

# The magnetostratigraphy of Barstovian mammals in southwestern Montana and implications for the initiation of Neogene crustal extension in the northern Rocky Mountains

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## ABSTRACT

Magnetostratigraphic and biostratigraphic data have been used to construct a chronologic framework for the deposition of the Hepburn's Mesa Formation in the Yellowstone Valley of southwestern Montana. Deposition spanned an interval from ~16.8 Ma to at least 14.3 Ma, and possibly to 13.8 Ma. The magnetic data help to constrain the Barstovian land-mammal age in the northern Rocky Mountains, as well as two interval zones defined within it. The major faunal boundary ages determined here are indistinguishable from ages for these same boundaries at the Barstovian type locality in southern California. Consequently, observed differences in generic and species composition between these regions are likely to reflect biogeographic and ecological variability, rather than temporal separation. When used in conjunction with biostratigraphic data from Jackson Hole, Wyoming, these new dates improve the time constraints that can be placed on the duration (~1 m.y.) of the "mid-Tertiary unconformity" in the northern Rockies and on the inception at ~17 Ma of the interval of crustal extension that led to extensive intermontane-basin development during the Neogene.

## INTRODUCTION

During the early to middle Miocene, a major tectonic transformation occurred in the region of the northern Rocky Mountains. With the exception of a few localities, such as in Jackson Hole, Wyoming, where proximal volcanoclastic sedi-

ments accumulated through much of this interval (Barnosky, 1984), a prominent unconformity separates early Miocene (Arikareean) strata from middle Miocene rocks of Barstovian and in some cases late Hemingfordian age. The uplift that generated this unconformity was succeeded by the initiation of an episode of regional extension and the incipient development of the intermontane basins of the northern Rockies. Although broadly dated by faunal data (Fields and others, 1985), the precise timing of the transition from Paleogene tectonic patterns to the Neogene regime of extensional tectonism has not been specified previously. By analogy with similar trends in other regions of the western United States (Christiansen and Lipman, 1972), an observed change from andesitic to bimodal volcanism in the Miocene Colter Formation in Jackson Hole suggests that the tectonic transition there may involve a change from compression to extension (Barnosky, 1984). Based on fossil mammals recovered from different members of the Colter Formation, the age of this tectonic change can be placed between 13–18 Ma (Barnosky, 1984). The long temporal range of many genera, the paucity of fossil mammal faunules superposed in local stratigraphic sections, and the imprecise chronologic constraints on Miocene land-mammal ages in the northern Rockies have resulted in no more specific biostratigraphic dating of these events. Consequently, refined dating of the tectonic events depends on a more detailed chronologic calibration of the fossil-bearing deposits.

In addition to the tectonic implications of the fossiliferous strata, the Barstovian mammals enclosed within the early intermontane sediments in the northern Rockies show distinct differences

from the type Barstovian fauna of southern California (Lindsay, 1972). Despite many similarities at the generic level, there are important variations at both generic and specific levels (Barnosky, 1986). Clearly, the large geographic separation between the northern Rockies and southern California, coupled with climatic differences and the development of intermontane basins bounded by substantial mountain barriers, could isolate faunas of the two regions to the extent that generic and species compositions could diverge. Therefore, in the absence of paleomagnetic or radiometric chronologies for the Barstovian mammals of both the northern Rockies and southern California, it has been impossible to determine whether the observed faunal differences between these regions reflect biogeographic variation among coeval local mammal assemblages, slightly different geologic ages of the faunas, or both. The lack of reliable chronological data has thwarted previous efforts to resolve these questions.

A recent magnetostratigraphic study of the Barstow Formation in southern California (MacFadden and others, 1990), however, has provided a detailed, independent chronology for the faunules used to typify the Barstovian land-mammal age (Wood and others, 1941; Lindsay, 1972). In this paper, we describe a similar study, based on magnetostratigraphic and biostratigraphic dating, of mainly Barstovian-aged deposits in the Yellowstone Valley of southwestern Montana. Because these sediments lie above the early Miocene regional unconformity, our results place some limiting dates on the initiation of extension. Moreover, the chronologic framework described here provides a temporal context within which to describe the local Barsto-

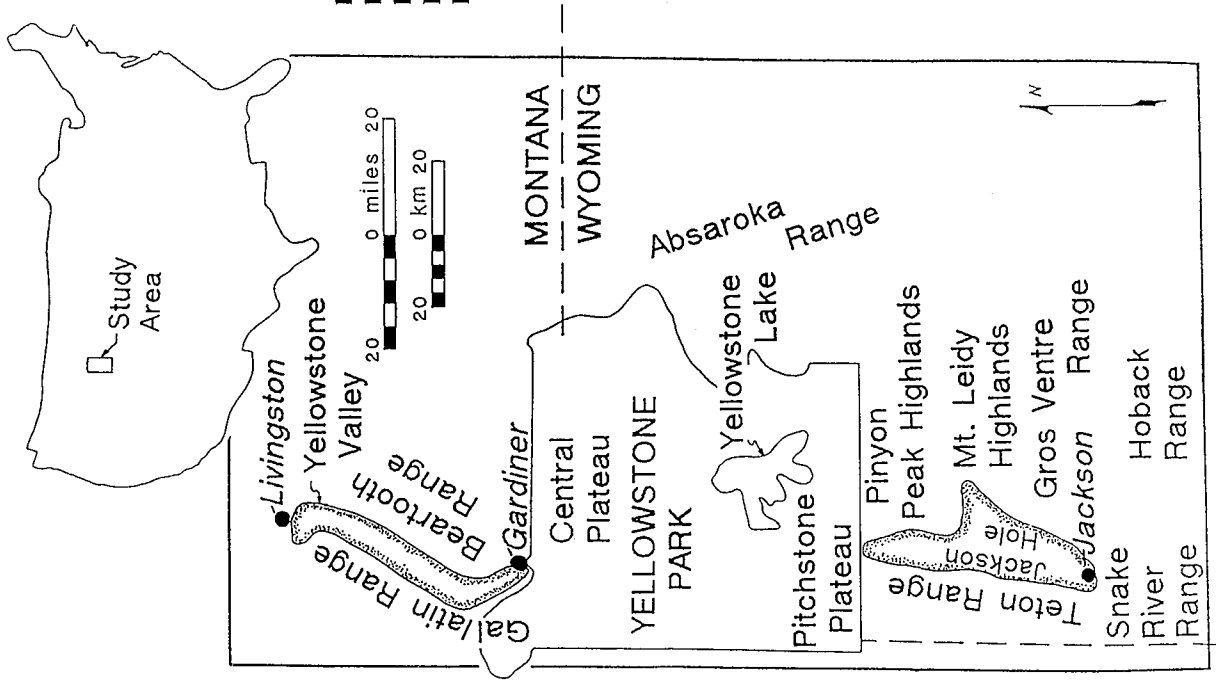


Figure 1. Location of study area. A. Location in relation to Yellowstone Park and Jackson Hole.

