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6. EOCENE-OLIGOCENE CLIMATIC CHANGE IN NORTH AMERICA: THE WHITE RIVER FORMATION NEAR DOUGLAS, EAST-CENTRAL WYOMING

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ABSTRACT

The White River Formation exposed near the town of Douglas in east-central Wyoming records a change from a moist subtropical climate in the latest Eocene to a semiarid warm temperate climate in the early Oligocene. These climates are indicated by the sedimentology and nonmarine gastropods (primarily land snails) of the formation. The area also contains a dated volcanic tuff and a magnetostratigraphic record that constrain the age of the boundary between the Chadronian and Orellan land mammal "ages." This land mammal "age" boundary is at or near the Eocene/Oligocene boundary.

INTRODUCTION

The White River Group, a fine-grained volcaniclastic sequence in the western United States, records faunal, depositional, and paleoclimatic changes across the Eocene/Oligocene boundary. It contains the most complete late Eocene and early Oligocene vertebrate record in North America, and somewhat less well known invertebrate, sedimentologic, and volcaniclastic records. The White River Group is an unconformity-bounded nonmarine sequence (*sensu* Hanneman, 1988, 1989) that extends across the northern Great Plains and central Rocky Mountains (Figure 6.1). It is treated as a formation in Colorado, Wyoming, and North Dakota, but is considered a group in Nebraska and South Dakota, where it includes the Chadron and Brule Formations. Four areas of White River exposures have received intensive study: the Big Badlands of South Dakota (Wanless, 1923; Clark, 1937; Clark and others, 1967; Retallack, 1983), the Pine Ridge of northwest Nebraska (Darton, 1899; Schultz and Stout, 1955; Harvey, 1960), northeast Colorado (Galbreath, 1953), and Flagstaff Rim in central Wyoming (Emry, 1973). Other areas in the Great Plains and Rocky Mountains with thick sections of White River rocks have received less attention but are nevertheless important for regional correlations and paleoenvironmental reconstructions.

An important but relatively unstudied area of White River exposures occurs southeast of the town of Douglas in Converse County, east-central Wyoming (Figure 6.1). Here, the White River Formation is exposed in 40 square kilometers of badland outcrops in two areas separated by the North Platte River (Figure 6.2). The oldest White River rocks are exposed in the southern or "Dilts Ranch" area. The upper half of the formation is best exposed in the northern area (the "Wulff Ranch" and "Morton Ranch" areas of Figure 6.2). Both areas are situated topographically on the southern margin of the Powder River basin, but are structually south of the northern boundary fault of the Laramie Mountains (Denson and Horn, 1975; Blackstone, 1988). The Precambrian core of the Laramie Mountains is 22 km to the southwest, but locally the formation overlies strongly folded Cretaceous rocks. The White River has been slightly folded and cut by normal faults on the east side of the Dilts Ranch area.

The 230 m thick exposures in the Douglas area contain abundant terrestrial fossils and 13 volcanic tuff beds, including a dated tuff near the Eocene/Oligocene boundary (Swisher and Prothero, 1990). This dated tuff and detailed magnetostratigraphic analysis (Prothero, 1982a, 1985) constrain the age of a major change in mammal faunas (the boundary between the Chadronian and Orellan land mammal ages) and provide a temporal framework for compar-

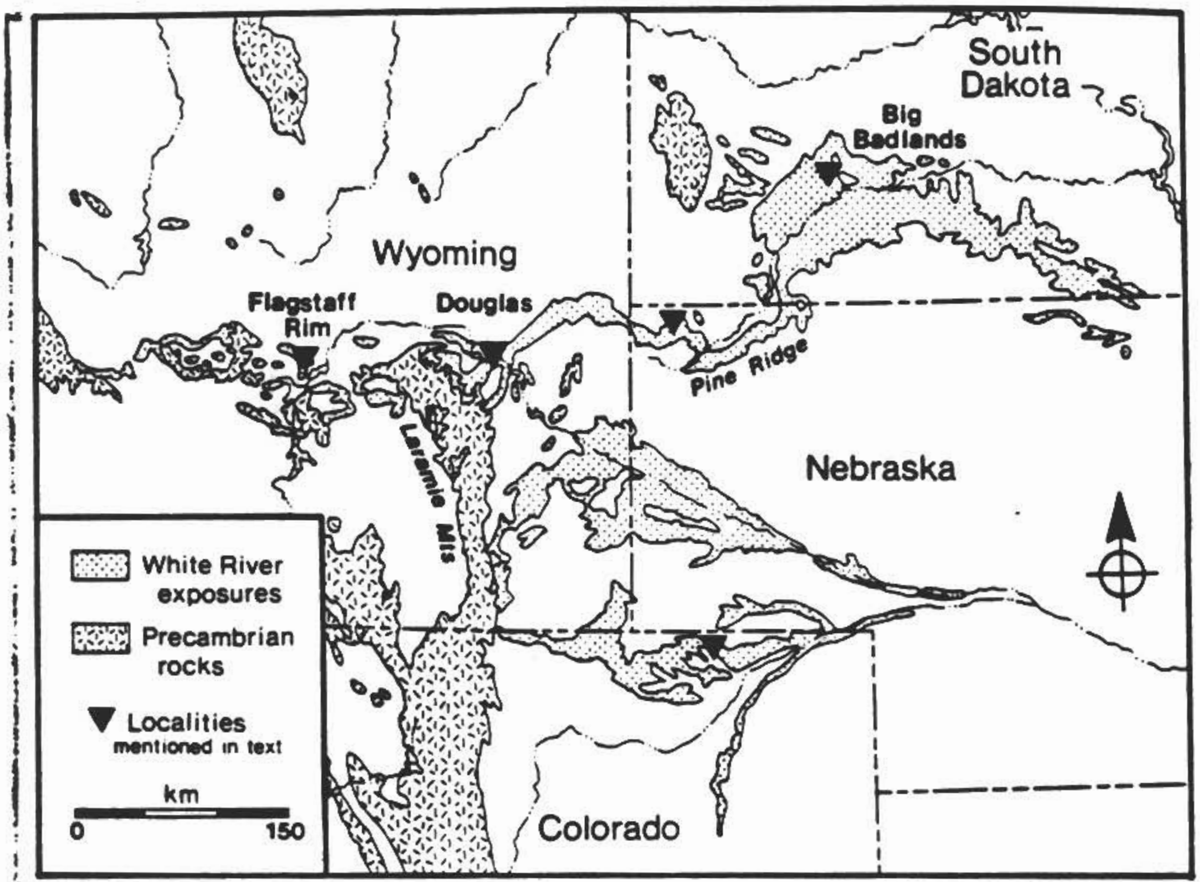


FIGURE 6.1. Distribution of the White River deposits, Precambrian cores of Laramide uplifts, and localities mentioned in the text. Base map from King and Beikman (1974), with additional information from Tweto (1979) and Love and Christiansen (1985), and Burchett (1986).

ing local events with regional and worldwide events. The sedimentology of the White River Formation records a progressive increase in aridity, as indicated by a shift from fluvial to dryland loess deposition. The fossil land snail fauna in the area also indicates increased aridity and a minor drop in temperature across the boundary.

