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MAGNETOSTRATIGRAPHY OF THE LEBO AND TONGUE RIVER MEMBERS OF THE FORT UNION FORMATION (PALEOCENE) IN THE NORTHEASTERN POWDER RIVER BASIN, MONTANA

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ABSTRACT. We analyzed paleomagnetic samples and documented the stratigraphy from two sections near Miles City, Montana to determine the geomagnetic polarity stratigraphy and to constrain the age and duration of the Lebo and Tongue River Members of the Fort Union Formation in the northeastern Powder River Basin. The resulting polarity sequence can be correlated to subchrons C29n–C26r of the geomagnetic polarity time scale. By interpolating measured sediment accumulation rates from the base of C28r to the top of C27n, and then extrapolating to the top of the Tongue River Member and the bottom of the Lebo Member, we developed two age models to estimate the durations of the Lebo and Tongue River Members. Based on the first model, which uses different sedimentation rates for the Lebo and Tongue River Members, we estimate the duration of deposition of the Lebo to be between 1.30 and 1.74 million years and of the Tongue River to be between 1.42 and 1.61 million years. Using the second model, which uses the same sedimentation rate for the Lebo and Tongue River Members, we estimate the duration of deposition of the Lebo to be between 1.33 and 1.76 million years and of the Tongue River to be between 1.00 and 1.25 million years. Our results indicate a decrease in sediment accumulation rates in C27r, which is likely the result of a 0.26 to 0.62 million-year long depositional hiatus in the middle of C27r, represented by the Lebo–Tongue River contact. This unconformity occurs ~2 million years earlier than previously suggested and is likely contemporaneous with unconformities in the Williston Basin and in southwestern Alberta, suggesting that it may be regionally significant.

Key words: Paleocene, magnetostratigraphy, Fort Union Formation, Lebo Member, Tongue River Member, Powder River Basin, unconformity

INTRODUCTION

The Paleocene and Cretaceous terrestrial fossil-bearing successions in the northern Great Plains of North America are ideal for assessing the terrestrial ecosystem's response to mass extinction and long term climatic change through that interval of time. Much of the current understanding about the Cretaceous-Paleogene (K-Pg) boundary extinctions, the evolution of floral and faunal communities in the early Cenozoic, and terrestrial climate change, is the result of study within the Western Interior of North America (for example, Wood and others, 1941; Woodburne, 1977, 1987, 2004; Nichols and Ott, 1978; Hickey, 1980; Tschudy and others, 1984; Johnson and others, 1989; Wing and others, 1995; Manchester, 1999; Wilf, 2000; Pearson and others, 2002; Wilf and Johnson, 2004; Fricke and Wing, 2004; Wing and others, 2005;

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Wilf and others, 2006; Peppe, 2010; Longrich and others, 2011). Many of the Paleocene sequences in North America have used mammalian biochronology (North American Land Mammal Ages or NALMA) (for example, Archibald and others, 1987; Lofgren and others, 2004) or pollen biostratigraphy (for example, Nichols and Ott, 1978; Nichols, 2003) to estimate the ages of the strata. However, the reliance on biostratigraphy to date patterns of faunal or floral change is somewhat circular. To fully assess rates of floral and faunal speciation and regional patterns of radiation following the K-Pg extinction, and to understand long-term trends of terrestrial climate change during the Cretaceous and early Cenozoic, geological sections with independent age control are vital.

In the northeastern corner of the Powder River Basin, a sequence of early to middle Paleocene rocks is exposed in a series of badlands near Miles City, Montana (fig. 1). These primarily terrestrial, fluvial deposits have been the focus of several paleontological and stratigraphic studies (for example, Leonard, 1907; Collier and Smith, 1909; Williams, ms, 1988; Vuke and others, 2001; Belt and others, 2002; Vuke and Colton, 2003; Belt and others, 2004; Wilf and others, 2006; Vuke and others, 2007; Peppe, ms, 2009) However, the Lebo and Tongue River Members of the Fort Union Formation are only constrained to the early and middle Paleocene based on lithostratigraphy and biostratigraphy and there are few estimates for the age of each member. Further, although there is evidence for an unconformity in the region at the Lebo–Tongue River contact (Belt and others, 2004), thus far the unconformity and its duration are poorly constrained geochronologically. This has direct bearing on the age of the fossils within the Lebo and Tongue River Members, and for correlations to early and middle Paleocene strata in the other North American Paleogene basins, such as to correlative strata in the adjacent Williston Basin (fig. 1).

In this study we document the stratigraphy of the Lebo and Tongue River Members of the Fort Union Formation exposed at Signal Butte and Cowboy Mesa near Miles City, Montana, and determine the geomagnetic polarity stratigraphy of the sections. We then correlate the polarity stratigraphy of the members to the Geomagnetic Polarity Time Scale (GPTS) and estimate the age and duration of deposition of each member. Finally, we use estimates of sedimentation rates and the polarity stratigraphy to document the age and duration of an unconformity at the Lebo–Tongue River contact and correlate the Powder River Basin strata to contemporaneous rocks in the Williston Basin. This work provides age estimates for the Lebo and Tongue River Members of the Fort Union Formation in the northeastern Powder River Basin, and constrains the age of the unconformity at the contact between the two members.

PREVIOUS WORK

Lithostratigraphy

The Paleocene Fort Union Formation is widely exposed across the Powder River Basin in eastern Montana and eastern Wyoming and the Williston Basin in the western Dakotas. The Powder River Basin is bounded by the Bighorn Mountains on the west and the Black Hills on the southeast (Foster and others, 1969; Curry, 1971; Blackstone, 1981; Dickinson and others, 1988). The boundary between the Powder River Basin and the adjacent Williston Basin is somewhat arbitrary, but most workers have placed the boundary at the Miles City arch and its extension northwest to the Yellowstone River (fig. 1) (for example, Dickinson and others, 1988; Brown, 1993; Belt and others, 2002; Belt and others, 2004).

Most of the previous work in the Powder River Basin has been focused in the northwestern, central, and southern parts of the basin (for example, Stone and Calvert, 1910; Rogers and Lee, 1923; Bryson and Bass, 1971; Ayers, 1986; Hanley and Flores, 1987; Warwick and Stanton, 1988; Rice and Flores, 1991; Nichols and Brown,

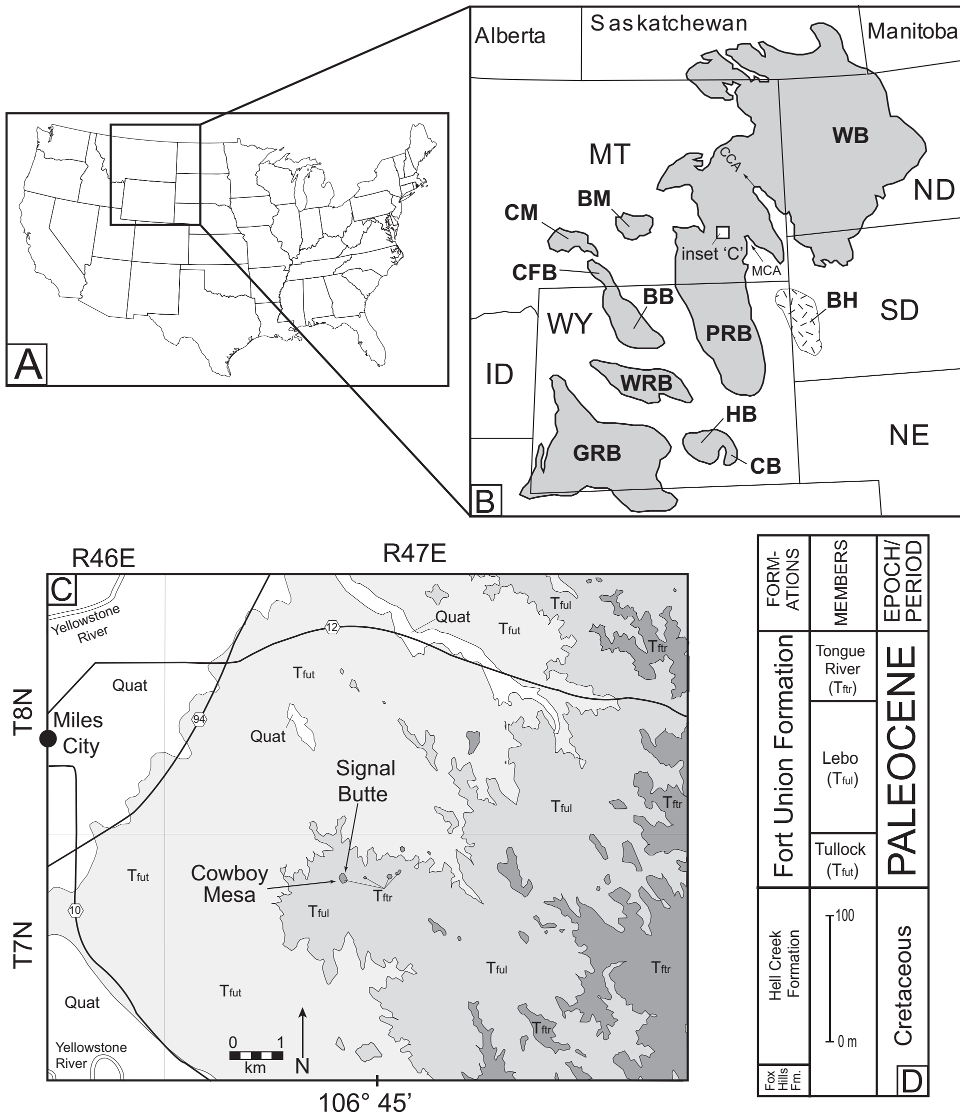

Fig. 1. (A) Locality map of the study area. (B) Major Paleogene basins in the Rocky Mountain Region of North America. WB = Williston Basin, BM = Bull Mountain, CM = Crazy Mountains, CFB = Clark's Fork Basin, BB = Bighorn Basin, PRB = Powder River Basin, WRB = Wind River Basin, HB = Hanna Basin, CB = Carbon Basin, GRB = Green River Basin, BH = Black Hills, CCA = Cedar Creek Anticline, MCA = Miles City Arch. (C) Locality map of study area in northeastern Powder River Basin in Montana showing location of Signal Butte and Cowboy Mesa. Quat = Quaternary sediments; Tfut = Tullock Member of the Fort Union Formation; Tful = Lebo Member of the Fort Union Formation; Tftr = Tongue River Member of the Fort Union Formation. Geology is modified from Vuke and others (2001) and Vuke and others (2007). (D) Generalized stratigraphy of Cretaceous and Paleocene sections of northeastern Powder River Basin.

1992; Nichols and others, 1992; Brown, 1993; Nichols, 1994; Rice and others, 2002; Nichols, 2003; Vuke and others, 2007). In the northeastern corner of the Powder River Basin near the Miles City Arch, the coal fields were intensely studied at the turn of the century for their mineral potential (Leonard, 1907; Collier and Smith, 1909; Bowen, 1910; Herald, 1910; Rogers, 1911; Calvert, 1912). Subsequently, the surface and subsurface of the area has been mapped (Rice, 1976; Ellis and Colton, 1995; Vuke and others, 2001; Vuke and Colton, 2003; Vuke and others, 2007). Across the Powder River Basin the Paleocene Fort Union Formation conformably overlies the Cretaceous Hell Creek Formation in the northeastern part of the basin, and the Lance Formation in the northwestern and southern portions of the basin. The formational contact between the Fort Union and Hell Creek/Lance Formations is placed at the base of the lowest persistent coal bed (for example, Rogers and Lee, 1923; Nichols and Brown, 1992; Nichols and others, 1992). The formational contact is also the approximate position of the pollen-defined K-Pg boundary (Nichols and Brown, 1992; Nichols and others, 1992). The thickness of the Fort Union Formation is extremely variable in the Powder River Basin and ranges from ~200 m in the northeast to as much as 1000 m in the south (for example, Rogers and Lee, 1923; Brown, 1993; Vuke and others, 2001; Vuke and Colton, 2003; Belt and others, 2004; Vuke and others, 2007, this study). The Fort Union Formation is divided into the Tullock, Lebo, and Tongue River Members. The Tullock Member is characterized by its light-buff color, even bedding, and thin coal beds, and it ranges from ~50 m thick in the northeast to 439 m thick in the south (Rogers and Lee, 1923; Dorf, 1940; Dorf, 1942; Brown, 1993; Vuke and others, 2001; Belt and others, 2004; Vuke and others, 2007). The Lebo Member is lithologically variable across the basin, but is primarily made up of poorly lithified gray to brown sandstone and siltstone beds that are often smectite-rich with continuous lignite deposits (for example, Stone and Calvert, 1910; Rogers and Lee, 1923; Vuke and others, 2001; Belt and others, 2004; Vuke and others, 2007). Near the Miles City Arch the Lebo Member is between 50 and 120 m thick (Vuke and others, 2001; Belt and others, 2004; Vuke and others, 2007). The contact between the Tullock and Lebo Members is based either on a major lithologic change between the members or by the presence of a thick (>1 m), laterally continuous lignite deposit (for example, Rogers and Lee, 1923). The Tongue River Member is characterized by siltstone and sandstone beds with a high clay fraction made up of kaolinite and illite that are yellow to buff color (Vuke and others, 2001; Belt and others, 2004; Vuke and others, 2007). Near Miles City, Montana, the Tongue River Member is up to 100 m thick (Vuke and others, 2001; Vuke and others, 2007). The contact between the Lebo and Tongue River Members is easily recognized by the lithologic change. In the northeastern Powder River, in addition to the lithologic change, a calcareous, rippled sandstone bed with abundant burrows marks the base of the Tongue River Member (Belt and others, 2004).