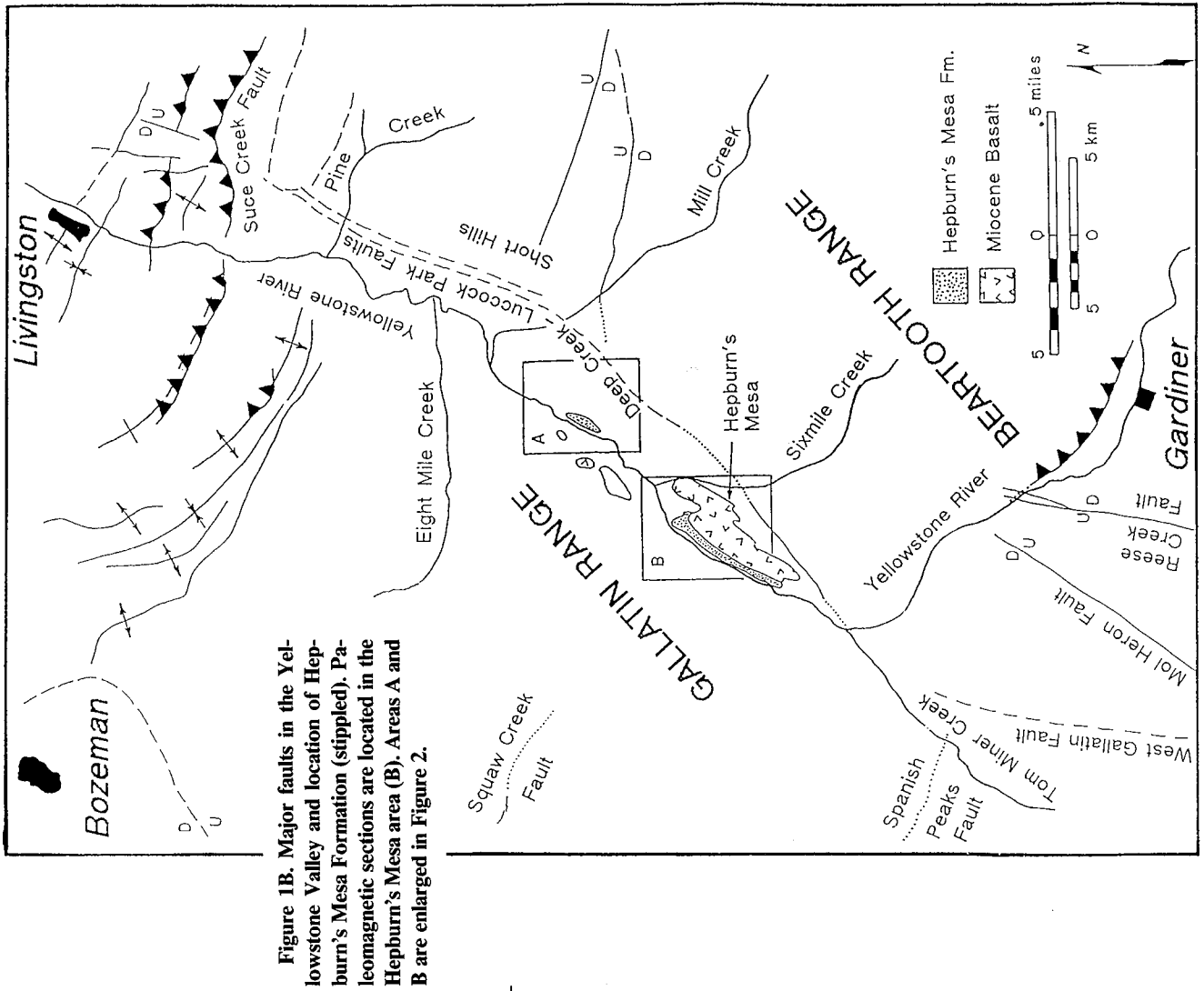


Figure 1B. Major faults in the Yellowstone Valley and location of Hepburn's Mesa Formation (stippled). Paleomagnetic sections are located in the Hepburn's Mesa area (B). Areas A and B are enlarged in Figure 2.

vian fauna of the northern Rockies and to compare it with dated faunal successions of similar ages in other regions.

### THE STUDY AREA

The Yellowstone Valley is a northeast-southwest-trending half-graben that is bordered on the east by the Beartooth Range and on the west by the Gallatin Range (Fig. 1). Three sides of the valley are bounded by faults, with the Suce Creek thrust to the north, the high-angle reverse Gardiner fault to the south, and the normal Deep Creek and Luccock Park faults to the east (Fig. 1). Differential tilting of superposed Miocene strata and the presence of visible scarps related to the Deep Creek-Luccock Park faults indicate that these faults have been active since some time in the Neogene. Within the Yellowstone Valley, there are numerous exposures of white, pink, and green claystones and siltstones that are distributed along the east side of the Yellowstone River from ~25–55 km north of Gardiner, Montana (Figs. 1 and 2). These exposures, recently designated as the “Hepburn’s

Mesa Formation” (Barnosky and Labar, 1989), constitute the Barstovian segment of the local geologic sequence. Their contact with the underlying strata is not exposed, but Eocene hypabyssal volcanic and volcanoclastic rocks crop out in other parts of the valley. Unconformably overlying the Hepburn’s Mesa Formation, there is a 40-m-thick, coarse conglomerate, which is itself capped by two basalt flows. The lower and upper flows have yielded K-Ar ages of 8.6 and 5.5 Ma, respectively (Chadwick, 1982; dates corrected according to Dalrymple, 1979).

This succession of Tertiary rocks indicates that Eocene volcanism in the Yellowstone Valley (and possibly mid-Tertiary terrestrial sedimentation) was followed by an interval of relative uplift and erosion. Mid-Miocene downwarping initiated the deposition of the Hepburn’s Mesa strata and signaled the initiation of crustal extension in this area. In the late Miocene, uplift in the Yellowstone Park area to the south (Fig. 1) provided a source for the coarse

conglomerates that truncate the Hepburn’s Mesa deposits. In the latest Miocene, basalts flowed from local vents or fissures and capped the entire Tertiary sequence.

Recent studies of the mineralogy and small-scale stratigraphy of the Hepburn’s Mesa strata (Barnosky and Labar, 1989) indicate that they were deposited in a shallow lake. The overwhelming abundance (typically 45%) of clinoptilolite, a zeolitic mineral derived from diagenetic alteration of volcanic glass, suggests that fine-grained volcanic ejecta contributed extensive detritus to the Neogene basin. This interpretation is reinforced by the presence in thin section of vitroclastic structure, bubble shards, glass fragments, and euhedral phenocrysts of biotite, quartz, and plagioclase. The lacustrine nature of the deposition is inferred from the abundance of clay (typically 45%), the presence of finely laminated deposits exhibiting soft-sediment deformation, and the occurrence of both gypsum and halite. Along with the re-

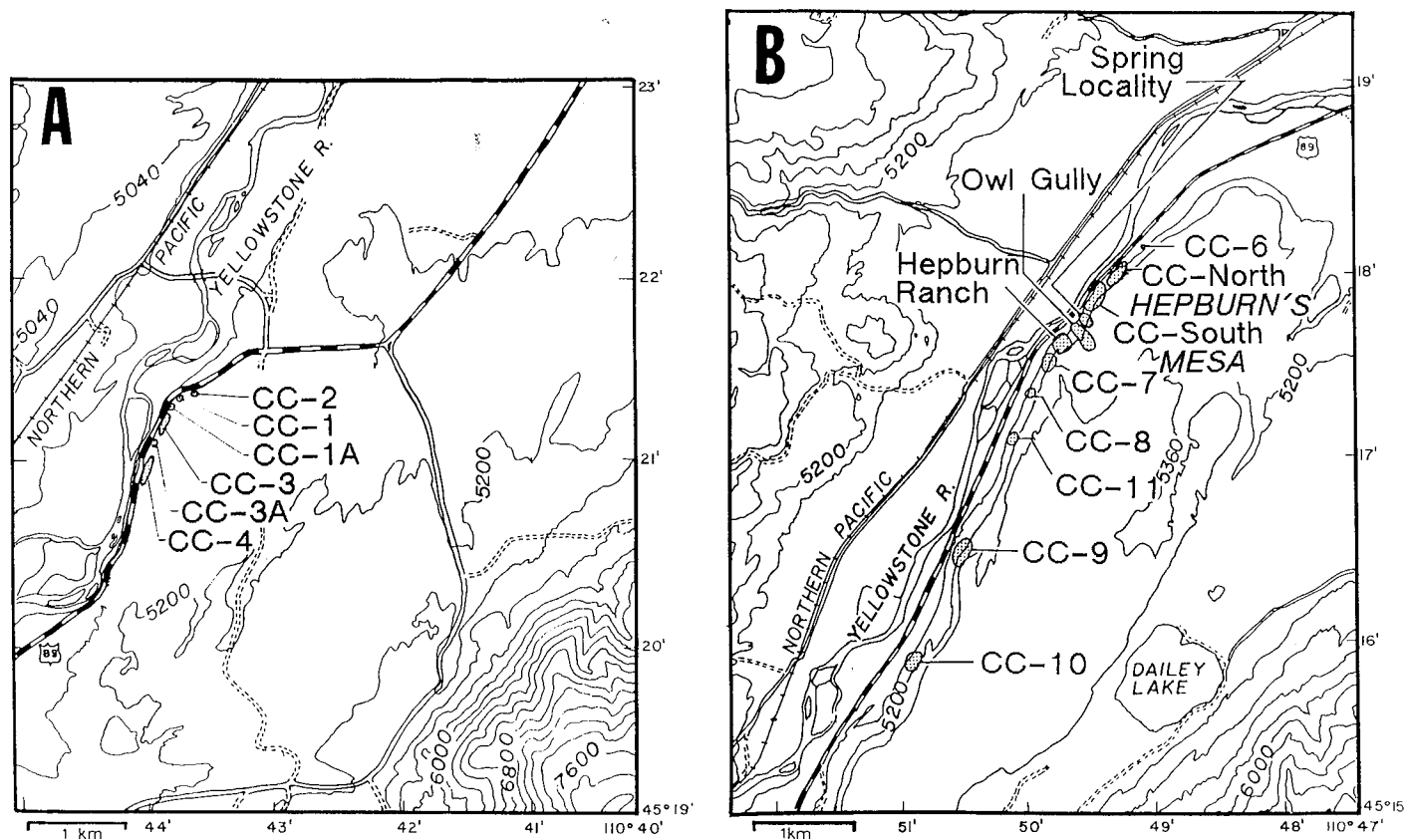


Figure 2. Outcrops of Hepburn’s Mesa Formation (stippled areas) within the Yellowstone Valley. Each outcrop is named (for example, CC-North) for convenience of discussion. Outcrops from CC-North to Hepburn Ranch were the focus of this study. The composite paleomagnetic section is constructed from detailed sampling of CC-North and Owl Gully. A and B are enlargements of respective areas shown in Figure 1. Base map for outcrops is traced from USGS Fridley Peak 15’ quadrangle.