STRATIGRAPHY

The White River Formation in the Douglas area is divided into the the Chadron and the Brule Members (Evanoff, 1990). These units are separated by the basal contact of a widespread, thick, white tuff bed (5 tuff of Evanoff, 1990; the "Glory Hole ash," purplish white layer, or persistent white layer of Prothero, 1982a, 1982b, 1985). The basal Chadron Member is characterized by green to brown clayey mudstones, brown to tan (typically nodular) sandy mudstones, thin sheet sandstones, and numerous thick ribbon sandstones. The overlying Brule Member is characterized by brown to tan nodular sandy mudstones, massive tan sandy siltstones, rare ribbon sandstones, and rare conglomeratic sheet sandstones. Use of the names Chadron and Brule for members in the Douglas area reflects: 1) the subtle lithologic differences between the "upper" and "lower" parts of the White River Formation; and 2) lithologic similarities between the Douglas area sequence and the Chadron and Brule formations in northwest Nebraska. However, the White River sequence in the Douglas area cannot logically be divided into formations, because the two members cannot always be distinguished in

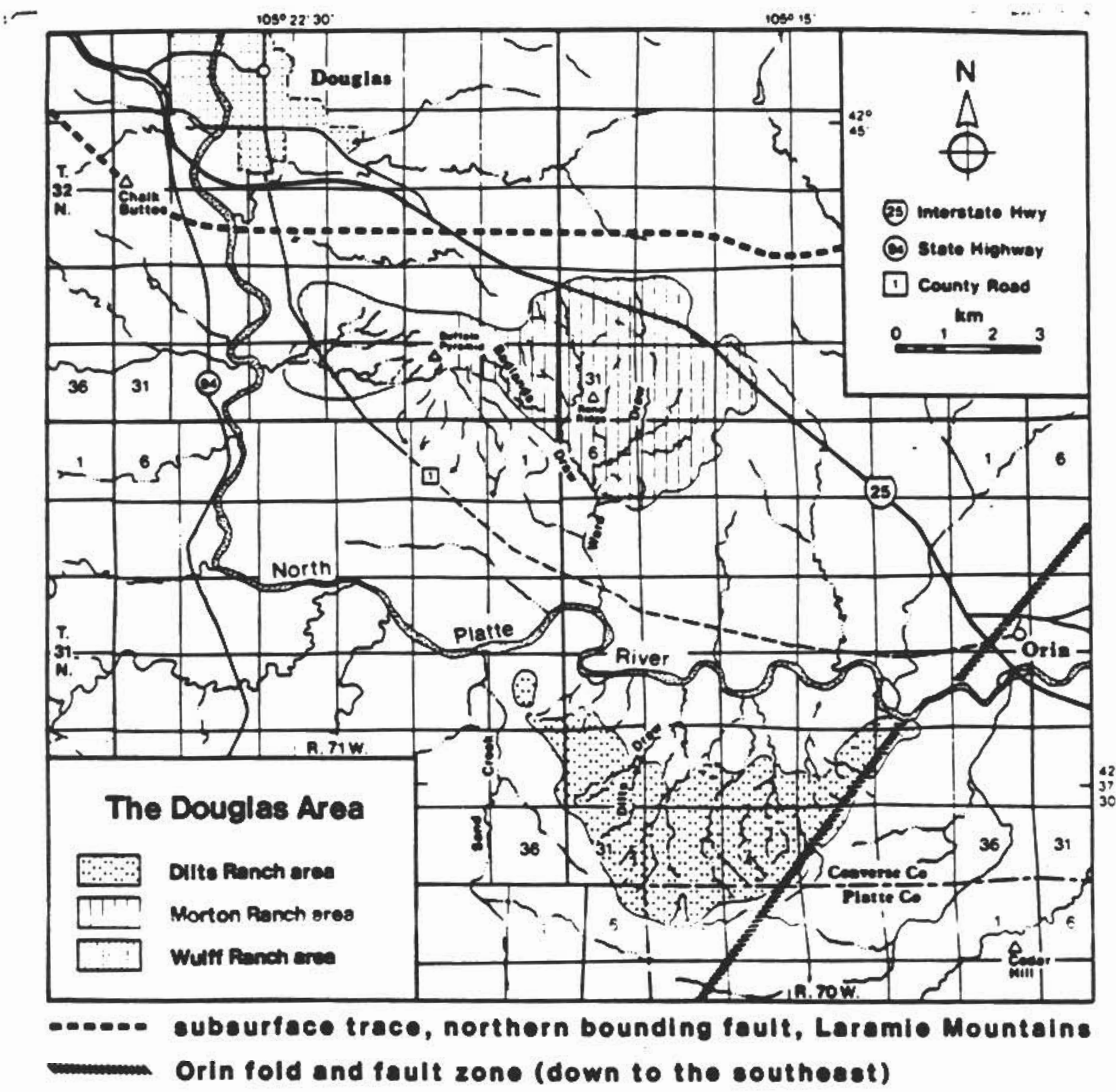


FIGURE 6.2. Distribution of White River Formation outcrops, fold and fault zones, and geographic features in the Douglas area. The northern exposures include the Morton Ranch and Wulff Ranch areas.

isolated outcrops and are not as distinct as their equivalent formations in Nebraska.

Tuff beds are prominent and typically can be traced throughout the area. The tuffs range in mean thickness from 0.5 m to 1.05 m, although some pinch out. Locally the tuffs contain depositional fabrics although in most places the fabric is disrupted by numerous root traces and burrows. Brule tuffs are glass-rich whereas most Chadron tuffs are wholly altered to opal-CT, clinoptilolite (a silica-rich zeolite), or smectite (Lander, 1985, 1987, 1991). White-colored Brule tuffs are generally characterized by rhyolitic glass and plagioclase feldspar compositions ranging from An37 to An45. Altered Chadron tuffs were also probably rhyolitic,