Near Miles City, Montana, the Paleocene strata exposed at Signal Butte and Cowboy Mesa (fig. 1) have been the focus of stratigraphic studies for over a century. Leonard (1907) measured a composite section over a ~6 km SW-NE transect from exposures along the Tongue River Member to the top of Signal Butte. Based on the presence of fossil leaves, identified by F. H. Knowlton to be diagnostic of the Fort Union Formation, Leonard (1907) inferred that the entire composite section belonged to the Fort Union Formation. However, he did note that only the uppermost 200 feet of his section, which were comprised of strata exposed on Signal Butte, appeared to resemble typical Fort Union beds. Based on the regional geology (for example, Vuke and others, 2001; Vuke and others, 2007), it is possible that Leonard's (1907) measured section incorporated strata from both the Hell Creek and Fort Union Formations.

Collier and Smith (1909) mapped the distribution of major, laterally continuous lignite or coal beds in the Miles City area, named three of the units that had been mined, and labeled all of the units on their regional geologic map using the letters A–F. The C, or the Laney, bed has been cited as representing the contact between the Tullock and Lebo Members in the Miles City area (for example, Belt and others, 2004). In addition to mapping lignite beds, Collier and Smith (1909) described the stratigraphy of the Fort Union Formation and divided it into unnamed upper and lower stratigraphic members. They noted that the lower member was comprised of alternating beds of claystone, sandstone, and lignite and had a "general dark-gray or somber hue" (Collier and Smith, 1909, p. 40) and the upper member was characterized by fine-grained, relatively homogeneous, yellow-colored strata. Given their stratigraphic descriptions, the upper member is probably the Tongue River Member and the lower member probably represents the Lebo and Tullock Members. There is a transition from lighter colored sandstone and shale beds with rare, thin lignite beds to gray and blue sandstone and shale beds with abundant, thick lignite beds at ~50 m above the base of their stratigraphic section in Collier and Smith's (1909) stratigraphic description of the lower member. This suggests that the lowermost ~50 m of Collier and Smith's (1909) lower member is probably correlative to the Tullock and the uppermost ~90 m is correlative to the Lebo Member.

Later, Belt and others (2004) measured the thickness of the Lebo and Tongue River Members of the Fort Union Formation at Signal Butte and correlated the sections to Lebo and Tongue River strata eastward in the Terry Badlands and the Pine Hills areas of the westernmost Williston Basin. Based on a series of paleo-valleys in the Terry Badlands and Pine Hills areas, the stratigraphic position of palynostratigraphic zone P3 (see Nichols, 2003), and a $^{40}Ar/^{39}Ar$ date from Signal Butte at 53 m in the Cowboy Mesa section (Appendix 1), they proposed that the Lebo–Tongue River Member contact was unconformable and occurred at ~63.5 Ma. The duration of the unconformity was not estimated.

Magnetostratigraphy

No paleomagnetic studies in the Paleocene Fort Union Formation have been undertaken in the northeastern Powder River Basin. However, several studies of the Hell Creek Formation and the Ludlow Member of the Fort Union Formation have been conducted in the adjacent Williston Basin in Montana and North Dakota, and in Paleocene rocks in southwestern Alberta, Canada. The first magnetostratigraphic study of lower Paleocene sediments in the area was carried out by Archibald and others (1982), who recognized two normal-polarity intervals bracketing a reversed-polarity interval containing the K-Pg boundary. They identified black, opaque minerals in the sediments, interpreted to be either magnetite or titanomagnetite, which they inferred to be the detrital remanence-bearing mineral. The section was later correlated to the GPTS and related to C30n–C28n by Swisher and others (1993). Additionally, Swisher and others (1993) recognized the detrital remanence-bearing mineral to be intermediate-composition titanohematite. Lerbekmo and Coulter (1984) completed a small magnetostratigraphic section in central Montana and related a reversed-polarity interval spanning the K-Pg boundary to C29r. Lund and others (2002) conducted rock-magnetic analysis and studied the magnetostratigraphy of four sections in central North Dakota and eastern Montana. They made regional correlations of the Hell Creek–Fort Union formational contact and identified the primary detrital magnetic mineral as hemo-ilmenite. Hicks and others (2002) conducted a magnetostratigraphic and geochronologic study of the K-Pg boundary in southwestern North Dakota. They located the position of C29r in six stratigraphic sections and recalibrated the age of the K-Pg boundary. Peppe and others (2009) studied the magnetic mineralogy and magnetostratigraphy of the Hell Creek Formation and the Ludlow Member of the Fort Union Formation. They correlated the polarity stratigraphy of the interval to C30n–C27r, and demonstrated that the principal magnetic carrier of the Ludlow Member was titanomaghemite. In southwestern Alberta, Lerbekmo and Sweet (2000) studied the magnetostratigraphy of Paleocene strata, identifying C29r–C26r, and related the magnetostratigraphy to pollen biostratigraphy. Lerbekmo and Sweet (2008) conducted a magnetostratigraphic study of the Paleocene Coalspur and Paskapoo Formation in Alberta and recognized the interval C29r–C24r.

METHODOLOGY

Lithostratigraphy

We trenched and measured two stratigraphic sections through the Lebo and Tongue River Members of the Fort Union Formation at Cowboy Mesa and Signal Butte in 2004 (Appendix 1, fig. 2). At both sections we dug continuous trenches deep enough to expose fresh bedrock and bedding contacts. Both sections were measured to the nearest centimeter; and the lithology, grain size, stratigraphic thickness, sedimentary structures, and any biological features such as root traces or fossil leaves were documented for each stratigraphic unit (Appendix 1). The Lebo Tongue River contact, which occurs in both sections (see discussion below), was used as the reference datum for correlating the sections. We collected paleomagnetic samples at regular intervals from both stratigraphic sections. At Cowboy Mesa, forty-seven horizons were sampled with a mean interval of 1.8 m (maximum interval: 4.06 m; minimum interval: 0.3 m). At Signal Butte, thirty horizons were sampled with a mean sampling interval of 1.5 m (maximum interval: 5.8 m, minimum interval: 0.5 m).

Paleomagnetic Analyses

We collected three to four paleomagnetic block samples from each sampling horizon. A flat face was shaved on the *in situ* specimen with a hand rasp, and the strike and dip orientation of the face was measured with a Brunton pocket transit compass. We collected samples from a range of lithologies from fine sandstone to mudstone. In the laboratory, the block samples were hand cut with a diamond bit saw into ~10 cm^3 cuboids.

We measured samples at Yale University using an automated three-axis DC-SQuID magnetometer housed inside a three-layer magnetostatic shield with a background field typically less than 200 nT. The samples were demagnetized using a combined alternating-field (AF) and thermal demagnetization strategy (Schmidt, 1993; Peppe and others, 2009), in which heating steps >100 °C were performed in a nitrogen atmosphere to minimize oxidation reactions. All samples were first given a low-AF pre-treatment to remove any low-coercivity viscous or isothermal remanence. Ten to twenty thermal demagnetization steps were performed from 75 °C to the maximum unblocking temperature (typically 250-400 °C) on at least one sample from every horizon. The other samples from each horizon were treated by step-wise AF demagnetization. In general, AF demagnetization results were similar to thermal demagnetization. Progressive thermal or AF demagnetization was carried out until the magnetic intensity of the samples fell below noise level, or more commonly, as the measured directions became erratic and unstable.

Extensive rock magnetic work on Paleocene sediments in the Williston Basin carried out by Peppe and others (2009) showed that the dominant magnetic carrier is titanomaghemite with a minor secondary component of goethite. Low-field magnetic susceptibility versus temperature curves showed predominantly irreversible behavior and in some samples there was an inflection in the curves at ~180 to 200 °C indicating titanomaghemite. SEM analysis, anhysteretic remanent magnetization, and magnetic hysteresis analysis were all consistent with the interpretation of titanomaghemite. The magnetic carrier, titanomaghemite, is interpreted to be detrital because (1) the deposits are clearly fluvial in origin and bear little evidence for diagenesis, (2) the remanent directions calculated from the sedimentary samples are scattered, but consistent with those expected for the Paleocene of North America, and (3) the paleomagnetic pole direction determined from the calculated directions is slightly far-sided relative to the Earth's rotation axis, suggesting potential inclination shallowing. IRM acquisition values of samples and thermal demagnetization data suggested an additional variable presence of goethite. The goethite present in the samples was interpreted to be the result of secondary precipitation related to water penetration in the sediments.

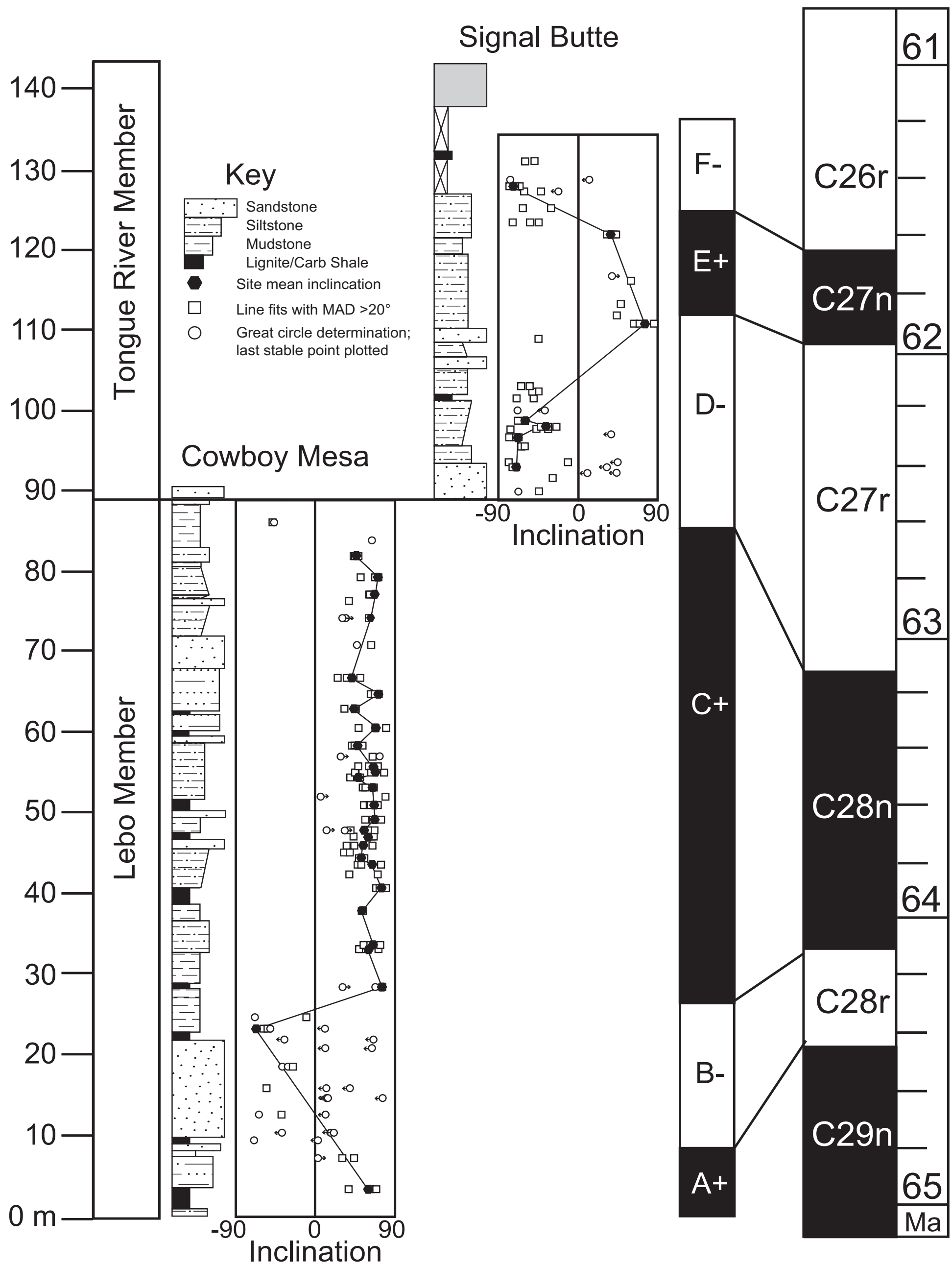

Fig. 2. Lithostratigraphic and magnetostratigraphic sections for Cowboy Mesa and Signal Butte. The two sections are aligned based on lithological correlations made in the field. Paleomagnetic remanence inclination vs. stratigraphic level (meters) is plotted for both sections. Arrows on great-circle determinations indicate the direction that samples were moving when the last stable point was measured. The composite polarity stratigraphy for both sections (black is normal, white is reversed) is related to the geomagnetic polarity time scale of Ogg and Smith (2004) on the far right of the figure.

The demagnetization behavior of samples from the Lebo and Tongue River Members analyzed in this study is identical to that observed by Peppe and others (2009) in Fort Union Formation sediments in the adjacent Williston Basin. This demagnetization behavior, coupled with low-field magnetic susceptibility versus temperature curves of samples from Signal Butte that show predominately irreversible behavior (D. J. Peppe, unpublished data), suggests that the dominant magnetic carrier in the sediments from Signal Butte and Cowboy Mesa is also likely detrital titanomaghemite with a minor secondary component of goethite.

The characteristic remanence for samples with quasi-linear trajectories was isolated using principal-component analysis (PCA) (Kirschvink, 1980). Best-fit lines were calculated when a minimum of three consecutive demagnetization steps that had a maximum angle of deviation (MAD) less than 20° and trended toward the origin (fig. 3). Specimens that were analyzed by great circles were used if they had a MAD less than 20° (fig. 3). Data from specimens that had erratic demagnetization behaviors were excluded. The site-mean direction of each horizon with three or more directions that were calculated by PCA, was determined using Fisher statistics (Fisher, 1953). Site means that had an alpha-95 (a95) greater than 35°, exceeding the cut-off value based on the randomness criteria of Watson (1956) were not used.

It was not possible to calculate statistically significant site means from all sampling horizons; therefore, reversal boundaries were placed at the stratigraphic midpoints between samples of opposing polarity (table 1, fig. 2). The stratigraphic position of each reversal was calculated relative to the base of the Cowboy Mesa section (the Tullock-Lebo contact) (table 1, fig. 2). The reversals can be placed with a resolution of 1.1 to 3.7 m, depending on spacing dictated by the suitability of lithologies for paleomagnetic sampling. The resulting polarity stratigraphy was then correlated to various Paleocene geomagnetic polarity time scales (GPTS) (see below).

