)	Gingerich (1975)	*Plesiadapis anceps*	*Plesiadapis rex*	Ti-2
Plesiadapis praecursor lineage zone Ca. 1000-1170 m interval (Douglass Quarry) of Hartman and Krause (1993): table 2 (for map see fig. 1, loc. cit.)	Gingerich (1975)	*Plesiadapis praecursor*	*Plesiadapis anceps*	Ti-1
Torrejonian land-mammal age (in part)				
Pronothodectes jepi lineage zone Ca. 60 m interval (Rock Bench Quarry) in Figure 3 (for maps see Fig. 1 and Gingerich and Klitz, 1985)	Gingerich (1975)	*Pronothodectes jepi*	*Plesiadapis praecursor*	To-4
Pronothodectes gidleyi lineage zone Ca. 560 m interval (Gidley Quarry) of Hartman and Krause (1993): table 2 (for map see fig. 1, loc. cit.)	Gingerich (1975)	*Pronothodectes gidleyi*	*Pronothodectes jepi*	To-3

Meniscotherium has proven particularly interesting and, as outlined below, suggests that there is still more to learn about the Clarkforkian-Wasatchian transition.

PALEOCENE-EOCENE STRATIGRAPHY IN MAP VIEW

The stratigraphy of the south end of Polecat Bench is surprisingly complex when studied in detail, which has led at different times to confusion and error in labeling of stratigraphic units, in mapping of localities, in recording the total thickness of the earliest Wasatchian Wa-0 interval, and in tracing beds laterally (Gingerich, 1989). Development of a consistent interpretation enabling such errors to be corrected has required detailed mapping of a 2 km^2 study area. This is in a region of hilly topography with limited visibility from valley to valley, making accurate recognition of map positions difficult. Consequently, field mapping was carried out with a portable differential global positioning system offering meter- to near meter-scale precision and accuracy.

Mapping methods

The Differential global positioning system [DGPS] used here included a battery-powered Starlink Invicta® 210S ten-channel GPS receiver attached to a Starlink MBA-4 GPS/L-band helix antenna on a 2.5 m pole, with an At Work Computers© portable Ranger computer running Tripod Data Systems© SoloField-for-Windows-CE software (Version 2.1 beta). The differential signal was provided by OmniStar® satellite.

The GPS unit was calibrated using the U. S. National Geodetic Survey [NGS] Miles triangulation station approximately 4.5 km NW of the study area (44° 48' 04.88685" N latitude, 108° 54' 33.70222" W longitude, and 1596.7 m elevation; *fide* U.S. National Geodetic Survey at http://

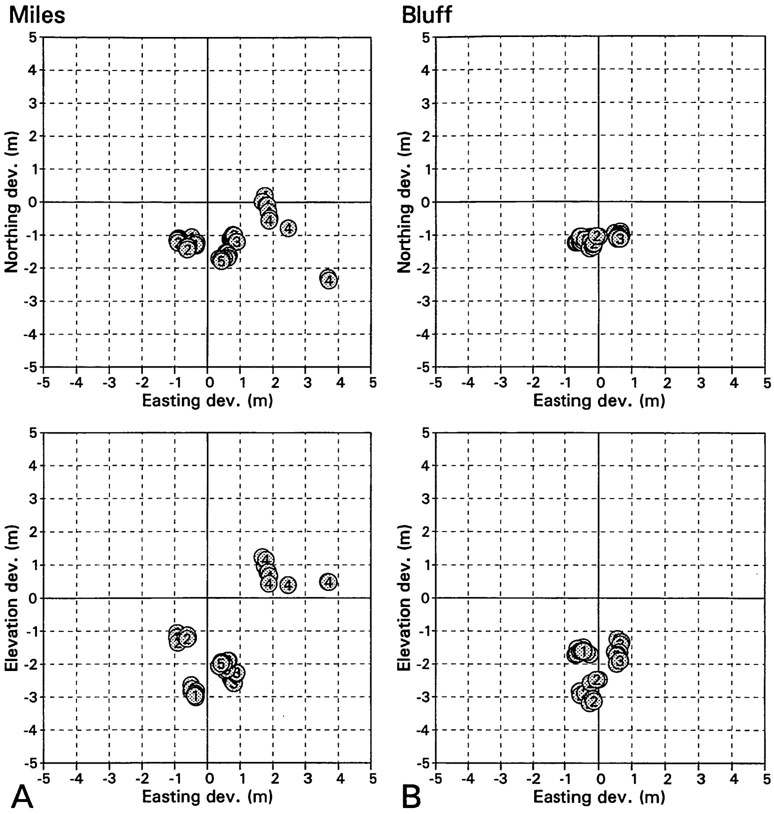

FIGURE 4 — Test of precision and accuracy of the differential global position system (DGPS) used to map strata at the south end of Polecat Bench. A, results for National Geodetic Survey station Miles (open triangle in Fig. 1): this is the point used for calibration of the DGPS unit. B, results for National Geodetic Survey station Bluff (open triangle in Fig. 1). All panels are ten meters on a side, with the known (and hence, here, expected) value of the easting, northing, and/or elevation of a recording falling at the center of the panel (known values are taken from http://www.ngs.noaa.gov/cgi-bin/ds_quads.prl). The upper panel in each test shows recorded points plotted in map view, with north at the top. Lower panel in each test shows recorded points plotted in a corresponding elevation view. Each record plotted here mimics a station used in mapping in being the average of 10 or more successive DGPS measurements ('epochs'), and each test included 10 records spaced about a minute apart (each cluster includes 10 records). Cluster 1 was recorded on 28 June 2000; 2 was recorded on 30 June 2000; 3 was recorded on 12 July 2000; 4 was recorded on 17 September 2000 (Miles only); and 5 was recorded on 20 September 2000 (Miles only). Note that clusters 1, 2, 3, and 5 together fall within a cube about two meters on a side, indicating near meter-scale precision, both at the calibration site and at the independent site. Cluster 4 fills a larger 3 or 4-meter volume centered several meters from the tighter clusters, showing that there are times when DGPS exceeds meter-scale precision. All of the more precise results are about 1 m south and 2-3 m lower in elevation than expected, indicating a systematic inaccuracy of unknown cause.

www.ngs.noaa.gov/cgi-bin/ds_quads.prl). Zone file settings included NADCON projection, NAD83 horizontal datum, ellipsoid elevation, and WGS84 vertical datum. The study area is in Universal Transverse Mercator zone 12, and all coordinates were recorded in meters on orthogonal UTM easting, northing, and elevation axes. Note that the horizontal datum used here, NAD83, is *not* the NAD27 datum of available USGS topographic maps (see below). Minimally 10 measurements (epochs) were averaged for each map station recorded, and the maximum acceptable horizontal dilution of precision (HDOP) was 2.0.

DGPS accuracy and precision

Differential GPS accuracy and precision were tested by recording three-dimensional coordinates of known points 10 times each during three successive visits spanning the duration of field work. Known points used were (1) the original Miles calibration point 4.5 km NW of the study area, and (2) the Bluff calibration point 12 km N of the study area, both on the west side of Polecat Bench (Fig. 1). Known coordinates of these points are provided at the NGS web site mentioned above. Results of the successive tests are shown graphically in Figure 4.

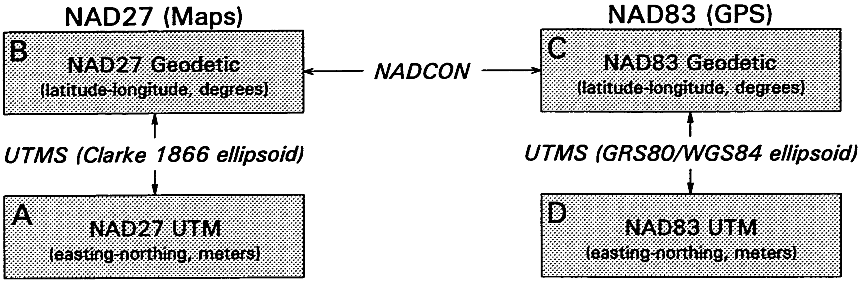

FIGURE 5 — Protocols required for transformation of North American Datum NAD27 geographic coordinates to NAD83 and vice versa. Geodetic coordinates (latitude and longitude recorded in degrees) can be converted from NAD27 to NAD83 or NAD83 to NAD27 in a single transformation step using publically-available NADCON software (Dewhurst et al., 1992; NADCON is the U.S. Federal standard for NAD27 to NAD83 transformations). Transformation of UTM coordinates is more complicated, with three steps required to convert NAD27 UTM to NAD83 UTM or vice versa. Transformation of datums can only be done in a geodetic framework, which means that NAD27 UTM must be converted to NAD27 Geodetic or NAD83 UTM must be converted to NAD83 Geodetic to start this tranformation. Recovery of UTM coordinates following transformation of datums requires conversion from Geodetic to UTM. UTM-Geodetic conversions can by made using publically-available UTMS software (Carlson and Vincenty (1993). UTMS works on either ellipsoid (Clarke 1866 ellipsoid of NAD27 or GRS80/WGS84 ellipsoid of NAD83) and it works in both directions (from UTM to Geodetic and vice versa). Stated simply with reference to the diagram here, B and C can be transformed in one step using NADCON. Transformation from A to D (or D to A) requires three steps passing through B and C, using UTMS, then NADCON, then UTMS again.

In each panel of Figure 4, coordinates for a particular series of ten measurements are represented by spheres labeled 1, 2, 3, 4, or 5, representing the visit number. Short-term precision is high and in most cases spheres of the same number in a panel generally fall within a meter of each other (with the exception of visit 4 at Miles). Short-term accuracy is a little lower and eastings vary within about ±1 m of expectation, northings are generally 1.0-1.5 m less than expectation, and elevations vary from about 1.0 to 3.0 m below expectation (again excepting visit 4 at Miles). Long-term precision is lower as all spheres in a panel taken together appear to fall within about two to three meters of each other. Long-term accuracy is approximately the same as short-termaccuracy: at both test localities eastings appear unbiased, northings are generally about 1 m less than expectation, and elevations are generally about 1 to 3 m less than expectation.

In this study, such near meter-scale accuracy is comparable to the accuracy or inaccuracy of determining horizontal outcrop limits of strata to be measured. However, meter- or near meter-scale accuracy is comparable to the vertical thickness of many of the stratigraphic units of interest here, and DGPS is not an adequate substitute for direct measurement of bed thicknesses in stratigraphic sections (note that use of DGPS to determine bed spacing in Figure 12 is constrained by the thickness of a comparable interval in an adjacent section).

NAD27 and NAD83 conversion

Simultaneous use of two different geodetic datums means that information registered on U. S. Geological Survey topographic maps (using the NAD27 geodetic datum) cannot be combined with information derived from the global positioning system (GPS or DGPS, using the NAD83 datum) without transformation. This is true for information recorded in geodetic coordinates (latitude and longitude), which require a single transformation step, as well as UTM zone coordinates (easting and northing in meters), which require three distinct transformation steps. The conversion procedure is illustrated in Figure 5. Software in the public domain is available to carry out the transformations. The two programs required are NADCON (Dewhurst et al., 1992; the NADCON algorithm is a U.S. government standard for NAD27 to NAD83 transformations), and UTMS (Carlson and Vincenty, 1993).

Registration on topography

Registration on topography provides an alternative to transformation of NAD83 GPS coordinates and NAD27 map coordinates. Fossil localities, distinctive geological strata, faults, and other features of interest were recorded in the field using DGPS (NAD83). These were then plotted at the same scale as the topographic base map being used (NAD27), and the two maps were superimposed and registered using topography. Outcrop limits encircling hills are particularly useful for registration.

Marker beds used for mapping were chosen on the basis of their identifiability, visibility, and to some extent their accessibility. Then an attempt was made to map marker beds using as many control points as possible. However, paleosols at the south end of Polecat Bench are commonly covered with spherical calcareous nodules, making them slippery, and many outcrop slopes are simply too steep to climb. Marker beds could

TABLE 2 — Bedding-plane orientation of key marker beds in the Paleocene-Eocene transition at the south end of Polecat Bench. Orientations were computed separately for seven local areas: SC-80, SC-206, etc., here listed from north to southwest to east, wrapping around the end of the bench. Within areas, beds are listed in stratigraphic sequence. Note: (1) systematic change of strike from east to west here (ignoring the bed above SC-80), circumscribing a shallow syncline at the southwest corner of Polecat Bench; (2) substantial variation in computed strike values, even within the same area, due to error associated with low dips (and possibly differential compaction of anisotropic sediments); and (3) consistently low dip values in the range of 1.5° to 3.2° (median at SC-67 is ca. 2.0° SW). Purple-4 bed near SC-80 was used to link the tops of the stratigraphic sections shown in Figs. 2 and 3.

Bed	Number of points	b_0	b_1	b_2	Strike	Dip
Above SC-80						
Purple-4	10	-129.2460	0.0140	0.0261	N 61.8° W	1.7° SW
SC-206 and vicinity						
Top Red-B	41	-176.3453	-0.0208	0.0253	N 50.5° E	1.9° SE
Top Red-A	43	-265.9125	-0.0341	0.0342	N 45.0° E	2.8° SE
Purple-4	18	-107.5272	-0.0284	0.0307	N 47.2° E	2.4° SE
Above SC-70						
Lower Boundary Sandstone	14	24.0704	-0.0264	0.0277	N 46.4° E	2.2° SE
SC-121 and vicinity						
Lower Boundary Sandstone	30	-167.7362	-0.0097	0.0291	N 71.5° E	1.8° SSE
SC-308 and vicinity						
Lower Boundary Sandstone	32	-782.2860	0.0295	0.0349	N 49.8° W	2.6° SW
SC-67 and vicinity						
Purple-4	13	166.3733	0.0239	0.0198	N 39.6° W	1.8° SW
Upper Double-Red (top)	23	490.5610	0.0283	0.0135	N 25.5° W	1.8° SW
Upper Double-Red (base)	20	119.2739	0.0262	0.0200	N 37.3° W	1.9° SW
Purple-2	44	-751.3870	0.0242	0.0349	N 55.3° W	2.4° SW
Lower Double-Red (top)	14	-1840.5437	0.0110	0.0550	N 78.7° W	3.2° SW
Lower Double-Red (base)	23	228.0517	0.0332	0.0170	N 27.1° W	2.1° SW
Brown mudstone series (top)	16	-132.6727	0.0333	0.0231	N 34.8° W	2.3° SW
Ledge sandstone	80	2.4455	0.0133	0.0233	N 60.3° W	1.5° SW
SC-343 and vicinity						
Brown mudstone series (top)	23	-324.9102	0.0179	0.0284	N 57.8° W	1.9° SW
Purple-0	29	-121.5387	0.0462	0.0211	N 24.6° W	2.9° SW

only be mapped in the field where they could be reached. Mapping was necessarily completed in the laboratory by interpolation after known points on each bed were superimposed and registered on the topographic base map. Interpolation could then be constrained by following contour lines on the underlying topography.

Map of the South End of Polecat Bench

A detailed map of Paleocene-Eocene stratigraphy at the south end of Polecat Bench is shown in Figure 6. The principal area of interest is in Section 10, T55N, R100W, Park County, Wyoming, on U.S. Geological Survey 1:24,000 scale Elk Basin SW and Elk Basin SE 7.5-minute topographic quadrangles. Both were published in 1966. Stratigraphic mapping was plotted on topography at a scale of 1:12,500, and the map in Figure 6 is reproduced at a scale of ca. 1:15,000. Topography ranges in elevation from about 4700 to 5200 ft (1430 to 1580 m) above sea level, with a 20 ft contour interval on the base map. Vertebrate fossil localities numbered on the map are all University of Michigan 'Sand Coulee' localities: e.g., 67 represents locality SC-67, etc.