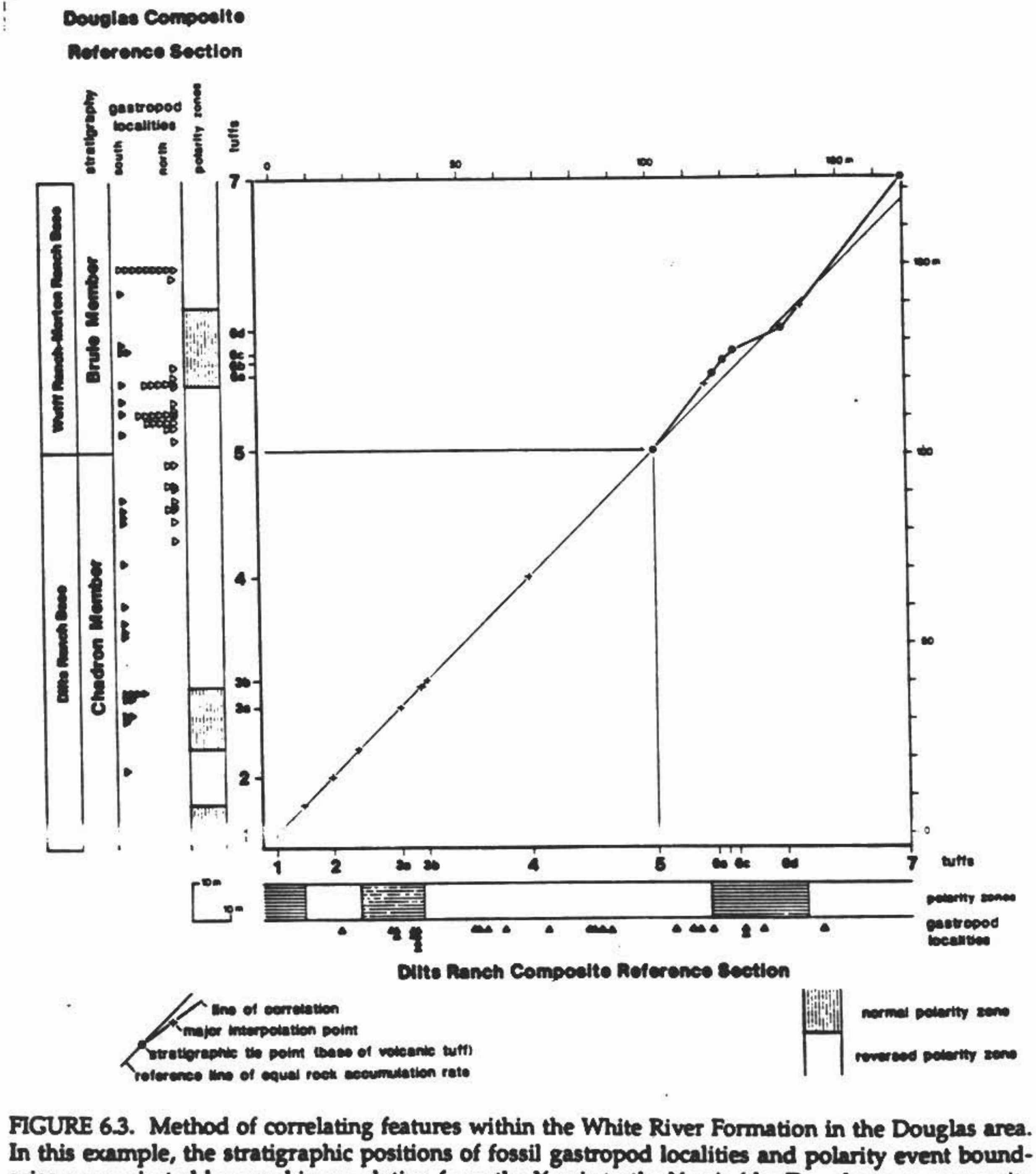


FIGURE 6.3. Method of correlating features within the White River Formation in the Douglas area. In this example, the stratigraphic positions of fossil gastropod localities and polarity event boundaries are projected by graphic correlation from the X-axis to the Y-axis (the Douglas area composite reference section) through the line of correlation. The mean stratigraphic position of tuffs in the two sections determines the position of the line of correlation. Evanoff (1990) describes the derivation of the Douglas area composite reference section, and Edwards (1984) discusses the graphic correlation procedure and its underlying assumptions.

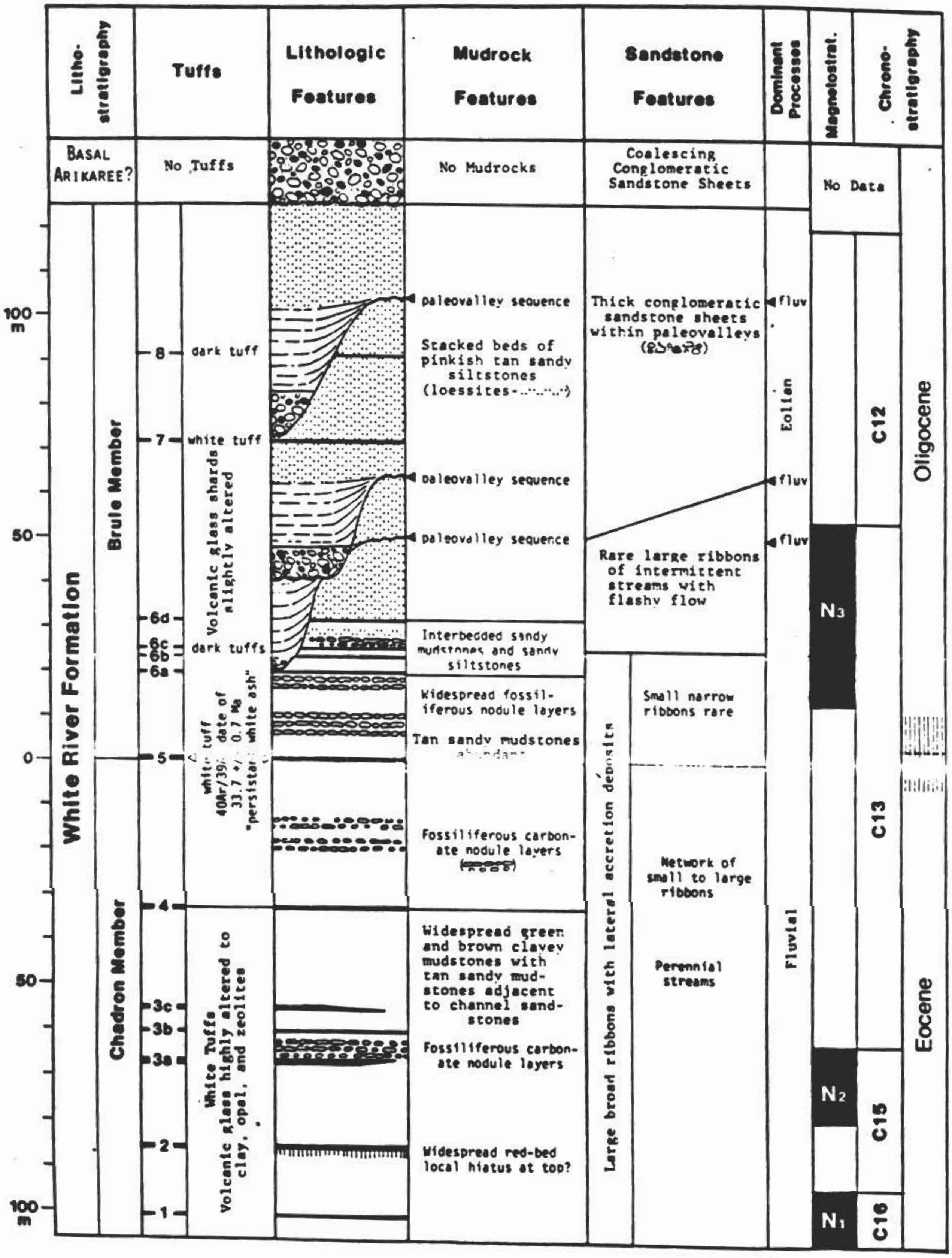
based on similar plagioclase feldspar compositions (Lander, 1991). Several Brule tuffs are dark gray and contain quartz-latite glass and considerably more calcic plagioclase (An65-85). Each tuff has a unique stratigraphic position, and some can be distinguished by associated overlying or underlying strata. The tuff beds are chronostratigraphic markers from which the positions of fossil localities, physical event horizons, and magnetopolarity zones can be determined with great accuracy (Figure 6.3).