RESULTS

Lithostratigraphy

There are marked sedimentological differences between the Lebo and Tongue River Members at Cowboy Mesa and Signal Butte. At Cowboy Mesa, the Lebo Member is 89 m thick, and the lithologies are dominated by drab-colored mudstone, silty mudstone, carbonaceous shale and lignite beds (fig. 2, fig. 4, Appendix 1). Most of the Lebo is also exposed on Signal Butte. However, the entire member was more easily trenched and measured on Cowboy Mesa, and thus we focused our stratigraphic study of the Lebo at Cowboy Mesa. The basal contact of the Lebo Member is a thick (>1 m) lignite bed. There is a considerable lithologic change below this thick lignite bed from buff-colored sediments characteristic of the Tullock Member to drab-colored beds characteristic of the Lebo Member. Given that the lignite is at the member contact between the Tullock and Lebo Members it may be the C-coal (for example, Collier and Smith, 1909; Rogers and Lee, 1923). However the term "C-coal" has applied regionally to all thick lignites near or at the Tullock-Lebo contact making it impossible to confidently correlate the lignite at Cowboy Mesa to the type C-coal bed of Collier and Smith (1909). Mudstone and silty mudstone beds are the dominant lithologies, making up more than 40 percent of the total thickness of strata. These beds typically show some evidence for pedogenesis including rooting or burrowing, iron-staining, pressure faces, and rare slickensides and mottling. These fine-grained beds are laterally variable in thickness and lithology. The clay fraction in the finer-grained beds of the Lebo Member is primarily smectite (Belt and others, 2004). Fine and very fine-grained sandstone beds make up 14 percent of the total strata and commonly have sedimentary structures such as ripples and cross-bedding, indicating that they were likely fluvial, channel deposits. The lignite and carbonaceous shale beds, which make up 35 percent

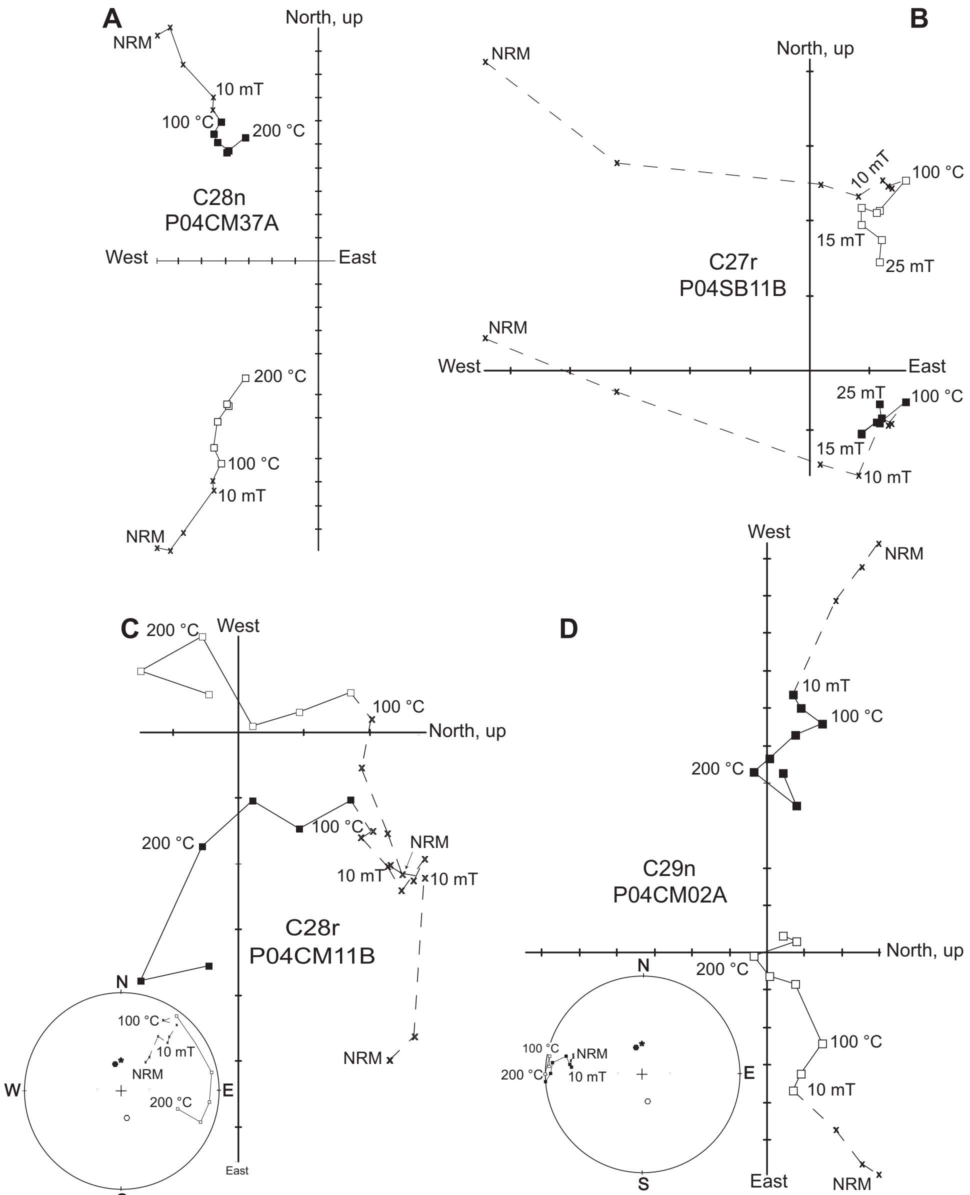

Fig. 3. Vector endpoint diagrams of samples from Cowboy Mesa and Signal Butte. (A) Demagnetization trajectory of a representative normal sample. (B) Demagnetization trajectory of a representative reversed sample. (C) Representative reversed polarity sample were calculated when a minimum of three consecutive with demagnetization trajectory characterized as a great circle. (D) Representative normal polarity sample with demagnetization trajectory characterized by a great circle.

of the strata, often form packages of sediment ≥1 m thick that are typically very laterally continuous. Fossil leaves are common in the mudstone, silty mudstone, and carbonaceous shale beds (Peppe, ms, 2009).

The basal unit of the Tongue River Member is a laterally continuous, 120 cm thick calcareous sandstone unit with current ripples and abundant burrows. This bed is exposed

TABLE 1

Stratigraphic position of polarity zone boundary

Section name	Magnetic Zone	Chron	Lowermost sample in chron	Uppermost sample in chron	Chron thickness (m)	Error[1] (m)
Cowboy Mesa	A+	29n	P04CM01	P04CM02	7.3	n/a
Cowboy Mesa	B-	28r	P04CM03	P04CM12	18.1	2.4
Cowboy Mesa	C+	28n	P04CM13	P04CM46	57.6	3.7
Cowboy Mesa/ Signal Butte	D-	27r	P04CM47	P04SB17	29.1	3.3
Signal Butte	E+	27n	P04SB18	P04SB25	12.1	1.1
Signal Butte	F-	26r	P04SB26	P04SB31	18.3	1.5

[1] Error is the distance in meters between samples of opposite polarity at the base of the magnetic zone (for example, for magnetic zone B−, an error of 2.4 is the stratigraphic distance between normal sample P04CM02 and reversed sample P04CM03.

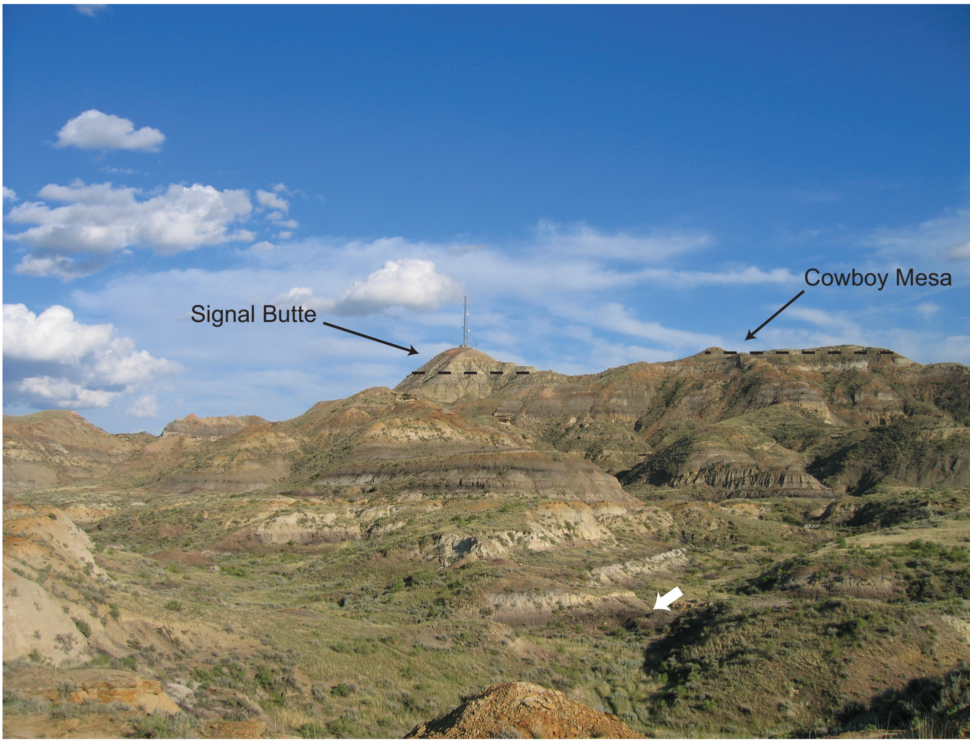

Fig. 4. Photo of Cowboy Mesa (foreground) and Signal Butte (background) taken facing northeast with the position of the Lebo–Tongue River Member contact indicated at each site by a dashed black line. The location of the base of the Lebo Member, is indicated by a white arrow in the foreground. There is a noticeable change from drab-colored mudstone, silty mudstones, and lignite beds in the Lebo Member to tan and yellow siltstone and silty mudstone strata in the Tongue River Member.

on both Cowboy Mesa and Signal Butte, and was also noted on Signal Butte by Belt and others (2004) who called it the "basal burrow bed." To correlate between our two stratigraphic sections, we physically traced the basal burrowed bed, as well as the underlying beds of the Lebo Member laterally from Cowboy Mesa to Signal Butte. The Tongue River Member is 55 m thick on Signal Butte and is dominated by tan, yellow, and buff colored silty mudstone and siltstone beds with a high clay fraction (fig. 2, fig. 4, Appendix 1). The clay minerals in the Tongue River Member are dominated by kaolinite and illite (Belt and others, 2004). In addition to the basal burrowed bed, there are multiple units with intense burrowing and bivalves. These burrowed horizons have been interpreted to represent marine or brackish facies (Belt and others, 2004). Some of the siltstone and silty mudstone beds have small rhizomorphs, suggesting some limited pedogenesis. There are rare, thin lignite beds in the Tongue River, as well as relatively thin channel sandstone deposits with cross bedding and ripples. Fossil leaves are present in siltstone beds in the Tongue River, but are considerably less abundant than in the Lebo Member (Peppe, ms, 2009). There is a significant difference in the fossil leaf species present in the Tongue River and Lebo Members (Peppe, ms, 2009).

The notable lithologic and color differences between the Lebo and Tongue River Member strata (fig. 2, fig. 4), the difference in fossil leaf species present in both members (Peppe, ms, 2009), and the presence of the basal burrowed bed in the Tongue River Member make the contact between the two members at Cowboy Mesa and Signal Butte easily recognizable.

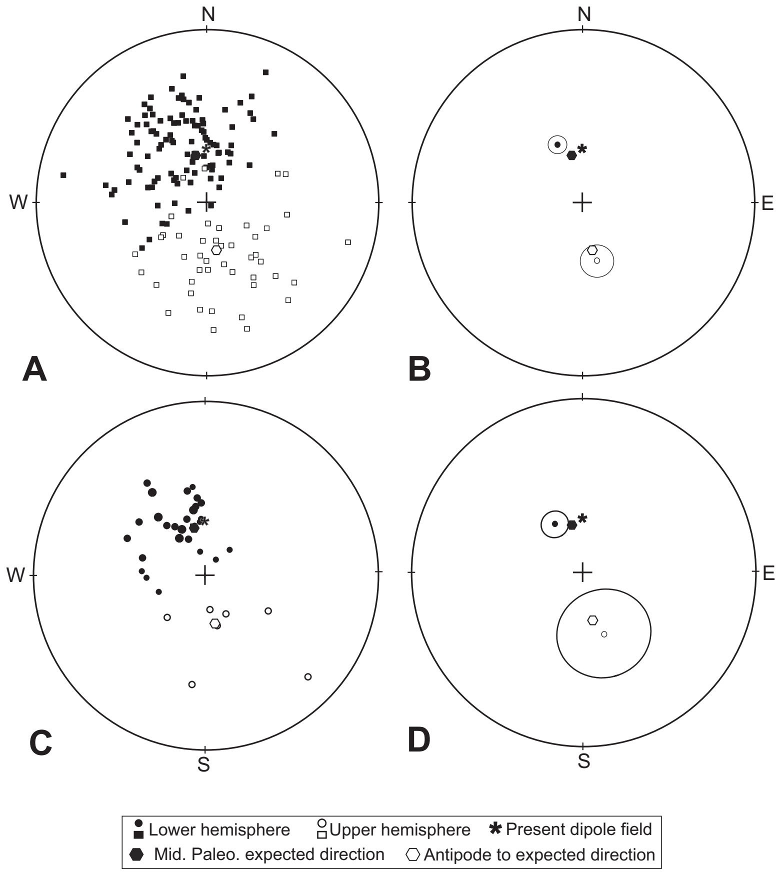

Fig. 5. (A) Equal-area plot of characteristic magnetization directions calculated from all lines measured in this study. (B) Mean normal and reversed polarity directions from lines, plotted with present-day field position, the middle Paleocene direction, and the antipode to the expected Paleocene direction. Ellipse around mean direction represents 95% confidence cone (Fisher, 1953). (C) Equal-area plot of all site-mean directions. (D) Mean normal and reversed directions of site means, plotted with present-day field position, the middle Paleocene direction (Diehl and others, 1983), and the antipode to the expected Paleocene direction. Ellipse around mean direction represents 95% confidence cone (Fisher, 1953).