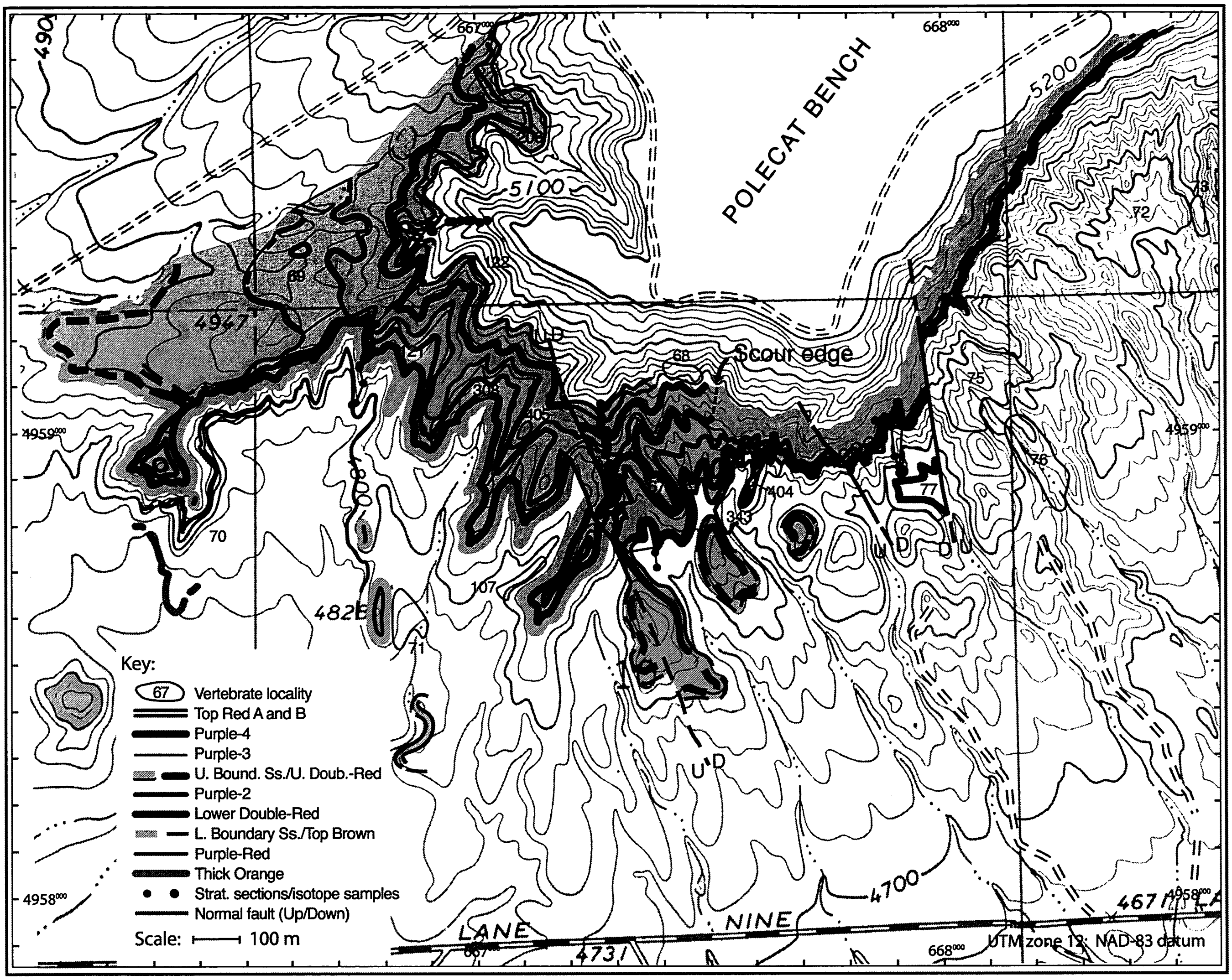

FIGURE 6 — Detailed geological map of the south end of Polecat Bench showing the positions of mammal-bearing fossil localities, the principal marker beds of interest here, the traces of measured stratigraphic sections, the locations of isotope samples, and normal faults displacing strata. All were mapped using a differential global positioning system and are registered on topography of U. S. Geological Survey 7.5' topographic quadrangles Elk Basin SE and Elk Basin SW. Note the presence of Lower and Upper Boundary Sandstones enclosing Wa-0 localities SC-69, SC-121, SC-308, and the western part of SC-67 on the west half of the map. These boundary sandstones are missing east of the western pair of faults in the middle of the map. A distinct ribbon sandstone near the base of SC-67 just east of the western pair of faults has long been confused with the Lower Boundary Sandstone. Two thick scour-fill sandstones in the upper part of the section east of the point labeled scour edge have long been confused with the Upper Boundary Sandstone.

Faults

Four faults were mapped that disturb strata to a significant degree (Fig. 6). These are all normal faults trending NNW-SSE. The two westernmost faults are approximately aligned and undoubtedly developed together. Both dip steeply to the ENE. Vertical displacement is minimal where the two overlap, and displacement increases to some 5-10 m both north and south of this. Hence the two are possibly manifestations of a single NNW-SSE-trending scissors fault. Neither has been traced farther than is shown on the map, and the northern of the two faults appears not to cut strata in the vicinity of locality SC-206. The third fault, more centrally located, dips steeply to the ENE and has a displacement of ca. 10 m. The easternmost fault is the most conspicuous. It dips steeply to the WSW and has a displacement of ca. 20 m. Taken together the four faults indicate development of a 0.7-0.8 km wide, shallowly down-dropped block or graben directly south of the south end of Polecat Bench.

Folding

All strata at the south end of Polecat Bench are shallowly dipping, with dips ranging from 1.5 to 3.2° relative to horizontal. Dips such as these are too great to ignore, but are very difficult to measure with handheld instruments in the field. DGPS mapping of the outcrop traces of strata in an area yields a set of points that can be used to determine bedding planes. Here equations of best-fit planes were determined by least-squares (Davis, 1986, p. 406), using differentially-corrected, three-dimensional, metric GPS coordinates of points recorded in the field for each bed in each area. Beta values (b) are the constant, easting coefficient, and northing coefficient, respectively, where $Z = b_0 + b_1 \cdot X + b_2 \cdot Y$ is the equation of the plane (planes were fit to UTM easting and northing coordinates stripped of their leading 66 and 49, respectively, to simplify computation). Strike and dip were calculated analytically from the beta values. Results are listed in Table 2. Note that there is a systematic change of strike from west to east across the study area, starting with a strikes of ca. N 45° E at SC-70 and SC-206 in the west and ending with strikes of ca. N 45° W at SC-343 in the east, circumscribing a shallow syncline at the southwest corner of Polecat Bench just west of the faulted graben.

Boundary sandstones

As outlined above, our efforts in the 1970s to clarify the existence and meaning of the Clarkforkian land-mammal age (Rose, 1981) led us to focus attention on the major multistory sheet sandstone marking the boundary between the Clarkforkian and Wasatchian land-mammal ages in the Clarks Fork Basin. Simultaneous discovery of the dawn horse *Hyracotherium* at locality SC-67 at the southwestern end of Polecat Bench, above strata yielding *Plesiadapis* and other typically Clarkforkian taxa, suggested the presence of a Clarkforkian-Wasatchian boundary sandstone at the base of SC-67. As Wa-0 mammals were found at other localities in the Clarks Fork Basin it became clear that these were coming from mudstones *within* the boundary sandstone unit. However, extension of this idea to the most productive Wa-0 locality, SC-67, led to confusion. The conspicuous sandstones at the base and top of SC-67 are now demonstrably not the same as the lower and upper boundary sandstone units exposed below and above a western extension of SC-67, below and above localities SC-308 and SC-121 to the north and west of SC-67, and below and above Wa-0 localities in the Clarks Fork Basin proper even farther to the north and west.

The lower boundary sandstone west of SC-67 is a major ridge-forming, 2-3 m thick, yellow, medium-to-coarse-grained sandstone (see SC-121 stratigraphic section below). The lower boundary sandstone is well exposed above late Clarkforkian localities SC-70, SC-71, and SC-107, and it is well exposed below Wa-0 localities SC-121 and SC-308. It is the lower channel sandstone in figure 6B of Kraus (1987, p. 608). The lower boundary sandstone is not found south of SC-71, nor is it found in SC-67 proper east of the western pair of faults in Figure 6.

The upper boundary sandstone west of SC-67 is also a major ridge-forming sandstone. It is a ca. 7 m thick, yellow, fine-to-medium-grained sandstone (see SC-121 stratigraphic section below). The upper boundary sandstone is well exposed above the western extension of SC-67, and above SC-121 and SC-308. Locality SC-405 is developed within the upper boundary sandstone, near its base where there is a lag of coprolites, reptilian and mammalian bones, and occasional mammalian teeth. The upper boundary sandstone is the upper channel sandstone in figure 6B of Kraus (1987, p. 608). This unit is not found east of the western pair of faults in Figure 6, and it appears to thin and disappear where it is exposed above locality SC-69.

The lower and upper boundary sandstones are correctly labeled in Figure 7 of Gingerich (1989, p. 14). They are parts of the major sheet sandstone complex described by Kraus (1980; for more on sheet sandstones see Kraus 1996, 1997, and this volume), and they appear to have been deposited by meandering channels of trunk rivers, which generally flowed to the north paralleling the structural axis of the developing basin (Kraus, this volume). It may be fortuitous that the eastern edge of both sheet sandstones coincides with the line formed by the western pair of faults mapped in Figure 6, or faulting may have been controlled by the edge of the sheet sandstones.

Ribbon sandstones

Ribbon sandstones may be similar in thickness to major sheet sandstones, but these are less extensive laterally and they are generally finer-grained. One ribbon sandstone at the southwestern corner of SC-67 (Fig. 6) is of particular interest because it has long been misidentified as representing an eastward extension of the lower boundary sandstone. The sandstone is 0.8 to 2.6 m thick, counting 1.8 m of thickness cut into the underlying red mudstone of Lower Double-Red A (see SC-67 stratigraphic section below). It is yellow, and very-fine-grained. The ribbon-like geometry of the unit is masked because it is principally exposed where it is cut longitudinally by erosion. This sandstone is labeled 'top of boundary sandstone' at the base of the SC-67 stratigraphic section of Badgley (Gingerich, 1989, p. 13). However, the ribbon sandstone is separated from the lower boundary sandstone by the westernmost of the western pair of faults mapped in Figure 6. It is transected by a valley, revealing that it is ribbon-like rather than sheet-like in cross-section. Further, it is stratigraphically above the Top Brown Mudstone to sandstone to Lower Double-Red A sequence that marks the lower boundary of Wa-0 here and elsewhere (see SC-67 stratigraphic section below). This particular ribbon sandstone cuts across a sequence of mudstones with well-developed, brightly-colored paleosols (see below).

Scour-fill sandstones

The sandstone taken to be the upper boundary sandstone north and east of locality SC-67 (marked by arrows in figure 5 of Gingerich, 1989, p. 12) is now recognized to be the higher

FIGURE 7 — Photograph of the South Polecat Bench SC-77 stratigraphic section at and just above locality SC-77. The Thick Orange marker bed occurs near the base of the section. The purplish red mudstone, red mudstones, Purple-0, and Lower Double-Red marker beds are present in the lower part of the section, capped by sandstones and drab mudstones of the scour-fill sequence higher up on the side of Polecat Bench. The Paleocene-Eocene boundary marked by the beginning of the carbon isotope excursion (ca. 1500 m level in the Polecat Bench master section) occurs in the interval marked P-E?.

of two sheet-like sandstones in a sequence of drab sediments filling a major erosional scour. The scour surface extends eastward and northeastward for a kilometer from the mapped scour edge shown in Figure 6. The lower of the sheet-like sandstone units is a 7-14 m thick, fine-to-medium-grained, yellow sandstone (see top of SC-77 stratigraphic section below). It has an erosional base, with a ca. 50 cm thick lag of reworked soil nodules in many places. Paleosols in the scour fill sequence are immature, and the whole scour appears to have been filled rapidly, probably during a sequence of channel avulsions (see Kraus, 1996, this volume).

The depth of this major erosional scour can be estimated by comparing the SC-77 and SC-67 stratigraphic sections shown below. The base of the scour-fill sandstone at the top of the SC-77 section lies some 2 m above the top of marker bed Purple-2. The lowest bed in the SC-67 section that can be traced across the top of the scour-fill sequence is Top Red A, meaning that all beds between the 15 and 40 m levels in the SC-67 section were removed by erosion. Thus the depth of the scour was approximately 25 m, which provides an estimate of local relief before the scour was filled.

Key marker beds

Most of the distinctive bright-colored sediments exposed at the south end of Polecat Bench are what Kraus (1996, 1997, this volume) terms mature cumulative paleosols, meaning that they were built up (accumulated) slowly in a long succession of many flooding episodes. This contrasts with the immature avulsive paleosols in the scour fill just mentioned, which were deposited much more rapidly in relatively few events. Key marker beds used for mapping are listed in the key to Figure 6, and all of the key marker beds (including some not mapped in Fig. 6) are described here from stratigraphically lowest to highest (oldest to youngest). Sections including these marker beds are described and illustrated below.

Thick Orange mudstones. The lowest marker bed mapped here is a distinctive 2-m thick sequence of orange mudstones. These are best exposed at the base of the SC-77 section in locality SC-77 itself at the eastern margin of the mapped area (Fig. 7). The Thick Orange mudstones are also well exposed just west and south of SC-70 at the western margin of the mapped area. The lower beds in the sequence of interest here are mostly covered and the orange mudstones have not been observed between SC-77 and SC-70.

Purple-Red mudstone. The Purple-Red mudstone mapped here marks the top of locality SC-70. This can be traced eastward to the base of the SC-121 section, and then southward to a level below SC-71 where it disappears. The Purple-Red mudstone may correspond to the red mudstones at the 14-16 m level in the SC-77 section, but this cannot be confirmed by tracing beds.

Purple-0. Purple-0 is a red to purple marker bed (Fig. 7) that can be traced from the SC-77 section westward to the SC-343 section. It occurs at the base of a sequence of 4-5 predominantly brown paleosols that were formerly thought to be Clarkforkian in age but yield abundant endocarps of characteristically Wasatchian *Celtis phenacodorum* and the mammalian condylarth *Menisotherium priscum.*

Top Brown mudstone. The Top Brown mudstone is the highest of the 4-5 predominantly brown paleosols just mentioned. This can be traced from the SC-77 section westward to the SC-343 section and on to the SC-67 section. North and west of SC-67 the Top Brown mudstone (and possibly some of the other brown mudstones underlying this) are removed by erosion and replaced by the Lower Boundary Sandstone described above.

Lower Double-Red mudstones. Some 2 m above the Top Brown mudstone is a much thicker pair of reddish orange to red mudstones (Fig. 7). The lower of these is called Lower Double-Red A and the higher Lower Double-Red B. The top of Lower Double-Red B is sometimes purple and represents a Purple-1 marker bed (not used here). Both of the lower double red mudstones can be traced from SC-77 westward to SC-343. The higher of the lower double reds is cut out by the ribbon sandstone at SC-67 described above, but the lower part of the unit is present. The lower double red mudstones are represented as a single thick red mudstone unit at SC-121. This single thick red mudstone unit is the lower of the stage-4 paleosols in the figure 6B stratigraphic section described by Kraus (1987, p. 608).

Purple-2 mudstone. The most laterally-extensive marker bed at the south end of Polecat Bench is the Purple-2 marker bed. This can be traced continuously from the eastern edge of the mapped area, where it occurs just below the major scour surface, to the western edge of the mapped area, where it encircles the low peak above locality SC-70. There are other purple beds that can be confused with Purple-2, but it is the only prominent purple bed lying in between the Lower Double-Red and the Upper Double-Red marker beds. Purple-2 illustrates too the importance of physically tracing marker beds because it was earlier thought to be three distinct beds and it is represented at three levels in the stratigraphic section previously published for SC-67 (Gingerich, 1989, p. 13). The lower 'maroon brown' unit at the 1-m level, the wash site at the 7-m level, and the *Coryphodon* at the 13-m level all represent the same Purple-2 marker bed at different places in SC-67. This reddish-purple to purple mudstone unit is the middle stage-4 paleosol in the figure 6B stratigraphic section described by Kraus (1987, p. 608).

