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The Ekalaka Member of the Fort Union Formation, Southeastern Montana: Designating a New Member and Making a Case for Estuarine Deposition and Bounding Unconformities

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Abstract

The Ekalaka Member is herein designated a new member of the Paleocene Fort Union Formation. It consists of greater than 50 percent sandstone with lesser amounts of mudrock. This contrasts with the unconformably underlying Ludlow Member, which consists of greater than 50 percent mudrock with lesser amounts of sandstone. Sandstone and mudrock in the Ludlow are dominated by smectite in the clay fraction, whereas the Ekalaka and Tongue River Members are dominated by kaolinite and illite. The Ekalaka Member contains a few thin coal beds; the Ludlow Member contains many thick coal beds. The Ekalaka Member is unconformably overlain by the lower Tongue River Member, which contains 40 m of subequal amounts of sandstone and shale, and in the study area, also contains a few, thin coal beds. Volcanic ash beds and ash-rich sandstones are common in the lower Ekalaka and lower Tongue River Members.

The Ekalaka Member contains the following trace fossils (the most abundant listed first): *Skolithos linearis* and *"Skolithos", Diplocraterion Thalassinoides, Ophiomorpha,* and *Planolites*. These occur in each of the three facies of the member but not all ichnotaxa are found together at the same horizon. Upper (but not lower) Ludlow strata contain *"Skolithos"* and *Skolithos linearis*, but none of the other ichnotaxa. Lower Tongue River strata contain only *Skolithos linearis* and *"Skolithos"*, which are restricted to the eastern part of the study area at Snow Creek. Thus, the Ekalaka Member has a higher diversity of ichnotaxa in the study area than is found in either the Ludlow or Tongue River Members.

The Ekalaka Member is distinct from the Cannonball Member because it is sandier, shows a more complex intertonguing of marine, estuarine and nonmarine deposits, and does not contain body fossils (forams, molluscs, vertebrates) indicative of deposition in an open marine environment. The Cannonball Member does not contain coal, but the Ekalaka Member does. The name, *Cannonball*, was recently applied to two massive sandstone cliffs formerly considered Tongue River Member in the Cave Hills of northwestern South Dakota (Cvancara and Hoganson, 1993). These sandstones may also be the Ekalaka Member; they are unlike Cannonball strata at the North Dakota type section.

The Ekalaka Member is composed of three facies associations interpreted as follows: facies association A: inner to central estuary, tide-dominated, with shallow subaqueous sand bars; facies association B: sandy, fluvial-dominated, inner-estuarine point-bar and central estuarine marine/brackish water deposits; and facies association C: sandy, tidal-flat, estuarine channel deposits that interfinger with thin estuary-margin facies.

Most of facies association A is preserved in megabreccia blocks. Detailed structural analysis of these blocks indicates they probably slumped into deeper water, possibly in response to mid-Paleocene earthquakes associated with tectonics in the Black Hills. A modern analog is the Turnagain Heights landslide triggered by the 1964 Good Friday Alaska earthquake.

The unconformities bounding the Ekalaka Member are here defined as the U_2 (below) and the U_3 (above). The primary evidence for the U_2 unconformity is that normally underlying units are locally missing, having been eroded during early Paleocene time down to as low as the middle of the Hell Creek Formation. The Ekalaka Member also contains an angular discordance, the MedRx unconformity, within a limited area. The U_3 unconformity above the Ekalaka Member is identified by thick paleosols (bleached beds and silcretes) that developed at the top of the youngest strata of the Ekalaka Member. Correlative paleosols identify the U_3 to the northwest and northeast of the study area where they developed at the top of the Lebo and Ludlow.

The MedRx and the U_2 unconformities terminate laterally. They are both absent from the Miles City coal field of Montana as well as from northwestern South Dakota and southwestern North Dakota. The U_3, on the other hand, can be traced regionally into the Miles City coal field, the Little Missouri River area, North Dakota, and the Cave Hills area, South Dakota. It is extensive throughout the western Williston Basin.

Biostratigraphic dates based on pollen and mammal teeth constrain the ages of the U_2, U_3, and MedRx unconformities. Mammal teeth at horizons on either side of the U_3 support the existence of a sizable time gap. The U_3 is likely a regional unconformity. It may not be related to tectonic movements in the Black Hills, but rather to eustatic movements in the Western Interior Basin as a whole. The U_2 unconformity and possibly also the MedRx unconformity are more localized and likely resulted from tectonic movement of the Black Hills. This uplift reorganized the paleodrainage of the western Williston Basin and Miles City Arch area from southeast to northeast. Ekalaka deposition commenced after this period of upwarping.

Ekalaka sediment lies within the P-3 pollen zone (Torrejonian mammal age). It was deposited in a persistent estuarine/marine embayment that developed between the Marmarth (upper Ludlow) Delta (Belt and others, 1984) of southwestern North Dakota and the positive topography of the Black Hills. This embayment, which received both estuarine and nonmarine sediment, opened eastward and southeastward into the Cannonball Sea of western South Dakota. Barrier islands or spits extending from the Marmarth Delta southward partly closed off the mouth of the Ekalaka Estuary.

Introduction

Strata of Paleocene age have been mapped for over a hundred years in both the Williston and the Powder River Basins (figure 1). The Williston Basin lies on the edge of the North American craton and is bounded on the southwest by the Black Hills. The Powder River Basin, on the other hand, lies between the Bighorn Mountains on the west and the Black Hills on the east. The boundary between the two basins is deliberately left ambiguous on figure 1, although most previous workers place it at the Miles City Arch (MCA, figure 1) and its extension along structural strike to the northwest across the Yellowstone River.

There has been some debate on the timing of the initial uplift of the Bighorn and the Black Hills, basement-cored Laramide uplifts. These areas were uplifted during the early Tertiary and supplied most of the sediment to the basins adjacent to them, although some of the sediment came from west of the Sevier overthrust belt. Paleocene strata should contain evidence (compositional changes, unconformities, changes in paleodrainage directions) useful for constraining the time of those uplifts.

Unconformities have only recently been reported in the Late Cretaceous and Paleocene strata of the western Williston Basin. Belt and others (1997b) proposed a Late Cretaceous unconformity that stretches across northern Wyoming and into the Cedar Creek Anticline area of southeastern Montana. This is called the U_1, and it lies between the Hell Creek Formation and underlying Fox Hills Formation. Moore (1976, p. 36) reports the earliest Paleocene unconformity at the top of the Ludlow Member in southwestern North Dakota. His conclusion is based on a widespread "white siliceous bed" that seems to

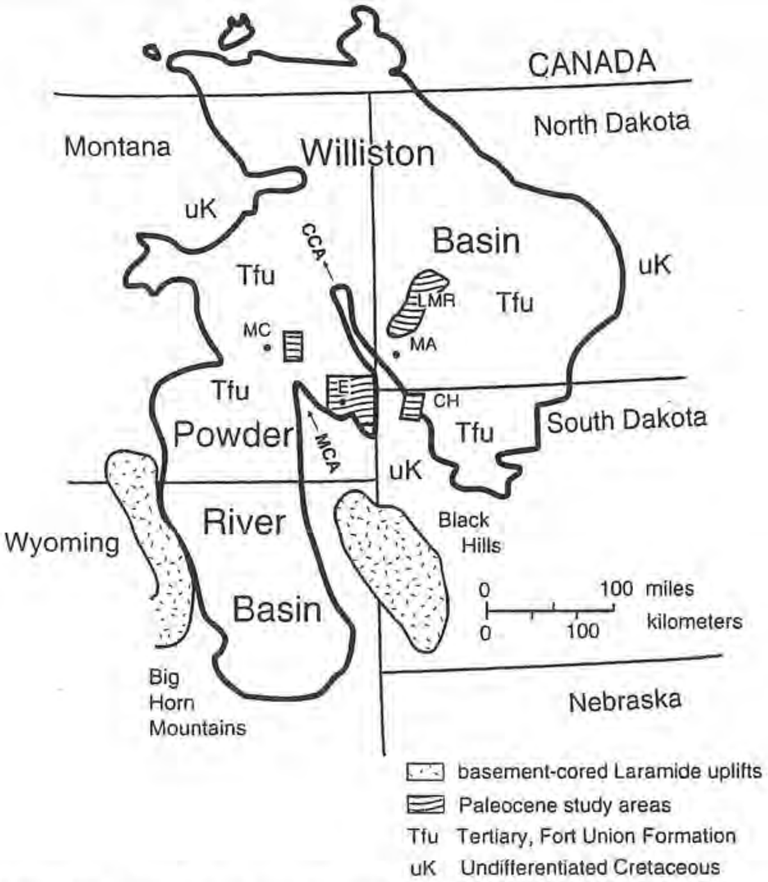


Figure 1. The Williston and Powder River Basins as outlined by the Hell Creek–Fort Union contact (heavy line), which approximates the K/T boundary at this scale. Note that the Fort Union Formation (Tfu) lies within the heavy line and that undifferentiated Cretaceous, and older rock, lies outside the heavy line. Areas of detailed study include the eastern Miles City coal field (east of MC; see Belt and others, 1992), Little Missouri River (LMR; see Belt and others, 1984), Ekalaka (E), Cave Hills (CH; see Goodrum, 1983; Best, 1987), and Marmarth area (MA). The locations of the Miles City Arch (MCA) and the Cedar Creek Anticline (CCA) are indicated.