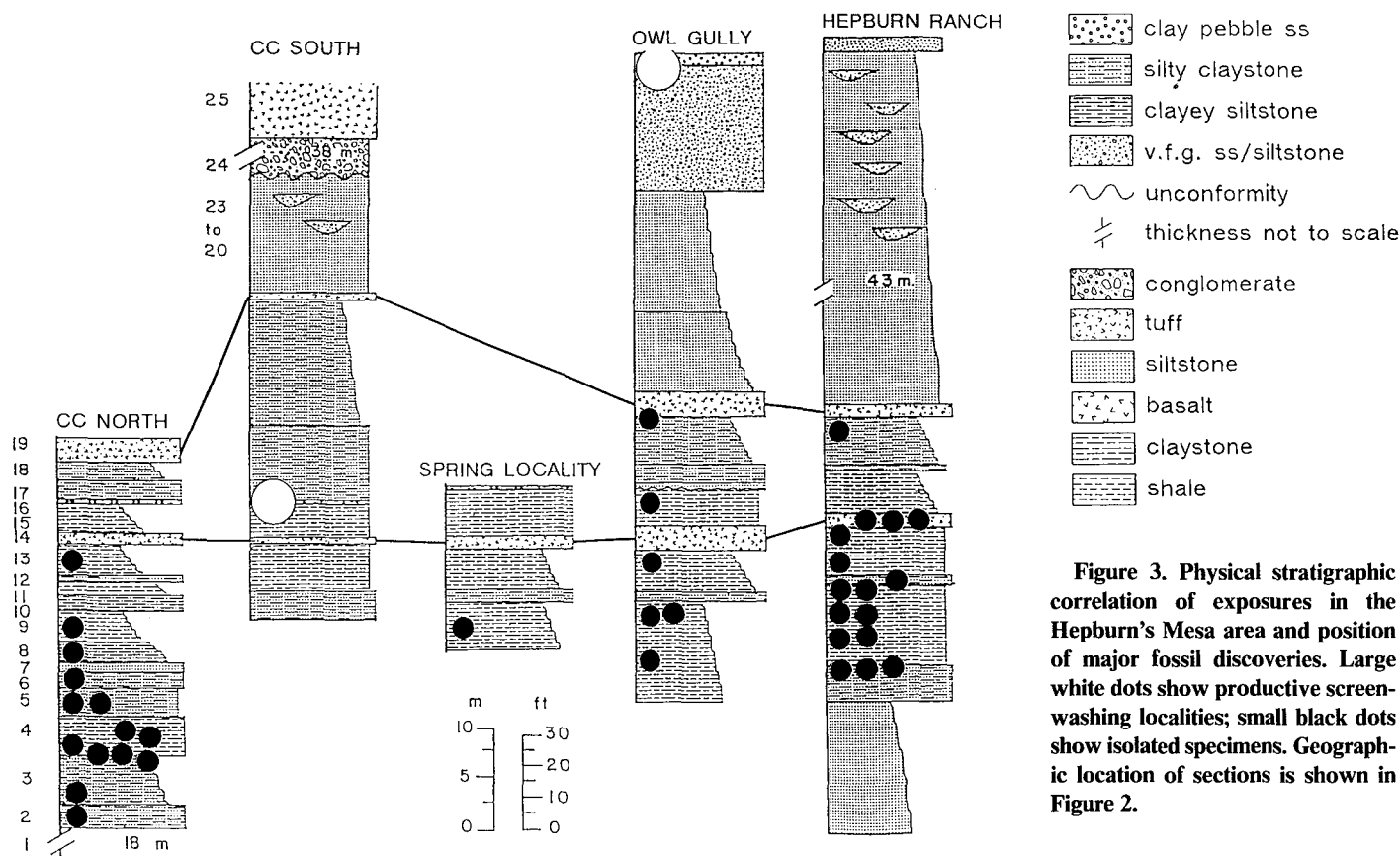


Figure 3. Physical stratigraphic correlation of exposures in the Hepburn's Mesa area and position of major fossil discoveries. Large white dots show productive screen-washing localities; small black dots show isolated specimens. Geographic location of sections is shown in Figure 2.

stricted extent of the Hepburn's Mesa strata, sedimentological features (laminations, mud cracks, mud flakes) and the suite of minerals (particularly clinoptilolite, gypsum, and halite) suggest deposition in a perennial saline lake. Over-all aridity for this setting also is strongly indicated by the fossil assemblage found associated with these strata (Barnosky and Labar, 1989).

## METHODOLOGY

The Hepburn's Mesa Formation was measured and described in detail in the vicinity of Hepburn's Mesa (Fig. 2). Lithologic similarities and distinctive tuffaceous marker beds that were readily traceable across the nearly continuous exposures were used to develop correlations between individual outcrops (Figs. 2B and 3). Two sections, Chalk Cliffs North (CC-North) and Owl Gully (OG), with an aggregate thickness of ~100 m, were the focus of paleomagnetic study.

On an initial sampling pass, paleomagnetic sites were spaced at ~2-m intervals through the two sections. Three or four oriented specimens were collected at each site. Subsequent sampling concentrated on areas where ambiguous results had been obtained from the previous sampling efforts.

A selection of paired specimens, chosen to represent the various lithologies encompassed by

the sequence and the stratigraphic range spanned by it, were subjected to step-wise, alternating-field and thermal demagnetization. The results of these procedures (Figs. 4 and 5) reveal generally uncomplicated magnetic behavior. Magnetic overprinting due to viscous remanence and limited, postdepositional alteration are generally removed by 200 °C and 250 oe. Above these levels, coherent directional data are usually obtained until temperatures of ~550 °C (Figs. 4 and 5) are reached.

Across this interval, steady decreases in intensity are observed at successively higher temperatures. Above 550 °C, unpredictable changes in both intensity and direction occur. About 5%–10% of the maximum observed intensity remains above 600 °C. These thermal demagnetization results suggest that (1) magnetite or titanomagnetite is the primary carrier of the characteristic remanence; (2) postdepositional overprints are readily removed from the detrital signal; (3) the orientation of the characteristic remanence is revealed at all temperatures between ~300 and 550 °C; and (4) a magnetically "hard" component, probably reflecting hematite, forms as much as 10% of the total remanence.

On the basis of these data, each of the remaining specimens was thermally demagnetized in multiple steps between 400 and 550 °C in order to reveal its characteristic remanence direction.

These specimen directions were then statistically averaged and evaluated at each site (Fisher, 1953). Only those sites exhibiting coherent directions and yielding a Fisher  $k > 10$  (classified as "Class I"; Johnson and others, 1982) were used in our subsequent analysis. The latitude of the virtual geomagnetic pole (VGP) and an alpha-95 error envelope on that latitude were calculated based on the mean vector orientation and on the coherency of specimen directions at each site, respectively. The northern and southern VGP latitudes form the basis for the local magnetic polarity zonation for each of the two sections, which were, in turn, correlated with the magnetic polarity time scale (Berggren and others, 1985).

Two contaminated tuff beds were discovered in each of the studied sections. Through the use of both fission-track (FT) dating of zircon in the ashes and single-crystal, laser-fusion, Ar-Ar dating, an attempt was made to provide calibrated tie-points for the correlation of the local magnetostratigraphy with the global magnetic time scale. The samples were prepared following the procedures of Naeser (1978), and the etching was designed to highlight the tracks in the most pristine, least abraded and clear crystals that were presumed to represent the youngest zircons that were coeval with the Hepburn's Mesa deposits. The FT samples were irradiated in the TRIGA facility at Oregon State University, and