Magnetostratigraphy

Many specimens' demagnetization trajectories turned toward the origin after a few steps and were fully demagnetized by 250 to 400 °C (fig. 3). A subset of the samples had demagnetization trajectories that were best characterized by a great circle, and thus only a plane containing the characteristic component of the samples was defined (fig. 3). We measured 190 samples from 75 sampling horizons that passed our selection criteria. Thirty-five of the sampling horizons passed our site-mean selection criteria (that is, sites with three or more samples that could be used to calculate a site mean with an alpha-95 value of less than 35°). Data from all lines and the site means at each statistically robust sampling horizon (alpha-95 value of less than 35°) are plotted on the equal-area projections in figure 5 (see Appendices 2 and 3 for data from all specimens and site means). Paleomagnetic directional data for each polarity zone were determined based on best-fit line calculations (table 2). Because some sites yielded more than one line at a single sampling horizon, the polarity-zone directional data may be susceptible to type I statistical error (spuriously high precision of the mean). However,

Table 2

Mean paleomagnetic directional data from the Lebo and Tongue River Members of the Fort Union Formation

Subset	**n***	**D†**	**I§**	**k#**	**a95****	**pole °N††**	**pole °E††**	**K§§**	**A95§§**
C29n - lines	5	341.8	49.8	19	18	71.2	124.6	16.9	19.1
C28r - lines	6	178.9	-45.2	6.05	29.7	72.6	73.3	5.0	33.5
C28n - lines	82	333.5	62.1	13.9	4.3	71.7	172.3	7.7	6.1
C27r - lines	12	191.4	-65.2	11.3	13.5	81.2	311.6	5.8	19.8
C27n - lines	6	326.3	48.1	17.4	16.5	59.2	145.7	12.4	19.8
C26r - lines	29	159.8	-61.6	7.8	10.2	80.8	154.5	4.3	14.6
All normal - sites	28	330.9	62.7	19.5	6.3	70.1	173.7	9.9	9.1
All reversed - sites	7	161.2	-59.1	8.8	21.5	77.7	156.6	6.7	25.1
Dual polarity - sites	35	333.1	62.1	16.3	6.2	71.7	171.5	9.2	8.4

* number of lines or sites included in the mean; † declination; § inclination; # Fisher's (1953) precision parameter; ** radius of 95% confidence cone around mean (ibid.); †† mean of virtual geomagnetic poles calculated from each line or site mean; §§ Fisher statistics of paleomagnetic pole.

Reversed-polarity paleomagnetic poles have been inverted to the northern hemisphere for comparison with normal-polarity poles.

Dual polarity lines and sites are for C29n–C26r, inclusive.

for some zones there were too few site-mean directions to calculate a meaningful paleomagnetic direction, thus individual lines were used.

Paleomagnetic directional data for all normal and reversed zones, and a dual-polarity mean direction, was calculated based on site mean data (table 2, fig. 5, Appendices 2 and 3). The mean normal declination and inclination for sites is 330.9° and 62.7° (n=28; a95=6.3°). The mean reversed declination and inclination for sites is 161.2° and −59.1° (n=7; a95=21.5°). The dual-polarity mean direction (that is, all declinations and inclinations converted to normal polarity) for sites is 333.1° and 62.1° (n=35; a95=6.2°). Using the mean normal and reversed directions for sites, the null hypothesis of anti-parallelism cannot be rejected with greater than 95 percent confidence, and the critical angle of the reversal test implies a positive result of class C (McFadden and McElhinny, 1990).

We calculate a combined dual-polarity paleomagnetic pole from the Lebo and Tongue River Members, from the mean of 35 site-mean virtual geomagnetic poles, at 71.7°N, 171.5°E (n=35; K=9.2, A95=8.4°). This result is indistinguishable from the equivalent site-mean pole derived from the approximately coeval (earliest Paleocene) Ludlow Member of the Fort Union Formation east of the Cedar Creek Anticline (Peppe and others, 2009), as well as from the Edmonton Group in polarity Chron C29 (Lerbekmo and Coulter, 1985) and from the Montana intrusions at 61 to 67 Ma (Diehl and others, 1983).

DISCUSSION

Relationship of Polarity Stratigraphy to GPTS

The pattern of magnetic polarity reversals in the Cowboy Mesa and Signal Butte sections is constrained by the K-Pg boundary and pollen biostratigraphy, which can be used to guide correlation of our local magnetostratigraphy to the GPTS. In the Powder River Basin, the K-Pg boundary is roughly coincident with the Fort Union–Hell Creek/Lance formational contact (Nichols and Brown, 1992; Nichols and others, 1992; Brown, 1993). The base of the Lebo Member in the northeastern Powder River Basin is at least 50 m above the basal Fort Union formational contact (for example, Vuke and others, 2001), thus the base of our magnetostratigraphic section is at least 50 m above the K-Pg boundary. In the adjacent Williston Basin, the K-Pg boundary has been well documented to be within C29r (Archibald and others, 1982; Lerbekmo and Coulter, 1984; Swisher and others, 1993; Hicks and others, 2002; Peppe and others, 2009). Therefore, the lower normal polarity interval at Cowboy Mesa (A+ in fig. 2) must correlate to one of the early Paleocene normal-polarity Chrons (C29n, C28n, C27n) because correlation to C30n would mean that the Tullock Member of the Fort Union Formation was deposited during the late Cretaceous, which is impossible based on well documented fossil evidence (for example, Williams, ms, 1988; Nichols and Brown, 1992; Nichols and others, 1992; Brown, 1993; Wilf and others, 2006; Peppe, ms, 2009).

The uppermost strata of the Lebo and all of the Tongue River strata at Cowboy Mesa and Signal Butte are within palynostratigraphic zone P3 (Belt and others, 2004). In the adjacent Williston Basin, this pollen zone first occurs in the Little Missouri River Valley within C28r at ~64.1 Ma (Warwick and others, 2004; Peppe and others, 2009) and in the Ekalaka area at ~64.0 Ma (Belt and others, 2002, 2004). $^{40}Ar/^{39}Ar$ dates from the Williston Basin suggest that the P3–P4 pollen zone boundary occurs at ~61 Ma (Nichols, 2003; Belt and others, 2004). Thus, it is unlikely that the uppermost reversed interval (F− in fig. 2) is younger than C26r. Given these minimum and maximum age constraints, we propose the following correlation to the GPTS for the polarity stratigraphy at Cowboy Mesa and Signal Butte: A+ to C29n, B− to C28r, C+ to C28n, D− to C27r, E+ to C27n, and F− to C26r (fig. 2).

An $^{40}Ar/^{39}Ar$ date of 64.56 ± 0.43 Ma from the upper Lebo Member at Signal Butte runs counter to our correlation (Belt and others, 2004). The radiometric date was from an ash bed 53 m above the base of the Lebo Member, which should correlate to polarity zone C+ at nearby Cowboy Mesa (fig. 2). Taken literally, the date would suggest that polarity zone C+ correlates to C29n [age range: 65.118-64.432 Ma in Ogg and Smith (2004)], and the entire set of polarity zone correlations from Cowboy Mesa and Signal Butte would be: A+ to 30n, B− to 29r, C+ to 29n, D− to 28r, E+ to 28n, F− to 27r. This correlation is highly improbable for two reasons. First, as discussed in Belt and others (2004) the ash was collected from a lignite bed assigned to pollen zone P3. The pollen zone P2–P3 boundary in the adjacent Williston Basin occurs at ~64 to 64.1 Ma. Thus, if correct, the date suggests a significant diachroneity of 400 to 500 kyr in the pollen zonation between the adjacent Powder River and Williston Basins. Second, it would mean that the lowermost Lebo strata at Cowboy Mesa, and thus the ~50 m thick Tullock Member is Cretaceous in age, which contradicts fossil evidence (see above discussion). Given that the magnetostratigraphic correlation implied by the date presented in Belt and others (2004) is implausible, we suggest that the $^{40}Ar/^{39}Ar$ date of 64.56 ± 0.43 Ma must be anomalously old for the interval. Belt and others (2004) mention the discrepancy in the date from Signal Butte and the pollen zonation, and they suggest that the difference in the dates between the Williston Basin ashes and the Signal Butte ash may be the result of inter-laboratory variation. Alternatively, the anomalously old date may be due to inheritance of older volcanic crystals into the erupted ash. Preliminary U-Pb dates of zircons from the same ash were also all anomalously old (Bowring and others, 2008), suggesting a potential bias in ages due to inheritance. Further work focused on dating this and the other ash beds from Cowboy Mesa and Signal Butte may help to resolve this discrepancy.

Duration of the Lebo and Tongue River Members

Using the stratigraphic thickness of each polarity zone (table 1) and age estimates from seafloor spreading models (Cande and Kent, 1995; Ogg and Smith, 2004) and stable, long eccentricity cyclicity calculations (Westerhold and others, 2008) we can calculate the sedimentation rate of each polarity zone in our magnetostratigraphic section and the duration of the Lebo and Tongue River Members (table 3). The primary calibration points used in this study were the base of C28r, which ranges from 64.572 Ma (Westerhold and others, 2008) to 63.976 Ma (Cande and Kent, 1995), and the top of C27n, which ranges from 62.154 Ma (Westerhold and others, 2008) to 60.920 Ma (Cande and Kent, 1995).

Assuming no hiatuses in deposition, there would appear to be a change in sedimentation rate in C27r, which spans the Lebo–Tongue River contact (fig. 6). The member boundary has been suggested to be unconformable by Belt and others (2004) based on a series of paleo-valleys in the Terry Badlands and the intensely burrowed unit at the base of the Tongue River Member. The change in sedimentation rates noted by our work is consistent with the hypothesis that the formational contact is unconformable. To estimate the duration of the Lebo and Tongue River Members and the duration of the unconformity represented by the lithologic contact, we constructed two age models. The first model uses different sedimentation rates for the Lebo and Tongue River Members, and the second model uses the same sedimentation rate for the Lebo and Tongue River Members. In the following discussion, the quoted ranges in estimated ages and durations of sedimentation arise from the four alternative GPTS calibrations (Cande and Kent, 1995; Ogg and Smith, 2004; and two estimates from Westerhold and others, 2008).

In the first model the duration and age of the Lebo Member is estimated using the average sedimentation rate from C28r and C28n, and the duration and age of the Tongue River is estimated using an average sedimentation rate for C27n (table 3). Using the former sedimentation rate and a total thickness of 89 m for the Lebo

Table 3

Sedimentation accumulation rates and calculated duration of Lebo and Tongue River Members of the Fort Union Formation using two different age models

Ogg & Smith (2004)

stratigraphic/chron interval	myr*	meters	m/myr†	base (Ma§)	top (Ma¥)
C29n (top portion)		8.5			
C28r	0.304	18.1	59.539	64.432	64.128
C28n	1.024	57.6	56.250	64.128	63.104
C27r (Lebo only)		4.8			
C27r (Tongue River only)		24.3			
C27r (total Lebo+Tongue River)	1.121	29.1	25.959	63.104	61.983
C27n	0.333	12.1	36.336	61.983	61.650
C26r (bottom portion)		18.3		61.650	
All complete chrons	2.782	116.9	42.020	64.432	61.650
Complete chrons except C27r	1.661	87.8	52.860		
Model 1					
Duration Lebo	1.561	89.0	57.003	64.581	63.020
Duration unconformity	0.368	n/a	n/a	63.020	62.652
Duration Tongue River	1.505	54.7	36.336	62.652	61.146
Model 2					
Duration Lebo 2	1.580	89.0	52.860	64.593	63.013
Duration unconformity 2	0.570	n/a	n/a	63.013	62.443
Duration Tongue River 2	1.139	54.7	52.860	62.443	61.304

Cande and Kent (1995)

stratigraphic/chron interval	myr*	meters	m/myr†	base (Ma§)	top (Ma¥)
C29n (top portion)		8.5			
C28r	0.342	18.1	52.924	63.976	63.634
C28n	1.135	57.6	50.749	63.634	62.499
C27r (Lebo only)		4.8			
C27r (Tongue River only)		24.3			
C27r (total Lebo+Tongue River)	1.223	29.1	23.794	62.499	61.276
C27n	0.356	12.1	33.989	61.276	60.920
C26r (bottom portion)		18.3		60.920	
All complete chrons	3.056	116.9	38.253	63.976	60.920
Complete chrons except C27r	1.833	87.8	47.900		
Model 1					
Duration Lebo	1.736	89.0	51.253	64.142	62.405
Duration unconformity	0.414	n/a	n/a	62.405	61.991
Duration Tongue River	1.609	54.7	33.989	61.991	60.382
Model 2					
Duration Lebo	1.755	89.0	47.900	64.153	62.399
Duration unconformity	0.615	n/a	n/a	62.399	61.783
Duration Tongue River	1.245	54.7	47.900	61.783	60.538

Table 3

(continued)

Westerhold et al. (2008) estimate 1 **stratigraphic/chron interval**	**myr***	**meters**	**m/myr†**	**base (Ma§)**	**top (Ma¥)**
C29n (top portion)		8.5			
C28r	0.177	18.1	102.260	64.205	64.028
C28n	0.949	57.6	60.695	64.028	63.079
C27r (Lebo only)		4.8			
C27r (Tongue River only)		24.3			
C27r (total Lebo+Tongue River)	0.981	29.1	29.664	63.079	62.098
C27n	0.324	12.1	37.346	62.098	61.774
C26r (bottom portion)		18.3		61.774	
All complete chrons	2.431	116.9	48.087	64.205	61.774
Complete chrons except C27r	1.450	87.8	60.552		
Model 1					
Duration Lebo	1.324	89.0	67.229	64.331	63.008
Duration unconformity	0.259	n/a	n/a	63.008	62.749
Duration Tongue River	1.465	54.7	37.346	62.749	61.284
Model 2					
Duration Lebo	1.346	89.0	60.552	64.345	63.000
Duration unconformity	0.500	n/a	n/a	63.000	62.499
Duration Tongue River	1.028	54.7	60.552	62.499	61.472

Westerhold et al. (2008) estimate 2 **stratigraphic/chron interval**	**myr***	**meters**	**m/myr†**	**base (Ma§)**	**top (Ma¥)**
C29n (top portion)		8.5			
C28r	0.187	18.1	96.791	64.572	64.385
C28n	0.922	57.6	62.473	64.385	63.463
C27r (Lebo only)		4.8			
C27r (Tongue River only)		24.3			
C27r (total Lebo+Tongue River)	0.995	29.1	29.246	63.463	62.468
C27n	0.314	12.1	38.535	62.468	62.154
C26r (bottom portion)		18.3		62.154	
All complete chrons	2.418	116.9	48.346	64.572	62.154
Complete chrons except C27r	1.423	87.8	61.701		
Model 1					
Duration Lebo	1.304	89.0	68.260	64.697	63.393
Duration unconformity	0.294	n/a	n/a	63.393	63.099
Duration Tongue River	1.419	54.7	38.535	63.099	61.679
Model 2					
Duration Lebo	1.325	89.0	61.701	64.710	63.385
Duration unconformity	0.523	n/a	n/a	63.385	62.862
Duration Tongue River	1.004	54.7	61.701	62.862	61.857

Age model 1 uses different sedimentation rates for the Lebo and Tongue River Members. The duration of the Lebo is calculated using the sedimentation rate for C28r and C28n. The duration of the unconformity uses the sedimentation rate for C28r and C28n for the Lebo portion of C27r and uses the rate for C27n for the Tongue River portion of C27r. The duration of the Tongue River uses the sedimentation rate for C27n.