correlate to a similar silcrete in the Ekalaka area. In this report, we recognize Moore's North Dakota unconformity in southeastern Montana. We call it the U_3, and suggest that an older unconformity, the U_2, also exists within Paleocene strata of southeastern Montana.

Fort Union strata can be traced continuously across eastern and southeastern Montana (Stoner and Lewis, 1980; Bergantino, 1980; Vuke-Foster and others, 1986; Vuke and others, 1989; Wilde and Vuke, 1991; Ellis and Colton, 1994), although the Miles City Arch and the Cedar Creek Anticline (figure 1) interrupt some of the continuity. Early U.S. Geological Survey studies by Collier and Smith (1909) and by Parker and Andrews (1939) showed abundant outcrops north of the Yellowstone River, and within the Pine Hills plateau that lies between the mouth of the Tongue River at Miles City (see MC, figure 1) and the mouth of the Powder River, near Terry, Montana. This early work was followed by Matson and Blumer (1973) and the U.S. Geological Survey quadrangle mapping program during the 1980s (e.g., Luft, 1986a, b; Luft and Meier, 1986; and Vuke and others, 2001). In their most recent report, Flores and Keighin (1999, figure WF-1) and Flores and Bader (1999, figure PS-1) do not discuss Paleocene strata in this area; their work focuses on currently active coal districts.

Nearly a century of study of Paleocene outcrops in southeastern Montana and western North Dakota shows that a significant lithologic change occurs within Paleocene strata at the base of the Tongue River Member (figure 2). This change is most recently reported in Montana from the Miles City area (Belt and others, 1992) eastward to the Cedar Creek Anticline (Vuke-Foster and others, 1986), and farther eastward to the Little Missouri River area (Belt and others, 1984) of North Dakota. The change is associated with the contrast between the light-yellow to light-gray color of the Tongue River Member and the dark-gray (*somber*) color of the Tullock, Lebo, and Ludlow Members beneath it. Even the Late Cretaceous Hell Creek Formation shows more lithological affinity to these *somber* members than it does to the Tongue River Member. This facies change is largely due to the common, though not ubiquitous, presence of smectite-rich mudstones and sandstones of the *somber* members, and to the near exclusion of smectite in the lighter-colored Tongue River Member (Belt and others, 1985).

Our search for additional causes of this significant lithologic change at the base of the Tongue River Member led us to examine the strata in the Ekalaka area. Field mapping by the Montana Bureau of Mines and Geology showed a marked thinning of the Ludlow Member below a sandy unit in the Fort Union Formation. That sandy unit was first mapped as the Tongue River Member of the Fort Union Formation by Bauer (1924, p. 244) and later by Bergantino (1980). It soon became apparent that an unconformity lay at the base of the sandy unit, and another 20 meters above, at the top of the sandy unit (Belt and others, 1996a). Ichnotaxa usually assigned to marine deposits were found (Belt and others, 1997a) in these sandy strata lying between the two unconformities. The decision was made to define the succession bounded by unconformities as a new member of the Fort Union Formation, and to call it the *Ekalaka Member*.

In this report, the Ekalaka Member is placed within a sedimentologic and a biostratigraphic framework. The basal U_2 unconformity is interpreted as related to the uplift of the Miles City Arch, which was presumably associated with an uplift of the Black Hills. The upper U_3 unconformity is more regionally extensive.

Criteria for Distinguishing Fort Union Members

A review of criteria for distinguishing the various members of the Fort Union Formation is useful as background for defining the new Ekalaka Member.

Late Cretaceous and Paleocene sedimentary deposits are approximately 900 meters thick in eastern Montana and the western Dakotas (figure 1). These strata are largely unconsolidated and of nonmarine origin. They are dominated by siliciclastic mudstone and fine- to medium-grained sandstone and contain a small percentage of coal and intraformational conglomerate. Limestone reported in the lower Fort Union Formation is largely diagenetic, representing the replacement of very fine-grained, rippled, quartz sand bicarbonates. Coarse-grained sand units, even thin ones, are rare and pebbles of extrabasinal origin are absent in Fort Union strata. Certain coal beds, especially in the Tongue River Member southwest of the Miles City Arch are of sufficient thickness and quality for current mining (Flores and Bader, 1999).

Strata above the marginal marine Fox Hills Sandstone (figure 2) were subdivided early last century into the Upper Cretaceous Hell Creek Formation (Brown, 1907), and six members (only the older five are shown in figure 2) of the Paleocene Fort Union Formation. The six Fort Union members and type areas are: Tullock (Tullock Creek between Miles City and Billings, Montana; Rogers and Lee, 1923), Ludlow (Cave Hills, South Dakota; Lloyd and Hares, 1915), Cannonball (south-central South Dakota; Lloyd, 1914), Lebo (Crazy Mountains Basin, south-central Montana; Stone and Calvert, 1910), Tongue River (Montana–Wyoming border; Taff, 1907), and Sentinel Butte (eastern Montana and western North Dakota; Leonard and Smith, 1909; Jacob, 1976). The Slope and Bullion Creek units were added to Fort Union stratigraphy later than the others (Clayton and others, 1977). Based on their work as well as earlier conventions (e.g., Norton, 1963), the North Dakota Geological Survey raised each Fort Union member to formation rank, and at the same time raised the Fort Union to group rank. In Montana, Wyoming, and South Dakota, the Fort Union in most reports is considered a formation.

Many of the physical criteria used to define and subdivide the largely nonmarine strata above the U_1 unconformity at the base of the Late Cretaceous Hell Creek Formation have remained essentially