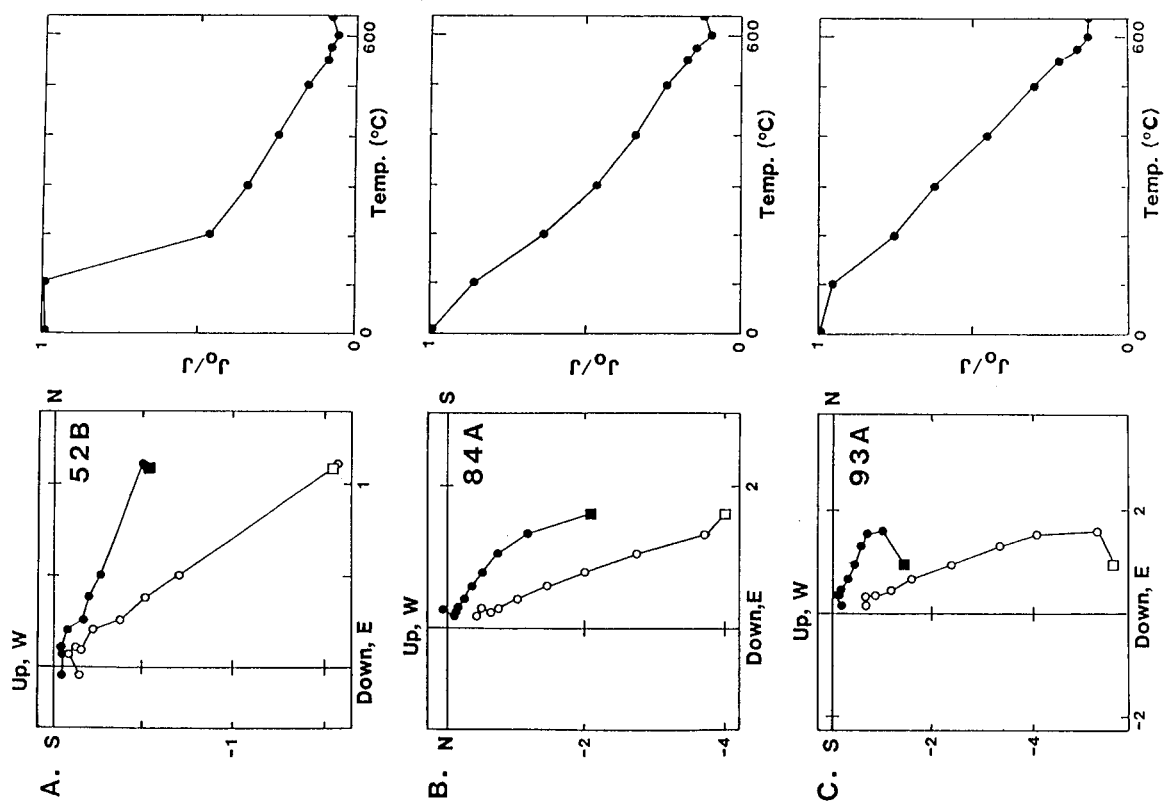


Figure 4. Thermal demagnetization figures for normally magnetized samples, showing uncomplicated magnetic behavior. The characteristic remanence directions are revealed consistently between 200 and 600 °C.

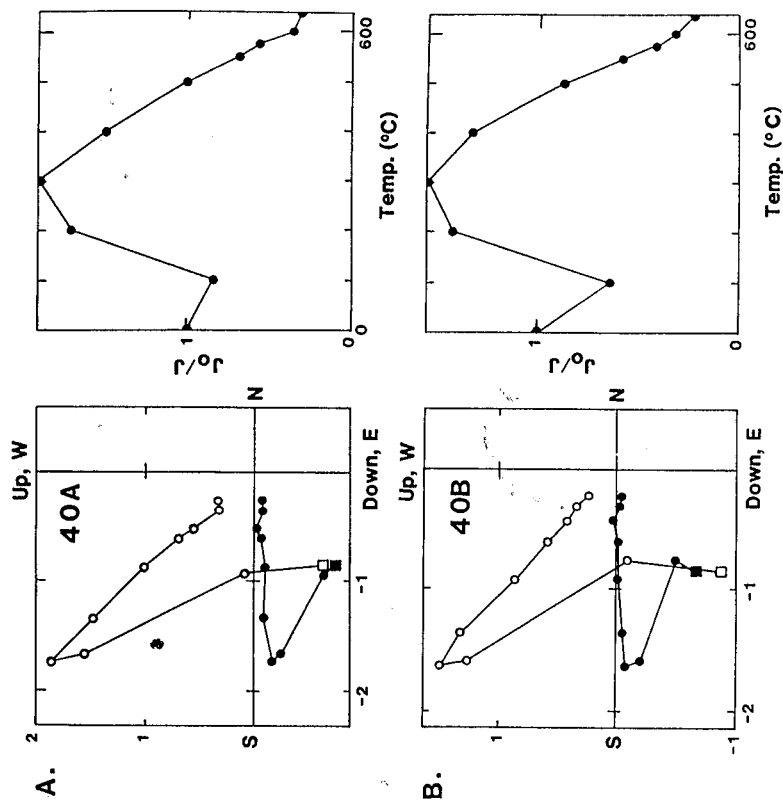
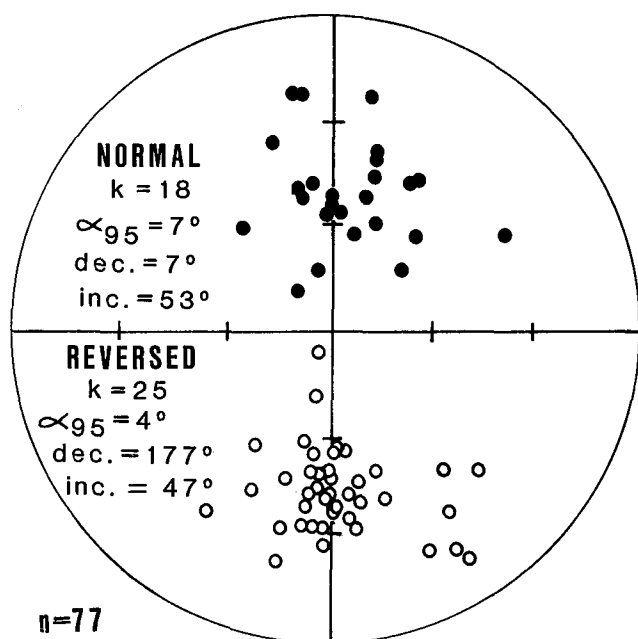


Figure 5. Thermal demagnetization figures for reversely magnetized samples, showing removal of a normal overprint at temperatures below 300 °C. Characteristic remanence directions are displayed between 300 and 600 °C.

## Chalk Cliffs



## Owl Gully

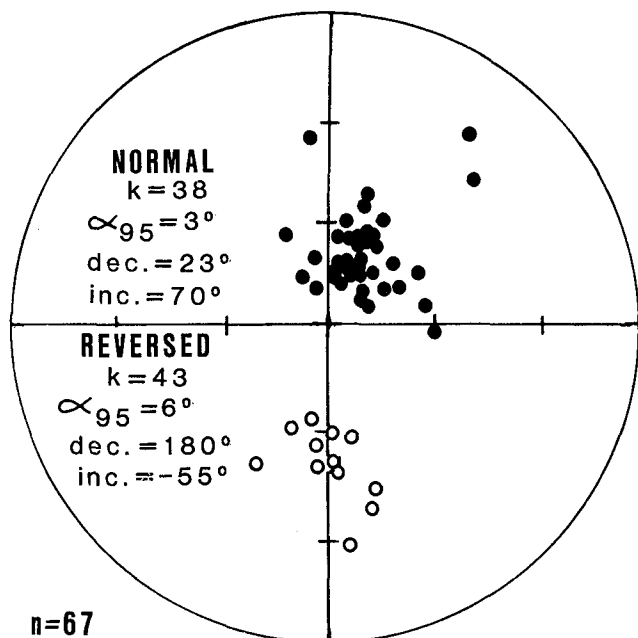


Figure 6. Stereoplots of normal and reversed Class I data, showing Fisher (1953) statistics and mean magnetic directions. (A) Chalk Cliffs North and (B) Owl Gully. The Owl Gully normally magnetized data appear to define a small clockwise rotation of  $\sim 20^\circ$ .

the dosage calibration was made using mica detectors on NBS glass standards and using zircons from the Fish Canyon Tuff.

## RESULTS

Stereoplots of the Class I data from each section reveal antipodal data (Fig. 6), clearly indicating that both sections pass the reversal test (McElhinny, 1973). The mean inclination for

the data is  $56^\circ$ . This is only  $7^\circ$  less than that expected for the present dipole field at this latitude ( $45^\circ\text{N}$ ), and within the uncertainty of the data, it accords well with the latest Tertiary paleopole position. As shown by the mean declinations, there is a small difference in the amount of postdepositional rotation of the two sections, with the more southerly section (OG) showing  $\sim 20^\circ$  of clockwise rotation. Several normal faults disrupt the outcrops that separate the two

measured sections. Although these faults have relatively minor throws of several meters, sufficient dextral shearing apparently occurred along them to rotate the Owl Gully outcrops by the observed amount. The VGP plots of the site data (Fig. 7) delineate multiple magnetozone within each section. Most of the magnetozone are defined by two or more Class I sites. In combination with the tight  $\alpha_{95}$  error envelopes on the VGP latitudes, this suggests that the over-all magnetic polarity pattern has been reliably described. Although CC-North and Owl Gully are separated by a few hundred meters of vegetation-covered slope and by localized faults, distinctive marker beds and detailed stratigraphic and geochemical studies (Barnosky and Labar, 1989) allow for confident physical-stratigraphic correlation of the coeval depositional units at each section (Fig. 3). This correlation is reinforced by the magnetic data, which agree in detail with the stratigraphic interpretation. There are only 10 m of overlapping magnetic sites between the two sections (units 15–19, Fig. 7), but within this zone, the pattern of magnetozone (R-N-R) and their relative durations match well between the two sections.

Even though the thickness of the sampled sequences is not large, suggesting that the magnetic stratigraphies are unlikely to span a long portion of the Neogene, the pattern of reversals discovered (Fig. 7) is sufficiently distinctive to be correlated to the magnetic polarity time scale (MPTS, Berggren and others, 1985) with considerable confidence (Fig. 8, right side). The correlation indicates that the base of the section dates from  $\sim 16.8$  Ma, and the top from  $\sim 14$  Ma.