Age model 2 uses the same sedimentation rate for the Lebo and Tongue River Members. The duration of the Lebo, the Tongue River, and the unconformity use the sedimentation rate for C28r, C28n, and C27n.

* million years; † meters/million years; § base of chron, million years ago; ¥ top of chron, million years age.

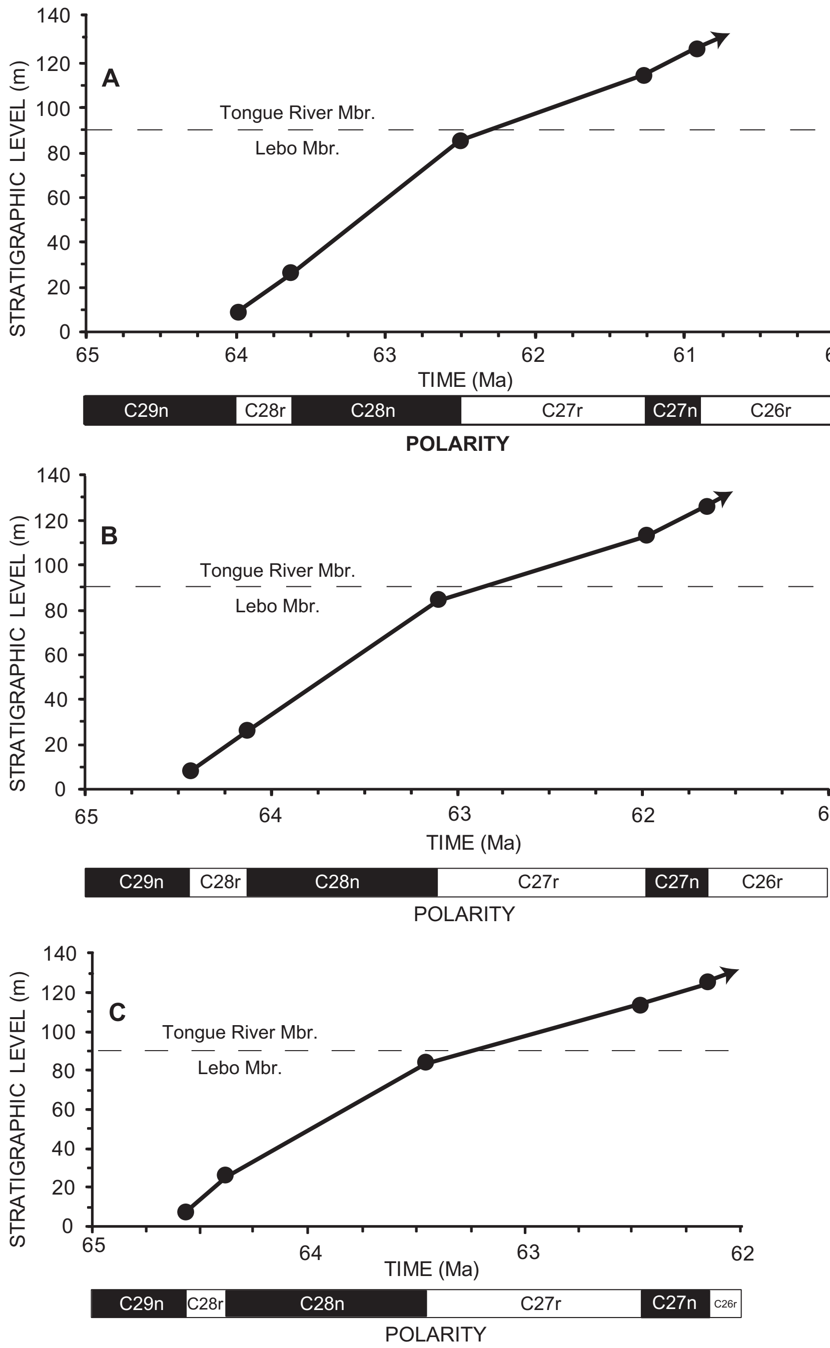

Fig. 6. Sedimentation rates of the Lebo and Tongue River Members of the Fort Union Formation. Change in slope at the top of C28n indicates an apparent decrease in sedimentation rates in C27r, which we interpret to represent a depositional hiatus at the Lebo–Tongue River contact. (A) Cande and Kent, 1995. (B) Ogg and Smith, 2004. (C) Westerhold and others, 2008, estimate 2. Mbr. = stratigraphic member.

Member, the calculated duration is estimated to be between 1.304 and 1.74 million years (table 3). Thus, our oldest estimated age for the top of the Lebo Member is 63.39 Ma, and the youngest is 62.41 Ma (table 3). Using the latter sedimentation rate and a total thickness of 54.7 m for the Tongue River Member, the calculated duration is estimated to be 1.42 to 1.61 million years (table 3). Therefore the youngest age estimate for the top of the Tongue River Member exposed at Signal Butte is 60.38 Ma, and the oldest is 61.68 Ma (table 3). Assuming that the member-contact unconformity coincided with the change in sedimentation rates in C27r (fig. 6), the duration of the unconformity is calculated using the sedimentation rate for C28r and C28n for the Lebo Member portion of C27r, and using the rate of C27n for the Tongue River portion of C27r. Using these two different rates, the duration of the unconformity at the Lebo–Tongue River contact is estimated to be 0.26 to 0.41 million years long.

In the second model the duration and age of the Lebo and Tongue River Members and the unconformity at the formational contact is calculated using average sedimentation rates from C28r, C28n, and C27n, but excluding C27r (table 3). We estimate the duration of the Lebo Member to be between 1.33 and 1.76 million years, and the youngest age for the top of the Lebo Member is 62.40 Ma and the oldest is 63.39 Ma (table 3). The duration of the Tongue River Member is estimated to be between 1.00 and 1.25 million years (table 3). The estimate for the youngest age for the top of the Tongue River Member at Signal Butte is 60.54 Ma and the oldest is 61.86 Ma (table 3). Using this combined constant sedimentation rate for strata correlated to the beginning and late stages of C27r, we estimate the duration of the unconformity to be between 0.50 and 0.62 million years (table 3).

The first age model is a more conservative approach for estimating the duration of the Lebo and Tongue River Members, because it uses different sedimentation rates to calculate their members' durations. The major sedimentological differences between the two members, such as the increase in clay content in the Tongue River Member, suggest that they most likely had different depositional rates, and thus favor using the first model to calculate the durations of deposition within the Lebo and Tongue River Members. However, the second model is a more conservative approach for calculating the duration of the hiatus, because it assumes a constant rate of deposition instead of predicting a change in sedimentation rate in the middle of the unconformity. Thus, the second model is probably a more accurate estimate for the duration of the unconformity. Future work dating the ash beds in the Cowboy Mesa and Signal Butte sequence may help to resolve this issue.

Unconformities and Age Relationships Across the Miles City Arch

It has been suggested that the Ludlow–Tongue River formational contact in the Williston Basin and the Lebo–Tongue River contact in the Powder River Basins are both unconformable (Moore, 1976; Belt and others, 2002; Belt and others, 2004; Peppe, ms, 2009; Peppe, 2010). Based primarily on palynostratigraphy and radiometric age determinations, Belt and others (2004) suggested that the Lebo–Tongue River contact was approximately 2 million years older in the northeastern Powder River Basin than the Ludlow–Tongue River contact in the Williston Basin. Our paleomagnetic results from the Powder River Basin can be correlated across the Miles City Arch to contemporaneous strata in the Williston Basin to test this hypothesis.

Based on sedimentation rates, the top of the Ludlow Member in the Williston Basin has been estimated to be ~63 Ma (minimum estimate = 62.9 Ma, maximum estimate = 63.2 Ma) (Peppe and others, 2009). Using the sedimentation rates coupled with radiometric age estimates, Peppe (2010) estimated the duration of the unconformity at the Ludlow–Tongue River contact to be approximately 2.2 Myr, from approximately 63 to 61.8 Ma. The age estimates presented here suggest that the top of the Lebo Member is ~63 Ma (minimum estimate = 62.40 Ma, maximum estimate = 63.39

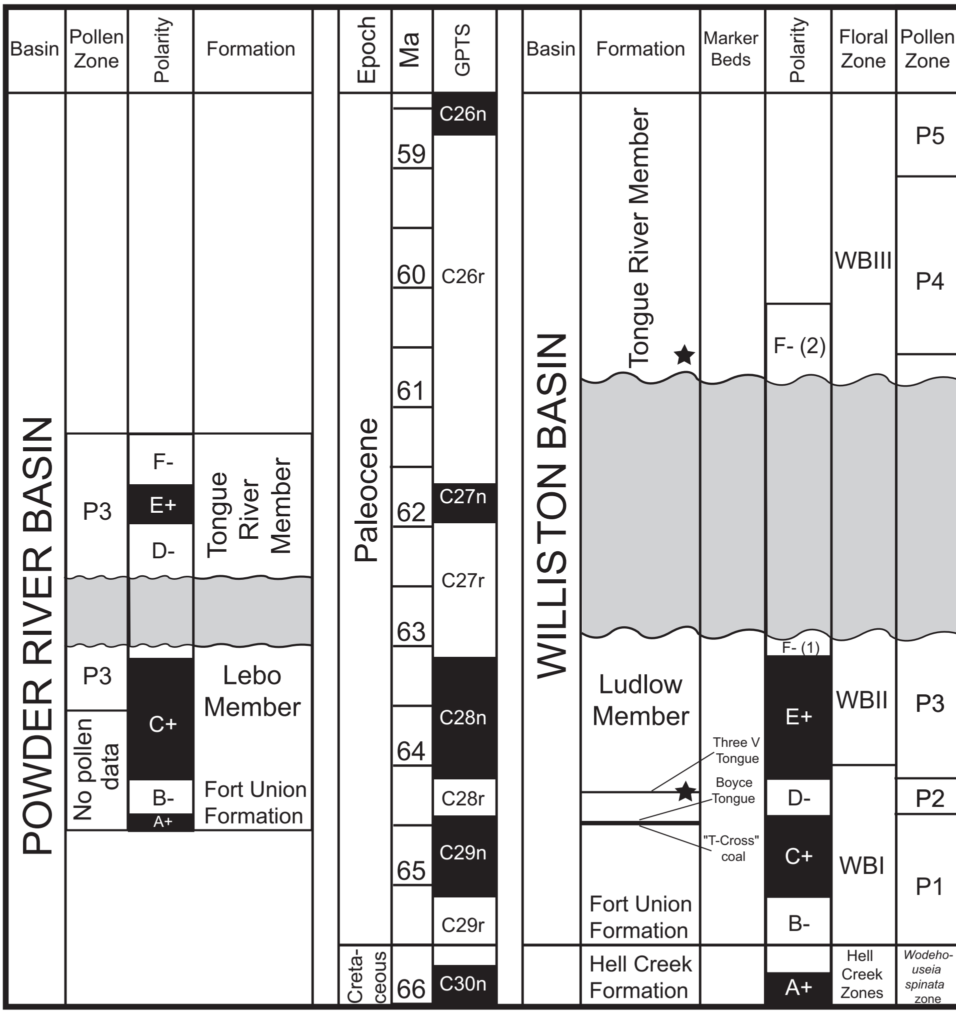

Fig. 7. Chronostratigraphy of early Paleocene strata in the Powder River and Williston Basin showing the approximate age and duration of unconformities at the Lebo–Tongue River and Ludlow–Tongue River formational contacts in each basin. The base of the unconformity occurs at ~63 Ma in both basins, but the duration of the unconformity is approximately 1.5 Myr longer in the Williston Basin. GPTS = Geomagnetic polarity time scale from Ogg and Smith (2004). Gray sections indicate the inferred temporal extents of the unconformities. Column labeled "Formation" indicates lithostratigraphic formations and members. Stars indicate the stratigraphic positions of the two ash beds that were isotopically dated. The lower ash bed is dated to 64.1 ± 1.8 Ma (Warwick and others, 2004), and the upper ash bed is dated to 61.06 ± 0.33 Ma (Belt and others, 2004). Marker beds = key stratigraphic beds in the Fort Union Formation in the Williston Basin. Polarity stratigraphy for the Williston Basin is after Peppe and others (2009) and Peppe (ms 2009, 2010) and for the Powder River Basin from this report. In the Powder River Basin, the polarity stratigraphy can be related to the following chrons of the GPTS: A+ = C29n, B− = C28r, C+ = C28n, D− = C27r, E+ = C27n, F− = C26r. Approximately 500 kyr of C27r is missing. In the Williston Basin, the polarity stratigraphy can be related to the following chrons of the GPTS: A+ = C30n, B− = C29r, C+ = C29n, D− = C28r, E+ = C28n, F-(1) = C27r, F-(2) = C26r. The top of C27r, all of C27n, and the base of C26r appear not to be present in the Williston Basin. Floral zone = megafloral biostratigraphic zones (Peppe, 2010). Pollen zone = palynostratigraphic zonation defined by Nichols and Ott (1978) and refined by Nichols (2003). The stratigraphic placements of the pollen zone boundaries are based on descriptions in Nichols (2003), Belt and others (2004), and Warwick and others (2004).