Upper Double-Red mudstones. The Upper Double-Red mudstones are similar in appearance to the Lower Double-Red mudstones described above, and the two are easily confused if not traced carefully and considered in relation to Purple-2. Here again, the lower unit is called Upper Double-Red A and the higher is called Upper Double-Red B. Both Upper Double-Red mudstones were completely removed by the major scour above and to the east of SC-67. The higher part of the Upper Double-Red mudstones is replaced by the Upper Boundary Sandstone west of the western pair of faults running through SC-67, and Upper Double-Red A is mapped as a unit with the upper boundary sandstone where the two occur together. Upper Double-Red A is the highest of the stage-4 paleosols in the figure 6B stratigraphic section described by Kraus (1987, p. 608).

Purple-3 mudstone. Purple-3 is a thin but conspicuous purple mudstone overlying the Upper Double-Red mudstones above SC-67. This unit marks the upper limit of the locality both geographically and stratigraphically. It is probably more or less correlative with the SC-405 level in the upper boundary sandstone, and together these appear to mark the stratigraphic upper limit of the Wa-0 mammalian fauna and the transition to a Wa-1 fauna. Purple-3 is truncated by the major scour surface east of SC-67, and it is replaced by the upper boundary sandstone west of SC-67.

Purple-4 mudstone. The thickest and most conspicuous purple mudstone at the south end of Polecat Bench is the Purple-4 mudstone. It is missing east of SC-67, where it was removed by the major scour event. Above SC-67 the unit is on the order of 1 m thick, and the color is a genuine grayish-red purple on a freshly fractured surface, as contrasted with the grayish red mudstones that weather purple found lower in the section. This bed can be traced from the scour edge above SC-67 westward to the western pair of faults, where it is offset. Then it can be traced northward above SC-405, SC-308, and SC-121, and then to a position below SC-206 (Fig. 6). Purple-4 can be traced farther northward on the west side of Polecat Bench to a point east of SC-80 (Fig. 1), where it provides an important tie at the 1541-1542 m level between stratigraphic sections on the west and east sides of Polecat Bench (Figs. 2-3).

Purple-4 is interesting too because it appears to line up stratigraphically with the top of the upper of the two sheet-like sandstones in the scour fill sequence east of SC-67. Hence the unusual maturity of Purple-4 as a paleosol may reflect oxidation during the time the section east of SC-67 was scoured and filled. Details of bedding contact between laterally-equivalent cumulative and avulsion facies at the scour edge are unfortunately obscured by erosion and slumping.

Top Red A mudstone. The Top Red A mudstone is the first prominent red bed above Purple-4. It is well exposed above SC-67 and it is important because it can be traced eastward across the top of the scour and fill sequence east of SC-67. This constrains the time of scouring and filling to lie between the time of deposition of the Purple-4 and the Top Red A mudstones. Top Red A can be traced westward to the western pair of faults, where it is offset, and then it can be traced north and east around the south end of Polecat Bench to SC-206 where it is one of the lower beds yielding fossils in that locality. SC-68 and SC-122 were not located precisely relative to marker beds when they were first collected, but their mapped positions suggest that they were developed on Top Red A. SC-68, SC-122, and SC-206 all yield Wa-1 faunas (see below).

Top Red B mudstone. The Top Red B mudstone is a slightly thinner red mudstone, also prominent, that is found above SC-67. Tracing this eastward, it is replaced by a thin channel or ribbon sandstone that is at approximately the same level as a carbonaceous shale above the scour and fill sequence farther to the east. Tracing Top Red B westward, it parallels Top Red A all the way to SC-206, where it is one of the higher beds yielding Wa-1 fossils.

Fossil localities

Eighteen mammal-bearing fossil localities are shown in Figure 6. Four of these (SC-72, SC-73, SC-75, and SC-76) are late Clarkforkian localities east of the study area and older than any considered in detail here (see Fig. 3). Five Clarkforkian localities are of interest here: SC-70, SC-71, SC-77, SC-107, and SC-343. Earliest Wasatchian localities include SC-404 that is stratigraphically lower than most Wa-0 localities, and SC-67, SC-69, SC-121, and SC-308 that yield a typical Wa-0 fauna. SC-405 may be the lowest Wa-1 locality, although it has not yielded a large fauna. SC-68, SC-122, and SC-206 all yield typical Wa-1 mammals. Faunas from the latter fourteen fossil localities are discussed in a following section on biotic change.

PALEOCENE-EOCENE STRATIGRAPHY IN VERTICAL SECTIONS

Five stratigraphic sections were measured at the south end of Polecat Bench, and stable isotopes were sampled from four of these (Bowen et al., this volume). Colored circles in Figure 6 show the positions of isotope samples, while solid circles show the trace of lithological sections (where these are different). The easternmost and lowest stratigraphic section was measured in the vicinity of locality SC-77. A second stratigraphic section was measured in the vicinity of SC-343. It duplicates part of the SC-77 section, and both are capped by the same scour-and-fill interval of drab avulsion sediment. The third stratigraphic section starts below and ends above locality SC-67. This supercedes and replaces the SC-67 section published previously (Gingerich, 1989, p. 13), with notable improvements due to more careful mapping and tracing of marker beds. The fourth stratigraphic section was measured in the vicinity of SC-121. This is a lateral equivalent of the SC-67 section, but no isotope samples were taken in the SC-121 section. The stratigraphic section in figure 6B of Kraus (1987, p. 608) was measured on the west side of locality SC-405, about half way between the SC-67 and SC-121 sections described here. Finally, the fifth stratigraphic section is effectively a continuation of the SC-121 section, and consists of a series of superposed isotope samples taken at the SC-206 end of the study area to extend sampling higher than is possible above SC-67.

The SC-77, SC-343, SC-67, and SC-121 sections were measured with a Jacob's staff and Abney level, starting at the base of the section and working up to the top. Lithological descriptions and colors were recorded as each section was measured. In the SC-206 section only the lithologies and colors of sampled paleosol horizons were recorded. The spacing of beds in the SC-206 section is based on positions and elevations determined by differential GPS and the calculated perpendicular height of each isotope site above the plane of the Purple-4 mudstone (rescaled slightly to match the Purple-4 to Top Red B thickness measured by leveling in the SC-67 section).

SC-77 Stratigraphic Section

The SC-77 stratigraphic section is illustrated diagrammatically in Figure 8. It is 50 m thick, starting in upper Clarkforkian strata and ending in lower Wasatchian strata. The predominant 'background' lithology is gray mudstone (colors are described in appendix Table A1). The Thick Orange mudstones mentioned above as key marker beds are exposed in locality SC-77 in the 2-4 m interval near the base of the section. Red mudstones possibly correlative with the Purple-Red mudstone marker bed exposed above SC-70 are found 14-16 m above the base of the section. Purple-0 lies in the 25-26 m interval here. This is overlain by the brown paleosol sequence in the interval from 27-31 m, with the Top Brown marker bed present at the top of the sequence. Lower Double-Red beds A and B are well exposed in the interval from 32-35 m above the base of the section. Purple-2 is thick here, spanning the interval from about 39-41 m. The section is truncated by the major scour-and-fill sequence, beginning at 43 m above the base of the section. Descriptions of these key marker beds and other notable beds are recorded in Figure 8, with their corresponding fresh colors. The positions of in situ paleosol soil nodules sampled for carbon and oxygen isotopes are shown at the right of the lithological column in Figure 8, yielding samples numbered from 2-8 and from 10-24 (see Bowen et al., this volume).

One mammal-bearing fossil locality, SC-77 itself, lies within the SC-77 section. This yields a late Clarkforkian fauna (Cf-3; see below), principally from gray mudstones just below the Thick Orange mudstone interval. The levels of two other nearby fossiliferous localities, SC-343 and SC-404, can be correlated with this section by tracing beds laterally. The base of the SC-77 section shown in Figure 8 is at about 1479.5 m above the Cretaceous-Tertiary boundary in the master Polecat Bench section, as measured on the southeast side of Polecat Bench (Fig. 3). This means that Purple-0 is at about the 1505 m level, the base of the Wa-0 interval is at about the 1510 m level, Purple-2 is at about the 1520 m level, and the base of the

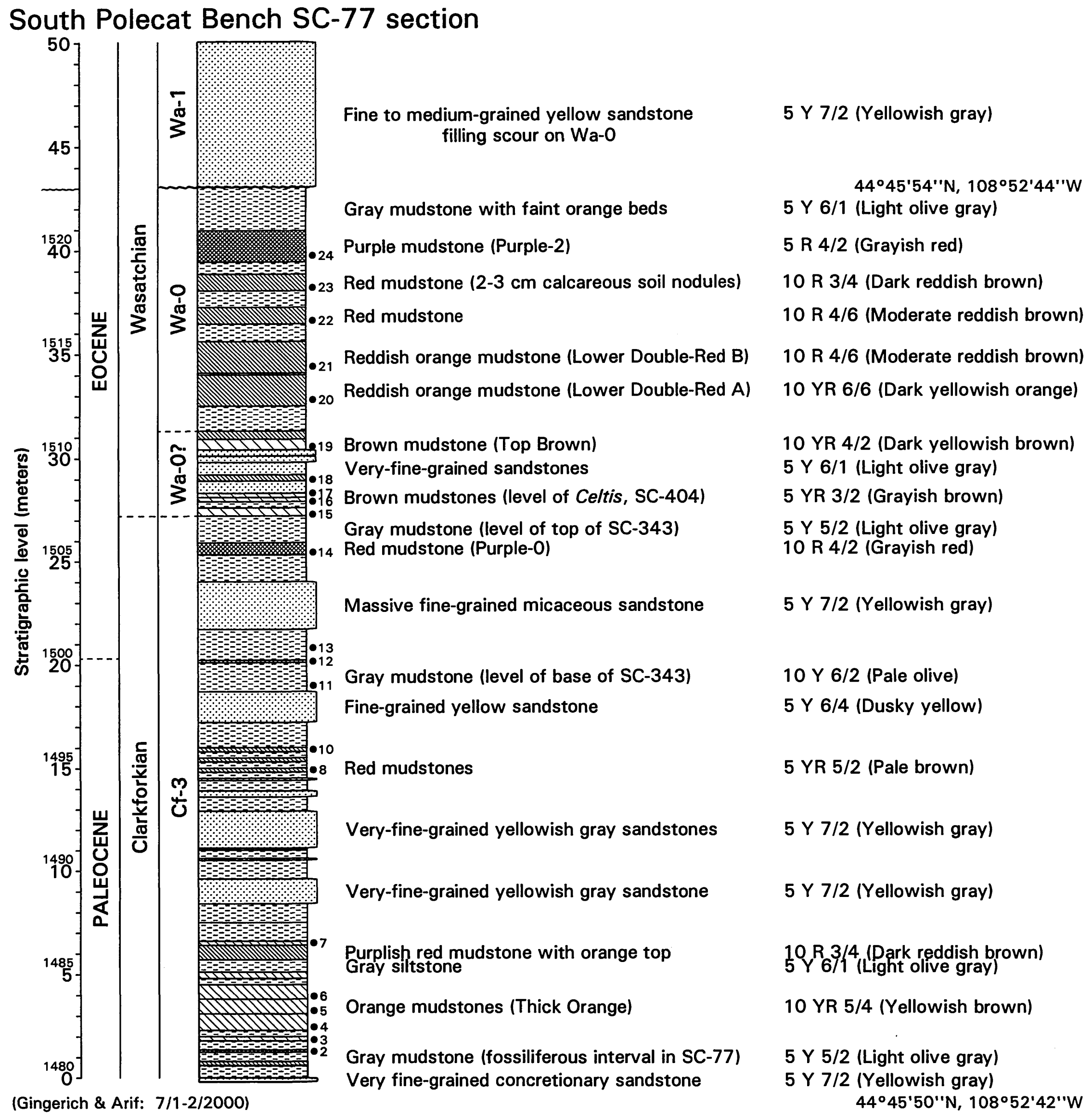

FIGURE 8 — South Polecat Bench SC-77 stratigraphic section. Ordinate is in meters above the base of the section (inset numbers on the ordinate are meter levels in the Polecat Bench master section). Lithologies include standard descriptions in the middle column and fresh colors in the right-hand column. Solid circles show stratigraphic positions of isotope samples (see Bowen et al., this volume). Paleocene-Eocene boundary marked by the beginning of the negative $\delta^{13}C$ isotope excursion is at about the 20 m level here (1500 m in Polecat Bench master section; Bowen et al., this volume). This is about 7 m lower than the beginning of Wasatchian zone Wa-0? marked by the appearance of *Celtis* and *Meniscotherium*, and about 11 m lower than the beginning of Wasatchian zone Wa-0 marked by the appearance of Perissodactyla, Artiodactyla, and Primates. Note the disconformity near the top of the section where sandstone of the scour-fill sequence overlies mudstone above the Purple-2 marker bed.

scour-and-fill sequence is at about the 1522 m level in the Polecat Bench section.

SC-343 Stratigraphic Section

The SC-343 stratigraphic section is illustrated in Figure 9. It is 25 m thick, starting in upper Clarkforkian strata and ending in lower Wasatchian strata. Lithologies, thicknesses, and colors match those in the SC-77 section very closely. Purple-0 lies in the 4-5 m interval here. This is overlain by the brown paleosol sequence in the interval from 6-10 m, with the Top Brown marker bed present at the top of the sequence. Lower Double Red beds A and B are well exposed in the interval from 11-14 m above the base of the section. Purple-2 is thick here,

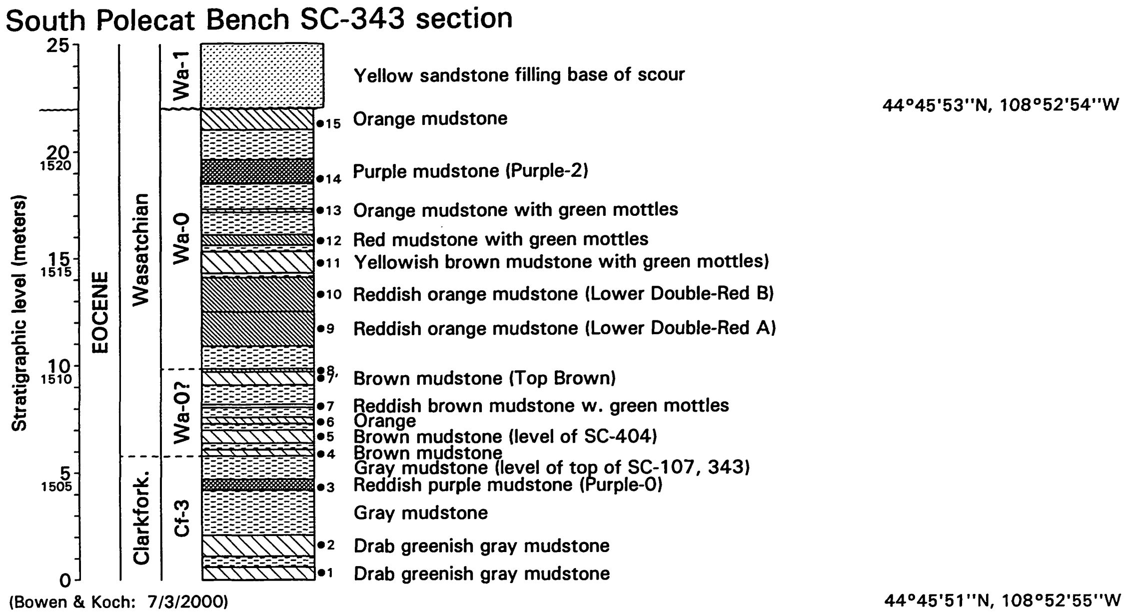

FIGURE 9 — South Polecat Bench SC-343 stratigraphic section. Ordinate is in meters above the base of the section (inset numbers on the ordinate are meter levels in the Polecat Bench master section). Lithologies include standard descriptions in the middle column. Colors here were not recorded systematically (see SC-77 section above). Solid circles show stratigraphic positions of isotope samples (see Bowen et al., this volume). Locality SC-404 yielding *Meniscotherium* occurs just above the level of SC-343 and other latest Clarkforkian Cf-3 localities, and just below the level of SC-67 and other earliest Wasatchian Wa-0 localities. Again note the disconformity near the top of the section where sandstone of the scour-fill sequence overlies mudstone above the Purple-2 marker bed.

spanning the interval from about 18.5-19.5 m. The section is truncated by the major scour-and-fill sequence, beginning at 22 m above the base of the section. The positions of in situ paleosol soil nodules sampled for carbon and oxygen isotopes are shown at the right of the lithological column in Figure 9, yielding samples numbered from 1-15 (see Bowen et al., this volume).