A radioisotopic date from the 5 tuff by single-crystal laser fusion $^{40}Ar/^{39}Ar$ analysis of biotite is 33.9 ± 0.1 Ma (Swisher and Prothero, 1990). This date is well within the age range of the Eocene/Oligocene boundary as determined from radioisotopic age dates of tuffs within pelagic limestones and marls that were continuously deposited across the Eocene/Oligocene boundary in the northeast Apennines (Montanari and others, 1988). This age date also constrains the magnetic polarity normal interval above the 5 tuff to C13N. Using the age estimates of 33.7 Ma for the Eocene/Oligocene boundary (Montanari and others, 1988) and 23.7 Ma for the Oligocene/Miocene boundary (Berggren and others, 1985), the age of the base of C13N is herein interpolated as approximately 33.1 Ma. The base of C13N is 13.7 m above the 5 tuff, so the position of the Eocene/Oligocene boundary is 3.4 m (± 8.6 m) above the 5 tuff (Figure 6.4) by simple interpolation assuming a constant depositional rate. The range of possible positions of the Eocene/Oligocene boundary includes the boundary between the Chadronian and Orellan land mammal ages (Figure 6.5), and a major transition in land snail faunas near the Chadron-Brule boundary. The radioisotopic date of the 5 tuff and the position of the C13R/C13N boundary in the Douglas area indicates the Chadron/Orellan boundary is at or very near the Eocene/Oligocene boundary.

The magnetic polarity of the White River Formation in the study area continues to be refined. The original sequence of polarity zones (Prothero, 1982a, 1985) was done with limited thermal demagnetization (in the case of the Wulff Ranch and Reno Ranch south of Tower sections--Fig. 6.6). All of these sections have been reinterpreted by using more extensive thermal demagnetization, using the tuffs as marker beds, and reanalyzing problematic intervals (Figure 6.6). A new section was run in the Reno Ranch East area to corroborate the pattern north of the river. Samples were thermally demagnetized in several steps, and the results obtained between 300° and 400°C gave the most consistent results. AF demagnetization and IRM acquisition studies were also conducted. They showed that the remanence is carried by a low coercivity mineral which magnetically saturates at 1 KOe, and therefore is probably some form of titanomagnetite. Means of the significant normal and reversed sites passed a reversal test. The revised polarity sequence has been interpolated onto the Douglas composite reference section by using the positions of tuffs as tie points (Figure 6.7). Three normal polarity zones and three reversed polarity zones are present.

Vertebrate fossils are abundant in the lower two-thirds of the White River Formation and include mammals of the Chadronian and Orellan land mammal ages. No unequivocal Whitneyan mammals are known from the area. Detailed vertebrate biostratigraphic data is available only for mammals of the upper Chadron Member and lower half of the Brule Member (Figure 6.5). Based on original faunal definition of the Chadronian Land Mammal "Age" (Wood and others, 1941), the highest occurrence of brontotheres marks the end of the Chadronian. However, this criterion has come under question because rare brontotheres can co-occur with taxa thought to reflect the Orellan Land Mammal "Age," and the absence of brontotheres in local lower Brule sequences does not necessarily indicate a non-Chadronian age (Emry and others, 1987). The Chadronian-Orellan boundary is currently being re-evaluated (Korth, 1989), but until more diagnostic criteria are accepted, the highest occurrence of

FIGURE 6.4. (opposite page) Physical features and events as indicated by the White River Formation in the Douglas area. Stippled area in the dominant processes column represents the transition between the fluvial- and eolian-dominated intervals; black areas in the magnetostratigraphy column are zones of normal polarity; and vertical lines between the Eocene and Oligocene indicate the range of possible positions of the series boundary.


Litho-stratigraphy
Tuffs
Lithologic Features
Mudrock Features
Sandstone Features
Dominant Processes
Magnetostrat.
Chrono-stratigraphy
BASAL ARIKAREE?
No Tuffs
No Mudrocks
Coalescing Conglomeratic Sandstone Sheets
No Data
100 m
50
0
50
100 m
White River Formation
Brule Member
Chadron Member
8 dark tuff
7 white tuff
Volcanic glass shards slightly altered
6d
6c
6b
6a
dark tuffs
5
white tuff 40Ar/39Ar date of 33.7 +/- 0.7 Ma "persistant white ash"
4
3c
3b
3a
2
1
White Tuffs Volcanic glass highly altered to clay, opal, and zeolites
paleovalley sequence
Stacked beds of pinkish tan sandy siltstones (loessites-)
paleovalley sequence
paleovalley sequence
Interbedded sandy mudstones and sandy siltstones
Widespread fossiliferous nodule layers
Tan sandy mudstones abundant
Fossiliferous carbonate nodule layers
Widespread green and brown clayey mudstones with tan sandy mudstones adjacent to channel sandstones
Fossiliferous carbonate nodule layers
Widespread red-bed local hiatus at top?
Thick conglomeratic sandstone sheets within paleovalleys
Rare large ribbons of intermittent streams with flashy flow
Small narrow ribbons rare
Network of small to large ribbons
Perennial streams
Large broad ribbons with lateral accretion deposits
fluv
fluv
fluv
Eolian
Fluvial
N3
N2
N1
C12
C13
C15
C16
Oligocene
Eocene

brontotheres (6.4 m above the 5 tuff) marks the Chadronian/Orellan boundary in the study area. The highest occurrence of the eomyid rodent *Yoderimys* sp. (D. G. Kron, personal communication, 1985), the lowest occurrences of the rabbit *Litolagus molidens* Dawson, 1958, and the cricetid rodent *Scottimus viduus* Korth, 1981, are at or near this boundary.