Ma) and that the duration of the unconformity at the Lebo–Tongue River contact is ~450 kyr (minimum = 258 kyr, maximum = 615 kyr). Together, these data indicate that the upper contact of the Lebo Member in the Powder River Basin and the Ludlow Member in the Williston Basin, and the onset unconformities in both basins, was contemporaneous at ~63 Ma (fig. 7). These results do not support the hypothesis of Belt and others (2004) that the Williston Basin unconformity was ~2 million years younger than the unconformity in the Powder River Basin, but instead suggest that the onset of the unconformities in both basins occurred at approximately the same time. Interestingly, these results also suggest that the duration of the Williston Basin unconformity at the Ludlow–Tongue River contact is ~1.75 million years greater than the duration of the unconformity at the Lebo–Tongue River contact in the Powder River Basin.

Magnetostratigraphic work in southwestern Alberta suggest that there are depositional hiatuses in C28r, C28n, C27r, C27n, and C26n (Lerbekmo and Sweet, 2008). In particular, Lerbekmo and Sweet (2008) document an approximately 1 Myr long unconformity in C27r and C27n, which is roughly coincident with the unconformities in the Powder River and Williston Basins. This suggests that there may have been a regionally extensive unconformity at ~63 Ma across the northern Great Plains of North America. Future geochronologic and geologic work should be focused on addressing this possibility and its potential causes.

CONCLUSIONS

Paleomagnetic analyses from the Lebo and Tongue River Members of the Fort Union Formation in the northeastern Powder River Basin, document a series of polarity reversals that can be correlated to C29n–C26r of the GPTS. Using these data and age estimates for the magnetic polarity chrons (Cande and Kent, 1995; Ogg and Smith, 2004; Westerhold and others, 2008), we have estimated the duration of the Lebo and Tongue River Members of the Fort Union Formation using two different sedimentation-rate models and provided additional evidence for an unconformity at the formational contact. The duration of deposition of the Lebo Member is between 1.31 and 1.76 million years, and the duration of deposition of the Tongue River Member exposed on Signal Butte is between 1.00 and 1.61 million years. There is an apparent decrease in sedimentation rates in C27r, which spans the formational contact, supporting the unconformity hypothesis of Belt and others (2004). Using sedimentation rates for the Tongue River Member, we estimate the duration of the hiatus to be 0.26 and 0.62 million years long. The base of the unconformity is at the oldest 63.39 and at the youngest 62.40 Ma and the top of the unconformity is at the youngest 61.78 and at the oldest 62.75 Ma. This evidence indicates that the unconformity is ~2 million years younger than suggested by Belt and others (2004). The unconformity may be similar in age to middle Paleocene unconformities in the Williston Basin (Moore, 1976; Belt and others, 2004; Peppe, ms, 2009; Peppe, 2010) and in the Alberta area (Lerbekmo and Sweet, 2008), suggesting that it may be regionally extensive in the northern Great Plains of North America.

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Appendix 1

Lithostratigraphic section for Cowboy Mesa and Signal Butte

Unit	Unit Thickness (cm)	Total Thickness (cm)	Lithology	Section	Member
1	40	40	ms	Cowboy Mesa	Lebo
2	20	60	zms	Cowboy Mesa	Lebo
3	60	120	zms	Cowboy Mesa	Lebo
4	20	140	lignite	Cowboy Mesa	Lebo
5	135	275	carb ms	Cowboy Mesa	Lebo
6	15	290	lignite	Cowboy Mesa	Lebo
7	3	293	carb sh	Cowboy Mesa	Lebo
8	12	305	lignite	Cowboy Mesa	Lebo
9	21	326	ms	Cowboy Mesa	Lebo
10	19	345	lignite	Cowboy Mesa	Lebo
11	407	752	sms	Cowboy Mesa	Lebo
12	50	802	carb ms	Cowboy Mesa	Lebo
13	90	892	vfg ss	Cowboy Mesa	Lebo
14	70	962	lignite	Cowboy Mesa	Lebo
15	724	1686	fg ss	Cowboy Mesa	Lebo
16	474	2160	fg ss	Cowboy Mesa	Lebo
17	70	2230	lignite	Cowboy Mesa	Lebo
18	623	2853	ms	Cowboy Mesa	Lebo
19	60	2913	lignite	Cowboy Mesa	Lebo
20	382	3295	ms	Cowboy Mesa	Lebo
21	8	3303	lignite	Cowboy Mesa	Lebo
22	160	3463	zs	Cowboy Mesa	Lebo
23	210	3673	zs	Cowboy Mesa	Lebo
24	70	3743	shale	Cowboy Mesa	Lebo
25	160	3903	shale	Cowboy Mesa	Lebo
26	30	3933	lignite	Cowboy Mesa	Lebo
27	23	3956	carb sh	Cowboy Mesa	Lebo
28	35	3991	lignite	Cowboy Mesa	Lebo
29	4	3995	tuff	Cowboy Mesa	Lebo
30	10	4005	lignite	Cowboy Mesa	Lebo
31	4	4009	tuff	Cowboy Mesa	Lebo
32	54	4063	lignite	Cowboy Mesa	Lebo
33	40	4103	ms	Cowboy Mesa	Lebo
34	453	4556	zms	Cowboy Mesa	Lebo
35	10	4566	carb sh	Cowboy Mesa	Lebo
36	12	4578	zms	Cowboy Mesa	Lebo
37	8	4586	carb sh	Cowboy Mesa	Lebo
38	32	4618	zms	Cowboy Mesa	Lebo
39	12	4630	carb sh	Cowboy Mesa	Lebo
40	20	4650	ms	Cowboy Mesa	Lebo
41	12	4662	ms	Cowboy Mesa	Lebo
42	80	4742	vfg ss	Cowboy Mesa	Lebo
43	9	4751	lignite	Cowboy Mesa	Lebo
44	18	4769	carb sh	Cowboy Mesa	Lebo
45	95	4864	zms	Cowboy Mesa	Lebo

Appendix 1
(continued)

Unit	Unit Thickness (cm)	Total Thickness (cm)	Lithology	Section	Member
46	20	4884	carb sh	Cowboy Mesa	Lebo
47	15	4899	ms	Cowboy Mesa	Lebo
48	20	4919	carb sh	Cowboy Mesa	Lebo
49	60	4979	ms	Cowboy Mesa	Lebo
50	60	5039	vfg ss	Cowboy Mesa	Lebo
51	13	5052	carb sh	Cowboy Mesa	Lebo
52	100	5152	fg ss	Cowboy Mesa	Lebo
53	75	5227	lignite	Cowboy Mesa	Lebo
54	407	5634	zms	Cowboy Mesa	Lebo
55	15	5649	carb sh	Cowboy Mesa	Lebo
56	288	5937	zms	Cowboy Mesa	Lebo
57	10	5947	carb sh	Cowboy Mesa	Lebo
58	50	5997	fg ss	Cowboy Mesa	Lebo
59	24	6021	lignite	Cowboy Mesa	Lebo
60	10	6031	carb sh	Cowboy Mesa	Lebo
61	218	6249	ms/ss	Cowboy Mesa	Lebo
62	20	6269	lignite	Cowboy Mesa	Lebo
63	10	6279	carb sh	Cowboy Mesa	Lebo
64	445	6724	ms/ss	Cowboy Mesa	Lebo
65	10	6734	carb sh	Cowboy Mesa	Lebo
66	231	6965	ms/ss	Cowboy Mesa	Lebo
67	130	7095	vfg ss	Cowboy Mesa	Lebo
68	15	7110	lignite	Cowboy Mesa	Lebo
69	110	7220	ss	Cowboy Mesa	Lebo
70	3	7223	lignite	Cowboy Mesa	Lebo
71	155	7378	ms	Cowboy Mesa	Lebo
72	200	7578	zms	Cowboy Mesa	Lebo
73	10	7588	carb sh	Cowboy Mesa	Lebo
74	50	7638	vfg ss	Cowboy Mesa	Lebo
75	30	7668	ms	Cowboy Mesa	Lebo
76	90	7758	zs	Cowboy Mesa	Lebo
77	330	8088	zms	Cowboy Mesa	Lebo
78	54	8142	carb sh	Cowboy Mesa	Lebo
79	70	8212	zs	Cowboy Mesa	Lebo
80	35	8247	ms	Cowboy Mesa	Lebo
81	122	8369	zs	Cowboy Mesa	Lebo
82	157	8526	zms	Cowboy Mesa	Lebo
83	13	8539	lignite	Cowboy Mesa	Lebo
84	20	8559	ms	Cowboy Mesa	Lebo
85	10	8569	lignite	Cowboy Mesa	Lebo
86	303	8872	carb sh	Cowboy Mesa	Lebo
87	30	8902	zs	Cowboy Mesa	Lebo

Appendix 1
(continued)

Unit	Unit Thickness (cm)	Total Thickness (cm)	Lithology	Section	Member
1	120	9022	calcareous ss	Cowboy Mesa/Signal Butte	Tongue River
2	50	9072	covered	Signal Butte	Tongue River
3	281	9353	vfg ss	Signal Butte	Tongue River
4	135	9488	zs	Signal Butte	Tongue River
5	25	9513	carb sh	Signal Butte	Tongue River
6	281	9794	zms	Signal Butte	Tongue River
7	20	9814	carb zs	Signal Butte	Tongue River
8	140	9954	zms	Signal Butte	Tongue River
9	4	9958	lignite	Signal Butte	Tongue River
10	23	9981	shale	Signal Butte	Tongue River
11	29	10010	zms	Signal Butte	Tongue River
12	14	10024	carb sh	Signal Butte	Tongue River
13	122	10146	zs	Signal Butte	Tongue River
14	19	10165	carb sh	Signal Butte	Tongue River
15	19	10184	lignite	Signal Butte	Tongue River
16	100	10284	zms	Signal Butte	Tongue River
17	10	10294	ms	Signal Butte	Tongue River
18	63	10357	zms	Signal Butte	Tongue River
19	16	10373	zms	Signal Butte	Tongue River
20	29	10402	zms	Signal Butte	Tongue River
21	12	10414	carb sh	Signal Butte	Tongue River
22	55	10469	zms	Signal Butte	Tongue River
23	21	10490	carb sh	Signal Butte	Tongue River
24	24	10514	zms	Signal Butte	Tongue River
25	10	10524	ms	Signal Butte	Tongue River
26	99	10623	vfg ss	Signal Butte	Tongue River
27	11	10634	ironstone	Signal Butte	Tongue River
28	160	10794	zms	Signal Butte	Tongue River
29	5	10799	ms	Signal Butte	Tongue River
30	97	10896	ms	Signal Butte	Tongue River
31	75	10971	vfg ss	Signal Butte	Tongue River
32	58	11029	ironstone	Signal Butte	Tongue River
33	103	11132	zms	Signal Butte	Tongue River
34	4	11136	carb sh	Signal Butte	Tongue River
35	98	11234	zms	Signal Butte	Tongue River
36	22	11256	carb sh	Signal Butte	Tongue River
37	80	11336	zms	Signal Butte	Tongue River
38	26	11362	carb sh	Signal Butte	Tongue River
39	284	11646	zms	Signal Butte	Tongue River
40	7	11653	lignite	Signal Butte	Tongue River
41	71	11724	zms	Signal Butte	Tongue River
42	130	11854	calcareous zs	Signal Butte	Tongue River
43	190	12044	zms	Signal Butte	Tongue River
44	90	12134	ms	Signal Butte	Tongue River

Appendix 1
(continued)

Unit	Unit Thickness (cm)	Total Thickness (cm)	Lithology	Section	Member
45	55	12189	ms	Signal Butte	Tongue River
46	303	12492	zs	Signal Butte	Tongue River
47	220	12712	zs	Signal Butte	Tongue River
48	90	12802	ironstone	Signal Butte	Tongue River
49	474	13276	covered	Signal Butte	Tongue River
50	12	13288	lignite	Signal Butte	Tongue River
51	543	13831	covered	Signal Butte	Tongue River
52	540	14371	clinker	Signal Butte	Tongue River

Unit = stratigraphic bed; unit thickness = total thickness of stratigraphic unit in centimeters; total thickness = total thickness of the stratigraphic section in centimeters. Lithology = lithologic description of each stratigraphic unit: vfg = very fine grained; fg = fine grained; ms = mudstone; zms = silty mudstone; carb sh = carbonaceous shale; sms = sandy mudstone; zs = siltstone; ss = sandstone; covered = no exposure.