Two mammal-bearing fossil localites, SC-343 itself and SC-404, lie within the SC-343 section. SC-343 yields a late Clarkforkian fauna (Cf-3; see below), principally from gray mudstones below the Purple-0 level (and extending several meters below the base of the measured section). The level of one other fossil locality, SC-107, can be correlated with this section by tracing beds laterally. The base of the SC-343 section shown in Figure 9 is at about 1500.5 m above the Cretaceous-Tertiary boundary in the master Polecat Bench section, as measured on the southeast side of Polecat Bench (Fig. 3). This means, as in the SC-77 section, that Purple-0 is at about the 1505 m level, the base of the Wa-0 interval is at about the 1510 m level, Purple-2 is at about the 1520 m level, and the base of the scour-and-fill sequence is at about the 1522 m level in the Polecat Bench section.

SC-67 Stratigraphic Section

The SC-67 stratigraphic section is illustrated diagrammatically in Figure 10. It is 53 m thick, and is entirely in lower Wasatchian strata. The predominant 'background' lithology is again gray mudstone (colors are described in appendix Table A2). The section starts in the brown paleosol sequence, with the Top Brown marker bed present at about 4.5 m above the base of the section. Lower Double-Red A is exposed in the interval from 6-8 m above the base of the section, but Lower Double-Red B has been cut out by erosion and replaced by the ribbon sandstone described above. Purple-2 is thick, spanning the interval from about 12-13 m. The section continues uninterrupted by the major scour-and-fill sequence found east of SC-67. Upper Double-Red A is thin here, at the 18 m level, but Upper Double-Red B is a thick red bed spanning the interval from about 19.5-21.5 m. Purple-4 is found at about 34 m above the base of the section. Top Red A lies at about the 42 m level, and Top Red B lies at about the 47 m level. Descriptions of these key marker beds and other notable beds are recorded in Figure 10, with their corresponding fresh colors. The positions of in situ paleosol soil nodules sampled for carbon and oxygen isotopes are shown at the right of the lithological column in Figure 10, yielding samples numbered from 1-15 and from 17-23 (see Bowen et al., this volume).

Two mammal-bearing fossil localites, SC-67 itself and SC-68, lie within the SC-67 section. SC-67 has yielded a large earliest Wasatchian fauna (Wa-0; see below), principally from the interval including the Lower Double-Red beds, Purple-2, and the Upper Double-Red beds. SC-68 has yielded a tooth of *Diacodexis metsiacus* and a dentary of *Copecion*

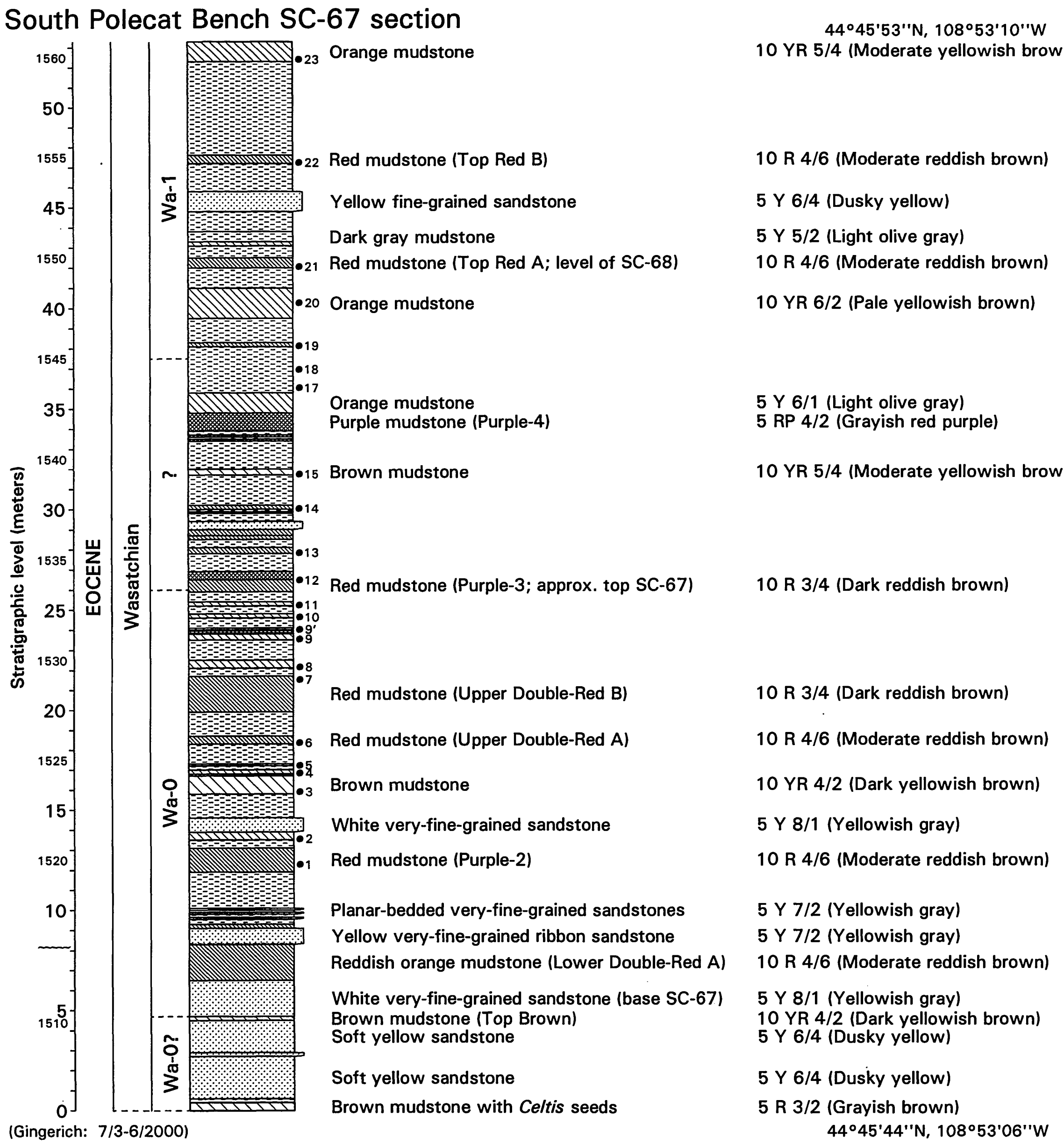

FIGURE 10 — South Polecat Bench SC-67 stratigraphic section. Ordinate is in meters above the base of the section (inset numbers on the ordinate are meter levels in the Polecat Bench master section). Lithologies include standard descriptions in the middle column and fresh colors in the right-hand column. Solid circles show stratigraphic positions of isotope samples (see Bowen et al., this volume). Note the disconformity near the base of the section where a ribbon sandstone replaces the Lower Double-Red B marker bed. There is no scour-fill sequence replacing strata above the Purple-2 marker bed as there is in the SC-77 and SC-343 sections above.

brachypternus indicative of a post-Wa-0 fauna. The base of the SC-67 section shown in Figure 10 is at about 1505.5 m above the Cretaceous-Tertiary boundary in the master Polecat Bench section, as measured on the southeast side of Polecat Bench (Fig. 3). This means that the Top Brown mudstone and the base of the Wa-0 interval are at about the 1510 m level, Lower Double-Red A is in the interval from 1512-1514 m, the base of the ribbon sandstone scour-and-fill is at about 1514 m, Purple-2 is at about the 1520 m level, Upper Double-Red beds A and B are in the interval from 1526-1529 m, Purple-3 is at

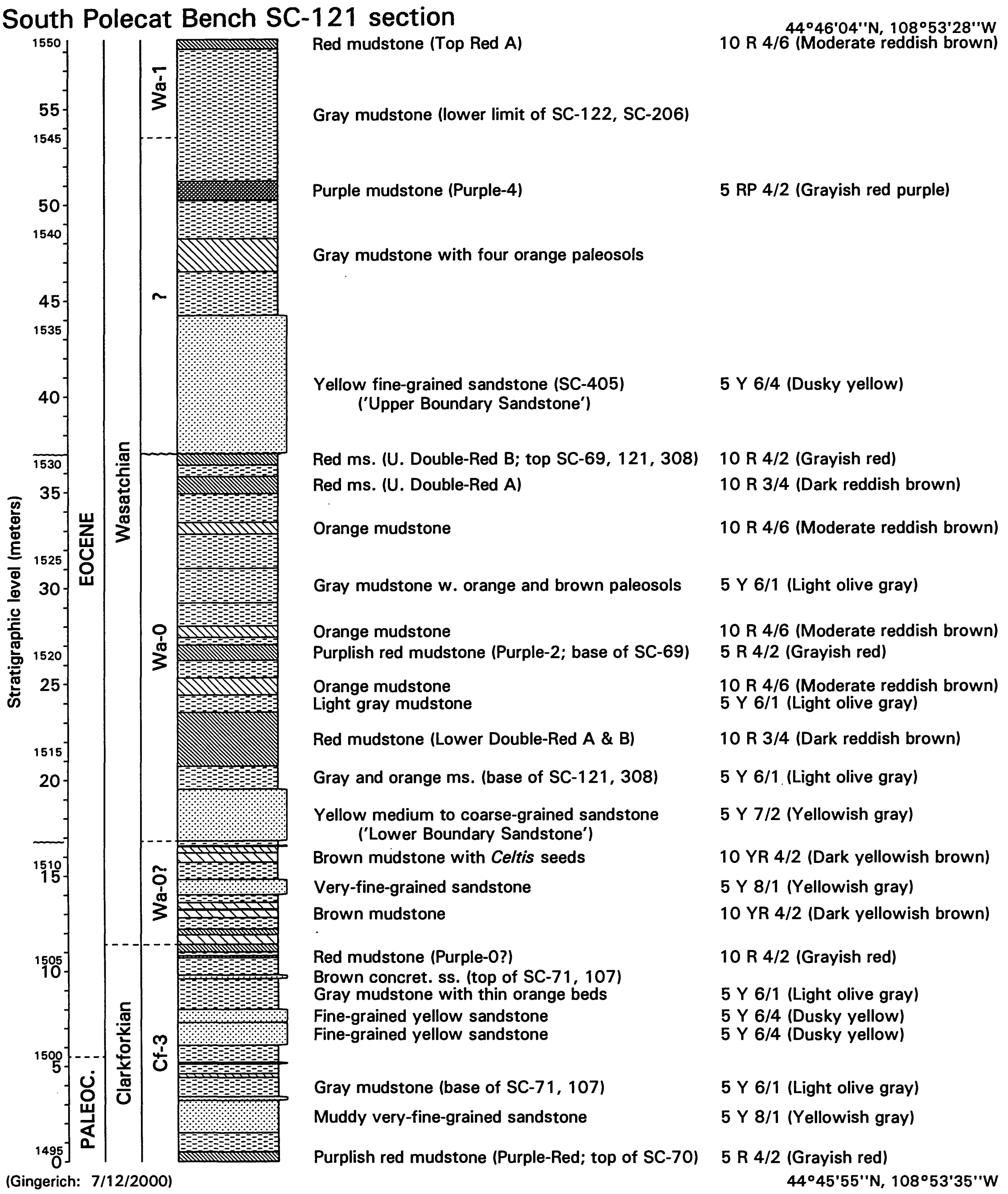

FIGURE 11 — South Polecat Bench SC-121 stratigraphic section. Ordinate is in meters above the base of the section (inset numbers on the ordinate are meter levels in the Polecat Bench master section). Lithologies include standard descriptions in the middle column and fresh colors in the right-hand column. No isotope samples were taken from this section. Paleocene-Eocene boundary marked by the beginning of the negative $\delta^{13}C$ isotope excursion is at about the 5 m level here (1500 m in Polecat Bench master section; Bowen et al., this volume). This is about 6 m lower than the beginning of Wasatchian zone Wa-0? marked by the appearance of *Celtis* and *Meniscotherium*, and about 11 m lower than the disconformity at the base of the Lower Boundary Sandstone that underlies earliest Wasatchian zone Wa-0. There is a second disconformity higher in the section at the base of the Upper Boundary Sandstone. This section enables comparison with a similar section lacking lower and upper boundary sandstones (e.g., SC-67 section above). The middle part of the section here is equivalent to that in figure 6B of Kraus (1987) with its stage 3 and stage 4 paleosols, which was measured and studied nearby.

about 1534 m, Purple-4 is at about 1542 m, Top Red A is at 1550 m, and Top Red B is at about 1555 m in the Polecat Bench section.

SC-121 Stratigraphic Section

The SC-121 stratigraphic section is illustrated diagrammatically in Figure 11. It is 58 m thick, starting in upper Clarkforkian strata and ending in lower Wasatchian strata. The predominant 'background' lithology is gray mudstone (colors are described in appendix Table A3). The section starts at the Purple-Red mudstone that marks the top of locality SC-70 and continues through a red mudstone that may represent Purple-0 at about 11 m above the base. The brown paleosol succession is in the interval from 11-17 m, but the Top Brown marker bed appears to have been removed by erosion during emplacement of the Lower Boundary Sandstone. This occupies the interval from about 17 to 20 m. Lower Double-Red A and B are exposed in the interval from about 20.5 to 23.5 m above the base of the section. Purple-2 spans the interval from about 26-27 m. Upper Double-Red A is thin here, at the 35-36 m level, and Upper Double-Red B at the 1530 m level is thin because most of it has been removed during deposition of the Upper Boundary Sandstone. The latter fills the interval from about 37-44 m above the base of the section. Purple-4 is found at about 50.5-51.5 m above the base of the section. Top Red A caps the section at about 58.0-58.5 m above the base. Descriptions of these key marker beds and other notable beds are recorded in Figure 11, with their corresponding fresh colors. No paleosol soil nodules were sampled for isotopes from this section.

The SC-121 section is important in tying together a number of important mammal-bearing fossil localities. First, the section starts with the Purple-Red bed marking the top of late Clarkforkian locality SC-70. Two late Clarkforkian localities, SC-71 and SC-107, lie in the interval between the Purple-Red marker bed and the red mudstone possibly representing Purple-0. Wa-0 localities SC-121 and SC-308 are lateral equivalents of SC-67, spanning the full stratigraphic interval between the Lower Boundary Sandstone and the Upper Boundary Sandstone. Wa-0 locality SC-69 has Purple-2 at its base and extends to the Upper Boundary Sandstone. Locality SC-405 is developed near the base of the Upper Boundary Sandstone on a long narrow ridge where the top of the unit has been removed by erosion. Finally, two Wa-1 localities, SC-122 and SC-206, have their bases above the Purple-4 mudstone. The base of the SC-121 section shown in Figure 11 is at about 1495 m above the Cretaceous-Tertiary boundary in the master Polecat Bench section, as measured on the southeast side of Polecat Bench (Fig. 3). This means that the brown paleosol sequence lies in the interval from 1506 to 1511 m, the Lower Boundary Sandstone is in the interval from 1511 to 1513 m. Lower Double-Red A and B are in the interval from 1514-1517 m, Purple-2 is at about the 1520 m level, Upper Double-Red beds A and B are in the interval from 1528-1530 m, the Upper Boundary Sandstone fills the interval from 1530-1536 m, Purple-4 is at about 1542 m, and Top Red A is at 1550 m.

SC-206 Stratigraphic Section

The SC-206 stratigraphic section is illustrated diagrammatically in Figure 12. It is 53.5 m thick, and is entirely in lower Wasatchian strata. The predominant 'background' lithology is gray mudstone (colors of paleosol horizons are described in appendix Table A4). The section starts at the Purple-4 marker bed. Top Red A is in the interval between about 8-9 m above the base of the section. Top Red B is at about the 13 m level Descriptions of these key marker beds and other notable beds are recorded in Figure 11, with their corresponding fresh colors. The positions of in situ paleosol soil nodules sampled for carbon and oxygen isotopes are shown at the right of the lithological column in Figure 12, yielding samples numbered 1, 3-6 and 8-16 (see Bowen et al., this volume).