LITHOLOGIES AND DEPOSITIONAL ENVIRONMENTS

The White River Formation is composed primarily of tuffaceous mudrocks. The fine-grained tuffaceous clasts in the mudrocks and tuff beds were derived from contemporary volcanic centers in Colorado and the Great Basin, several hundred kilometers to the south and west (Mutschler and others, 1987). These volcaniclasts were transported to the area primarily by winds and secondarily by local streams. Plagioclase compositions and smectite Fe and Ti abundances in mudrocks indicate that the bulk of pyroclastic material was dacite to latite in composition. Coarse, gravelly sandstone and thin tuff beds are volumetrically minor lithologic components. The coarse sandstones are composed of arkosic detritus that was transported by streams flowing from the Laramie Mountains (Evanoff, 1990). The contrasting sizes of fine volcaniclastic and coarse epiclastic sediment greatly enhance the differences in lithofacies.

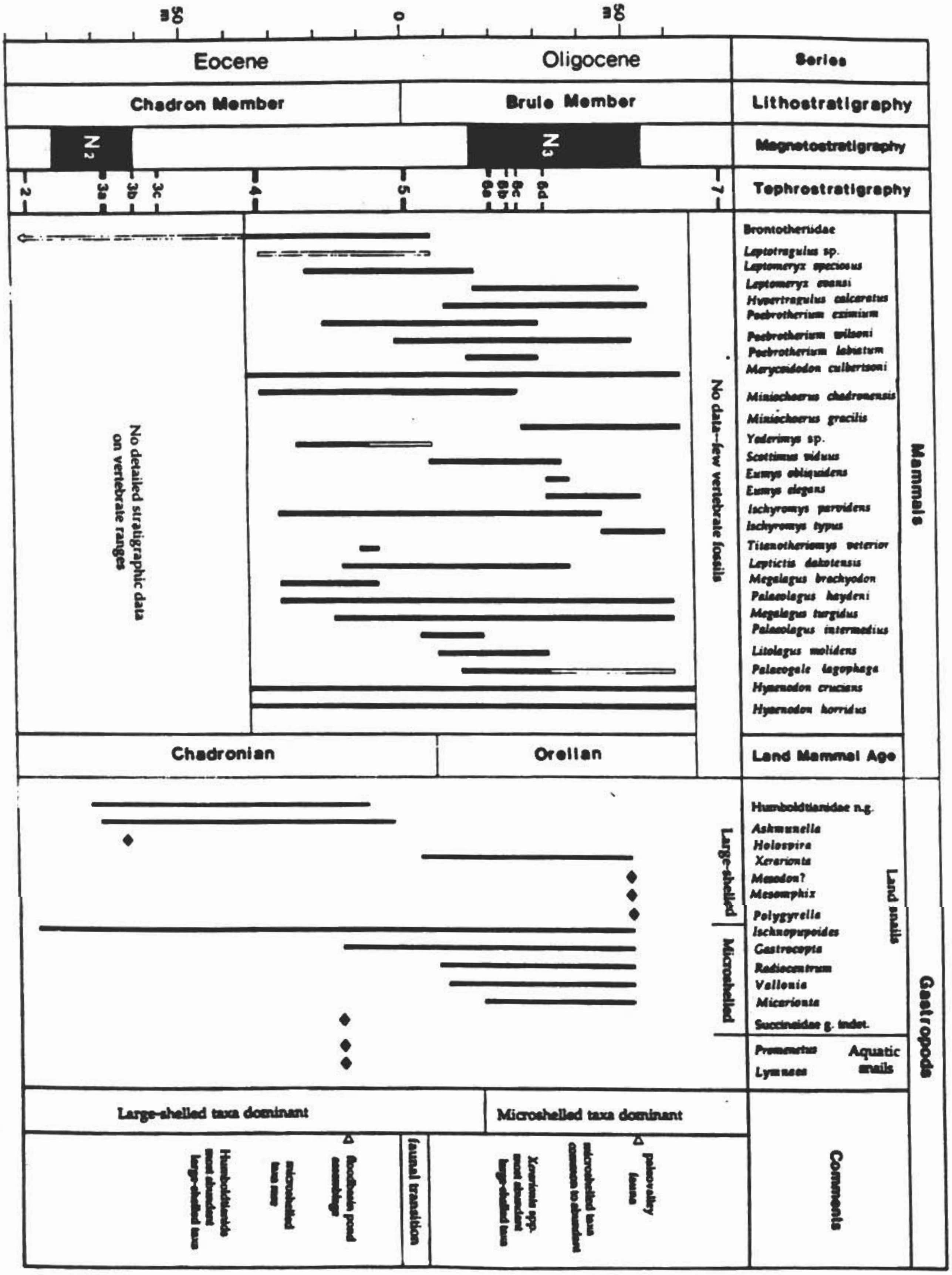
Sandstones and conglomerates

Sandstone and conglomerate beds record changes in the stream systems during deposition of the White River Formation. Chadron sandstones are dominated by ribbon bodies of various sizes arranged in complex networks. Large Chadron ribbons have low sinuosities and widths ranging from 10 m to 60 m. Stratification in these ribbons includes basal conglomeratic sands arranged in trough crossbed sets, and upper beds inclined normal or oblique to original stream flow that represent lateral accretion deposits. These large Chadron ribbons are the channel deposits of single-channel, low-sinuosity, perennial streams. Smaller ribbons (less than 10 m wide) are either nonstratified or have few trough crossbed sets, and are normal or oblique to larger sandstone bodies. These small ribbons represent crevasse and flood channels. Chadron streams were part of a complex network of low-sinuosity, laterally migrating channels that shifted by avulsion.

The Brule Member has fewer sandstone bodies than the Chadron Member. Small ribbon sandstones are almost absent in all of the Brule. The few large ribbons in the lower Brule (between the 5 and 6c tuffs) resemble the large Chadron ribbons in internal stratification. The large ribbons of the middle Brule (between the 6c and 7 tuffs) have complex internal stratification dominated by alternating, thin to very thin beds of sandstone and sandy mudstone. The thin sandstone beds have abundant parting lineation and the sandy mudstones contain mudcracks. The stratification and geometry of these ribbons indicate shallow, unconfined, and flashy flow in channels of low-sinuosity, intermittent streams.

Large conglomeratic sheet sandstones occur within very large cut-and-fills representing paleovalley sequences in the middle and upper Brule Member. These sheet sandstones are very thick (as much as 11 m), wide (as much as 875 m), and elongate with low sinuosities. They contain large cobbles and boulders, the largest clasts of all sandstone bodies in the area. Stratification in these sheets is characterized by large lenticular packages as much as 5.5 m thick of trough and tabular crossbed sets and the absence of lateral accretion deposits. These sheet sandstones were deposited by powerful, low sinuosity streams which transported very coarse sediment.

FIGURE 6.5. (opposite page) Ranges of White River mammal and gastropod taxa in the Douglas area. The range data for mammalian taxa are derived primarily from the collections of Skinner (1958-1959), as presented in Prothero (1982a, Figure 24), with modifications from unpublished data by D. G. Kron (1991, written communication). Solid bars are ranges determined by Skinner; open bars are range modifications by Kron. Gastropod ranges are from Evanoff (1990); diamonds represent isolated stratigraphic occurrences. The stippled area shown in the tephrochronology column represents the transition between the fluvial- and eolian-dominated intervals.