Appendix 2

Paleomagnetic data for each sample used in polarity determination

Section name	Formation	Member	Stratigraphic level (section)	Stratigraphic level (composite)	Sample prefix	Sample number	Line or Circle	GD*	GI†	MAD§
Cowboy Mesa	Fort Union	Lebo	350	350	P04CM	01A	Line	348	38	9.9
Cowboy Mesa	Fort Union	Lebo	350	350	P04CM	01B	Line	7	62	4.5
Cowboy Mesa	Fort Union	Lebo	350	350	P04CM	01C	Line	341	70	7.7
Cowboy Mesa	Fort Union	Lebo	732	732	P04CM	02A	Circle	359	-22	18.8
Cowboy Mesa	Fort Union	Lebo	732	732	P04CM	02B	Line	332	31	7.6
Cowboy Mesa	Fort Union	Lebo	732	732	P04CM	02C	Line	331	45	5.1
Cowboy Mesa	Fort Union	Lebo	972	972	P04CM	03A	Circle	321	11	9.5
Cowboy Mesa	Fort Union	Lebo	972	972	P04CM	03B	Circle	35	-18	14.8
Cowboy Mesa	Fort Union	Lebo	1002	1002	P04CM	04A	Circle	43	-5	12.2
Cowboy Mesa	Fort Union	Lebo	1002	1002	P04CM	04B	Circle	167	50	0.4
Cowboy Mesa	Fort Union	Lebo	1002	1002	P04CM	04C	Circle	53	-22	10.6
Cowboy Mesa	Fort Union	Lebo	1272	1272	P04CM	05A	Circle	358	23	1.8
Cowboy Mesa	Fort Union	Lebo	1272	1272	P04CM	05A	Circle	99	21	5.7
Cowboy Mesa	Fort Union	Lebo	1272	1272	P04CM	05B	Line	183	-37	17.1
Cowboy Mesa	Fort Union	Lebo	1474	1474	P04CM	08A	Circle	326	0	19.0
Cowboy Mesa	Fort Union	Lebo	1474	1474	P04CM	08B	Circle	68	-17	19.3
Cowboy Mesa	Fort Union	Lebo	1474	1474	P04CM	08C	Circle	92	-8	13.3
Cowboy Mesa	Fort Union	Lebo	1596	1596	P04CM	07B	Circle	50	24	4.3
Cowboy Mesa	Fort Union	Lebo	1596	1596	P04CM	07C	Circle	65	7	19.4
Cowboy Mesa	Fort Union	Lebo	1596	1596	P04CM	07A	Line	159	-54	17.8
Cowboy Mesa	Fort Union	Lebo	1827	1827	P04CM	06A	Circle	49	-7	11.4
Cowboy Mesa	Fort Union	Lebo	1827	1827	P04CM	06B	Circle	30	-35	7.2
Cowboy Mesa	Fort Union	Lebo	1827	1827	P04CM	06B	Line	140	-27	8.4
Cowboy Mesa	Fort Union	Lebo	2150	2150	P04CM	09A	Circle	85	-28	18.9
Cowboy Mesa	Fort Union	Lebo	2150	2150	P04CM	09C	Circle	43	-29	4.5
Cowboy Mesa	Fort Union	Lebo	2240	2240	P04CM	10A	Circle	41	8	13.7
Cowboy Mesa	Fort Union	Lebo	2240	2240	P04CM	10B	Circle	20	4	7.3
Cowboy Mesa	Fort Union	Lebo	2330	2330	P04CM	11A	Circle	21	-23	18.3
Cowboy Mesa	Fort Union	Lebo	2330	2330	P04CM	11B	Circle	131	0	9.9
Cowboy Mesa	Fort Union	Lebo	2330	2330	P04CM	11A	Line	260	-53	5.6

Appendix 2

(continued)

Section name	Formation	Member	Stratigraphic level (section)	Stratigraphic level (composite)	Sample prefix	Sample number	Line or Circle	GD*	GI[†]	MAD[§]
Cowboy Mesa	Fort Union	Lebo	2330	2330	P04CM	11A	Line	260	-53	5.6
Cowboy Mesa	Fort Union	Lebo	2330	2330	P04CM	11C	Line	179	-58	10.5
Cowboy Mesa	Fort Union	Lebo	2472	2472	P04CM	12D	Circle	120	-62	15.8
Cowboy Mesa	Fort Union	Lebo	2472	2472	P04CM	12B	Line	185	-9	11.3
Cowboy Mesa	Fort Union	Lebo	2843	2843	P04CM	13A	Circle	33	1	14.3
Cowboy Mesa	Fort Union	Lebo	2843	2843	P04CM	13C	Circle	317	1	7.2
Cowboy Mesa	Fort Union	Lebo	2843	2843	P04CM	13C	Line	32	77	8.9
Cowboy Mesa	Fort Union	Lebo	3313	3313	P04CM	14A	Line	352	53	1.0
Cowboy Mesa	Fort Union	Lebo	3313	3313	P04CM	14B	Line	329	72	4.2
Cowboy Mesa	Fort Union	Lebo	3313	3313	P04CM	14C	Line	357	50	3.1
Cowboy Mesa	Fort Union	Lebo	3363	3363	P04CM	15A	Line	10	74	5.0
Cowboy Mesa	Fort Union	Lebo	3363	3363	P04CM	15B	Line	347	60	2.1
Cowboy Mesa	Fort Union	Lebo	3363	3363	P04CM	15C	Line	356	55	2.4
Cowboy Mesa	Fort Union	Lebo	3783	3783	P04CM	16A	Line	308	54	6.8
Cowboy Mesa	Fort Union	Lebo	3783	3783	P04CM	16B	Line	332	53	7.1
Cowboy Mesa	Fort Union	Lebo	3783	3783	P04CM	16C	Line	322	55	11.6
Cowboy Mesa	Fort Union	Lebo	4065	4065	P04CM	18A	Line	41	81	8.2
Cowboy Mesa	Fort Union	Lebo	4065	4065	P04CM	18B	Line	303	74	11.1
Cowboy Mesa	Fort Union	Lebo	4065	4065	P04CM	18C	Line	360	73	15.4
Cowboy Mesa	Fort Union	Lebo	4235	4235	P04CM	20B	Line	344	71	5.6
Cowboy Mesa	Fort Union	Lebo	4235	4235	P04CM	20C	Line	319	39	12.1
Cowboy Mesa	Fort Union	Lebo	4355	4355	P04CM	21A	Line	338	47	6.3
Cowboy Mesa	Fort Union	Lebo	4355	4355	P04CM	21B	Line	297	53	12.3
Cowboy Mesa	Fort Union	Lebo	4355	4355	P04CM	21C	Line	339	75	12.4
Cowboy Mesa	Fort Union	Lebo	4435	4435	P04CM	22A	Line	354	53	4.4
Cowboy Mesa	Fort Union	Lebo	4435	4435	P04CM	22B	Line	351	50	4.8
Cowboy Mesa	Fort Union	Lebo	4435	4435	P04CM	22C	Line	358	56	6.7
Cowboy Mesa	Fort Union	Lebo	4505	4505	P04CM	23A	Line	19	39	4.5
Cowboy Mesa	Fort Union	Lebo	4505	4505	P04CM	23B	Line	23	33	6.4
Cowboy Mesa	Fort Union	Lebo	4505	4505	P04CM	23C	Line	329	40	4.3

Appendix 2
(continued)

Section name	Formation	Member	Stratigraphic level (section)	Stratigraphic level (composite)	Sample prefix	Sample number	Line or Circle	GD*	GI†	MAD§
Cowboy Mesa	Fort Union	Lebo	4590	4590	P04CM	24A	Line	354	45	5.8
Cowboy Mesa	Fort Union	Lebo	4590	4590	P04CM	24C	Line	347	36	4.2
Cowboy Mesa	Fort Union	Lebo	4590	4590	P04CM	24D	Line	339	65	3.6
Cowboy Mesa	Fort Union	Lebo	4702	4702	P04CM	25A	Line	297	64	7.6
Cowboy Mesa	Fort Union	Lebo	4702	4702	P04CM	25B	Line	244	67	18.9
Cowboy Mesa	Fort Union	Lebo	4702	4702	P04CM	25C	Line	275	44	15.2
Cowboy Mesa	Fort Union	Lebo	4779	4779	P04CM	26B	Circle	57	-26	14.3
Cowboy Mesa	Fort Union	Lebo	4779	4779	P04CM	26C	Circle	53	-28	16.2
Cowboy Mesa	Fort Union	Lebo	4779	4779	P04CM	26A	Line	344	68	5.8
Cowboy Mesa	Fort Union	Lebo	4779	4779	P04CM	26B	Line	24	60	12.2
Cowboy Mesa	Fort Union	Lebo	4779	4779	P04CM	26C	Line	350	41	17.7
Cowboy Mesa	Fort Union	Lebo	4910	4910	P04CM	27A	Line	331	57	6.2
Cowboy Mesa	Fort Union	Lebo	4910	4910	P04CM	27B	Line	269	75	5.1
Cowboy Mesa	Fort Union	Lebo	4910	4910	P04CM	27C	Line	346	66	13.2
Cowboy Mesa	Fort Union	Lebo	5090	5090	P04CM	28A	Line	319	56	15.8
Cowboy Mesa	Fort Union	Lebo	5090	5090	P04CM	28B	Line	10	62	8.7
Cowboy Mesa	Fort Union	Lebo	5090	5090	P04CM	28C	Line	305	71	6.8
Cowboy Mesa	Fort Union	Lebo	5247	5247	P04CM	29A	Circle	81	1	17.9
Cowboy Mesa	Fort Union	Lebo	5247	5247	P04CM	29A	Line	322	78	12.3
Cowboy Mesa	Fort Union	Lebo	5307	5307	P04CM	30A	Line	296	54	8.0
Cowboy Mesa	Fort Union	Lebo	5307	5307	P04CM	30C	Line	266	67	11.6
Cowboy Mesa	Fort Union	Lebo	5307	5307	P04CM	30D	Line	237	58	6.5
Cowboy Mesa	Fort Union	Lebo	5431	5431	P04CM	31A	Line	280	40	5.3
Cowboy Mesa	Fort Union	Lebo	5431	5431	P04CM	31B	Line	285	51	7.5
Cowboy Mesa	Fort Union	Lebo	5431	5431	P04CM	31C	Line	324	49	5.8
Cowboy Mesa	Fort Union	Lebo	5491	5491	P04CM	32A	Line	302	46	12.4
Cowboy Mesa	Fort Union	Lebo	5491	5491	P04CM	32B	Line	10	79	13.5
Cowboy Mesa	Fort Union	Lebo	5491	5491	P04CM	32C	Line	311	46	9.2
Cowboy Mesa	Fort Union	Lebo	5491	5491	P04CM	32C	Line	23	65	3.9
Cowboy Mesa	Fort Union	Lebo	5568	5568	P04CM	33A	Line	309	72	17.1
Cowboy Mesa	Fort Union	Lebo	5568	5568	P04CM	33B	Line	341	49	9.2

Appendix 2

(continued)

Section name	Formation	Member	Stratigraphic level (section)	Stratigraphic level (composite)	Sample prefix	Sample number	Line or Circle	GD*	GI†	MAD§
Cowboy Mesa	Fort Union	Lebo	7901	7901	P04CM	44C	Line	358	52	6.3
Cowboy Mesa	Fort Union	Lebo	8162	8162	P04CM	45A	Line	12	44	6.1
Cowboy Mesa	Fort Union	Lebo	8162	8162	P04CM	45C	Line	337	46	12.5
Cowboy Mesa	Fort Union	Lebo	8162	8162	P04CM	45D	Line	346	50	10.6
Cowboy Mesa	Fort Union	Lebo	8252	8252	P04CM	46C	Circle	65	-17	13.9
Cowboy Mesa	Fort Union	Lebo	8579	8579	P04CM	47A	Circle	113	19	9.8
Cowboy Mesa	Fort Union	Lebo	8579	8579	P04CM	47B	Line	234	-48	15.1
Signal Butte	Fort Union	Tongue River	431	9333	P04SB	01B	Circle	19	-26	9.9
Signal Butte	Fort Union	Tongue River	431	9333	P04SB	01A	Line	148	-47	16.3
Signal Butte	Fort Union	Tongue River	653	9505	P04SB	03C	Circle	138	22	8.5
Signal Butte	Fort Union	Tongue River	603	9505	P04SB	02B	Line	163	-31	6.5
Signal Butte	Fort Union	Tongue River	653	9555	P04SB	03D	Circle	56	-19	10.9
Signal Butte	Fort Union	Tongue River	738	9640	P04SB	04C	Circle	84	12	6.7
Signal Butte	Fort Union	Tongue River	738	9640	P04SB	04A	Line	186	-65	8.9
Signal Butte	Fort Union	Tongue River	738	9640	P04SB	04B	Line	120	-68	10.8
Signal Butte	Fort Union	Tongue River	803	9705	P04SB	05B	Circle	350	-14	10.7
Signal Butte	Fort Union	Tongue River	803	9705	P04SB	05A	Line	162	-24	11.1
Signal Butte	Fort Union	Tongue River	803	9705	P04SB	05C	Line	219	-70	9.4
Signal Butte	Fort Union	Tongue River	895	9797	P04SB	06A	Line	113	-59	9.4
Signal Butte	Fort Union	Tongue River	895	9797	P04SB	06B	Line	186	-53	4.4
Signal Butte	Fort Union	Tongue River	995	9897	P04SB	07A	Line	153	-76	3.8
Signal Butte	Fort Union	Tongue River	995	9897	P04SB	07B	Line	164	-59	3
Signal Butte	Fort Union	Tongue River	995	9897	P04SB	07C	Line	180	-62	4.8
Signal Butte	Fort Union	Tongue River	1045	9947	P04SB	08C	Circle	74	4	9
Signal Butte	Fort Union	Tongue River	1115	10017	P04SB	09A	Line	248	-72	16.4
Signal Butte	Fort Union	Tongue River	1115	10017	P04SB	09B	Line	132	-31	19.7
Signal Butte	Fort Union	Tongue River	1115	10017	P04SB	09C	Line	190	-45	7.2
Signal Butte	Fort Union	Tongue River	1180	10082	P04SB	10A	Line	211	-43	7.4
Signal Butte	Fort Union	Tongue River	1180	10082	P04SB	10B	Line	177	-37	16.9
Signal Butte	Fort Union	Tongue River	1180	10082	P04SB	10C	Line	177	-26	15.6
Signal Butte	Fort Union	Tongue River	1290	10192	P04SB	11A	Line	99	-51	8.4

Appendix 2
(continued)