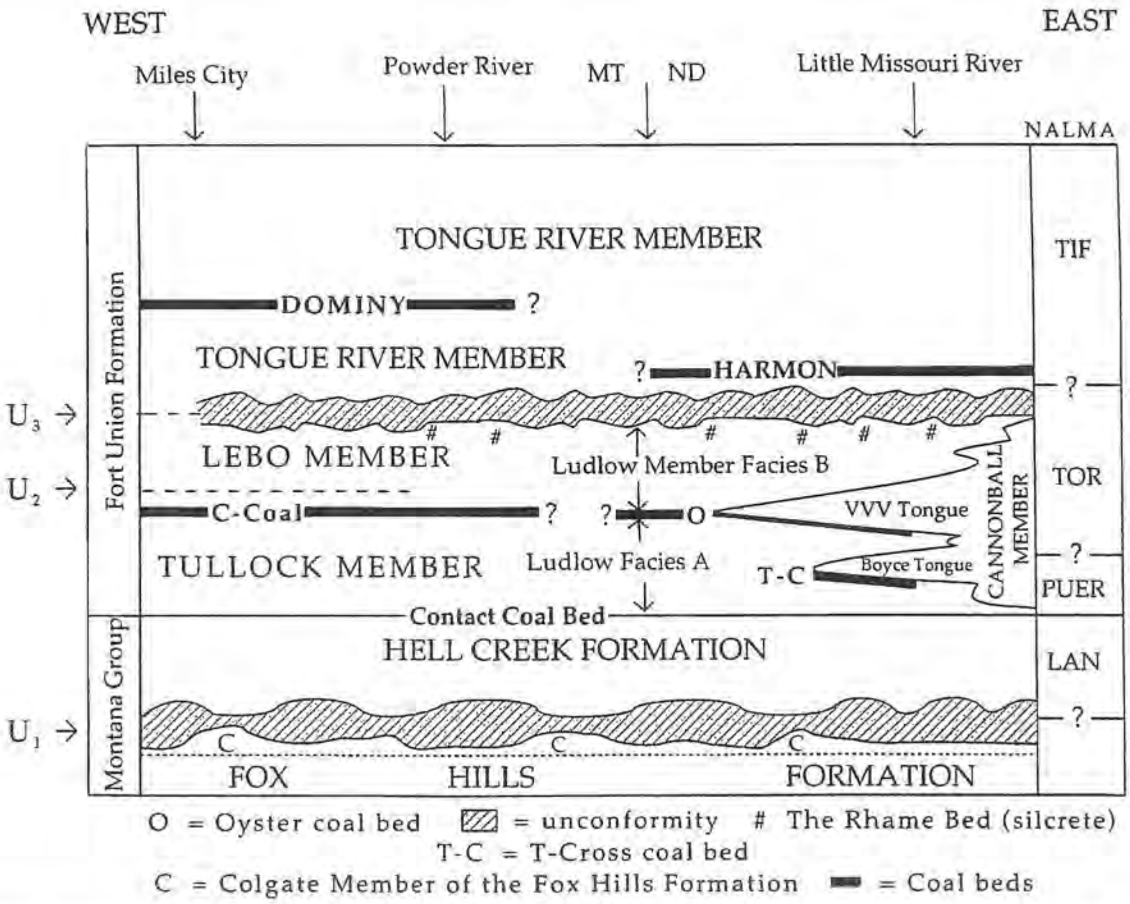


Figure 2. Correlation of Late Cretaceous and Early Tertiary lithostratigraphic units between the Miles City and Little Missouri study areas. Only part of the Tongue River Member is indicated; the Sentinel Butte Member, if shown, would lie above the top of the diagram. This chart modifies that of previous workers by showing: (a) a U_1 regional unconformity between the Fox Hills and Hell Creek formations (Belt and others, 1997); (b) a U_3 unconformity in the Little Missouri River area between the Ludlow and Tongue River Members (Diemer and others, 1996; unpubl. pollen data, Donald Engelhardt, ESRI, Univer. South Carolina, Columbia, SC, 1998–99); and (c) an unconformity between the Lebo and the Tongue River Members in Montana, which correlates to the U_3 unconformity in the Little Missouri River area. Radiometric dates are based on Hartman and Kihm (1996) and Warwick and others (1995). The North American Land Mammal Ages (NALMA) include Lancian (LAN), Puercan (PUER), Torrejonian (TOR), and Tiffanian (TIF). The Contact coal bed is the most prominent lithologic contact between the Hell Creek and Fort Union Formations. It can differ by several meters from the K/T boundary (Murphy and others, 1995), not shown in this diagram.

unchanged since the 1920s (Brown, 1962). These criteria include color, bedding thickness, weathering aspects, persistent marker beds, and diagnostic fossils. The problem of defining and correlating lithostratigraphic units in Paleocene strata has been complicated in the past by an imperfect though evolving scheme of time zonation. Fortunately, progress has been made over the past several decades (Archibald and others, 1987; Hartman and Kihm, 1996; Hunter and others, 1997; Nichols and Ott, 1978; Nichols, 1996, 1998, 1999a, 1999b). The Paleocene unconformities proposed in this report may ultimately be verified by a combination of additional biostratigraphy (based mainly on land mammals and pollen), and of magnetic reversal and isotopic chronostratigraphy. Such an approach was used by Jason Hicks (Belt and others, 1997b) for constraining the U_1 unconformity at the base of the Hell Creek and Lance Formations across northern Wyoming.

The color of weathered strata has been used during the past century for defining and subdividing the Fort Union Formation. Color differences can be traced for kilometers in flat-lying strata exposed within badland topography, especially when these strata are viewed at a distance. In general, light-grayish yellow and medium-gray beds characterize the Tongue River Member and distinguish it from grayish orange (*buckskin*) beds of the Tullock Member and from dark- to medium-gray (*somber*) beds of the Lebo Member, both of central and eastern Montana. The yellow and medium-gray beds of the Tongue River Member are also distinguished from the dark- to medium-gray units of the Ludlow Member in northwestern South Dakota and in the adjacent parts of southeastern Montana east of the Powder River.

Color, however, is an imperfect criterion when defining lithostratigraphic units from outcrops. Each of the *somber*-colored members listed above contains units of grayish yellow sandstone of varying thickness. For example, in the Little Missouri River study area, the Ludlow Member contains up to 20 percent of thick grayish yellow sandstones that contrast with dark- to medium-gray interbedded units of mudstone. The Ludlow type section in the Cave Hills of South Dakota contains less than 15 percent of yellow sandstone units and consists mainly of dark mudstone and sandstone. The Lebo Member contains numerous thin very persistent, grayish yellow sandstones in the upper 30 meters in the Miles City coal field, but in the lower 70 meters, these units are lacking, and light-gray sandstone comprises 20 percent of the strata, the remainder being dark mudstone. Furthermore, even though the Cannonball Member of central North Dakota and north-central South Dakota is dominated by medium-gray shale, locally it contains bundles of thin, grayish yellow sandstone beds with mudstone interbeds (Cvancara, 1965, 1976; Stevenson, 1956, 1957). The Hell Creek Formation is usually medium-gray, but contains grayish yellow sandstone units near its base in the Ekalaka area (Belt and others, 1997b), and near its top in the Powderville area, 32 kilometers southwest of Ekalaka. Thus, the practice of using yellow sandstone to distinguish the Tongue River Member from various *somber*-colored underlying units is usually ambiguous when no more than 20 meters of outcrop is exposed.

Coal beds, common in the Fort Union Formation, are rare in the Hell Creek Formation. The sparse Hell Creek coal beds are thin and locally developed. Although many of the individual coal beds in the Fort Union Formation split laterally, thin, and pinch out, stratigraphic packets of coal beds and their interbedded clastics can be correlated over wide areas. These are termed a coal zone if the packet of strata contains more than 50 percent coal.

Only a few of the coal beds and zones in the Fort Union Formation in southeastern Montana are mentioned here in order to simplify the stratigraphic organization (figure 2). The Boundary coal bed separates the Hell Creek Formation from the Tullock or Ludlow Members, the C-coal zone separates the Tullock from the Lebo Member, the Contact coal bed separates the Lebo from the Tongue River Member, and the Dominy coal zone lies within the Tongue River Member, roughly 100 meters above its base (Belt and others, 1992, figure 2). The key beds used for correlation in North Dakota are the Oyster coal bed and the overlying VVV marine tongue of the Cannonball Member, and the Harmon-Hansen coal zone (Belt and others, 1984). The T-Cross coal bed is overlain by the Boyce marine tongue of the Cannonball Member in western North Dakota. Both units are useful only within the Little Missouri River area. The Cannonball Member in central North Dakota does not contain coal beds (A. M. Cvancara, Univ. North Dakota, personal communication, 1996).

The C-coal zone, an important marker, is found in the Miles City coal field (Collier and Smith, 1909) and to the south in the Mizpah coal field (Parker and Andrews, 1939). It has been removed by erosion in the gently upwarped strata along the Powder River, south of Mizpah, Montana (Luft, 1986a, 1986b; Luft and Meier, 1986). It presumably pinches out east of the Powder River, in eastern Montana (Sholes, 1988; Hunter and others, 1997) and in the Dakotas, although it is likely represented in North Dakota by the Oyster coal bed (figure 2) and may be represented by the Wilder coal bed (Bauer, 1924; Gill, 1959) in the Ekalaka area. The regional switch of paleodrainage directions from southeast to northeast coincides with the C-coal zone in Montana (Belt and others, 1992, see their figure 22; Belt, 1993) and the Oyster coal bed in North Dakota (Belt and others, 1984), hence we correlate the C-coal with the Oyster coal, although others (Warwick and others, 1995) correlate the C-coal bed with the T-Cross coal bed.