50 m
0
50 m
Eocene
Oligocene
Series
Chadron Member
Brule Member
Lithostratigraphy
N2
N3
Magnetostratigraphy
2
3a
3b
3c
4
5
6a
6b
6c
6d
7
Tephrostratigraphy
No detailed stratigraphic data on vertebrate ranges
No data—few vertebrate fossils
Brontotheriidae
Leptotragulus sp.
Leptomeryx speciosus
Leptomeryx evansi
Hypertragulus calcaratus
Poebrotherium eximium
Poebrotherium wilsoni
Poebrotherium labiatum
Merycoidodon culbertsoni
Miniochoerus chadronensis
Miniochoerus gracilis
Yoderimys sp.
Scottimus viduus
Eumys obliquidens
Eumys elegans
Ischyromys parvidens
Ischyromys typus
Titanotheriomys veterior
Leptictis dakotensis
Megalagus brachyodon
Palaeolagus haydeni
Megalagus turgidus
Palaeolagus intermedius
Litolagus molidens
Palaeogale lagophaga
Hyaenodon crucians
Hyaenodon horridus
Mammals
Chadronian
Orellan
Land Mammal Age
Humboldtianidae n.g.
Ashmunella
Holospira
Xerarionta
Monadenia?
Mesomphix
Large-shelled
Polygyrella
Ischnopupoides
Gastrocopta
Radiocentrum
Vallonia
Micrarionta
Microshelled
Succineidae g. indet.
Land snails
Promenetus
Lymnaea
Aquatic snails
Gastropods
Large-shelled taxa dominant
Microshelled taxa dominant
Humboldtianids most abundant large-shelled taxa
microshelled taxa rare
floodbasin pond assemblage
faunal transition
Xerarionta spp. most abundant large-shelled taxa
microshelled taxa common to abundant
paleovalley fauna
Comments

Mudrocks

Mudrocks of the White River Formation in the Douglas area indicate a shift from dominantly fluvial to eolian depositional processes. The mudrocks include clay-rich and sand-rich mudstones deposited in a fluvial system, and sandy siltstones deposited as loess in an eolian system.

The Chadron and lower Brule Members are characterized by widespread horizontal beds of structureless, commonly bioturbated mudstones typically less than 1 m thick. Where preserved, volcanic glass shards in these mudstones are fragmented. Clayey mudstones, which are most abundant in the Chadron Member, are so altered that no shards are preserved. Mudstones in the Douglas area are fluvially reworked volcaniclastic dust deposits, that were subsequently bioturbated and altered by weathering and diagenesis.

One of the most prominent feature of mudstones in the Douglas area is the abundance of carbonate nodules. Individual nodules are spherical to oblate in shape and range from 0.1 to over 2 m thick. Nodules may be isolated, stacked into vertical strings, or laterally linked into layers. Carbonate nodules are best developed in sandy mudstones but are present in any of the other lithologies. Some nodule layers contain abundant fossils including rhizoliths, invertebrate burrows, pupa cases, fecal pellets, shells of land snails, and reptile and mammal bones. Most of the fossiliferous nodule layers in the study area do not extend laterally for more than a few hundred meters. However, some lower Brule fossiliferous nodule layers extend for several kilometers, making prominent marker beds that reflect large areas of land-surface stability. The fossiliferous nodule layers are not evenly distributed throughout the White River Formation, but cluster into stratigraphic bundles (Figure 6.4). Lander and others (1992, in press) have suggested that these carbonate nodules formed at the groundwater table shortly after deposition.

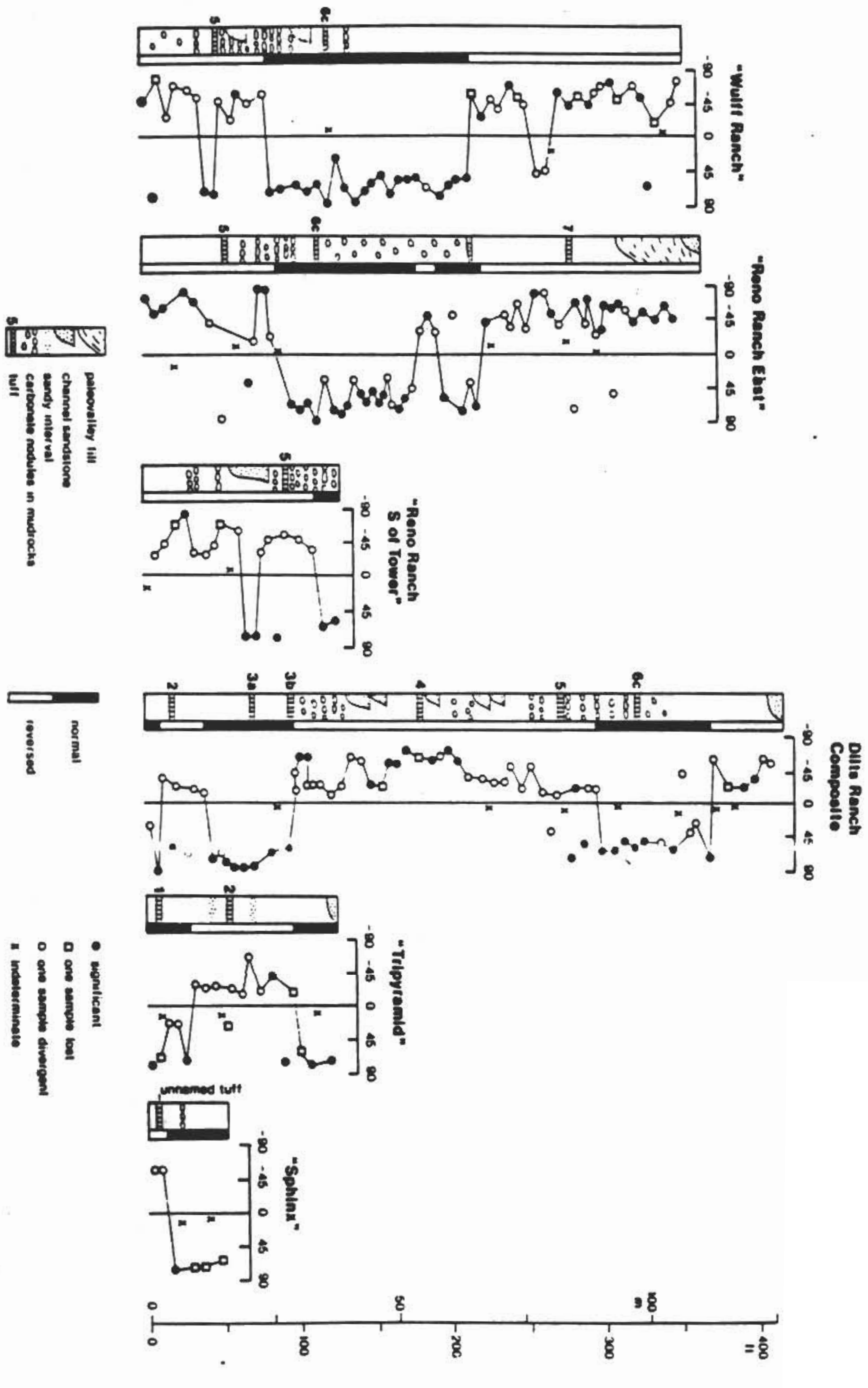
The middle and upper Brule Member are characterized by very thick beds of homogeneous sandy siltstones. Glass shards in the siltstones are only slightly altered and unbroken, retaining fine needle-like terminations and bubble chambers. Siltstone beds are typically more than 1 m thick, internally structureless, and arranged in stacked sequences up to 28 m thick. Fossils are well preserved, but are rare and scattered. These siltstones represent ancient volcaniclastic loess deposits, as indicated by their homogeneous fine-grained lithology, abundance of delicate angular glass shards, lack of stratification within beds, sheet geometry, and general lack of associated channel deposits.