The uppermost strata could be as old as 14.3 Ma, given that the reversed subchron (5AC-r) at 14.2 Ma was not revealed by this fairly dense sampling scheme. Such a correlation, however, would require an increase in the mean sediment-accumulation rate from 3–4 cm/k.y. during magnetozone R2-R5 to  $>9$  cm/k.y. during magnetozone N5. Alternatively, it could be argued that the top of the section dates from as young as 13.8 Ma. In this case, either nondeposition during subchron 5AD-r, later erosion, or irregular sample spacing with respect to time could account for its absence in the local magnetostratigraphy. A horizon that could possibly represent such a time gap may be found at the base of unit 22 in the Owl Gully section (Fig. 9). In this latter interpretation, the mean sediment-accumulation rate in the upper section would remain comparable to that found in the lower section. Sufficient data are not available at present to discriminate between these two options.

For the correlation depicted here, magnetozone N5 (Figs. 7 and 8) is not correlated with any well-established normal subchron in the MPTS. Its presence in both the Owl Gully and

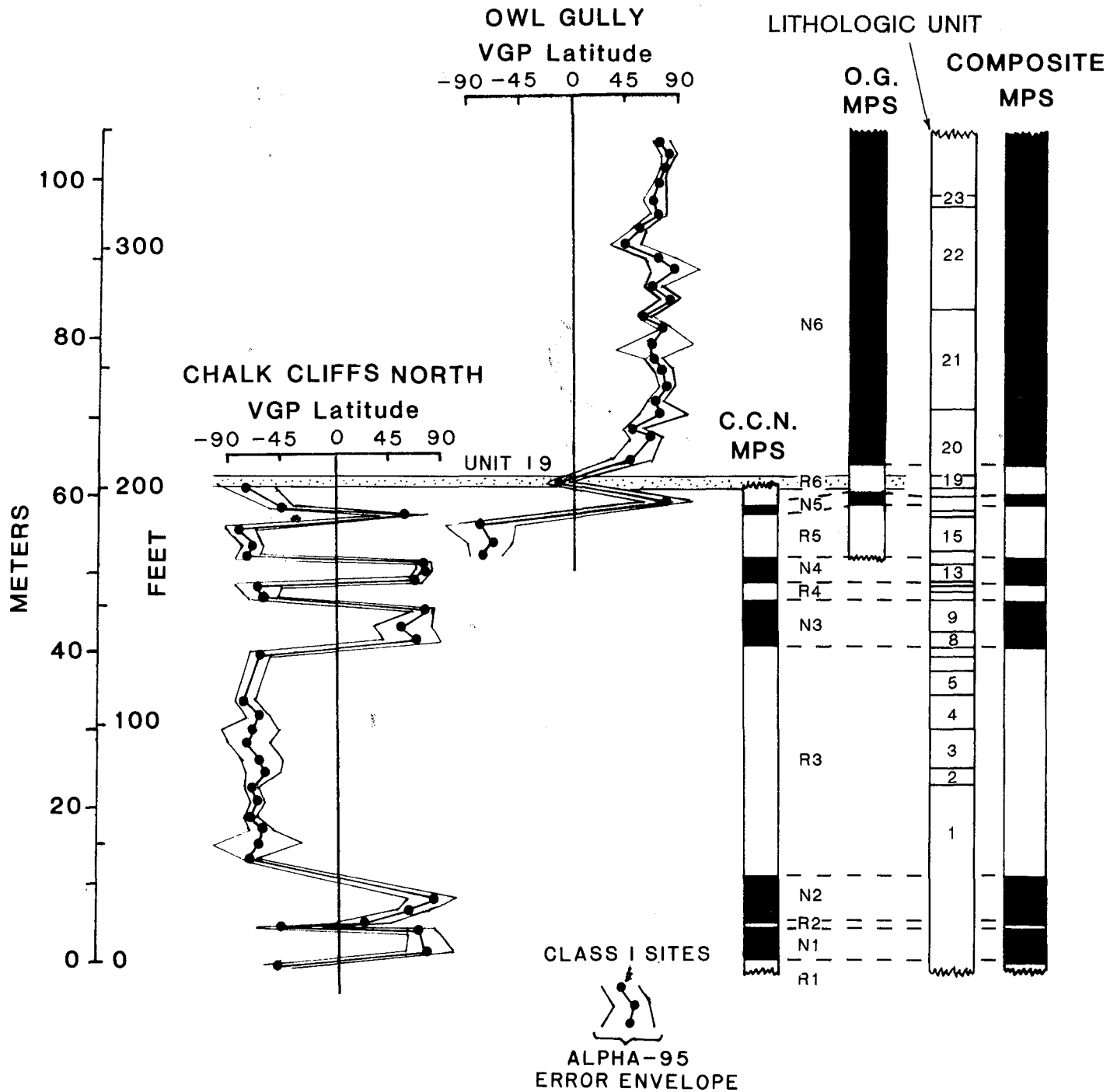


Figure 7. Magnetic polarity stratigraphy from Chalk Cliffs North and Owl Gully. The latitude of the virtual geomagnetic pole (VGP) is shown in degrees for each site. Only Class I sites (Fisher  $k > 10$ ) are plotted, and each is enclosed by an alpha-95 error envelope on the VGP latitude. Unit 19 is a correlative lithostratigraphic unit between the two sections. The composite magnetic polarity stratigraphy (MPS) reflects the combination of magnetozoneations from the two sections.

the Chalk Cliffs North section indicates that it is likely to represent a valid local magnetozone. The fact that, in both sections, it is depicted by a single site, despite the close sample spacing, suggests that it represents a brief (<20 k.y.) interval of normal polarity within Chron C5AD-r that has not been well documented in the MPTS.

Short-duration subchrons of this sort are expected to occur within the record of polarity reversals (Johnson and McGee, 1983), but, because of their brevity, they are rarely well defined. Potentially, it is correlative with magnetozone N7 in the Barstow magnetic stratigraphy (Fig. 8A).

Given that fossils indicative of Barstovian (middle Miocene) age or, at the earliest, of late Hemingfordian (early Miocene) age are found in the Hepburn's Mesa exposures, the correlation shown here of the local magnetic stratigraphy with the MPTS is the most logical one in this part of the Neogene time scale. In order to rein-

INFORMATION FROM BARSTOW

BARSTOW COMPOSITE  
MAGNETIC POLARITY  
ZONATION

HEPBURN'S MESA  
COMPOSITE MPS

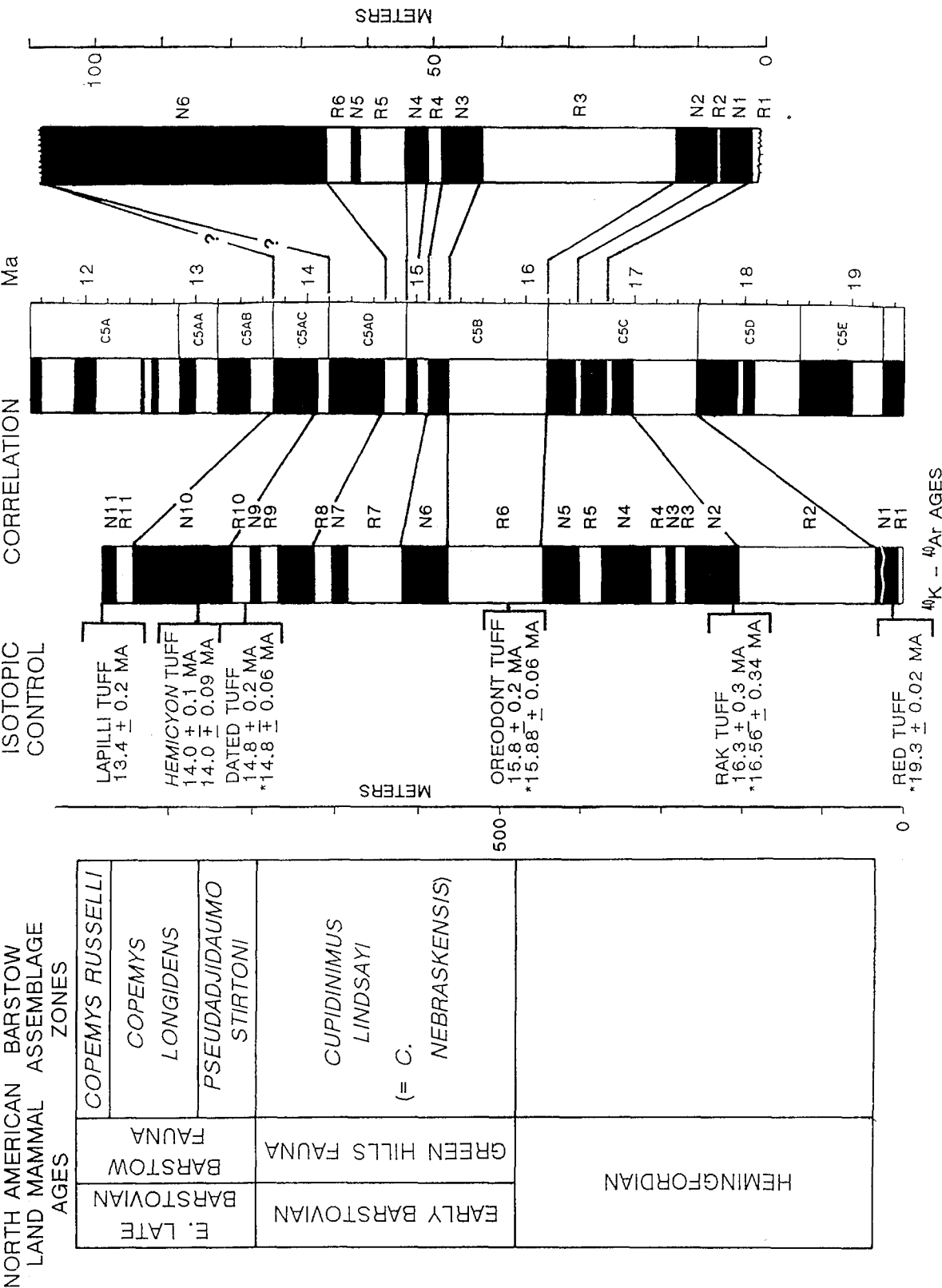


Figure 8A. Correlation of composite section at Hepburn's Mesa with magnetic polarity time scale, and with faunal, radiometric, and paleomagnetic data from the Barstow Formation. Barstow data are summarized from Woodburne and Tedford (1985) and MacFadden and others (1990).