Where the C-coal zone cannot be recognized in the western Williston Basin, the name *Ludlow*, rather than Tullock and Lebo, is used for the strata between the Hell Creek Formation and the Tongue River Member (Vuke-Foster and others, 1986). Ludlow is used in the vicinity of Ekalaka.

The Fort Union Formation contains mature paleosols that make excellent marker horizons for correlation, but immature paleosols, because they are extremely common, make poor marker horizons. Mature paleosols often show a variety of colors atypical of the rest of the formation in which they occur. The anomalous colors include brilliant white, light gray, pale to grayish purple and very pale green. Root and stem impressions are recognized in these deposits where bleaching or silicification has not destroyed them. Certain mature paleosols are discontinuously recognized at the same stratigraphic positions over large areas in the western Williston Basin. These positions occur near the top of the Ludlow Member, the top of the Lebo Member, and the top of the Ekalaka Member as well as within the lower Tongue River Member in some areas (Christensen, 1984; Belt and others, 1984; Vuke, 1989; Vuke and others, 1989; Luft and Vuke, 1989; Belt and others, 1992; Diemer and others, 1996).

In summary, Paleocene lithostratigraphic units can be mapped through a vast region in eastern Montana. Mapping criteria include lithologic comparisons, the use of marker horizons (such as coal beds and paleosols), and the use of fossils as environmental indicators and for dating the strata. In this report, we define the new *Ekalaka Member*, which is described and placed within a stratigraphic, paleogeographic, tectonic, and eustatic context. Figure 3 shows its distribution in the study area.

Sedimentology

The Ekalaka Member crops out in the vicinity of the town of Ekalaka, Montana, and eastward to the Cave Hills of South Dakota (figures 1, 3, 4). It ranges from 15 to 45 meters thick. Strata in the Ekalaka area are selectively lithified; for this reason, the terms *sandstone* and *mudstone* are used in this report rather than the terms *sand* and *mud*. Ekalaka strata are dominated by fine- to medium-grained sandstone and contain subordinate mudstone and shale (defined as a fissile mudstone). The type section of the Ekalaka Member is shown in figure 5; other sections are shown in figures 6, 7, and 8.

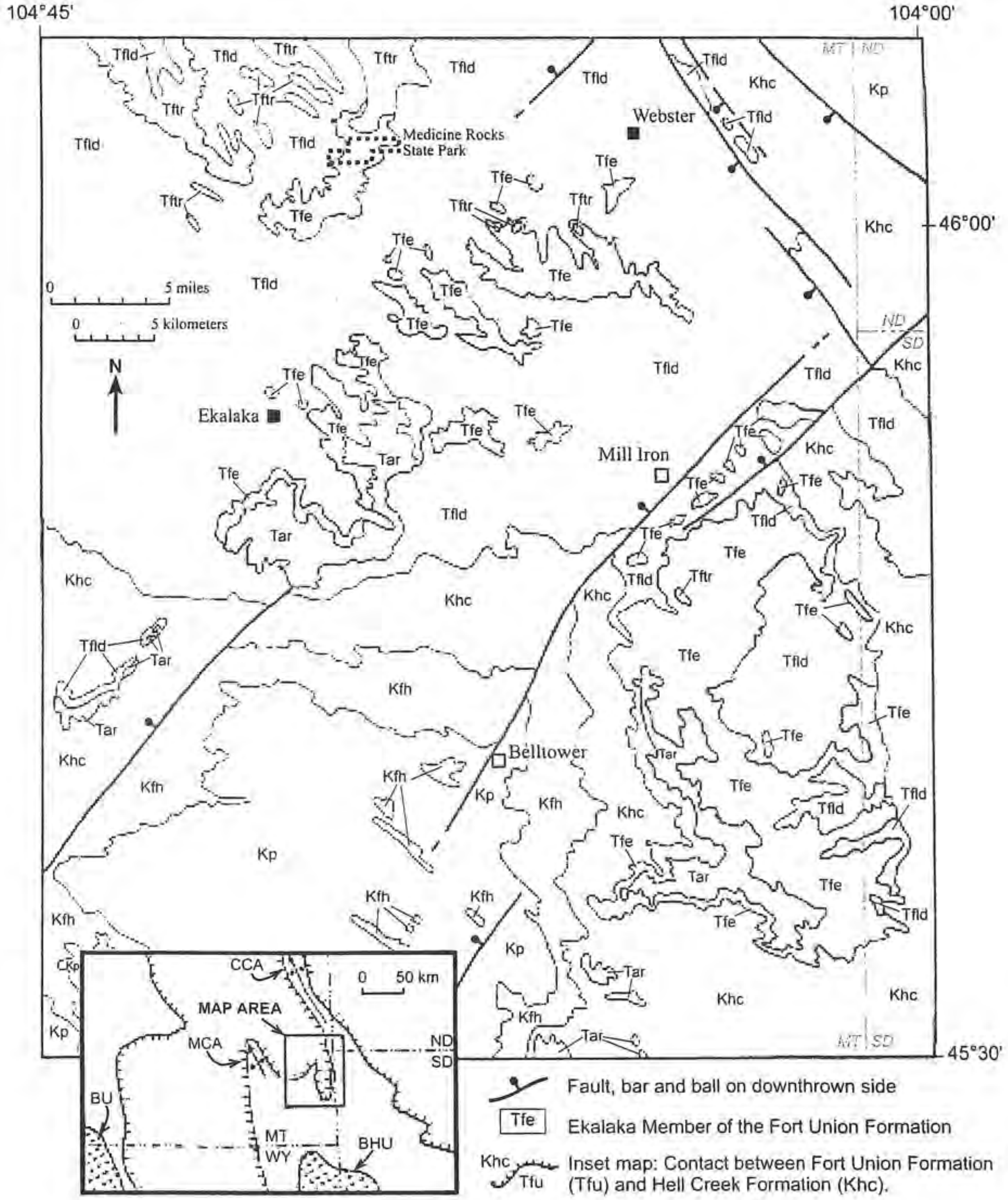
The Ekalaka Member is subdivided into three facies associations (figures 5–8). Facies associations A and B are dominantly sandstone, whereas facies association C is composed of nearly equal amounts of sandstone and mudstone. Facies association C contains minor coal, whereas the others have no coal beds. The physical relationships of these facies associations within the Ekalaka Member are shown in figure 9. Note that facies association B is sometimes underlain by facies associations A and C, and that facies association C is laterally equivalent in part to A and B.

Facies Association A

Description

Facies association A consists of stacked sets of thin (centimeters to decimeters) units of horizontally laminated (plane-bedded) and cross-laminated (ripple-bedded) grayish yellow, fine to very fine grained, sandstone and siltstone. The sandstone beds vary from 5 to 20 centimeters thick and alternate with thinner shale interbeds. Ripple bedforms are draped by millimeter thick mudstones and consist of asymmetrical ripples in sets up to 20 centimeters thick. Ripple forms locally record bipolar flow directions that most commonly have an east–west orientation. Symmetrical ripple forms are rare. Sand-sized microspherules of analcime (probably derived from altered volcanic ash) occur with the more abundant quartz grains in stratigraphic intervals that are more typical of lower Ekalaka Member. Trace fossils are abundant locally in this facies; in addition to *"Skolithos," Skolithos linearis, Diplocraterion, Thalassinoides, Ophiomorpha,* and *Planolites* are also found in this facies (Belt and others, 1997a).

Thick packets of this facies have been torn apart and broken into large (5–15 meters) megabreccia blocks, although smaller blocks also are found, such as the 4-cm thick brick-size block just below the



Rock units from youngest to oldest:
Arikaree Fm. (Tar, Eocene)
Tongue River Member of the Fort Union Fm. (Tftr, Paleocene)
Ekalaka Member of the Fort Union Fm. (Tfe, Paleocene)
Ludlow Member of the Fort Union Fm. (Tfld, Paleocene)
Hell Creek Fm. (Khc, Late Cretaceous)
Fox Hills Fm. (Kfh, Late Cretaceous)
Pierre Shale (Kp, Late Cretaceous)

Figure 3. Geologic map of the Fort Union Formation in the study area showing the distribution of the Ekalaka Member (Vuke and others, 2001). Inset map shows the location of the study area within the western Williston Basin (BU is the Bighorn uplift; BHU is the Black Hills Uplift; other acronyms appear on figure 1).