The SC-206 section includes mammal-bearing fossil locality SC-206 itself in the interval between about 2 and 17 m above the base of the section. This locality yields Wa-1 mammals, and the productive levels include Top Red A and Top Red B and the gray mudstones just below, between, and just above these marker beds. The base of the SC-206 section shown in Figure 12 is at about 1542 m above the Cretaceous-Tertiary boundary in the master Polecat Bench section, as measured on the southeast side of Polecat Bench (Fig. 3). This is the level of Purple-4, meaning, as before, that Top Red A is at about 1550 m and Top Red B is at about 1555 m in the Polecat Bench section.

BIOTIC CHANGE ACROSS THE PALEOCENE-EOCENE BOUNDARY

Mammalian faunas are known from fourteen localities representing seven distinctive, successive, stratigraphic intervals in the area studied here (not considering the four localities east of the easternmost fault in Fig. 6). Three of these intervals yield upper Clarkforkian faunas of late Clarkforkian age (Cf-3). One yields a new stratigraphically-intermediate fauna that is probably earliest Wasatchian in age (Wa-0?). One yields a basal Wasatchian fauna of earliest Wasatchian age (the original Wa-0 fauna). One yields a lower Wasatchian fauna that is Wa-0 or Wa-1 in age. Finally, one yields a lower Wasatchian fauna that is definitely Wa-1 in age.

Clarkforkian Biota

The lowest stratigraphic interval considered here is the Thick Orange mudstone interval centered at the 1480 m level in the Polecat Bench stratigraphic section. All fossils in this interval come from locality SC-77 at the base of the SC-77 stratigraphic section (Fig. 8). Four identifiable mammalian specimens are known (Table 3), of which *Haplomylus simpsoni* is indicative of Clarkforkian age. Superposition well above the highest range datum of *Plesiadapis cookei* in the Polecat

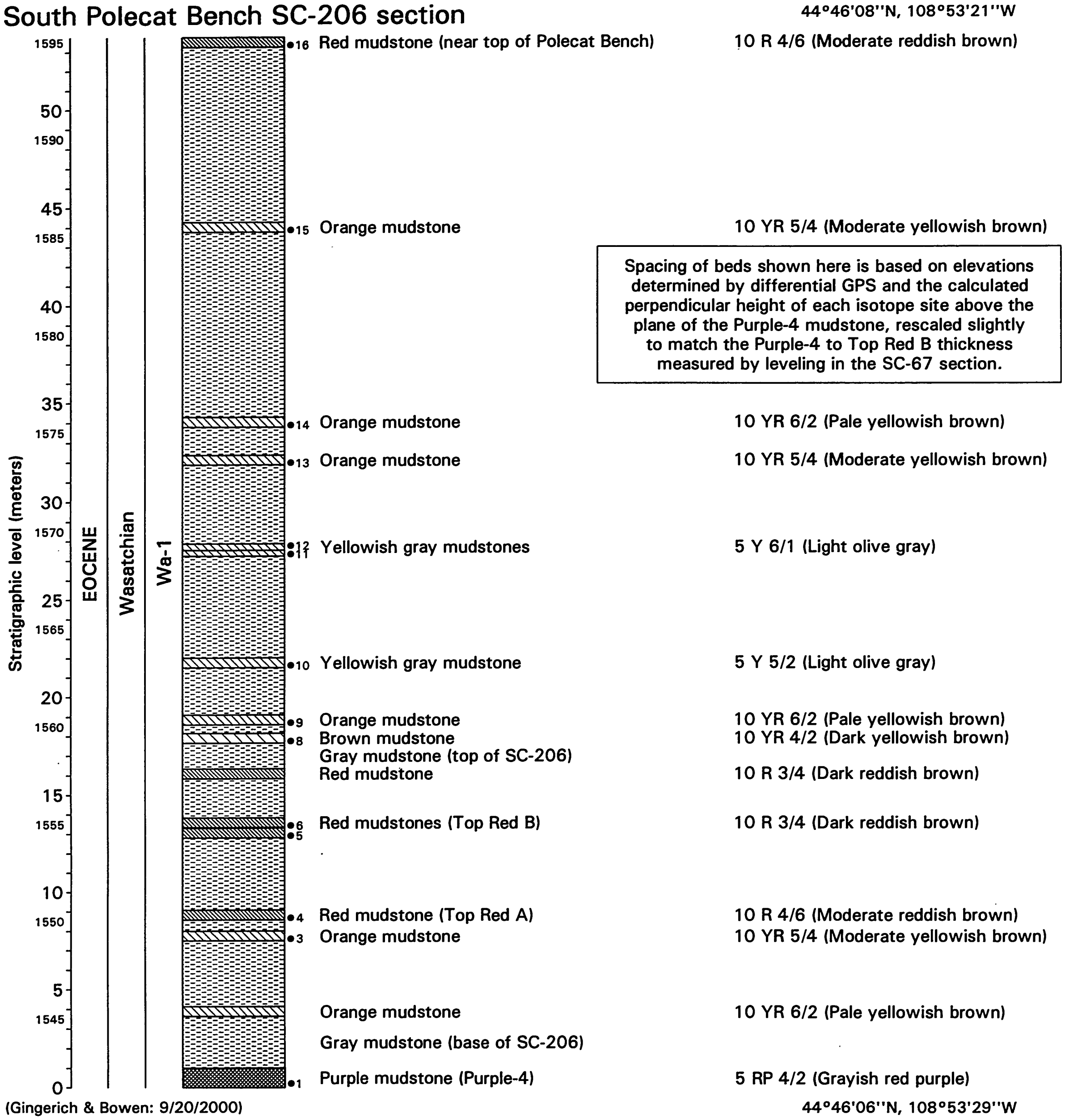

FIGURE 12 — South Polecat Bench SC-206 stratigraphic section. Ordinate is in meters above the base of the section (inset numbers on the ordinate are meter levels in the Polecat Bench master section). Lithologies include standard descriptions in the middle column and fresh colors of sampled intervals in the right-hand column. Solid circles show stratigraphic positions of isotope samples (see Bowen et al., this volume). Isotopes were sampled from this section because it includes strata some 35 m higher in the Polecat Bench master section than those sampled in the SC-67 section.

Bench section indicates that the age is late Clarkforkian (Cf-3; Fig. 3).

The second fossiliferous interval in the Clarkforkian part of the section is found on the opposite side of the mapped area at locality SC-70. The base of SC-70 overlies the Thick Orange mudstone interval, while the top of SC-70 can be traced to the base of the SC-121 section. Thus the SC-70 fossiliferous interval is centered at the 1490 m level in the Polecat Bench stratigraphic section. Thirteen identifiable mammalian specimens are known (Table 4), with *Probathyopsis praecursor*,

TABLE 3 — Mammalian fauna from late Clarkforkian locality SC-77 in a collecting interval centered on 1480 m in the Polecat Bench stratigraphic section. The presence of *Haplomylus simpsoni* indicates a Clarkforkian age, and superposition above the highest range datum of *Plesiadapis cookei* narrows this to Cf-3. *UM*, University of Michigan Museum of Paleontology; *m*, lot number for miscellaneous teeth.

Genus and species	Specimen count	Voucher specimen(s)	Reference(s)
Niptomomys doreenae	1	UM 66176	Rose (1981: 53)
Azygonyx grangeri	1	UM 108656	
Haplomylus simpsoni	1	UM 66177m	Rose (1981: 78)
Dissacus praenuntius	1	UM 66175	Rose (1981: 86)

TABLE 4 — Mammalian fauna from late Clarkforkian locality SC-70 in a collecting interval centered on 1490 m in the Polecat Bench stratigraphic section. The presence of *Probathyopsis praecursor*, *Aletodon gunnelli*, *Apheliscus nitidus*, and *Haplomylus simpsoni* indicates a Clarkforkian age, and superposition above the highest range datum of *Plesiadapis cookei* narrows this to Cf-3. *UM*, University of Michigan Museum of Paleontology; *m*, lot number for miscellaneous teeth.

Genus and species	Specimen count	Voucher specimen(s)	Reference(s)
Azygonyx grangeri	1	UM 76859	
Probathyopsis praecursor	1	UM 66146	Rose (1981: 93), Thewissen and Gingerich (1987: 209)
Oxyaena transiens	1	UM 66148m	Rose (1981: 105)
Viverravus politus	1	UM 66853	Rose (1981: 101), Polly (1997: 4)
Aletodon gunnelli	1	UM 66850	Gingerich (1977: 240)
Apheliscus nitidus	1	UM 66147	Rose (1981: 83)
Copecion brachypternus	1	UM 66852	Rose (1981: 73), Thewissen (1990: 68)
Ectocion osbornianus	4	UM 66846, etc.	Rose (1981: 73)
Haplomylus simpsoni	1	UM 66847	Rose (1981: 78)
Dissacus praenuntius	1	UM 66854	Rose (1981: 86)

Aletodon gunnelli, *Apheliscus nitidus*, and *Haplomylus simpsoni* all indicating Clarkforkian age.

The highest fossiliferous interval in the Clarkforkian part of the section is represented by three localities, SC-71, SC-107, and SC-343, distributed across the middle part of the study area. These are above the level of the Red-Purple bed overlying SC-70 (possibly equivalent to the red mudstones in the SC-77 stratigraphic section; Fig. 8), and just above or at the level of Purple-0 in the SC-77 and SC-343 stratigraphic sections (Figs. 8 and 9). Thus this highest Clarkforkian interval is centered at the 1502 m level in the Polecat Bench stratigraphic section. Eighteen identifiable mammalian specimens are known (Table 5), with *Aletodon gunnelli* being the only taxon clearly diagnostic of Clarkforkian age. Another characteristic of late Clarkforkian faunas is the relative abundance of *Phenacodus* and *Ectocion* (Rose, 1981), and 7 of the 18 identifiable specimens (39%) are *Ectocion osbornianus*. Most specimens were found below Purple-0, but a typically Clarkforkian-looking dark-colored specimen of *Ectocion osbornianus* was found by I. Zalmout in 2000 just above the level of Purple-0 (UM 108647from SC-343), which is the principal indication that Purple-0 lies within the uppermost Clarkforkian faunal interval.

Meniscotherium priscum Biota

It is generally recognized that stony endocarps of the elm-related shrub or tree *Celtis phenacodorum* are found in Wasatchian but not Clarkforkian strata in the Bighorn Basin (e.g., Rose, 1981, p. 138). In 1989 I described *Celtis* endocarps from several 'latest Clarkforkian' localities where there is no possibility of contamination from overlying sediments (Gingerich, 1989, p. 15). In present terms, the 4-m-thick brown mudstone sequence between 1506 and 1510 m in the Polecat

TABLE 5 — Mammalian fauna from late Clarkforkian localities SC-71, SC-107, and SC-343 in a collecting interval centered on 1502 m in the Polecat Bench stratigraphic section. The presence of *Aletodon gunnelli* indicates a Clarkforkian age, and superposition above the highest range datum of *Plesiadapis cookei* narrows this to Cf-3. *UM*, University of Michigan Museum of Paleontology; *m*, lot number for miscellaneous teeth.

Genus and species	Specimen count	Voucher specimen(s)	Reference(s)
Arctodontomys cf. *A. wilsoni*	1	UM 80851	Gunnell (1989: 92)
Ignacius sp.	1	UM 102531	
Palaeanodon sp.	1	UM 97883	
Paramyid sp.	1	UM 102532	
Uintacyon rudis	1	UM 76861	Gingerich (1983b: 203)
Viverravus politus	1	UM 66618	Rose (1981: 101), Polly (1997: 4)
Aletodon gunnelli	2	UM 83649, etc.	
Copecion brachypternus	1	UM 83648	Thewissen (1990: 68)
Ectocion osbornianus	7	UM 66619, etc.	Rose (1981: 73), Thewissen (1990: 40)
Phenacodus intermedius	1	UM 83619, etc.	Thewissen (1990: 40)
Thryptacodon antiquus	1	UM 103073	

TABLE 6 — Mammalian fauna from transitional highest Clarkforkian to lowest Wasatchian locality SC-404 in a collecting interval centered on 1507 m in the Polecat Bench stratigraphic section. *Meniscotherium* has only been found in this transitional zone in the Bighorn Basin. It is known from later Wasatchian faunas in southern Wyoming and New Mexico. Association with endocarps of *Celtis phenacodorum* suggests that the biota is probably earliest Wasatchian (early Wa-0) in age. *UM*, University of Michigan Museum of Paleontology; *m*, lot number for miscellaneous teeth.

Genus and species	Specimen count	Voucher specimen(s)	Reference(s)
Meniscotherium priscum	1	UM 108645	This paper (see Fig. 13)

Bench section, centered on 1507 m, yields *Celtis* endocarps by the hundreds if not thousands. These are most easily found lying on a weathered outcrop, but they can also be found in situ in the brown paleosols. The 1506-1510 m interval ranges from just above Purple-0 up to and including the Top Brown mudstone unit just below the base of beds yielding the original Wa-0 fauna. A small area of the 1506-1510 m brown mudstones, what is now locality SC-404, was prospected carefully in 2000 by M. Arif. This locality is exposed on a saddle where it cannot be contaminated from above. *Celtis* endocarps are common, and one mammalian specimen found here in 2000 is a small, light-colored, left dentary with worn M_{1-2} (University of Michigan [UM] 108645; Fig. 13G-H; Table 6). The molars, though worn, show the distinctive lophoselenodont pattern of shearing crests that is only found in *Meniscotherium* among North American late Paleocene to early Eocene mammals (Granger, 1915; Gazin, 1965; Williamson and Lucas, 1992).

Granger (1915, p. 360) named *Meniscotherium priscum* based on a small, light-colored dentary found by W. J. Sinclair in 1911 (American Museum of Natural History [AMNH] 16145), and described it as coming from Clarkforkian strata at the head of Big Sand Coulee in the Clarks Fork Basin. Unfortunately the specimen does not have an entry in Sinclair and Granger's field book for 1911, so it is impossible to be certain where it came from geographically or stratigraphically. Rose (1981, p. 76), following Granger, considered it to be Clarkforkian. I argued in 1982 and again in 1989 that *Meniscotherium priscum* probably came from the vicinity of locality SC-67 at the south end of Polecat Bench (Gingerich, 1982b, p. 490; 1989, p. 55— we know that Sinclair collected here for two days in 1911 while Granger collected at the head of Big Sand Coulee).

The second specimen of *Meniscotherium priscum* to be found in the Bighorn Basin was found in 1987 (UM 91419 from locality MP-71; Fig. 13A-F). It came from a fauna thought

TABLE 7 — Mammalian fauna from early Wasatchian localities SC-67, SC-121, and SC-308 in a collecting interval centered on 1520 m in the Polecat Bench stratigraphic section. The presence of *Cantius torresi*, *Arfia junnei*, *Copecion davisi*, *Diacodexis ilicis*, and *Hyracotherium sandrae* indicates an earliest Wasatchian Wa-0 age. *UM*, University of Michigan Museum of Paleontology; *m*, lot number for miscellaneous teeth.