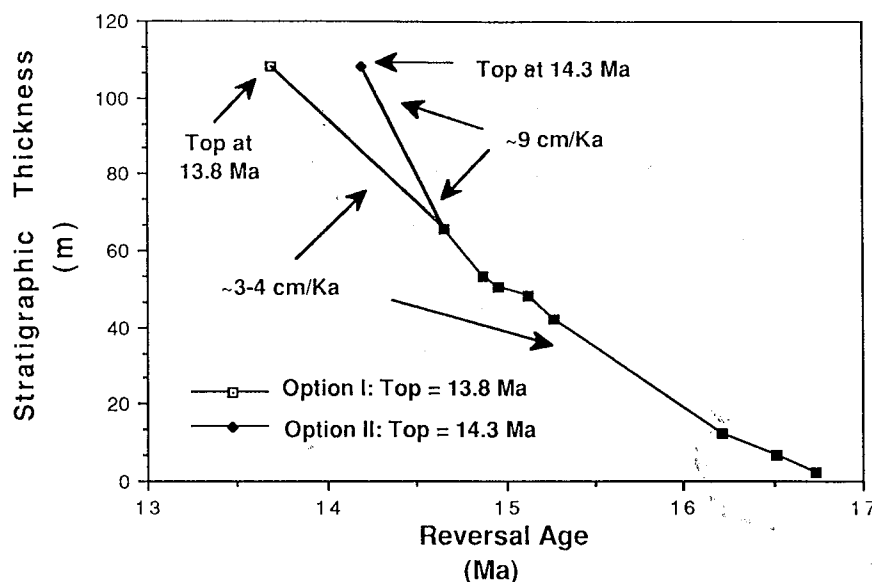


Figure 8B. Present stratigraphic thickness versus time plot for Hepburn's Mesa Formation, showing two alternative correlations for the upper portion of the local magnetic zonation.

force this correlation, attempts were made, using the fission-track and Ar-Ar methods, to date the two contaminated tuffs that constitute units 14 and 19 (Fig. 3). Fossil mammals provide evidence that these tuffs are of late Barstovian age, as are all strata above ~35–40 m (units 16–23) in the composite section (Fig. 9). At least two, morphologically distinct populations of zircons were readily discriminated in each of the FT samples. This suggests that the ashes had been contaminated with older detrital material. The two populations of zircons yielded a pair of widely separated ages for each tuff. The younger ages, which resulted from longer etch times and counting of more pristine grains, averaged ~10.8 m.y., whereas the older ages averaged ~17.4 m.y. Acceptance of the younger ages would imply that a late Barstovian fauna persisted in the northern Rockies more than 2 m.y. after Clarendonian fauna emerged in California at ~13 Ma (D. P. Whistler and D. W. Burbank, unpub. data) and ~1 m.y. after Clarendonian taxa took over elsewhere (Tedford and others, 1987). The older dates would require late Barstovian faunas in the Rockies to have co-existed with Hemingfordian faunas elsewhere (Tedford and others, 1987). We find neither of these alternatives as likely as the ages that are implied by the magnetic stratigraphy. The tuff samples from our composite section were either too contaminated or too fine grained to be dated successfully using the Ar-Ar method (C. Swisher, 1988, personal commun.). Consequently, there are presently no radiometric ages available to confirm the chronological framework provided by the magnetic data. Nonetheless, the high quality of the magnetic data and the good match

of these data with the MPTS indicate that they provide reliable temporal constraints on the faunal record.

The faunal record defines the lower part (units 3 to 13) of the Hepburn's Mesa composite section as late Hemingfordian or earliest Barstovian land-mammal age (Fig. 9; see also Table 1 in Barnosky and Labar, 1989). The presence of *Dromomeryx*, *Hypolagus*, and *Peridomys* implies that this interval is not earlier than late Hemingfordian, because these taxa elsewhere are unknown in earlier deposits. The upper age boundary of this interval is constrained by the presence of *Parahippus* (includes *Desmatippus* in our usage) and *Mesogaulus*, neither of which survived the early Barstovian elsewhere. It is not possible to characterize faunally this lower interval at Hepburn's Mesa exclusively as either late Hemingfordian or early Barstovian. The presence of a genus that elsewhere first appears in the Barstovian (*Peridomys*), however, indicates that the most reasonable age assignment is early Barstovian. Our magnetostratigraphically determined date for units 3 to 13 ranges from younger than 16.2 to ~15.0 Ma. Thus, the timing of what we consider the early Barstovian interval at Hepburn's Mesa is consistent with the current placement of the Hemingfordian-Barstovian boundary at 16.0 Ma, which is based on K-Ar, Ar-Ar, and fission-track dates from tuffs in association with Hemingfordian and Barstovian faunas near the type areas for these land-mammal ages (MacFadden and others, 1990).

Fauna from the upper part of the Hepburn's Mesa section (units 16 to 23) indicate an early late Barstovian age (Fig. 9). Most of the taxa occur in particularly productive screen-washing

localities near the middle (unit 16) and top (unit 23) of the stratigraphic section (Figs. 3 and 9). In each of the two localities, all fossils come from within a single clay-pellet conglomerate lens less than 1 m thick. Because each lens represents a geologically instantaneous event, the fossils within them are only minimally time-averaged.

All of the genera from this upper interval are present in Barstovian deposits elsewhere (see detailed locality listings for most of these taxa in Barnosky (1986 and references therein). Four genera first appear elsewhere in the early Barstovian (*Copemys*, *Perognathus*, *Peridomys*, *Mojavemys*). Seven are unknown from deposits younger than Barstovian (*Blastomeryx*, *Peridomys*, *Mojavemys*, *Pseudotheridomys*, *Shaubeumys*, *Tardontia*, *Oreolagus*). Two have not been discovered in deposits younger than early Barstovian (*Mesoscalops*, *Mesogaulus*), whereas six first appear in the late Barstovian (*Diprionomys*, *Lignimus*, *Pseudadjidaumo*, *Tardontia*, *Tamias*, *Spermophilus*). The predominance of late Barstovian indicators, with a smaller number of "early" Barstovian forms, suggests an age early in the late Barstovian.

The early-late Barstovian as previously dated at the type area begins at ~14.8 Ma (MacFadden and others, 1990; Tedford and others, 1987; Woodburne and Tedford, 1982). This age represents an average of several Ar-Ar and K-Ar dates of the "Dated Tuff" between the Green Hills Fauna (early Barstovian) and the Barstow Fauna (late Barstovian). Our magnetostratigraphic data place the beginning of the late Barstovian in the northern Rockies prior to 14.7 Ma. The early late Barstovian interval at Hepburn's Mesa begins no higher than unit 16, which in the magnetic polarity profile falls in a reversed magnetozone (Chron 5AD-r) spanning from 14.7 to 14.9 Ma (Fig. 8). It would not be unreasonable to assume that unit 16 represents a time very near the beginning of the late Barstovian, inasmuch as two "early" Barstovian genera (*Mesoscalops*, *Mesogaulus*) linger into what is predominantly a late Barstovian faunule. If this is the case, the beginning of the late Barstovian in the northern Rockies matches very closely the date (14.8 Ma) for the boundary between the early and late Barstovian at Barstow (MacFadden and others, 1990).