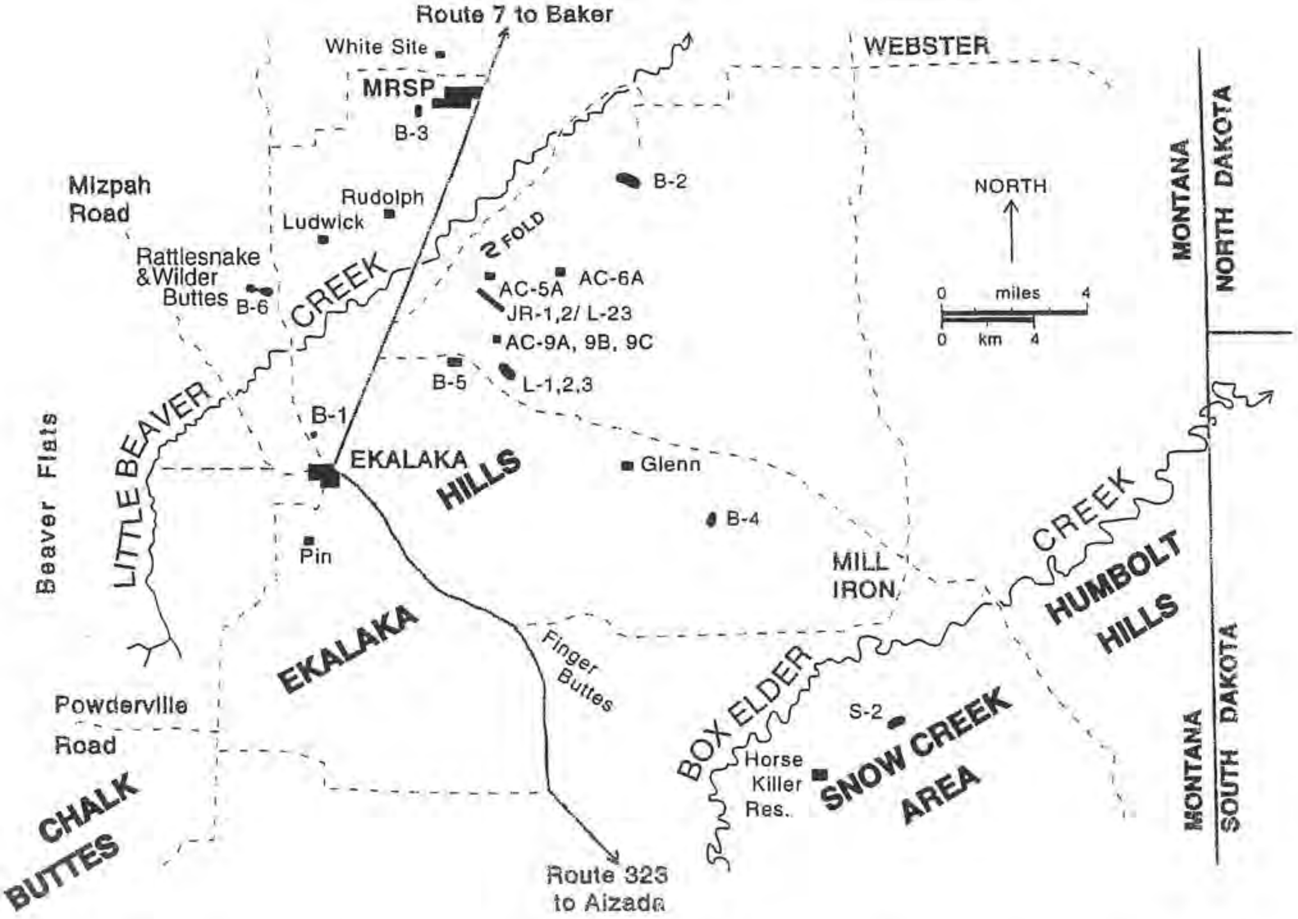


Figure 4. Locations of outcrops and measured sections in the Ekalaka area, including Medicine Rocks State Park (MRSP), Pinpoint Butte (Pin), and S-fold. The sections were measured by Abell and Cole (AC), Lambert (L), Robertson (JR), Belt (B), and Vuke (S). Horse Killer Reservoir is the northernmost exposure within an area where the angular unconformity, U_2, separates the Ekalaka Member from the underlying Hell Creek Formation. The Ludlow Member is not found between these units in this area. The U_2 unconformity has been mapped along the southern end of the Humboldt Hills to Belltower (figure 3). The outcrops that lie within the area 13 kilometers (8 miles) directly south of Horse Killer Reservoir and 8 kilometers (5 miles) east of Belltower have been more thoroughly studied.

scale in figure 10. The disruption that produced megabreccia and smaller blocks occurred during deposition of the Ekalaka Member. For example in figure 10, *Skolithos linearis* burrowed the disrupted strata between the blocks, and after the burrow was abandoned, it was distorted by slight horizontal movement in the sediment.

Because of the disruption of facies association A, it is difficult to reconstruct the original depositional thickness in many places. However in a few places where no brecciation is found, the flat-lying successions of this facies can be measured. These areas vary from a few meters to forty meters thick.

The megabreccia is exposed as a series of tilted blocks that are overlain and underlain by flat-lying strata (figures 6, 11). Usually the smectite-rich Ludlow Member underlies the Ekalaka blocks. The vertical (not stratigraphic) thickness of these disturbed zones ranges from 15 to 40 meters. The individual megabreccia blocks are cut by small fractures that often display offset planes along which lithification has occurred. The direction of movement has been determined, but more importantly, research suggests that the pre-disturbance thickness was likely 80 meters, as will be discussed in more detail below.