Section name	Formation	Member	Stratigraphic level (section)	Stratigraphic level (composite)	Sample prefix	Sample number	Line or Circle	GD*	GI†	MAD§
Cowboy Mesa	Fort Union	Lebo	5568	5568	P04CM	33C	Line	4	61	10.6
Cowboy Mesa	Fort Union	Lebo	5687	5687	P04CM	34A	Circle	120	23	7.2
Cowboy Mesa	Fort Union	Lebo	5687	5687	P04CM	34C	Circle	89	1	5.6
Cowboy Mesa	Fort Union	Lebo	5687	5687	P04CM	34B	Line	14	66	16.4
Cowboy Mesa	Fort Union	Lebo	5687	5687	P04CM	34C	Line	350	81	6.3
Cowboy Mesa	Fort Union	Lebo	5824	5824	P04CM	35A	Line	278	45	11.6
Cowboy Mesa	Fort Union	Lebo	5824	5824	P04CM	35B	Line	327	54	6.0
Cowboy Mesa	Fort Union	Lebo	5824	5824	P04CM	35C	Line	323	42	4.6
Cowboy Mesa	Fort Union	Lebo	6041	6041	P04CM	36A	Line	256	60	13.8
Cowboy Mesa	Fort Union	Lebo	6041	6041	P04CM	36B	Line	245	81	7.3
Cowboy Mesa	Fort Union	Lebo	6041	6041	P04CM	36C	Line	249	69	9.7
Cowboy Mesa	Fort Union	Lebo	6279	6279	P04CM	37A	Line	322	47	3.9
Cowboy Mesa	Fort Union	Lebo	6279	6279	P04CM	37C	Line	345	46	3.4
Cowboy Mesa	Fort Union	Lebo	6279	6279	P04CM	37D	Line	317	34	6.5
Cowboy Mesa	Fort Union	Lebo	6459	6459	P04CM	38A	Line	292	63	9.6
Cowboy Mesa	Fort Union	Lebo	6459	6459	P04CM	38B	Line	357	68	6.6
Cowboy Mesa	Fort Union	Lebo	6459	6459	P04CM	38C	Line	7	73	9.5
Cowboy Mesa	Fort Union	Lebo	6659	6659	P04CM	39A	Line	350	26	6.6
Cowboy Mesa	Fort Union	Lebo	6659	6659	P04CM	39B	Line	19	52	16.2
Cowboy Mesa	Fort Union	Lebo	6659	6659	P04CM	39C	Line	329	36	10.3
Cowboy Mesa	Fort Union	Lebo	7065	7065	P04CM	40B	Circle	84	-6	3.7
Cowboy Mesa	Fort Union	Lebo	7065	7065	P04CM	40A	Line	27	64	6.6
Cowboy Mesa	Fort Union	Lebo	7398	7398	P04CM	41A	Circle	349	-12	6.7
Cowboy Mesa	Fort Union	Lebo	7398	7398	P04CM	41B	Circle	138	33	8.8
Cowboy Mesa	Fort Union	Lebo	7398	7398	P04CM	41C	Line	284	61	8.9
Cowboy Mesa	Fort Union	Lebo	7608	7608	P04CM	42A	Line	356	39	3.6
Cowboy Mesa	Fort Union	Lebo	7688	7688	P04CM	43A	Line	14	66	12.8
Cowboy Mesa	Fort Union	Lebo	7688	7688	P04CM	43B	Line	326	61	8.9
Cowboy Mesa	Fort Union	Lebo	7688	7688	P04CM	43C	Line	5	63	10.3
Cowboy Mesa	Fort Union	Lebo	7901	7901	P04CM	44A	Line	10	72	8.0
Cowboy Mesa	Fort Union	Lebo	7901	7901	P04CM	44B	Line	310	68	2.2

Appendix 2

(continued)

Section name	Formation	Member	Stratigraphic level (section)	Stratigraphic level (composite)	Sample prefix	Sample number	Line or Circle	GD*	GI†	MAD§
Signal Butte	Fort Union	Tongue River	1290	10192	P04SB	11B	Line	125	-61	6.2
Signal Butte	Fort Union	Tongue River	1290	10192	P04SB	11C	Line	137	-51	10.7
Signal Butte	Fort Union	Tongue River	1485	10387	P04SB	12A	Circle	341	-1	9
Signal Butte	Fort Union	Tongue River	1485	10387	P04SB	12C	Circle	130	40	3.8
Signal Butte	Fort Union	Tongue River	1565	10467	P04SB	13B	Line	166	-71	5.6
Signal Butte	Fort Union	Tongue River	1565	10467	P04SB	13D	Line	235	-52	8.4
Signal Butte	Fort Union	Tongue River	1645	10547	P04SB	14B	Line	68	-35	7.9
Signal Butte	Fort Union	Tongue River	1645	10547	P04SB	14B	Line	70	-49	8
Signal Butte	Fort Union	Tongue River	1705	10607	P04SB	15B	Line	141	-56	13.8
Signal Butte	Fort Union	Tongue River	1705	10607	P04SB	15C	Line	150	-66	13.1
Signal Butte	Fort Union	Tongue River	2285	11187	P04SB	16B	Line	146	-46	8.9
Signal Butte	Fort Union	Tongue River	2370	11272	P04SB	17A	Line	317	-74	14
Signal Butte	Fort Union	Tongue River	2477	11379	P04SB	18A	Line	30	68	10.9
Signal Butte	Fort Union	Tongue River	2477	11379	P04SB	18B	Line	122	87	5.4
Signal Butte	Fort Union	Tongue River	2477	11379	P04SB	18D	Line	49	63	6.3
Signal Butte	Fort Union	Tongue River	2567	11469	P04SB	19A	Line	45	43	13.2
Signal Butte	Fort Union	Tongue River	2567	11469	P04SB	19C	Line	30	44	14.2
Signal Butte	Fort Union	Tongue River	2623	11525	P04SB	20A	Line	286	63	7.7
Signal Butte	Fort Union	Tongue River	2718	11620	P04SB	21B	Line	323	47	10.5
Signal Butte	Fort Union	Tongue River	2783	11685	P04SB	22B	Circle	124	41	17.6
Signal Butte	Fort Union	Tongue River	2996	11898	P04SB	23A	Line	359	59	14.9
Signal Butte	Fort Union	Tongue River	3563	12465	P04SB	25A	Line	313	40	12.9
Signal Butte	Fort Union	Tongue River	3563	12465	P04SB	25B	Line	325	38	8.7
Signal Butte	Fort Union	Tongue River	3563	12465	P04SB	25C	Line	343	31	9
Signal Butte	Fort Union	Tongue River	3710	12612	P04SB	26A	Line	137	-55	13.3
Signal Butte	Fort Union	Tongue River	3710	12612	P04SB	26B	Line	357	-74	12.8
Signal Butte	Fort Union	Tongue River	3710	12612	P04SB	26C	Line	150	-44	18.9
Signal Butte	Fort Union	Tongue River	3882	12784	P04SB	27B	Line	233	-64	2.5
Signal Butte	Fort Union	Tongue River	3882	12784	P04SB	27C	Line	199	-32	10.3
Signal Butte	Fort Union	Tongue River	4096	12998	P04SB	28C	Circle	153	56	13.4

Appendix 2
(continued)

Section name	Formation	Member	Stratigraphic level (section)	Stratigraphic level (composite)	Sample prefix	Sample number	Line or Circle	GD*	GI†	MAD§
Signal Butte	Fort Union	Tongue River	4096	12998	P04SB	28A	Line	223	-44	6.6
Signal Butte	Fort Union	Tongue River	4096	12998	P04SB	28B	Line	232	-63	5.9
Signal Butte	Fort Union	Tongue River	4146	13048	P04SB	29A	Line	161	-68	3.7
Signal Butte	Fort Union	Tongue River	4146	13048	P04SB	29B	Line	175	-80	5.1
Signal Butte	Fort Union	Tongue River	4146	13048	P04SB	29C	Line	185	-72	6
Signal Butte	Fort Union	Tongue River	4241	13143	P04SB	30A	Circle	72	-1	13.2
Signal Butte	Fort Union	Tongue River	4241	13143	P04SB	30C	Circle	328	-8	1.5
Signal Butte	Fort Union	Tongue River	4456	13358	P04SB	31B	Line	190	-51	11.2
Signal Butte	Fort Union	Tongue River	4456	13358	P04SB	31C	Line	202	-62	12.4

* geomagnetic declination; † geomagnetic inclination; § mean angular deviation.

APPENDIX 3

Site mean data for each stratigraphic level with 3 or more samples used in polarity determination

Section name	Formation	Member	Stratigraphic level (section)	Stratigraphic level (composite)	Sample prefix	Sample number	n‡	GD*	GI†	alpha-95
Cowboy Mesa	Fort Union	Lebo	350	350	P04CM	1	3	351.9	57.2	27.45
Cowboy Mesa	Fort Union	Lebo	732	732	P04CM	2	3	301.6	27.1	64.6
Cowboy Mesa	Fort Union	Lebo	1002	1002	P04CM	4	3	148.2	37.7	90
Cowboy Mesa	Fort Union	Lebo	1272	1272	P04CM	5	3	268.3	73.4	80
Cowboy Mesa	Fort Union	Lebo	1827	1827	P04CM	6	3	134.8	-17.6	15.8
Cowboy Mesa	Fort Union	Lebo	1596	1596	P04CM	7	3	143	-53.2	56.6
Cowboy Mesa	Fort Union	Lebo	1474	1474	P04CM	8	3	204.6	79.9	90
Cowboy Mesa	Fort Union	Lebo	2330	2330	P04CM	11	4	222	-63	34.3
Cowboy Mesa	Fort Union	Lebo	2843	2843	P04CM	13	3	34.2	81.3	25.8
Cowboy Mesa	Fort Union	Lebo	3313	3313	P04CM	14	3	349.5	58.7	21.3
Cowboy Mesa	Fort Union	Lebo	3363	3363	P04CM	15	3	355.5	63.4	16.7
Cowboy Mesa	Fort Union	Lebo	3783	3783	P04CM	16	3	320.8	54.5	10.7
Cowboy Mesa	Fort Union	Lebo	4065	4065	P04CM	18	3	347.1	78.8	17.3
Cowboy Mesa	Fort Union	Lebo	4355	4355	P04CM	21	3	322	60.3	29.6
Cowboy Mesa	Fort Union	Lebo	4435	4435	P04CM	22	3	353.9	53.1	5.8
Cowboy Mesa	Fort Union	Lebo	4590	4590	P04CM	24	3	347.8	48.9	24.2
Cowboy Mesa	Fort Union	Lebo	4702	4702	P04CM	25	3	273.4	59.8	27
Cowboy Mesa	Fort Union	Lebo	4779	4779	P04CM	26	5	356.7	55.7	15.2
Cowboy Mesa	Fort Union	Lebo	4910	4910	P04CM	27	3	324.6	68.8	25.2
Cowboy Mesa	Fort Union	Lebo	5090	5090	P04CM	28	3	332.7	65.8	25.8
Cowboy Mesa	Fort Union	Lebo	5307	5307	P04CM	30	3	267.3	62.1	25.8
Cowboy Mesa	Fort Union	Lebo	5431	5431	P04CM	31	3	295.1	48.7	26.9
Cowboy Mesa	Fort Union	Lebo	5491	5491	P04CM	32	3	327.7	63	29.4
Cowboy Mesa	Fort Union	Lebo	5568	5568	P04CM	33	3	341.6	62.2	24.9
Cowboy Mesa	Fort Union	Lebo	5687	5687	P04CM	34	3	12.8	49.8	55.2
Cowboy Mesa	Fort Union	Lebo	5824	5824	P04CM	35	3	308.6	49.4	30.4
Cowboy Mesa	Fort Union	Lebo	6041	6041	P04CM	36	3	250.1	66.6	24.8
Cowboy Mesa	Fort Union	Lebo	6279	6279	P04CM	37	3	327.2	42.7	20.1
Cowboy Mesa	Fort Union	Lebo	6459	6459	P04CM	38	3	334.7	71.4	24
Cowboy Mesa	Fort Union	Lebo	6659	6659	P04CM	39	3	350.2	39.6	35.4

Appendix 3

(continued)

Section name	Formation	Member	Stratigraphic level (section)	Stratigraphic level (composite)	Sample prefix	Sample number	n[‡]	GD*	GI[†]	alpha-95
Cowboy Mesa	Fort Union	Lebo	7398	7398	P04CM	41	3	285.2	59.1	16.2
Cowboy Mesa	Fort Union	Lebo	7688	7688	P04CM	43	3	354	64.8	17.9
Cowboy Mesa	Fort Union	Lebo	7901	7901	P04CM	44	3	347.6	66.2	24.5
Cowboy Mesa	Fort Union	Lebo	8162	8162	P04CM	45	3	351.7	47.4	19.6
Signal Butte	Fort Union	Tongue River	738	9640	P04SB	4	3	152.2	-69.3	30.4
Signal Butte	Fort Union	Tongue River	803	9705	P04SB	5	3	178.3	-55.1	78.7
Signal Butte	Fort Union	Tongue River	995	9897	P04SB	7	3	168	-66.2	16.1
Signal Butte	Fort Union	Tongue River	1115	10017	P04SB	9	3	170.4	-57.3	52.4
Signal Butte	Fort Union	Tongue River	1180	10082	P04SB	10	3	187	-36.4	27.5
Signal Butte	Fort Union	Tongue River	1290	10192	P04SB	11	3	119.8	-55.6	20.5
Signal Butte	Fort Union	Tongue River	2370	11272	P04SB	18	3	43.9	73.6	22.7
Signal Butte	Fort Union	Tongue River	3563	12465	P04SB	25	3	327.6	37.2	20.1
Signal Butte	Fort Union	Tongue River	3710	12612	P04SB	26	3	136	-66.8	52.9
Signal Butte	Fort Union	Tongue River	4096	12998	P04SB	28	3	219.8	-48	43
Signal Butte	Fort Union	Tongue River	4146	13048	P04SB	29	3	172.6	-73.6	10.9

[‡] number of samples used for site mean calculation; * geomagnetic declination; [†] geomagnetic inclination.

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