Genus and species	Specimen count	Voucher specimen(s)	Reference(s)
Ectypodus tardus	1	UM 86572m	Gingerich (1989: 22)
Mimoperadectes labrus	3	UM 92347, etc.	Gingerich (1989: 22)
Apatemyid	1	UM 97900	
Macrocranion n. sp.	1	UM 93378	
Arctodontomys wilsoni	1	UM 86572m	Gingerich (1989: 23)
Niptomomys (cf.) sp.	1	UM 85591	Gingerich (1989: 23)
Phenacolemur praecox	1	UM 79890m	Gingerich (1989: 23)
Cantius torresi	10	UM 83467, etc.	Gingerich (1986: 319; 1989: 23; 1995: 188)
Ectoganus bighornensis	12	UM 66617m, etc.	Gingerich (1989: 30)
Azygonyx gunnelli	9	UM 71768m, etc.	Gingerich (1989: 26)
Azygonyx sp.	3	UM 66616m, etc.	Gingerich (1989: 28)
Esthonyx spatularius	1	UM 87354m	Gingerich (1989: 24)
Coryphodon sp.	10	UM 79890m, etc.	Gingerich (1989: 29)
Palaeanodon nievelti	7	UM 83464m, etc.	Gingerich (1989: 63)
Palaeanodon parvulus	1	UM 101141	
Acritoparamys atwateri	7	UM 76237m, etc.	Gingerich (1989: 40)
Acritoparamys (cf.) *atavus*	1	UM 86003m	Gingerich (1989: 40)
Paramys taurus	6	UM 66617m, etc.	Gingerich (1989: 40)
Acarictis ryani	2	UM 86572m, etc.	Gingerich (1989: 33)
Arfia junnei	20	UM 67664, etc.	Gingerich (1989: 33)
Dipsalidictis platypus	11	UM 66137, etc.	Gingerich (1989: 31), Gunnell and Gingerich (1991: 158)
Dipsalidictis transiens	1	UM 82387m	Gingerich (1989: 32)
Palaeonictis sp.	1	UM 92889	Gingerich (1989: 33)
Prolimnocyon eerius	1	UM 87353	Gingerich (1989: 36)
Prototomus deimos	3	UM 66140m	Gingerich (1989: 33)
Didymictis proteus	14	UM 71765, etc.	Gingerich (1989: 39), Polly (1997: 4)
Miacis winkleri	1	UM 77203m	Gingerich (1989: 39)
Viverravus acutus	1	UM 87339	Gingerich (1989: 37), Polly (1997: 2)
Viverravus politus	1	UM 87857	Gingerich (1989: 36), Polly (1997: 4)
Chriacus badgleyi	6	UM 79887, etc.	Gingerich (1989: 41)
Copecion davisi	35	UM 66611, etc.	Gingerich (1989: 53), Thewissen (1990: 69)
Ectocion osbornianus	1	UM 66612	Gingerich (1989: 52), Thewissen (1990: 40)
Ectocion parvus	67	UM 66138, etc.	Gingerich (1989: 49), Thewissen (1990: 43)
Hyopsodus loomisi	48	UM 66614, etc.	Gingerich (1989: 47)
Phenacodus vortmani	6	UM 77203m, etc.	Gingerich (1989: 52), Thewissen (1990: 59)
Thryptacodon barae	1	UM 85669	Gingerich (1989: 40)
Dissacus praenuntius	6	UM 83477, etc.	Gingerich (1989: 44)
Diacodexis ilicis	11	UM 66613, etc.	Gingerich (1989: 56)
Hyracotherium grangeri	2	UM 66615, etc.	Gingerich (1989: 62)
Hyracotherium sandrae	33	UM 66139, etc.	Gingerich (1989: 58)

to be at the Clarkforkian-Wasatchian boundary, where *Phenacodus* and *Ectocion* are again associated with an endocarp of *Celtis* (Gingerich, 1989, p. 56). Consideration of the newly discovered third specimen in this light suggests a pattern: (1) *Meniscotherium* is very rare in the Bighorn Basin, indicating that it comes from an age or environment that is rarely sampled; (2) two of the three *Meniscotherium* found to date in the Bighorn Basin come from strata first thought to be latest

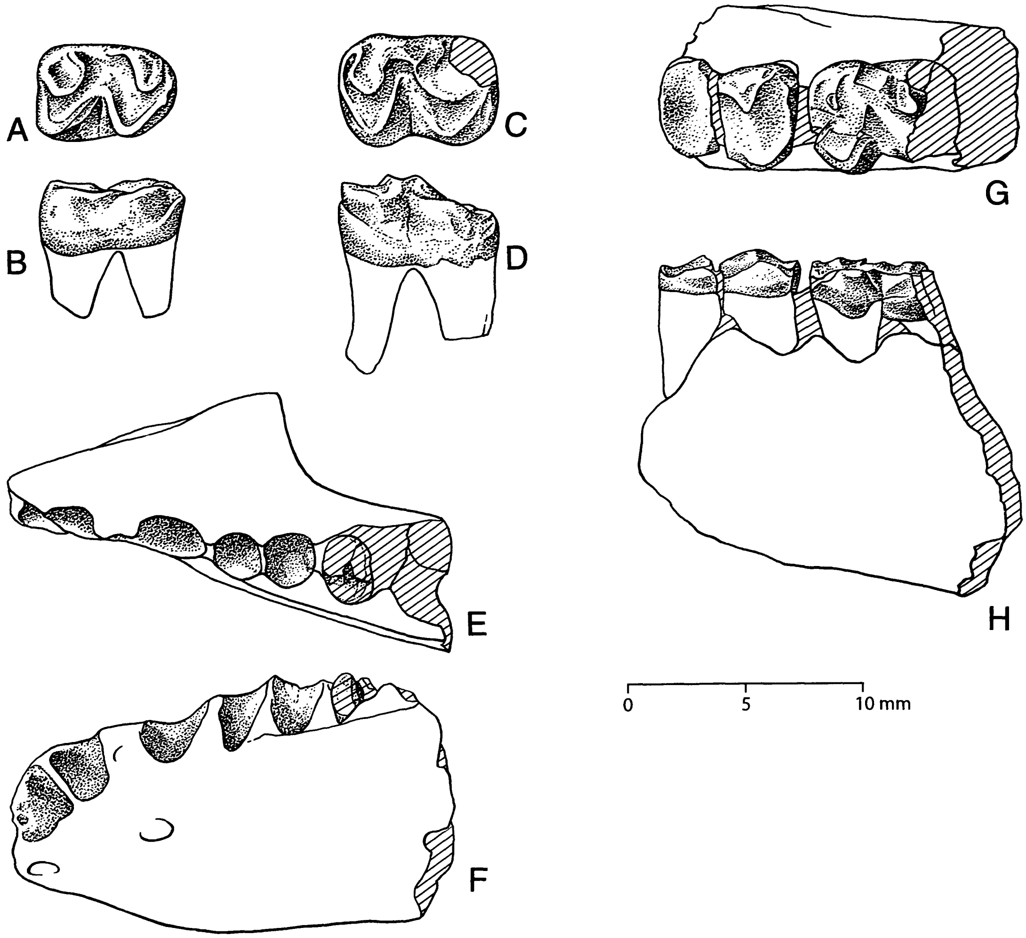

FIGURE 13 — New specimens of *Meniscotherium priscum* from transitional Clarkforkian-Wasatchian strata (Wa-0? interval here) that have *Celtis* but lack Wasatchian Perissodactyla, Artiodactyla, and Primates marking the beginning of Wa-0 time. A-F, University of Michigan [UM] 91419 from locality MP-71 (A-B, right M_1 in occlusal and lateral view; C-D, left M_2 in occlusal and lateral view; E-F, left dentary with alveoli for I_{2-3}, C_1, and P_{1-2}). G-H, UM 108645, left dentary with M_{1-2} in occlusal and lateral view. Lower molars of *Meniscotherium* are distinctive in having a cristid obliqua that joins the protocristid near the metaconid, yielding a more lophoselenodont tooth than is seen in other condylarths.

Clarkforkian but associated with endocarps of *Celtis* (and the provenance of the exception, the type, is not known). I propose as a working hypothesis that *Meniscotherium priscum* and *Celtis phenacodorum* made their first appearance in the Bighorn Basin during the narrow interval of time represented by the brown mudstone sequence spanning the 1506-1510 m interval in the Polecat Bench stratigraphic section. They almost certainly represent a new pre-Wa-0 biota, here called, tentatively, Wa-0?, pending further discoveries that will clarify its composition. Wa-0? is included in the Wasatchian because both *Celtis* and *Meniscotherium* are known from later Wasatchian biotas (*Celtis* is abundant in overlying Wasatchian strata of the Bighorn and Clarks Fork Basins, while *Meniscotherium* is common in later Wasatchian strata of southern Wyoming and New Mexico; this age interpretation is queried because the zone is still poorly known faunally).

It should be noted that locality SC-404 was previously part of latest Clarkforkian SC-343 discussed above, and the beds sampled in SC-404 are exposed at the top of SC-343 in many places. There are *Celtis phenacodorum* endocarps included with some lots of miscellaneous teeth and bone collected from SC-343, but these are regarded, as before (Gingerich, 1989, p. 15), as contaminants from strata of the SC-404 interval.

Early Wasatchian Wa-0 Biota

The lowest part of the Wasatchian that is well known faunally is the stratigraphic interval including Lower Double-

TABLE 8 — Mammalian fauna from early Wasatchian locality SC-69 in a collecting interval centered on 1530 m in the Polecat Bench stratigraphic section. The presence of *Cantius torresi*, *Copecion davisi*, *Arfia junnei*, and *Hyracotherium sandrae* indicates an earliest Wasatchian (Wa-0) age. *UM*, University of Michigan Museum of Paleontology; *m*, lot number for miscellaneous teeth.

Genus and species	Specimen count	Voucher specimen(s)	Reference(s)
Mimoperadectes labrus	1	UM 66144	Bown and Rose (1979: 93), Gingerich (1989: 22)
Cantius torresi	2	UM 66143, etc.	Gingerich (1989: 23)
Arfia junnei	1	UM 86135	Gingerich (1989: 33)
Copecion davisi	5	UM 83822, etc.	Gingerich (1989: 53), Thewissen (1990: 69)
Ectocion parvus	1	UM 83824	Gingerich (1989: 49), Thewissen (1990: 44)
Hyopsodus loomisi	2	UM 86130, etc.	Gingerich (1989: 47)
Hyracotherium sandrae	1	UM 86137m	Gingerich (1989: 58)

TABLE 9 — Mammalian fauna from early Wasatchian locality SC-405 in a collecting interval centered on 1535 m in the Polecat Bench stratigraphic section. Specimens listed here were previously considered to have come from locality SC-67 (Gingerich, 1989), but enclosure within the Upper Boundary Sandstone, absence of any distinctively Wa-0 taxon, brown-to-black color of bones and teeth, and presence of *Hyracotherium grangeri* suggests an early Wasatchian Wa-1 age. *UM*, University of Michigan Museum of Paleontology; *m*, lot number for miscellaneous teeth.

Genus and species	Specimen count	Voucher specimen(s)	Reference(s)
Coryphodon sp.	2	UM 79892, etc.	Gingerich (1989: 29)
Hyracotherium grangeri	1	UM 83637m	Gingerich (1989: 62; 1991: 187)

TABLE 10 — Mammalian fauna from early Wasatchian localities SC-68, SC-122, and SC-206 in a collecting interval centered on 1550 m in the Polecat Bench stratigraphic section. Superposition, close proximity to beds yielding a Wa-0 fauna, and the presence of *Cantius ralstoni*, *Haplomylus speirianus*, and *Diacodexis metsiacus* combine to indicate an early Wasatchian Wa-1 age. *UM*, University of Michigan Museum of Paleontology; *m*, lot number for miscellaneous teeth.

Genus and species	Specimen count	Voucher specimen(s)	Reference(s)
Cantius ralstoni	2	UM 69421, etc.	
Paramys taurus	1	UM 69419	Ivy (1990: 35)
Didymictis leptomylus	1	UM 69417	Polly (1997: 5)
Copecion brachypternus	1	UM 77014	Thewissen (1990: 68)
Haplomylus speirianus	3	UM 69418, etc.	
Hyopsodus loomisi	5	UM 69416, etc.	
Diacodexis metsiacus	2	UM 71771, etc.	
Hyracotherium grangeri	4	UM 66857, etc.	Gingerich (1991: 187)

Red A and B, Purple-2, and Upper Double-Red A and B marker beds. This interval is distinctive lithologically in having conspicuously thick and brightly colored orange-red and purple mudstones representing paleosols that are thicker and more mature than those found in adjacent stratigraphic intervals. This interval is distinctive paleontologically in yielding the classic

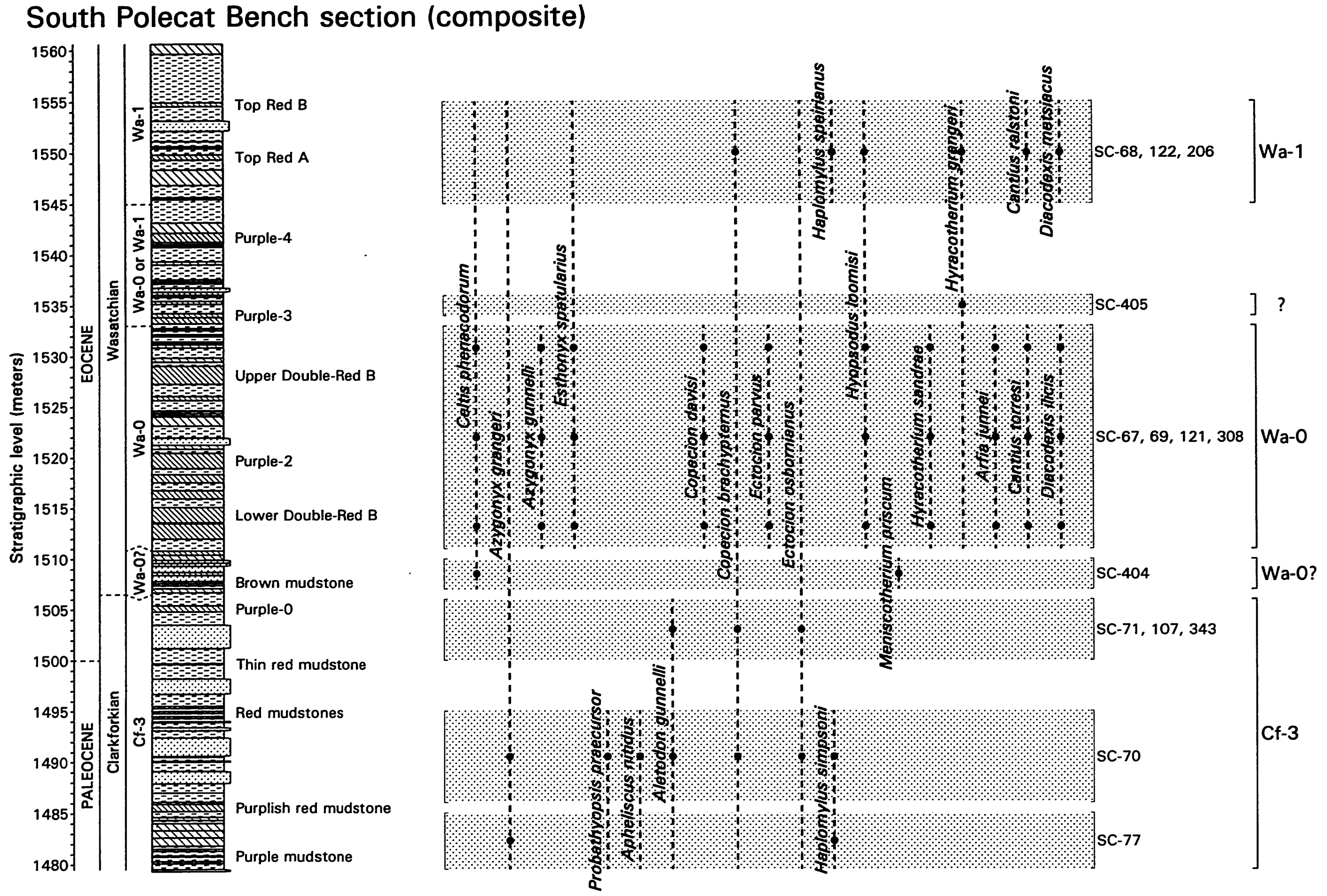

FIGURE 14 — Stratigraphic range chart of *Celtis* and the principal mammalian taxa crossing the Paleocene-Eocene boundary at the south end of Polecat Bench. Composite is based on individual sections shown in detail in Figures 8-11. Fourteen mammal-bearing fossil localities are known, representing seven distinct stratigraphic intervals (shaded). These can be grouped into four notable time-successive associations based on their biota. The first, a Cf-3 association, includes five localities in the lowest three intervals, which have one or more of the distinctively Clarkforkian taxa *Probathyopsis praecursor*, *Apheliscus nitidus*, *Aletodon gunnelli*, and/or *Haplomylus simpsoni*. The second association, here labeled Wa-0?, includes one locality from the fourth interval, with *Celtis phenacodorum* and *Meniscotherium priscum*. The third, a Wa-0 association, includes four localities from the fifth interval, with *Copecion davisi*, *Hyracotherium sandrae*, *Arfia junnei*, *Cantius torresi*, and *Diacodexis ilicis* as diagnostic taxa. This is followed by a poorly-sampled interval, labeled Wa-0 or Wa-1, with one locality yielding *Hyracotherium grangeri* that could be either Wa-0 or Wa-1 in age. Finally, the fourth association, representing Wa-1, includes three localities from the seventh stratigraphic interval, with *Haplomylus speirianus*, *Cantius torresi*, and *Diacodexis metsiacus* as diagnostic taxa.