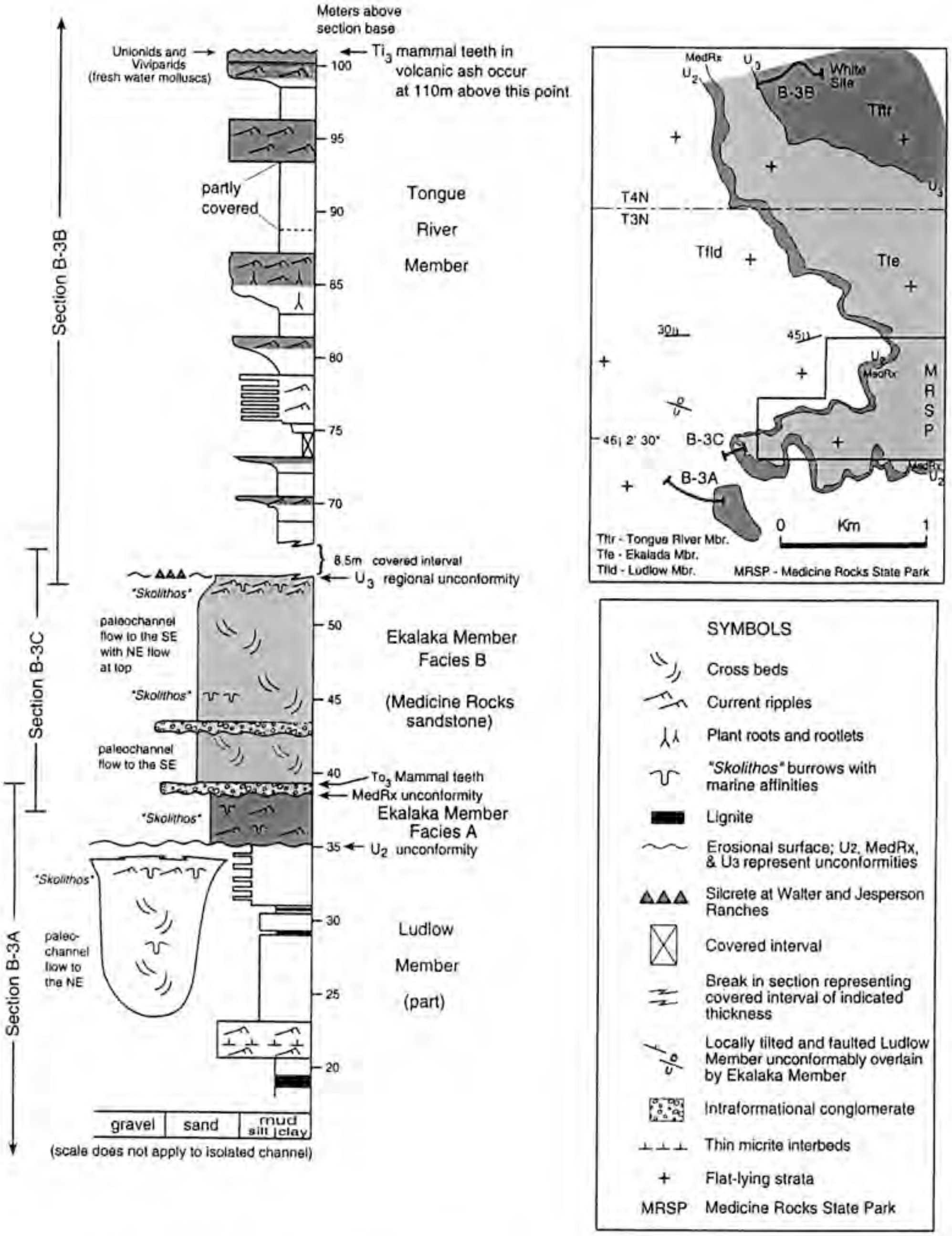


Figure 5. Type section of the Ekalaka Member (section B-3, upper part of B-3A, and all of B-3C). See figure 4 for study area location. Note that section is immediately west and southwest of the Medicine Rocks State Park (MRSP). The Ekalaka Member is shaded in the section and on the inset map. A section that includes the top of the Ekalaka Member and the entire Tongue River Member of this area (Section B-3B) is located at the White Site, north of the MRSP. To_3 (Torrejonian-3) and Ti_3 (Tiffanian-3) are NALMA dates. On the inset map, Tfe Facies A is facies association A of the Ekalaka Member.

Depositional Interpretation

Beds of well-sorted, thin, fine-grained sandstone to siltstone containing horizontal and cross-laminated bedforms that alternate with thinner shale beds are consistent with deposition on shallow subaqueous sand bars in a tide-dominated estuarine setting (Dalrymple and others, 1992, figure 8; Reading and Collinson, 1996). These sand bars probably formed on either upper flow regime sand flats

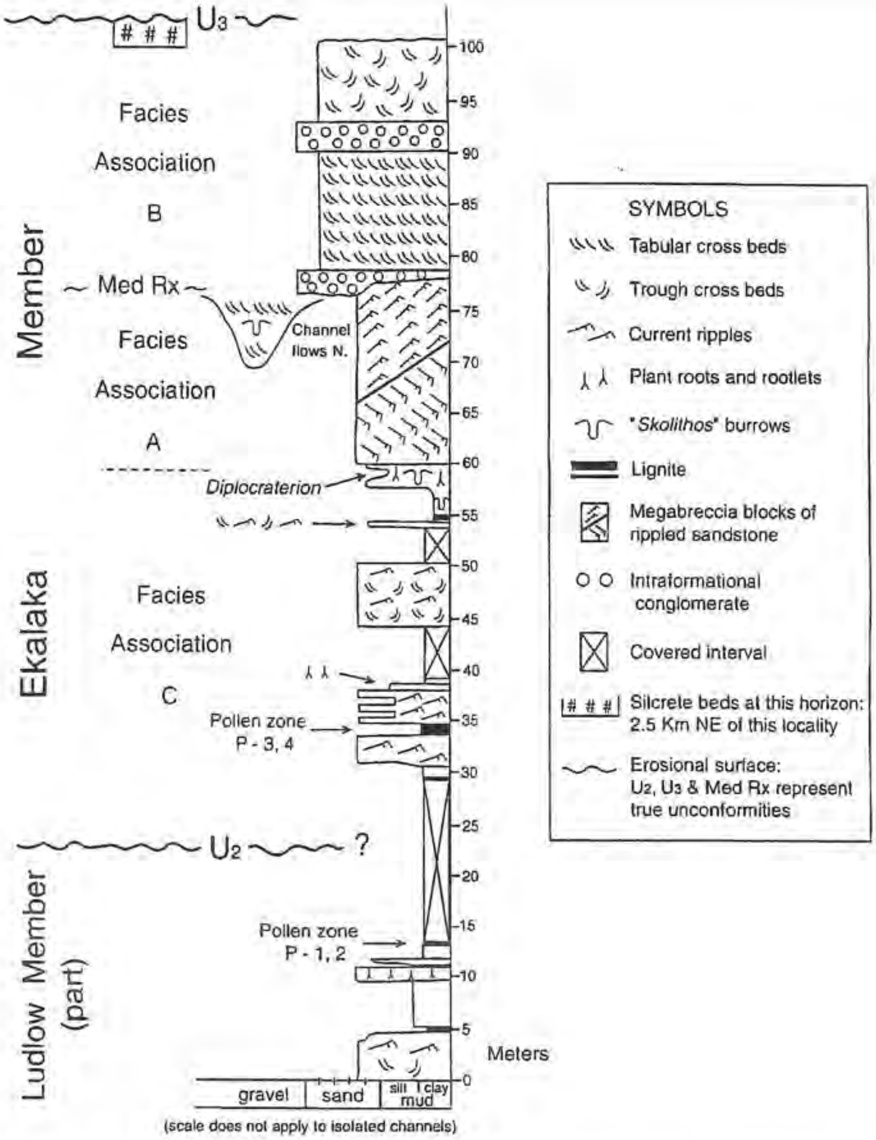


Figure 6. Stratigraphic section B-5 (see figure 4 for location) includes the three facies associations of the Ekalaka Member. The contact with the Ludlow Member is partly covered. Note that tilted megabreccia blocks of fine-grained, rippled sandstone occur above a decollement (shown by dashed line, figure 11). The marine-influenced ichnogenus Diplocraterion (Belt and others, 1997a) occurs in undeformed strata just below these tilted blocks. The silcrete at the top of the section is on the Walter's Ranch (figure 4, sections L-1, 2, 3).

or on tidal sand bars, depending on whether plane bed or current-ripple laminae were dominant. Tidal marine influence is deduced from local bipolar, current-ripple cross laminae and from members of the *Skolithos* ichnofacies (Bjerstedt, 1987; Belt and others, 1997a). This and other ichnofacies were formally defined by Pemberton and others, (1992). Not all modern tidal sand deposits show bipolar directions; horizontal mudstone drapes above current ripples are produced typically by slack water velocities during tidal reversals. Mud drapes, which typically consist of numerous multiple sets of current-rippled and plane-bedded sandstone, are uncommon in facies association A. Reworking of the sediment by tidal currents likely removed the clay and fine-silt fraction and resulted in the well-sorted, fine-grained sandstone and siltstone beds.

Facies association A shows spring/neap tidal cycles (figure 10). Careful examination of laminae in the breccia block beneath the scale shows three cycles. Thirteen laminae were found in each cycle. The