The middle and upper parts of the Brule Member also contain three very large cut-and-fill features that represent ancient valleys (Figure 6.4). These paleovalleys are characterized by scours, at least 20 m deep, filled with very large conglomeratic sandstone sheets, and medium to thick beds of alternating muddy sandstone and mudstone. The sides of the paleovalleys are marked by inclined nodular mudstone beds derived from mass movement of the surrounding sandy siltstones. The paleovalley fills were formed from a combination of fluvial, eolian, and mass movement processes (Evanoff, 1990).

GASTROPOD FAUNAS

Fossil nonmarine gastropods are abundant in the area and occur from the middle part of the Chadron Member to the middle Brule Member (Figure 6.5). Of 75 known fossil gastropod lo

FIGURE 6.6. (opposite page) Revised magnetic polarity stratigraphy of the Douglas area, after Prothero (1982a, p. 18; 1985, Figure 6). Sections located as follows: "Wulff Ranch" - center, NW1/4 sec. 36, T. 32 N., R. 71 W., Irvine, WY (1949) 7 1/2 minute quadrangle; "Reno Ranch East" - W1/2N W1/4 sec. 32, and W1/2 sec. 29, T. 32 N., R. 70 W., Irvine, WY (1949) 7 1/2 minute quadrangle; "Reno Ranch S of Tower: - SW1/4 sec. 31, T. 32 N., R. 70 W., Irvine, WY (1949) 7 1/2 minute quadrangle; Dilts Ranch Composite - SE1/4 sec. 29, NE1/4 sec. 32, and E1/2 sec. 33, T. 31 N., R. 70 W., Irvine, WY (1949) and Dilts Ranch, WY (1949) 7 1/2 minute quadrangles; "Tripyramid"- SW1/4 NW1/4 NW1/4 sec. 30, T. 31 N., R. 70 W., Irvine, WY (1949) 7 1/2 minute quadrangle; "Sphinx" - SW1/4 SW1/4 NE1/4 sec. 24, T. 31 N., R. 71 W., Irvine, WY (1949) 7 1/2 minute quadrangle. The "Wulff Ranch", "Reno Ranch East", and "Reno Ranch S of Tower" sections are in the Morton Ranch area; the Dilts Ranch Composite, "Tripyramid", and "Sphinx" sections are in the Dilts Ranch area.


"Wulff Ranch"
"Reno Ranch East"
"Reno Ranch S of Tower"
Dilts Ranch Composite
"Tripyramid"
"Sphinx"
-90 -45 0 45 90
5
6c
7
1
2
3a
3b
4
unnamed tuff
paleovalley fill
channel sandstone
sandy interval
carbonate nodules in mudrocks
tuff
normal
reversed
● significant
□ one sample lost
○ one sample divergent
x indeterminate
0
50
100 m
100
200
300
400 ft