Wa-0 mammalian fauna, which is unusual both in terms of taxonomic composition and in terms of the size of the animals represented (Gingerich, 1989; Clyde and Gingerich, 1998). The Wa-0 fauna includes the first representatives of cosmopolitan Artiodactyla, Perissodactyla, Primates, and hyaenodontid Creodonta that make the Eocene so different from the Paleocene on northern continents. The Wa-0 fauna also has many taxa that are conspicuously smaller in tooth size and overall body size than their congeners before and/or after Wa-0 time.

The Wa-0 fauna has been sampled in two overlapping intervals at the south end of Polecat Bench. Three of the four Wa-0 localities, SC-67, SC-121, and SC-308, span the full thickness of the interval, which is centered on the 1520 m level in the Polecat Bench section. These localities have yielded most of the mammals known from the Wa-0 interval (Table 7). The remaining Wa-0 locality at the south end of Polecat Bench, SC-69, spans the interval from Purple-2 to Upper Double-Red A, which is centered on the 1530 m level in the Polecat Bench section. The faunal sample from SC-69 is listed in Table 8. There is nothing about the fauna from SC-69 to suggest that it is anything other than a smaller subset of the fauna from SC-67, SC-121, and SC-308. Hence all are treated as a single Wa-0 faunal interval (*Meniscotherium*, in contrast, has not been found at any of these localities in spite of intensive collecting and careful scrutiny of all fossils found).

The taxa restricted to Wa-0 are *Cantius torresi*, *Arfia junnei*, *Copecion davisi*, *Diacodexis ilicis*, and *Hyracotherium sandrae*. The two most common taxa are *Ectocion parvus* and *Hyopsodus loomisi*. *Ectocion parvus* is characteristic of Wa-0, but not diagnostic as a few specimens are known from Clarkforkian and later Wasatchian faunas (Thewissen 1990, p. 42). *Hyopsodus loomisi* in Wa-0 is indistinguishable from *H. loomisi* in Wa-1.

In addition, locality SC-405 (Table 9; this locality was only recently separated from SC-67) is developed in a channel lag deposit within the Upper Boundary Sandstone. The Upper Boundary Sandstone here has cut into and removed much of the Upper Double-Red B marker bed, and it is overlain some 7 m up section by Purple-4. SC-405 is considered to lie at about the 1535 m level in the Polecat Bench stratigraphic section. The lag at SC-405 includes numerous coprolites, bones of turtles and crocodiles, bones of *Coryphodon* (including parts of the skeleton of a developmentally immature individual), and the crown of a molar of *Hyracotherium grangeri*. There are no distinctively Wa-0 taxa present, and bones and teeth are dark brown in color like those of overlying Wa-1 fossils. It is uncertain whether SC-405 taxa are part of the Wa-0 fauna, in which case the locality represents an unusual depositional environment not sampled elsewhere, or whether these are the lowest representatives of the overlying Wa-1 fauna.

Early Wasatchian Wa-1 Biota

The early Wasatchian Wa-1 biota is known with certainty from one interval at the south end of Polecat Bench. Three localities, SC-68, SC-122, and SC-206, have yielded a substantial fauna with taxa that clearly represent Wa-1 rather than Wa-0 (Table 10). These localities lie above Purple-4 in the stratigraphic interval including Top Red A and Top Red B. This is centered at the 1550 m level in the Polecat Bench stratigraphic section. *Cantius ralstoni*, *Copecion brachypternus*, and *Diacodexis metsiacus* are all larger and more advanced than congeners from Wa-0. *Haplomylus speirianus* is common in Wa-1 and Wa-2, but *Haplomylus* has not been found in Wa-0 faunas. In addition, *Hyracotherium grangeri* is common in this interval while it appears to be a very rare component of Wa-0 faunas.

Summary of Biotic Change

Detailed mapping of conspicuous marker beds, faults, and a major scour-and-fill feature at the south end of Polecat Bench has yielded a more complicated but clearer picture of the stratigraphy here. This enables recognition of seven distinct collecting units, as illustrated by stippling in Figure 14. These represent four faunal units (Cf-3, Wa-0?, Wa-0, and Wa-1). The first three collecting units are placed in Cf-3, following Rose (1981), because their faunas do not differ in any way from earlier late Clarkforkian faunas. The fourth collecting unit, Wa-0? in the brown mudstone sequence just below Wa-0, is the newly recognized *Meniscotherium* zone that includes the lowest range datum of *Celtis*. As noted above, Wa-0? is included in the Wasatchian because both *Celtis* and *Meniscotherium* are known from later Wasatchian biotas (*Celtis* are abundant in overlying Wasatchian strata of the Bighorn and Clarks Fork Basins, while *Meniscotherium* is common in later Wasatchian strata of southern Wyoming and New Mexico; this assignment is queried because the zone is still poorly known faunally). The fifth collecting unit yields the original Wa-0 mammalian fauna (Gingerich, 1989). The sixth collecting unit has too small a fauna to be diagnostic of Wa-0 or Wa-1. Finally, the seventh collecting unit, Wa-1, has a typical Sand Couleean or early Wasatchian fauna.

The average rate of sediment accumulation for the Clarkforkian and early Wasatchian of the Polecat Bench master section is about 470 to 475 m/m.y. (Gingerich, 2000; Bowen et al., this volume), meaning that each meter of sediment represents, on average, about 2.1 k.y. of geological time. Appearance of the *Celtis-Meniscotherium* association in Wa-0?, some 4-5 m below the beginning of Wa-0 proper, suggests that the Wasatchian biota appeared about 9-10 k.y. earlier than previously recognized. The thickness of the classic Wa-0 zone indicates that it probably represents only about 50 k.y. of geological time, which is much less than my previous estimate of 250 k.y. (Gingerich, 1989, p. 77).

PROSPECTUS

Detailed mapping of marker beds in the continental Paleocene-Eocene transition at the south end of Polecat Bench shows both what is possible, and what is required for future high-resolution studies. Initial discovery of the Wa-0 mammalian fauna and recognition of its distinctiveness resulted from a broad stratigraphic survey of the Clarkforkian-Wasatchian transition in the northern Bighorn Basin and in the Clarks Fork Basin, where fossil localities are generally bounded by sheet sandstones defining natural collecting intervals on the order of 10 m thick. The Wa-0 interval is often even thicker. There are some ongoing questions of contamination, involving, as examples, the presence of *Ectocion osbornianus* and the presence of *Hyracotherium grangeri* in the Wa-0 fauna, that could have been avoided if the precise meter level of all specimens had been recorded when they were collected. However, such uncertainty is unavoidable in any broad survey effort, and our earlier survey was carried out knowing that we would later focus more detailed attention on intervals that proved to be particularly interesting.

Now that the Wa-0 fauna is known, it is clear that meter-scale stratigraphic sampling, involving resolution an order of magnitude finer than that used in the initial surveying, will be required to resolve the transitions from Cf-3 to Wa-0 and from Wa-0 to Wa-1. Mammalian faunas documenting these transitions need to be collected anew in a high-resolution framework. Meter-scale stratigraphic sampling is literally paleosol- scale sampling. Similarly, such meter-scale stratigraphic resolution, corresponding to ca. 2-3 k.y. temporal resolution, will be required to correlate events and intervals in the Paleocene-Eocene transition accurately, both within and outside the Bighorn and Clarks Fork basins. Now that we know where to focus attention, such resolution is possible.

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APPENDIX

TABLE A1 — South Polecat Bench SC-77 stratigraphic section. Beds are listed in stratigraphic order from bottom to top. Color codes are from Goddard et al. (1948). Bed thickness is in meters.

Bed	Thick.	Description	Fresh color		Mottling color		Weathered color	
65	7.00	Fine to medium-grained yellow sandstone	5 Y 7/2	Yellowish gray			10YR 6/2	Pale yellowish brown
64	2.10	Gray mudstone with faint orange beds	5 Y 6/1	Light olive gray			N 7	Light gray
63	1.50	Purple mudstone (Purple-2)	5 R 4/2	Grayish red			5 YR 6/1	Light brownish gray
62	0.60	Gray mudstone	5 GY 6/1	Greenish gray			5 Y 8/1	Yellowish gray
61	0.80	Red mudstone (2-3 cm calc. soil nodules)	10 R 3/4	Dark reddish brown	5 Y 6/1	Light olive gray	10 R 6/6	Moderate reddish orange
60	0.80	Gray mudstone	5 Y 8/1	Yellowish gray			5 Y 8/1	Yellowish gray
59	0.80	Red mudstone	10 R 4/6	Moderate reddish brown			10 R 5/4	Pale reddish brown
58	0.85	Gray mudstone	5 Y 8/1	Yellowish gray			5 Y 8/1	Yellowish gray
57	1.50	Reddish orange ms. (Lower Double-Red B)	10 R 4/6	Moderate reddish brown			10 R 6/6	Moderate reddish orange
56	0.10	Gray mudstone	5 Y 8/1	Yellowish gray			5 Y 6/1	Light olive gray
55	1.50	Reddish orange ms. (Lower Double-Red A)	10 YR 6/6	Dark yellowish orange			10 R 6/6	Moderate reddish orange
54	1.20	Gray mudstone	5 GY 6/1	Greenish gray			5 Y 8/1	Yellowish gray
53	0.40	Red mudstone	10 R 4/2	Dark grayish red	N 6	Medium light gray	10 R 6/2	Pale red
52	0.50	Brown mudstone (Top Brown)	10 YR 4/2	Dark yellowish brown			5 YR 6/1	Light brownish gray
51	0.30	Very fine-grained sandstone	5 Y 6/1	Light olive gray			5 YR 5/2	Pale brown
50	0.30	Very-fine-grained sandstone	5 Y 6/1	Light olive gray			5 YR 5/2	Pale brown
49	0.60	Very-fine-grained sandstone	5 Y 6/1	Light olive gray			5 Y 7/2	Yellowish gray
48	0.30	Red mudstone	5 R 4/2	Grayish red			10 R 6/2	Pale red
47	0.60	Very-fine-grained sandstone	5 Y 6/1	Light olive gray			5 Y 7/2	Yellowish gray
46	0.20	Brown mudstone	5 YR 3/2	Grayish brown			10 YR 6/2	Pale yellowish brown
45	0.20	Brown mudstone	5 YR 3/2	Grayish brown			10 YR 6/2	Pale yellowish brown
44	0.30	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 7/2	Yellowish gray
43	0.40	Brown mudstone	5 R 4/2	Grayish red			10 YR 6/2	Pale yellowish brown
42	1.30	Gray mudstone	5 Y 5/2	Light olive gray			5 Y 6/1	Light olive gray
41	0.60	Red mudstone (Purple-0)	10 R 4/2	Grayish red			10 R 6/2	Pale red
40	1.30	Gray mudstone	5 Y 5/2	Light olive gray			5 Y 8/1	Yellowish gray
39	2.30	Massive fine-grained micaceous sandstone	5 Y 7/2	Yellowish gray			10 YR 4/2	Dark yellowish brown
38	1.50	Gray mudstone	5 Y 5/2	Light olive gray			5 Y 8/1	Yellowish gray
37	0.10	Red mudstone	5 R 4/2	Grayish red			10 R 6/2	Pale red
36	1.40	Gray mudstone	10 Y 6/2	Pale olive			5 Y 7/2	Yellowish gray
35	1.50	Fine-grained yellow sandstone	5 Y 6/4	Dusky yellow			10 YR 4/2	Dark yellowish brown
34	1.20	Gray mudstone	5 Y 5/2	Light olive gray				
33	0.20	Red mudstone	5 YR 5/2	Pale brown			10 R 6/2	Pale red
32	0.30	Gray mudstone	5 Y 5/2	Light olive gray				
31	0.20	Red mudstone	5 YR 5/2	Pale brown			10 R 6/2	Pale red
30	0.30	Gray mudstone	5 Y 5/2	Light olive gray				
29	0.20	Red mudstone	5 YR 5/2	Pale brown			10 R 6/2	Pale red
28	0.30	Gray mudstone	5 Y 5/2	Light olive gray				
27	0.10	Very-fine-grained friable sandstone	10 YR 4/2	Dark yellowish brown			10 Y 6/2	Pale olive
26	0.50	Gray mudstone	5 GY 6/1	Greenish gray			5 Y 6/1	Light olive gray
25	0.30	Fine-grained flaggy micaceous sandstone	5 Y 8/1	Yellowish gray			10 YR 6/2	Pale yellowish brown
24	0.70	Gray mudstone	5 Y 7/2	Yellowish gray			5 Y 6/1	Light olive gray
23	1.80	Very-fine-grained yellowish gray sandstones	5 Y 7/2	Yellowish gray			5 Y 6/1	Light olive gray
22	0.10	Orange mudstone	10 YR 4/2	Dark yellowish brown				
21	0.40	Gray mudstone	5 Y 6/1	Light olive gray				
20	0.10	Sandstone						
19	0.90	Gray mudstone	5 Y 6/1	Light olive gray				
18	1.20	Very-fine-grained yellowish gray sandstone	5 Y 7/2	Yellowish gray			5 Y 6/1	Light olive gray
17	0.90	Gray mudstone	5 Y 4/1	Olive gray			5 Y 6/1	Light olive gray
16	0.90	Gray mudstone	5 Y 5/2	Light olive gray			5 Y 6/1	Light olive gray
15	0.20	Orange mudstone	10 YR 5/4	Yellowish brown	10 YR 6/2	Pale yellowish brown	10 YR 7/4	Grayish orange
14	0.70	Purplish red mudstone	10 R 3/4	Dark reddish brown			10 R 5/4	Pale reddish brown
13	0.60	Gray siltstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
12	0.30	Orange mudstone	10 YR 5/4	Yellowish brown	10 YR 6/2	Pale yellowish brown	10 YR 7/4	Grayish orange
11	0.30	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
10	0.70	Orange mudstone	10 YR 5/4	Yellowish brown	10 YR 6/2	Pale yellowish brown	10 YR 7/4	Grayish orange
9	0.70	Orange mudstone (Thick Orange)	10 YR 5/4	Yellowish brown	10 YR 6/2	Pale yellowish brown	10 YR 7/4	Grayish orange
8	0.80	Orange mudstone	10 YR 5/4	Yellowish brown	10 YR 6/2	Pale yellowish brown	10 YR 7/4	Grayish orange
7	0.30	Finely laminated gray silty clay	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
6	0.20	Brown mudstone	10 YR 4/2	Dark yellowish brown			10 YR 6/2	Pale yellowish brown
5	0.45	Gray mudstone	5 Y 4/1	Olive gray			5 Y 6/1	Light olive gray
4	0.10	Purple mudstone	10 R 4/2	Grayish red			10 R 6/2	Pale reddish brown
3	0.45	Gray mudstone	5 Y 5/2	Light olive gray			5 Y 6/1	Light olive gray
2	0.20	Red mudstone	10 R 3/4	Dark reddish brown	5 Y 5/2	Light olive gray	10 R 6/2	Pale reddish brown
1	0.60	Gray mudstone	5 GY 7/2	Grayish yellow green			5 Y 8/1	Yellowish gray
0	0.20	Very fine-grained concretionary sandstone	5 Y 7/2	Yellowish gray			5 YR 5/2	Pale brown

TABLE A2 — South Polecat Bench SC-67 stratigraphic section. Beds are listed in stratigraphic order from bottom to top. Color codes are from Goddard et al. (1948). Bed thickness is in meters.