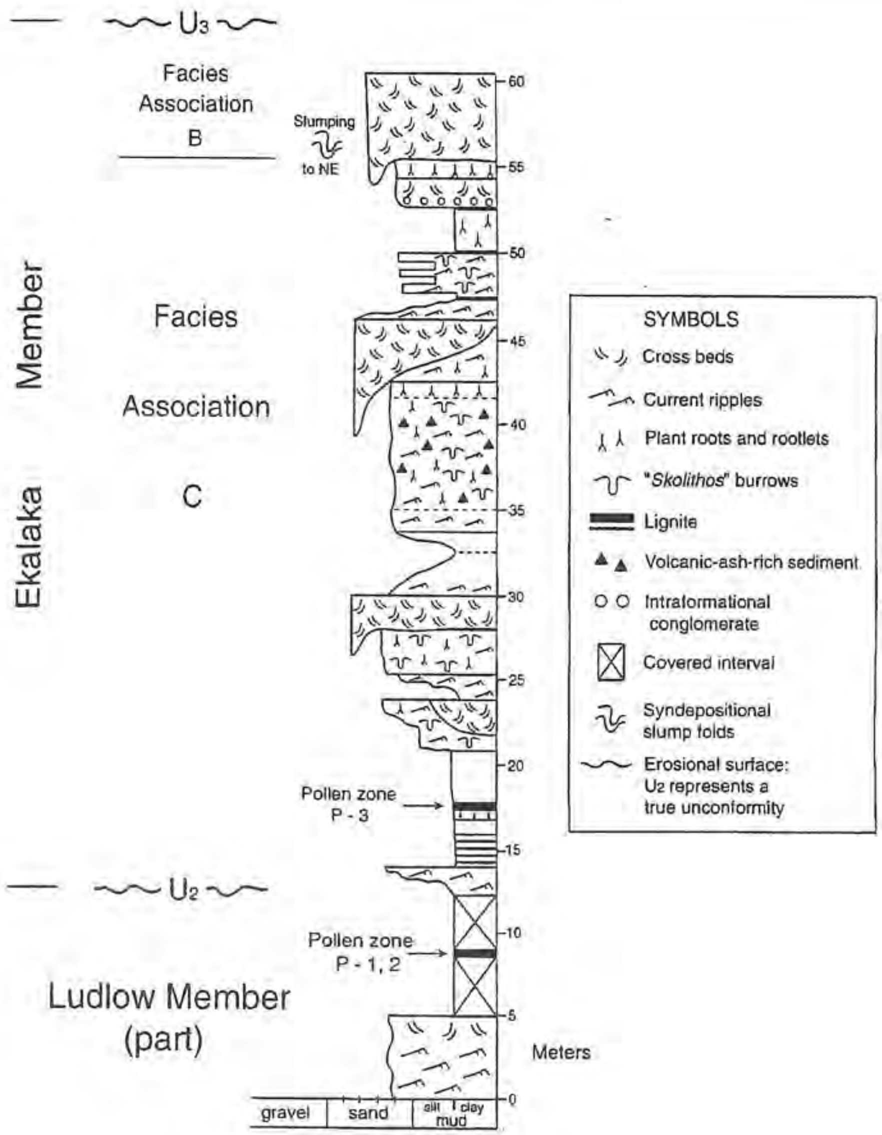


Figure 7. Stratigraphic section B-1 (see figure 4 for location and figure 15 for photograph). This section occurs in the rimrock escarpment just below the Radio Towers at the northern edge of the town of Ekalaka (note photo, figure 15).

light-colored laminae are likely spring, and the darker-colored laminae are likely neap tidal laminae (Ron Martino, Marshall University, personal communication, Dec. 2000).

Facies Association B

Description

Facies association B consists of grayish yellow, fine- to medium-grained trough crossbedded sandstone in single and multistoreyed bodies that occur in units up to 22 meters thick (figures 5, 12). The base of each storey is typically marked by lenses of intraformational conglomerate up to one meter thick. The Medicine Rocks sandstones of this association (name used by Hare, 1959, at Medicine Rocks State Park) are sublitharenites and litharenites with many sedimentary lithic clasts and up to 10 percent volcanic lithic clasts (Abell, 1993). The individual clasts in these intraformational conglomerates consist of very fine-grained sandstone and siltstone that are finely laminated to cross-laminated internally. Some clasts are slightly deformed, suggesting that they were semi-consolidated at the time of deposition. Some clasts consist of carbonate nodules that were completely lithified prior to deposition. Mammal teeth have been found in these deposits.

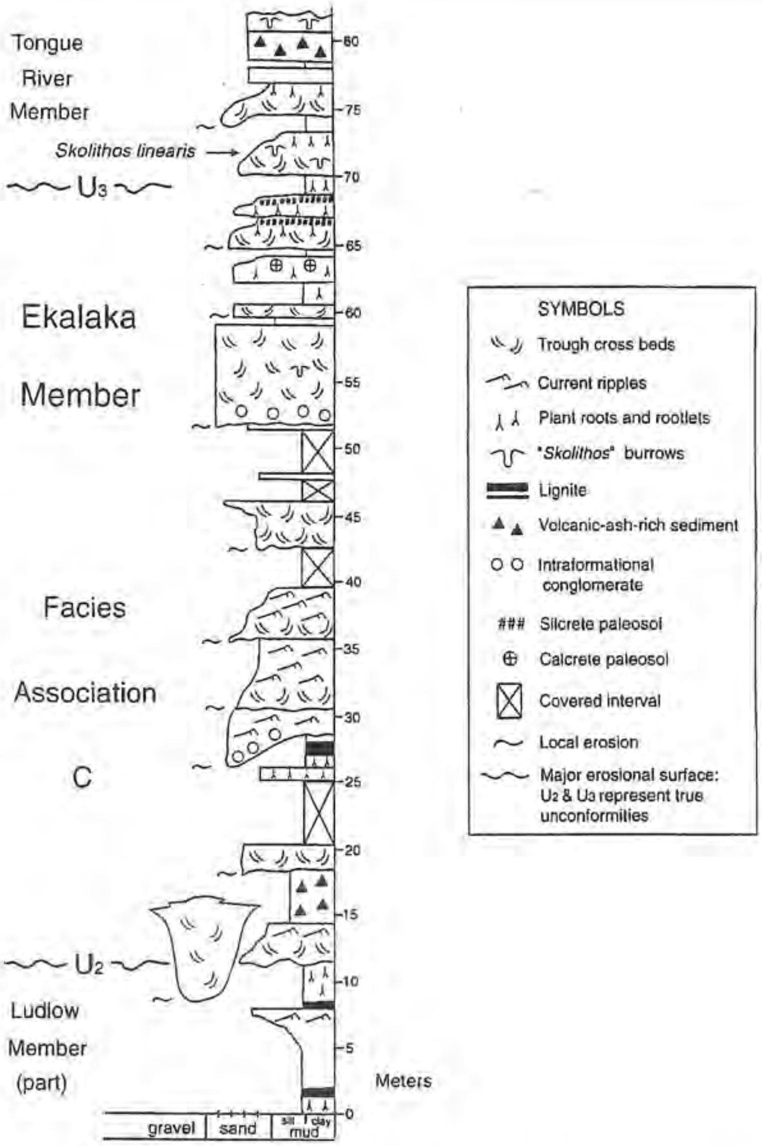


Figure 8. Stratigraphic section S-2 (see figure 4) is typical of the Ekalaka Member in the Snow Creek area. Note the fine-grained sandstone rich in volcanic ash near the base of the section and the two silcrete beds near the top. The marine-influenced ichnospecies (Belt and others, 1997a), Skolithos linearis, *occurs near the top of this section and above the uppermost silcrete bed.*

Cross stratification in facies association B is on a decimeter scale and occurs in sets up to two meters thick (figure 12). The sets are separated by minor erosion surfaces that generally truncate part of the underlying set. These cosets of trough cross-stratified sandstone occupy most of each storey. When viewed parallel to paleoflow, the minor erosion surfaces dip at angles of less than 10° extending from the tops to bases of storeys. The tops of storeys generally fine upward to cross-laminated, very fine-grained sandstone.

Multistorey sandstone bodies, when considered as a whole, can exhibit longhorn geometries, with the bases of the longhorns as much as 10 meters below the more sheetlike upper storeys. The incised lower channels of these longhorns have steep erosional margins and typically contain abundant intraformational material. Individual storeys within multistoreyed sandstones are recognized by erosion surfaces overlain by intraformational conglomerates that separate cross-stratified sandstones with markedly different paleoflows. Paleoflow directions are dominantly easterly, although westerly paleoflow directions are evident locally.