Early late Barstovian age extends to the top bed of the Hepburn's Mesa section, as unit 23 yielded a faunule that essentially is identical to that of unit 16, except both of the "early" Barstovian indicators (*Mesoscalops* and *Mesogaulus*), as well as *Pseudadjidaumo* are absent (Fig. 9). Therefore, the early late Barstovian at Hepburn's Mesa lasts at least to either 14.3 or 13.8 Ma, according to the two possible magnetostratigraphic correlations. The Hepburn's Mesa composite section stops short of 12.5 Ma, which

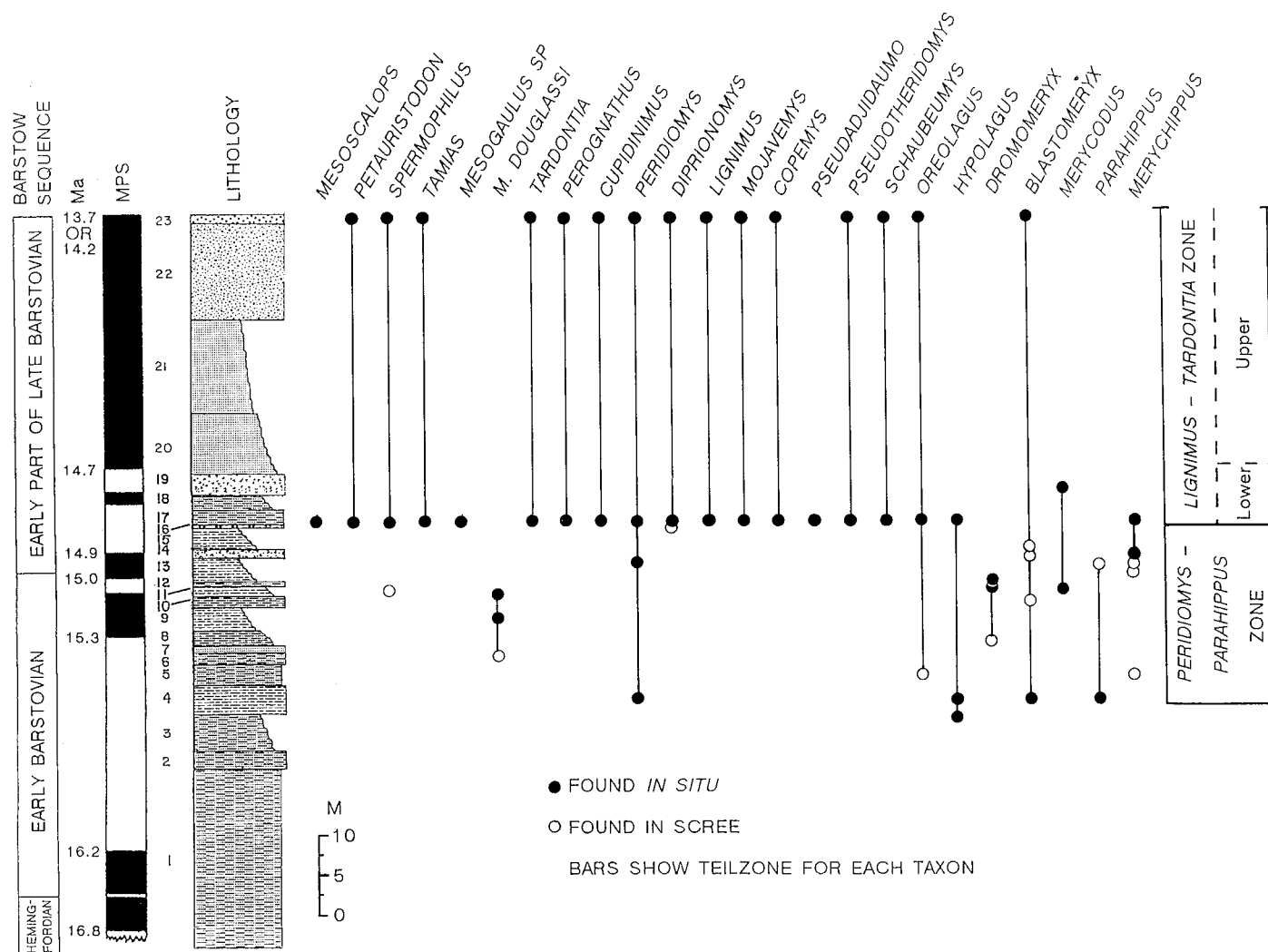


Figure 9. Correlation of local magnetostratigraphy, lithology, and faunal zones of the Hepburn's Mesa Formation with the radiometric time scale and land-mammal ages.

Tedford and others (1987) take to mark the end of the early late Barstovian.

The presence of *Pseudajdaumo* at Hepburn's Mesa is consistent with the temporal extent of the same genus in the Barstow Formation. There, the bottom of the *Pseudajdaumo stirtoni* Assemblage Zone lies just below a date of 14.8 Ma ("Dated" Tuff), and the top lies below dates of ~14.0 Ma (Hemicyon Tuff; MacFadden and others, 1990). At Hepburn's Mesa, the genus has been found in strata ranging from 14.7 and 14.9 Ma.

## DISCUSSION

### Initiation of Neogene Extension

In most intermontane basins of the northern Rocky Mountains, dating the mid-Tertiary unconformity and the onset of Neogene extensional tectonism has relied mainly, if not solely,

on biostratigraphy (Fields and others, 1985), which depends on the assumption that the boundaries of land-mammal ages do not transgress time. This assumption is validated at Hepburn's Mesa by calibration of the Barstovian land-mammal age with the paleomagnetic time scale and by the temporal correspondence of the faunal boundaries there with those at Barstow in southern California. The transition from Hemingfordian to Barstovian (~16.0 Ma) and early Barstovian to late Barstovian (ca. 14.8 Ma) at these two widely separated sites appears virtually simultaneous within the resolution of magnetic and radiometric chronologies.

In the study area itself, because the youngest, pre-unconformity strata are the well-dissected Eocene volcanic rocks, it is difficult to date precisely the inception of uplift that generated the mid-Tertiary unconformity. Similarly, there is

an absence of well-dated strata in most other basins of the northern Rockies that could be used to constrain tightly this interval of Neogene erosion. Biostratigraphically based correlations consistently place the mid-Tertiary unconformity, which preceded the onset of Neogene extensional tectonics in the northern Rockies, somewhere between ca. 21 Ma (late Arikarean) and 13 Ma (late Barstovian), and in the best cases between about 20 Ma and 16 Ma (during the Hemingfordian; Fields and others, 1985). The magnetic stratigraphy at Hepburn's Mesa permits closer constraints to be placed on the age of the middle Tertiary unconformity and subsequent extension in southwestern Montana and northwestern Wyoming.

The onset of Neogene extension previously was most securely bracketed on the basis of biostratigraphic data from the Colter Formation of Jackson Hole, Wyoming. Fossil sites near the

top of the Crater Tuff-breccia Member and near the bottom of the overlying Pilgrim Conglomerate Member suggest that the unconformity lies between 18 and 13 Ma. The thickness of strata, however, that separates these two dates is more than 400 m (Barnosky, 1984). If the marked lithologic change between the two members was generated by the same episode of uplift that created the widespread unconformity in Montana, including that found below the Hepburn's Mesa Formation, then the faunal dates from the Colter Formation would indicate that uplift commenced in the late Hemingfordian at some time <18 Ma. In the Yellowstone Valley, the Hepburn's Mesa Formation indicates that the cessation of the erosive event that caused the mid-Tertiary unconformity, as well as the onset of extensional block faulting, had occurred by ~16.8 Ma. Sedimentation patterns in the Yellowstone Valley and Jackson Hole appear genetically related (Barnosky and Labar, 1989); therefore, the date from the bottom of the Hepburn's Mesa Formation, in conjunction with the date from the upper Crater Tuff-breccia Member of the Colter Formation, brackets the development of the mid-Tertiary unconformity and the shift to Neogene extensional tectonic styles as occurring between ~17 and 18 Ma.

Support for the likely genetic relationship between the unconformities in northwestern Wyoming and southwestern Montana is provided by lithological data from each. The post-unconformity Colter strata are quite proximal volcanoclastic sediments interstratified with rhyolitic tuffs. Below the unconformity, the volcanic rocks are andesitic, trachytic, and latitic. Not only does this lithologic change across the unconformity reflect the compositional variation that would be expected as a compressional tectonic regime is superceded by an extensional one (Christiansen and Lipman, 1972; Stewart, 1978), but the extensive explosive volcanism recorded by the upper Colter Formation would provide a source for the large input of fine-grained (that is, distal) volcanogenic sediments into the Hepburn's Mesa Formation (Barnosky and Labar, 1989). At present, the volcanic center in northern Jackson Hole which supplied proximal volcanoclastics to the Colter Formation is the only one identified in the northern Rockies of a suitable age and location to provide the abundant distal airfalls incorporated in the Hepburn's Mesa Formation.

The nature of extension and related subsidence was clearly highly variable in different locations in the northern Rockies. Whereas quite limited thicknesses (<200 m) of Barstovian and younger Miocene strata are preserved in the Yellowstone Valley, at least 2,700 m of coeval strata are found in Jackson Hole. Late Barstovian sediment-accumulation rates in Jackson Hole were between 20–40 cm/k.y.

During the Clarendonian and Hemphillian, these rates probably increased to nearly 50 cm/k.y. in the lacustrine deposits of the Teewinot Formation. In contrast, the Barstovian sediment-accumulation rates in the Yellowstone Valley averaged 3–6 cm/k.y., and the Clarendonian and/or Hemphillian intervals are represented by only about 40 m of conglomerate and basalt. Although Neogene extension and subsidence had clearly begun in the Yellowstone Valley by the Barstovian, it was very subdued, and only a relatively thin veneer of sediments accumulated (or were preserved) under this tectonic regime. The 5- to 10-fold higher rates recorded in Jackson Hole indicate a much more dynamic subsidence, even though major morphogenic uplift of the Teton Range, which bounds the western margin of Jackson Hole along the Teton fault, did not begin until after 9 Ma (Love and others, 1973).