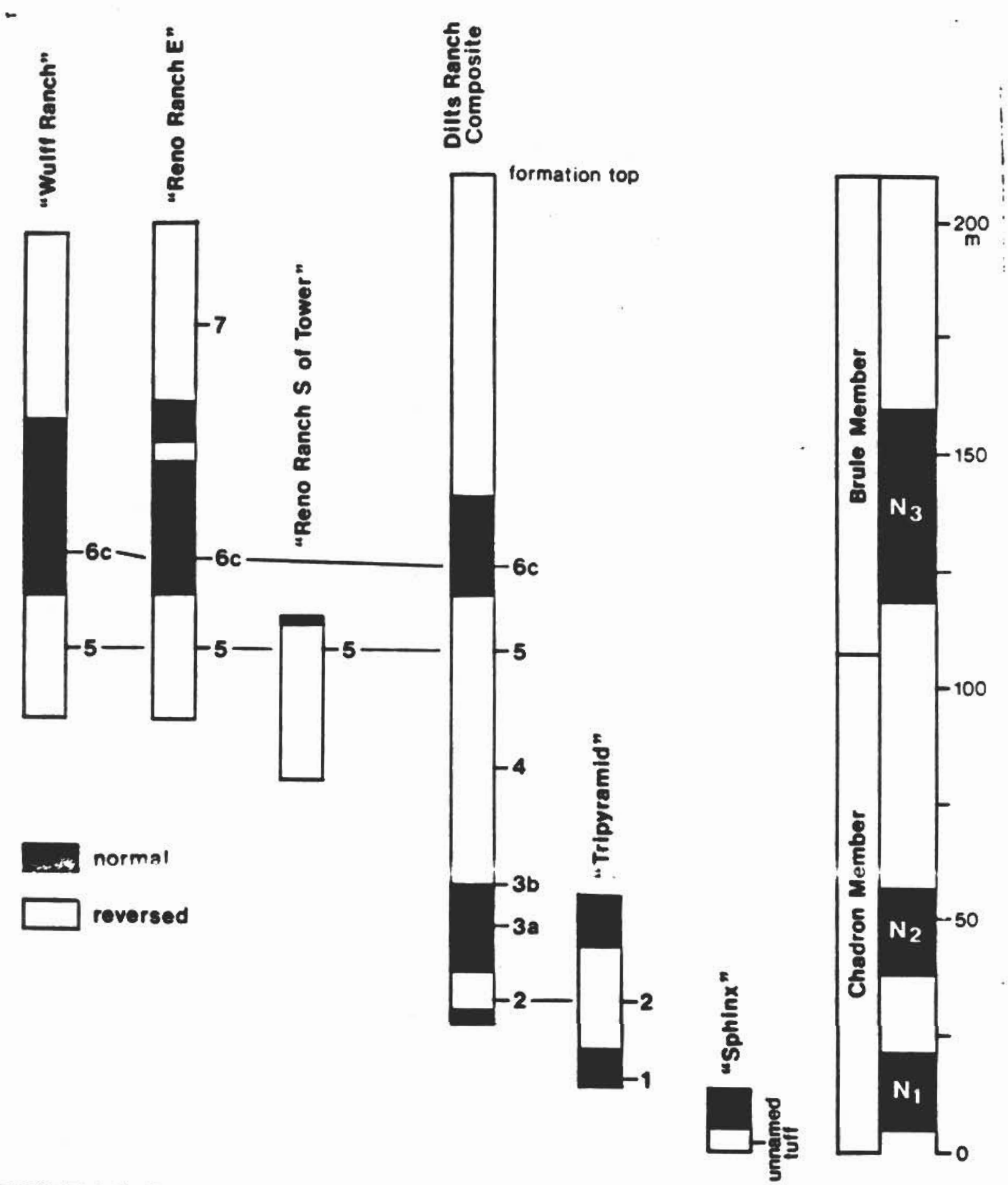


FIGURE 6.7. Revised magnetostratigraphy of the White River Formation in the Douglas area, based on correlations of tuffs and reanalysis of problematic intervals. According to the interpretation of Swisher and Prothero (1990) and Prothero and Swisher (this volume), the N_1 normal interval is Chron C16N, N_2 is Chron C15N, and N_3 is Chron C13N. The 5 ash is dated at 33.9 Ma, and lies just beneath the Chadronian-Orellan transition.

calities in the area, only one contains freshwater snails (Pulmonata: Basommatophora), indicating that habitats suitable for aquatic snails were rare. The other 74 localities contain only land snails (Pulmonata: Stylommatophora). All the taxa can be referred to modern families, and in most cases to modern genera (Evanoff, 1990). In general the taxa can be separated into groups by shell size: large-shelled taxa with diameters larger than 10 mm, and microshelled taxa with smaller diameters (Figure 6.5). The habitat and climatic implications of the fossil land snails are inferred from the habitats and climatic parameters of related modern analog taxa.

Land snail faunas of the Chadron Member are almost exclusively large-shelled forms (Humboldtianidae n. gen., *Ashmunella*, *Holospira*) which are now found in the central Mexican Plateau and the southern-most Rocky Mountains. The land snail fauna of the lower and middle Brule Member includes taxa now living in southern California and northern Baja California (*Xerarionta*, *Micarionta*, and *Radiocentrum*), and in the modern Rocky Mountains (*Ischnopupoides*, *Gastrocopta*, *Vallonia*, and *Radiocentrum*). Brule faunas were initially dominated by large-shelled forms, but microshell forms became much more abundant in the upper part of the lower Brule. The oldest paleovalley sequence of the middle Brule has the most diverse land snail fauna, and is dominated by large-shelled forms. This paleovalley fauna contains taxa typical of the lower and middle Brule, mixed with taxa now found in the Eastern United States (*Mesodon*?, *Mesomphix*, *Omphalina*) and in the northwest Rocky Mountains (*Polygyrella*).

The distributions of modern analogue taxa of the fossil land snails provide estimates of ancient temperatures and precipitation. For example, the distributions of modern *Humboldtiana*, *Holospira*, and *Ashmunella* indicate a mean annual temperature of 16.5°C and a mean annual precipitation of 450 mm during deposition of the Chadron Member (Evanoff, 1990). The mean annual temperature estimate is not far from the temperature estimate of 14°C from the correlative Florissant flora of Colorado (Meyer, 1986). Work is currently in progress to determine additional temperatue and precipitation estimates for the land snail faunas.

CLIMATIC IMPLICATIONS

The White River Formation in the Douglas area records a paleoclimatic shift toward drier conditions from the late Eocene to the early Oligocene. This increased drying is indicated by both the rocks and land snail faunas.

The most important depositional change in the area was the shift from a fluvial depositional system in the Chadron and lower Brule members to a predominantly eolian depositional system in the middle and upper Brule. This transition represents a paleoclimatic change from moist to dry conditions. The fluvial system which deposited the Chadron Member became less active during deposition of the lower Brule, as indicated by the decrease in channel sandstones. Eventually this fluvial system was not able to rework the volcaniclastic dust that continued to fall in the area, and thick beds of loess accumulated to form the middle and upper Brule Member. Dry conditions during loess deposition are indicated by rare channel sandstones of intermittent streams that were subject to flashy flow. The lack of extensive fluvial reworking and weathering of the loessites indicates that these dust deposits accumulated under dry, probably semiarid conditions, based on modern conditions of dryland loess accumulation (Pye and Tsoar, 1987; Pye, 1987). The alternation between loess deposition and paleovalley cuts and fills by streams suggests alternating dry and wet conditions during deposition of the middle and upper Brule Member.

The fossil gastropods mirror the paleoclimatic changes indicated by the rocks. Chadronian snails indicate a woodland habitat in a subtropical climate with seasonal precipitation. Snails of the lower Brule Member indicate open woodland habitats in a warm temperate climate with a pronounced dry season. The shift in the lower Brule from a fauna dominated by large-shelled taxa to a fauna dominated by microshelled taxa indicates a reduction in the amount of leaf-litter shelter, suggesting a shift from an open woodland to a bushland environment. The microshell-dominant fauna persists into the loessites of the middle Brule, suggesting that bushlands were the primary trap for dust, as they are in modern dryland sites (Gerson and Amit, 1987). The snail fauna of the lowest paleovalley indicates dense woodlands with moisture available for longer periods of time throughout the year. Whether this increase in moisture reflects increased precipitation or local environmental conditions within the valley is uncertain. In summary, the land snail faunas of the Douglas area suggest overall drying during deposition of the White River Formation, with only a minor decrease in temperature near the Eocene/Oligocene boundary.

The climatic changes indicated by the White River Formation near Douglas have also been recognized at other areas in the region. Increased drying from the late Eocene (Chadronian) through the middle Oligocene (Whitneyan) has been recognized in the sequences at the Big Badlands (Clark and others, 1967; Retallack, 1983, 1986) and northwest Nebraska (Harvey, 1960). Temperature indicators in these areas suggest a minor cooling trend from subtropical to warm temperate climates across the Chadronian/Orellan boundary. This is especially evident from the distribution of large, non-burrowing tortoises (*Hesperotestudo, Stylemys*) across the boundary. These large tortoises are abundant in Chadron and Brule rocks throughout the region and could not have withstood average winter temperatures below 13° C (Hutchison, 1982).

The timing of climatic events may not be the same over the entire region. For example, the fluvial-to-eolian transition occurs near Ash I (late Chadronian) at Flagstaff Rim; at the top of the lower Brule Member (end of the early Orellan) at Douglas; near the top of the Orella Member (end of the late Orellan) at northwest Nebraska; and in the upper Poleslide Member (late Whitneyan) in the central Big Badlands (Evanoff, unpublished field data). This trend suggests a west-to-east progression of dryland deposition, but this hypothesis needs to be tested with additional sedimentologic and stratigraphic studies. The stratigraphy, sedimentology, and paleomalacology of the Douglas area provide a valuable reference for such paleoclimatic work.

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