Bed	Thick.	Description	Fresh color		Mottling color		Weathered color	
80	1.00	Orange mudstone	10 YR 5/4	Moderate yellowish brown	5 Y 6/1	Light olive gray	5 Y 6/4	Dusky yellow
79	4.70	Gray mudstone	5 Y 6/1	Light olive gray			10 Y 8/1	Yellowish gray
78	0.40	Red mudstone (Top Red B)	10 R 4/6	Moderate reddish brown	5 Y 6/1	Light olive gray	10 R 6/6	Moderate reddish orange
77	1.40	Gray mudstone	5 Y 6/1	Light olive gray			10 Y 8/1	Yellowish gray
76	1.00	Yellow fine-grained sandstone	5 Y 6/4	Dusky yellow			5 Y 7/2	Yellowish gray
75	1.00	Gray mudstone	5 Y 6/1	Light olive gray			10 Y 8/1	Yellowish gray
74	0.50	Dark gray mudstone	5 Y 5/2	Light olive gray			5 Y 6/1	Light olive gray
73	0.20	Yellow mudstone	5 Y 5/2	Light olive gray	10 YR 5/4	Moderate yellowish brown	5 Y 7/2	Yellowish gray
72	0.60	Gray mudstone	5 Y 6/1	Light olive gray			10 Y 8/1	Yellowish gray
71	0.50	Red mudstone (Top Red A)	10 R 4/6	Moderate reddish brown	5 Y 6/1	Light olive gray	10 R 5/4	Pale reddish brown
70	1.00	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
69	1.50	Orange mudstone	10 YR 6/2	Pale yellowish brown			10 YR 7/4	Grayish orange
68	1.20	Gray mudstone	5 Y 6/1	Light olive gray			10 Y 8/1	Yellowish gray
67	0.20	Red mudstone	10 R 4/2	Grayish red	5 Y 5/2	Light olive gray	10 R 6/2	Pale red
66	2.30	Gray mudstone	5 Y 6/1	Light olive gray			10 Y 8/1	Yellowish gray
65	1.00	Orange mudstone	5 Y 6/1	Light olive gray	5 R 4/2	Grayish red	10 R 5/4	Pale reddish brown
64	0.90	Purple mudstone (Purple-4)	5 RP 4/2	Grayish red purple			5 RP 6/2	Pale red purple
63	0.20	Gray mudstone	5 GY 6/1	Greenish gray			5 GY 8/1	Light greenish gray
62	0.10	Red mudstone	10 R 4/6	Moderate reddish brown			Covered	
61	0.10	Gray mudstone	5 GY 6/1	Greenish gray			5 GY 8/1	Light greenish gray
60	0.10	Red mudstone	10 R 4/6	Moderate reddish brown			Covered	
59	1.40	Gray mudstone	5 GY 6/1	Greenish gray			5 GY 8/1	Light greenish gray
58	0.30	Brown mudstone	10 YR 5/4	Moderate yellowish brown			10 YR 6/2	Pale yellowish brown
57	1.50	Gray mudstone	10 Y 8/1	Yellowish gray			10 Y 8/1	Yellowish gray
56	0.20	Red mudstone	10 R 4/2	Grayish red	10 R 6/6	Moderate reddish orange	10 R 6/2	Pale red
55	0.12	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
54	0.08	Brown mudstone	10 YR 7/4	Grayish orange			10 R 6/2	Pale red
53	0.40	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
52	0.40	Gray sandstone	5 Y 8/1	Yellowish gray			5 Y 8/1	Yellowish gray
51	0.30	Red mudstone	10 R 4/2	Grayish red			10 R 5/4	Pale reddish brown
50	0.20	Red mudstone	10 YR 6/2	Pale yellowish brown			10 R 6/2	Pale red
49	0.40	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
48	0.30	Red mudstone	10 YR 6/2	Pale yellowish brown			10 R 6/2	Pale red
47	0.90	Gray mudstone	5 Y 8/1	Yellowish gray			5 Y 8/1	Yellowish gray
46	0.40	Purple mudstone (Purple-3)	5 R 4/2	Grayish red	5 Y 5/2	Light olive gray	5 RP 6/2	Pale red purple
45	0.60	Red mudstone (Purple-3 at top)	10 R 3/4	Dark reddish brown			10 R 5/4	Pale reddish brown
44	0.50	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
43	0.20	Orange mudstone	10 R 4/2	Grayish red			10 R 6/6	Moderate reddish orange
42	0.40	Gray mudstone	5 GY 6/1	Greenish gray			5 Y 8/1	Yellowish gray
41	0.20	Orange mudstone	10 R 4/2	Grayish red			10 R 6/6	Moderate reddish orange
40	0.50	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
39	0.10	Orange mudstone	10 R 4/2	Grayish red	10 YR 5/4	Moderate yellowish brown	10 YR 7/4	Grayish orange
38	0.05	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
37	0.10	Red mudstone	10 R 4/6	Moderate reddish brown			10 R 5/4	Pale reddish brown
36	0.05	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
35	0.30	Orange mudstone	10 YR 4/4	Moderate brown			5 YR 6/4	Light brown
34	1.00	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
33	0.40	Orange mudstone	10 R 4/6	Moderate reddish brown	10 YR 5/4	Moderate yellowish brown	10 R 5/4	Pale reddish brown
32	0.40	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
31	1.80	Red mudstone (Upper Double-Red)	10 R 3/4	Dark reddish brown			10 R 5/4	Pale reddish brown
30	1.20	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
29	0.40	Red mudstone	10 R 4/6	Moderate reddish brown			10 R 5/4	Pale reddish brown
28	1.00	Gray mudstone	5 Y 8/1	Yellowish gray			5 Y 8/1	Yellowish gray
27	0.10	Orange mudstone	10 YR 5/4	Moderate yellowish brown	5 Y 6/1	Light olive gray	5 GY 6/1	Greenish gray
26	0.20	Gray mudstone	5 Y 8/1	Yellowish gray			5 Y 8/1	Yellowish gray
25	0.20	Orange mudstone	10 YR 6/2	Pale yellowish brown			10 YR 8/2	Very pale orange
24	0.10	Red mudstone	10 R 4/6	Moderate reddish brown	10 YR 5/4	Moderate yellowish brown	10 R 5/4	Pale reddish brown
23	0.90	Orange mudstone	10 YR 4/2	Dark yellowish brown			10 YR 6/2	Pale yellowish brown
22	1.20	Gray mudstone	5 Y 5/2	Light olive gray			5 Y 6/1	Light olive gray
21	0.70	White very-fine-grained sandstone	5 Y 8/1	Yellowish gray			5 Y 8/1	Yellowish gray
20	0.40	Orange mudstone	10 R 4/6	Moderate reddish brown	5 Y 8/1	Yellowish gray	5 Y 8/1	Yellowish gray
19	0.40	Gray mudstone	5 GY 5/2	Dusky yellow green			5 Y 6/1	Light olive gray
18	1.20	Red mudstone (Purple-2)	10 R 4/6	Moderate reddish brown			10 R 6/2	Pale red
17	1.80	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
16	0.10	Planar-bedded very-fine-grained sandstone	5 Y 7/2	Yellowish gray			5 YR 5/2	Pale brown
15	0.10	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
14	0.10	Planar-bedded very-fine-grained sandstone	5 Y 7/2	Yellowish gray			5 YR 5/2	Pale brown
13	0.15	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
12	0.10	Planar-bedded very-fine-grained sandstone	5 Y 7/2	Yellowish gray			5 YR 5/2	Pale brown
11	0.25	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
10	0.20	Red mudstone	10 R 3/4	Dark reddish brown				
9	0.80	Yellow very-fine-grained channel sandstone	5 Y 7/2	Yellowish gray			5 YR 5/2	Pale brown
8	1.80	Reddish orange ms. (Lower Double-Red)	10 R 4/6	Moderate reddish brown			10 R 6/6	Moderate reddish orange
7	1.80	White very-fine-grained sandstone	5 Y 8/1	Yellowish gray			5 Y 8/1	Yellowish gray
6	0.20	Brown mudstone (Top Brown)	10 YR 4/2	Dark yellowish brown			10 YR 6/2	Pale yellowish brown
5	1.60	Soft yellow sandstone	5 Y 6/4	Dusky yellow			5 Y 7/2	Yellowish gray
4	0.20	Fine-grained ledge-forming sandstone	5 Y 6/4	Dusky yellow			10 R 4/2	Dark yellowish brown
3	2.10	Soft yellow sandstone	5 Y 6/4	Dusky yellow			5 Y 7/2	Yellowish gray
2	0.20	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
1	0.40	Brown mudstone with *Celtis*	5 R 3/2	Grayish brown			10 YR 6/2	Pale yellowish brown

TABLE A3 — South Polecat Bench SC-121 stratigraphic section. Beds are listed in stratigraphic order from bottom to top. Color codes are from Goddard et al. (1948). Bed thickness is in meters.

Bed	Thick.	Description	Fresh color		Mottling color		Weathered color	
54	0.50	Red mudstone (Top Red A)						
53	6.90	Gray mudstone						
52	1.00	Purple mudstone (Purple-4)	5 RP 4/2	Grayish red purple			5 RP 6/2	Pale red purple
51	2.00	Gray mudstone						
50	1.70	Gray mudstone with four orange paleosols						
49	2.30	Gray mudstone						
48	7.20	Yellow fine-grained sandstone	5 Y 6/4	Dusky yellow	5 Y 7/2	Yellowish gray	10 YR 6/2	Pale yellowish brown
47	0.60	Red mudstone (Upper Double-Red B)	10 R 4/2	Grayish red			10 R 5/4	Pale reddish brown
46	0.60	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
45	0.90	Red mudstone (Upper Double-Red A)	10 R 3/4	Dark reddish brown			10 R 5/4	Pale reddish brown
44	1.50	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
43	0.60	Orange mudstone	10 R 4/6	Moderate reddish brown			5 YR 6/4	Light brown
42	1.80	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
41	1.80	Gray ms. w. orange and brown paleosols	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
40	1.20	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
39	0.60	Orange mudstone	10 R 4/6	Moderate reddish brown	10 YR 5/4	Moderate yellowish brown	5 YR 6/4	Light brown
38	0.40	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
37	0.80	Purplish red mudstone (Purple-2)	5 R 4/2	Grayish red			5 RP 6/2	Pale red purple
36	0.90	Gray mudstone	5 GY 6/1	Greenish gray			5 Y 8/1	Yellowish gray
35	0.90	Orange mudstone	10 R 4/6	Moderate reddish brown	10 YR 5/4	Moderate yellowish brown	10 R 5/4	Pale reddish brown
34	0.90	Light gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
33	2.80	Red mudstone (Lower Double-Red A & B)	10 R 3/4	Dark reddish brown			10 R 5/4	Pale reddish brown
32	1.20	Gray and orange mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
31	2.70	Yellow medium to coarse-grained sandstone	5 Y 7/2	Yellowish gray			10 YR 6/2	Pale yellowish brown
30	0.25	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
29	0.05	Brown marl	10 YR 7/4	Grayish orange			5 YR 4/4	Moderage brown
28	0.32	Orange mudstone	10 YR 5/4	Moderate yellowish brown			5 YR 6/4	Light brown
27	0.50	Brown mudstone with *Celtis* endocarps	10 YR 4/2	Dark yellowish brown			10 YR 6/2	Pale yellowish brown
26	0.90	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
25	0.80	Very-fine-grained sandstone	5 Y 8/1	Yellowish gray			10 YR 6/2	Pale yellowish brown
24	0.40	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
23	0.35	Brown mudstone	10 YR 4/2	Dark yellowish brown			10 YR 6/2	Pale yellowish brown
22	0.05	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
21	0.40	Brown mudstone	10 YR 4/2	Dark yellowish brown			10 YR 6/2	Pale yellowish brown
20	0.60	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
19	0.30	Orangish red mudstone	10 R 4/2	Grayish red			10 R 6/2	Pale red
18	0.50	Brown mudstone	5 YR 3/2	Grayish brown			10 R 6/2	Pale red
17	0.40	Orangish red mudstone	10 YR 5/4	Moderate yellowish brown			10 R 6/2	Pale red
16	0.20	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
15	0.10	Red mudstone (level of Purple-0?)	10 R 4/2	Grayish red				
14	0.90	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
13	0.20	Brown concretionary sandstone						
12	1.60	Gray mudstone with thin orange beds	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
11	0.70	Fine-grained yellow sandstone	5 Y 6/4	Dusky yellow			5 Y 7/2	Yellowish gray
10	1.20	Fine-grained yellow sandstone	5 Y 6/4	Dusky yellow			5 Y 7/2	Yellowish gray
9	0.90	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
8	0.10	Platy sandstone	5 Y 7/2	Yellowish gray			10 YR 6/2	Pale yellowish brown
7	0.50	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
6	0.20	Orange mudstone	5 Y 5/2	Light olive gray	10 YR 4/2	Dark yellowish brown	10 YR 6/2	Pale yellowish brown
5	1.00	Gray mudstone	5 Y 6/1	Light olive gray			5 Y 8/1	Yellowish gray
4	0.20	Planar-bedded very-fine-grained sandstone	5 Y 7/2	Yellowish gray			10 YR 6/2	Pale yellowish brown
3	1.70	Muddy very-fine-grained sandstone	5 Y 8/1	Yellowish gray	5 Y 6/1	Light olive gray	5 Y 8/1	Yellowish gray
2	1.00	Gray mudstone	5 Y 4/1	Olive gray			5 Y 8/1	Yellowish gray
1	0.50	Purplish red mudstone	5 R 4/2	Grayish red			10 R 6/2	Pale red

TABLE A4 — South Polecat Bench SC-206 stratigraphic section. Beds are listed in stratigraphic order from bottom to top. Color codes are from Goddard et al. (1948). Spacing of paleosols is based on elevations determined by differential GPS. Bed thickness is in meters.

Bed	Thick.	Description	Fresh color		Mottling color		Weathered color	
31	0.50	Red mudstone (near top of Polecat Bench)	10 R 4/6	Moderate reddish brown				
30	8.98	Gray mudstone						
29	0.50	Orange mudstone	10 YR 5/4	Moderate yellowish brown				
28	9.47	Gray mudstone						
27	0.50	Orange mudstone	10 YR 6/2	Pale yellowish brown				
26	1.42	Gray mudstone						
25	0.50	Orange mudstone	10 YR 5/4	Moderate yellowish brown				
24	4.01	Gray mudstone						
23	0.13	Yellowish gray mudstone	5 Y 6/1	Light olive gray				
22	0.00	Gray mudstone						
21	0.50	Yellowish gray mudstone	5 Y 6/1	Light olive gray				
20	5.23	Gray mudstone						
19	0.50	Yellowish gray mudstone	5 Y 5/2	Light olive gray				
18	2.42	Gray mudstone						
17	0.50	Orange mudstone	10 YR 6/2	Pale yellowish brown				
16	0.44	Gray mudstone						
15	0.50	Brown mudstone	10 YR 4/2	Dark yellowish brown				
14	1.32	Gray mudstone (top of SC-206)						
13	0.50	Red mudstone	10 R 3/4	Dark reddish brown				
12	2.00	Gray mudstone						
11	0.50	Red mudstone (middle part of Top Red B)	10 R 3/4	Dark reddish brown				
10	0.03	Gray mudstone						
9	0.50	Red mudstone (lower part of Top Red B)	10 YR 4/2	Dark yellowish brown				
8	3.73	Gray mudstone						
7	0.50	Red mudstone (Top Red A)	10 R 4/6	Moderate reddish brown				
6	0.58	Gray mudstone						
5	0.50	Orange mudstone	10 YR 5/4	Moderate yellowish brown				
4	3.37	Gray mudstone						
3	0.50	Orange mudstone	10 YR 6/2	Pale yellowish brown				
2	2.62	Gray mudstone (base of SC-206)						
1	1.00	Purple mudstone (Purple-4)	5 RP 4/2	Grayish red purple	5 Y 8/1	Yellowish gray	5 RP 6/2	Pale red purple