### Comparisons of Barstovian Faunas

In the absence of the predominantly large mammals that Tedford and others (1987) used to define faunal-age boundaries of the Barstovian, it has been difficult to differentiate clearly late Hemingfordian, early Barstovian, and late Barstovian faunas in the northern Rockies. (The absent large mammals at Hepburn's Mesa include *Plithocyon*, whose first appearance defines early Barstovian, and proboscideans, *Pseudocyon*, and *Pseudoceras*, whose first record defines late Barstovian.) Refined subdivision of these land-mammal ages has been even more difficult because of the scarcity of superposed Hemingfordian and Barstovian faunas in the region. The superpositional relationships of taxa and their correlation with an independent time scale at Hepburn's Mesa, combined with their known temporal relationships elsewhere (Barnosky, 1986; Barnosky and Labar, 1989), however, allow recognition of two interval zones (*sensu* Article 50(2) in the North American Stratigraphic Code, 1983) that can be well dated in the Yellowstone Valley. The *Peridomys-Parahippus* Zone is the interval demarcated on the lower end by the first appearance of *Peridomys*, and on the upper end by the last appearance of *Parahippus*. This zone also includes the total known range of *Mesogaulus douglassi* (Fig. 9). The temporal extent of the *Peridomys-Parahippus* Zone as presently understood at Hepburn's Mesa is from ~15.0 to ~16.0 Ma. Both the faunal assemblage (see Table 1 in Barnosky and Labar, 1989, and Results section) and the temporal extent are consistent with placing this zone in the early Barstovian.

The *Lignimus-Tardontia* Interval Zone has as its lower boundary the first occurrence of *Lignimus* and as its upper boundary the last occurrence of *Tardontia*. Within this interval, the first

appearances of *Pseudadjidaumo*, *Tardontia*, *Diprionomys*, and *Spermophilus* also occur. Faunal data at hand suggest that the last appearances of *Mesoscalops*, *Mesogaulus*, and *Pseudadjidaumo* can be used as a boundary to subdivide the *Lignimus-Tardontia* Zone into lower and upper parts (Fig. 9). Whether the absence of these genera in unit 23 reflects the smaller sample size from that horizon remains to be determined when more sites and fossils come to light. *Mesogaulus* and *Mesoscalops* have their youngest dated occurrence anywhere in unit 16, however, and so it is not unreasonable to assume that they were extinct by unit 23, especially in view of the faunal similarity of units 16 and 23 in other respects. The *Lignimus-Tardontia* Zone at Hepburn's Mesa begins at ~14.8 Ma and persists into the youngest preserved middle Miocene strata (either 14.3 or 13.8 Ma, Fig. 8). Faunally and temporally, it correlates with the early part of the late Barstovian.

These interval zones so far only have been demonstrated by direct superposition at Hepburn's Mesa. It would be desirable to establish their temporal significance more fully through recognition of similarly superposed and independently dated taxa at other Rocky Mountain localities. The thick, fossiliferous sequences necessary for such comparisons with Hepburn's Mesa, however, have not been discovered.

Nevertheless, recognition of the superposed interval zones at Hepburn's Mesa has implications for the temporal placement of other late Barstovian local faunas in the northern Rockies, notably from Cunningham Hill and North Pilgrim 2 in Jackson Hole, Wyoming (Barnosky, 1986) and from Anceney, in the Three Forks Basin of Montana (Sutton, 1977). The Jackson Hole local faunas in general resemble those of units 16 and 23 at Hepburn's Mesa in generic composition, except for lacking *Tardontia*. Like unit 23 at Hepburn's Mesa, the Jackson Hole local faunas also lack *Mesoscalops*, *Mesogaulus*, and *Pseudadjidaumo*, even though the Jackson Hole faunules are represented by reasonable sample sizes, are from a similar depositional setting, and were collected by techniques identical to those employed at Hepburn's Mesa. The absence of these forms, if not resulting from sample bias, would place the Jackson Hole local faunas near the top of the *Lignimus-Tardontia* Zone. The Anceney fauna appears to fall near the lower part of the *Lignimus-Tardontia* Zone, based on the presence of *Mesogaulus*, *Diprionomys*, and *Spermophilus*. The absence of *Mesoscalops*, *Lignimus*, *Tardontia*, and *Pseudadjidaumo*, despite a sample size of thousands of teeth, remains to be explained, however. The absence of the latter three might indicate a slightly older age than represented by the *Lignimus-Tardontia* Zone. Alternatively, the presence or absence of a few taxa among the

different intermontane basins may simply reflect taphonomic and ecological biases. Independent dating of the Jackson Hole and Ancney deposits is needed in order to decide which alternative is more reasonable.

Biogeographically, the fauna of the *Lignimus-Tardontia* Zone supports the contention that the Barstovian Rocky Mountains housed an assemblage of species that mingled Western taxa with Great Plains taxa. Outside of Hepburn's Mesa, *Pseudajdajidamo* also appears first in the late Barstovian of Barstow and is restricted to western faunas. *Tardontia* likewise is a western form, known from late Barstovian faunas in eastern Oregon, but not from younger ones anywhere (Shotwell, 1958; Tedford and others, 1987). *Diprionomys* and *Lignimus* appear first in late Barstovian faunas from the Great Plains and Rocky Mountains, but they are not found farther west until perhaps Clarendonian time. *Spermophilus* makes its appearance throughout the Great Plains, northern Rockies, and more westerly sites in the late Barstovian (see Barnosky, 1986, for detailed locality listings of most of these taxa). Also of interest are the local first appearances of *Copemys*, *Mojavemys*, *Perognathus*, *Cupidinimus*, and *Petauristodon* in the *Lignimus-Tardontia* Zone. These taxa are unknown from pre-late Barstovian sites in the northern Rockies, Columbia Plateau, or Great Plains, but are found in early Barstovian (*Copemys*, *Mojavemys*, *Perognathus*) and even Hemingfordian (*Cupidinimus*, possibly *Petauristodon*) sites in southern California (Barnosky, 1986; Whistler, 1984; Reynolds, 1985). Either these genera found their way to California considerably earlier than they dispersed northeast, or else the sampling of early Barstovian strata outside of California is too sparse to have recovered them. Presently it is not possible to distinguish between these possibilities.

## CONCLUSIONS

A new chronology for strata of middle Miocene age in the northern Rockies has been developed through magnetostratigraphic and biostratigraphic studies of the Hepburn's Mesa Formation in the Yellowstone Valley of southwestern Montana. The oldest sediments exposed at Hepburn's Mesa date from ~16.8 Ma, and the youngest ones extend to at least 14.3 Ma, and perhaps 13.8 Ma. These data provide new temporal constraints on the Barstovian land-mammal age in the northern Rocky Mountains and on two geographically restricted interval zones defined within it. In the Yellowstone Valley, the Hemingfordian-Barstovian boundary cannot be precisely determined, because the

lowest part of the Hepburn's Mesa Formation yields few fossils. The section at Hepburn's Mesa, however, demonstrates that the boundary is younger than 16.2 Ma, but older than 15.0 Ma in the northern Rockies, which is consistent with its newly determined age (16.0–16.1 Ma) at the type locality for the Barstovian (MacFadden and others, 1989). The strata dating from 15.0–16.2 Ma at Hepburn's Mesa include the *Peridiomys-Parahippus* Interval Zone. In Hepburn's Mesa deposits, the boundary between early and late Barstovian occurs near 14.8 Ma, and fauna from the beds dated between 14.8 and ~14.0 Ma define the *Lignimus-Tardontia* Interval Zone, which correlates with the early part of the late Barstovian.

The dates determined for land-mammal boundaries in Montana coincide with the ages for these same boundaries at the type locality of Barstovian land-mammal age in southern California. This suggests that previously observed differences in generic and species compositions among Barstovian faunas from the two regions reflect ecological and biogeographic differences, rather than temporal separation.

In conjunction with biostratigraphic data from Jackson Hole, Wyoming, the new dates from Montana allow tighter constraints to be placed on several events in the Rockies of the Montana-Wyoming border region: (1) the initiation of Neogene crustal extension leading to deposition in restricted intermontane basins, (2) the duration of the episode of uplift and erosion often referred to as the "mid-Tertiary" unconformity, and (3) the possible transition from a compressional to an extensional tectonic regime as interpreted from tuff compositions. These events appear to have begun no earlier than late Hemingfordian, that is, ~18 Ma. Erosion of the mid-Tertiary unconformity was completed by 16.8–17.0 Ma, at which time extensional tectonism was underway, indicated by relative subsidence that caused deposition to recommence in the Yellowstone Valley. Subsequent extension and subsidence has been highly variable in the Rockies, with sediment-accumulation rates varying by an order of magnitude between nearby basins.

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