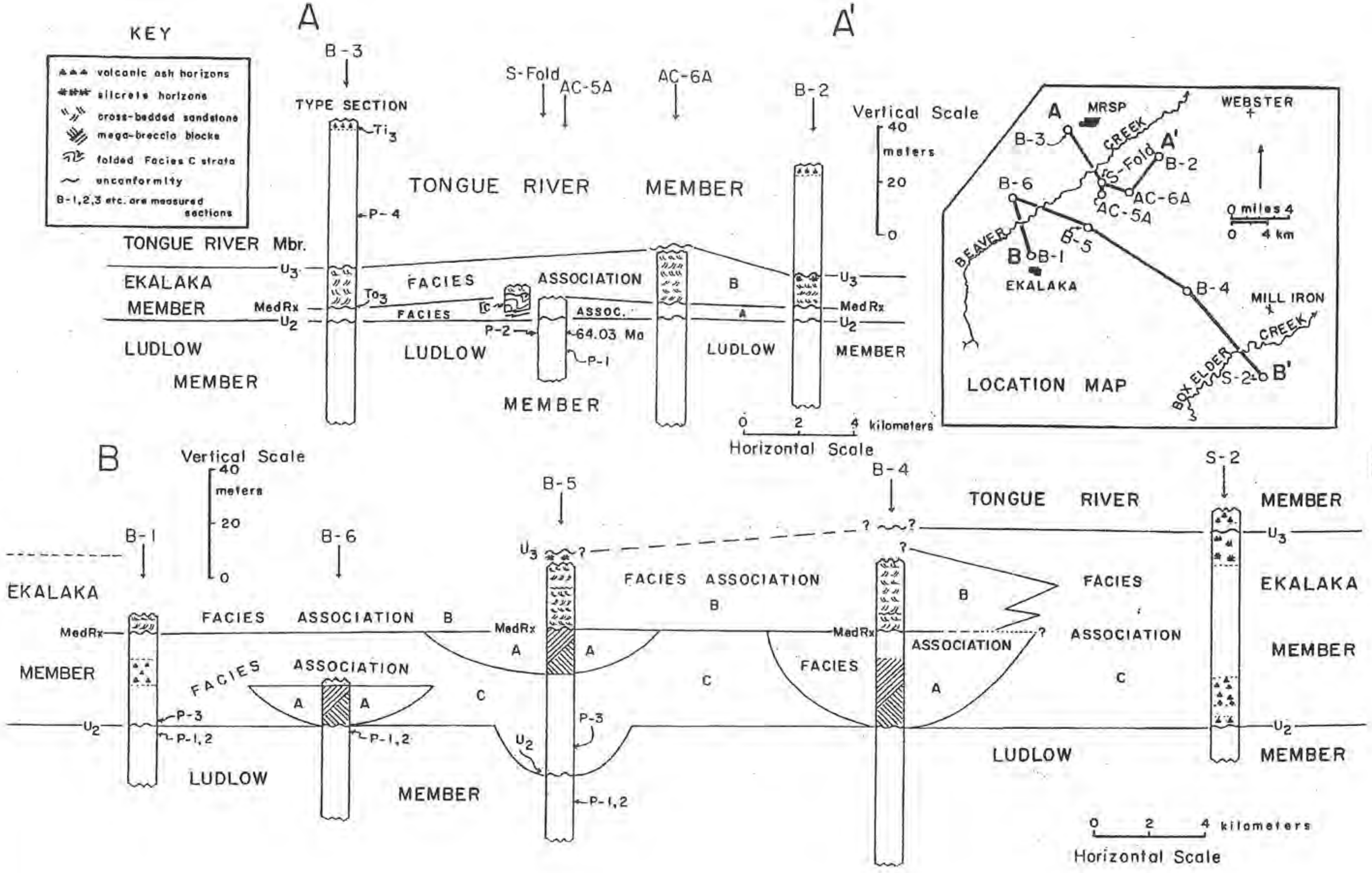


Figure 9. Correlation of measured sections within the Ekalaka Member in the Ekalaka area. See figure 19 for absolute dates of the pollen and mammal zone boundaries. To_3 is Torrejonian mammal age; Ti_3 is Tiffanian mammal age. A, B, C are facies associations of the Ekalaka Member. 62.03 Ma shown in AC-5A is the one radiometric date. U_2, U_3, and MedRx represent unconformities.

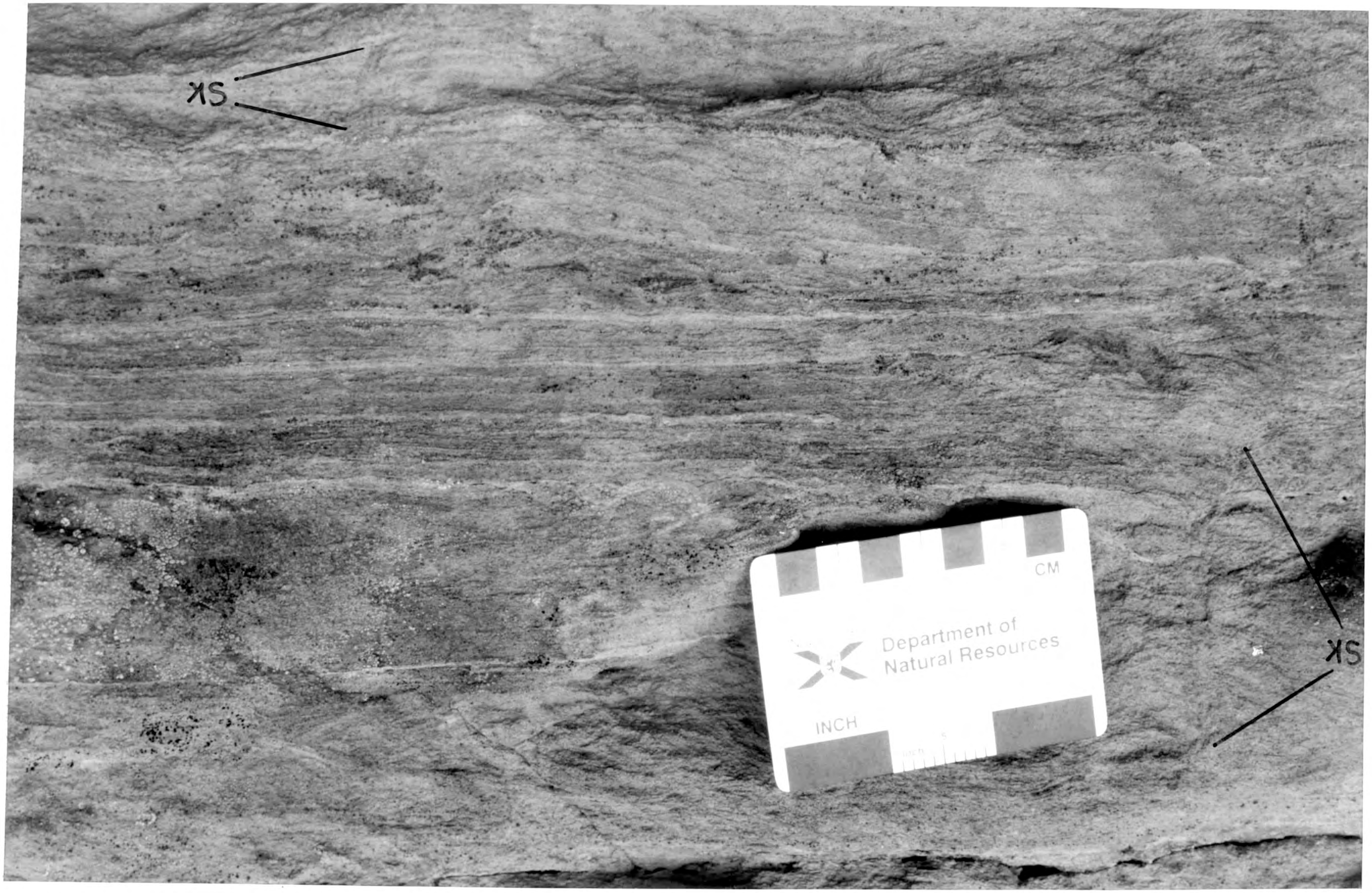


Figure 10. Rhythmic horizontal laminae of very fine sandstone, siltstone, and claystone in facies association A, at locality Pin (figure 4). Post-depositional brecciation has resulted in breccia blocks at different angles, each block containing only a few sets of rhythmic laminae. Note the 4-cm thick breccia block directly below the centimeter scale that contains three set cycles. Each set appears to contain around 13 laminae and hence are probably of spring-neap tidal origin (Ron Martino, Marshall University, personal communication, Dec. 00). The spring events are lighter in color than the neap events; a spring/neap cycle takes about 2 weeks of deposition. SK indicates Skolithos linearis *burrows. These were distorted from a vertical straight tube by movement of the sediment mass after the initial brecciation event.*

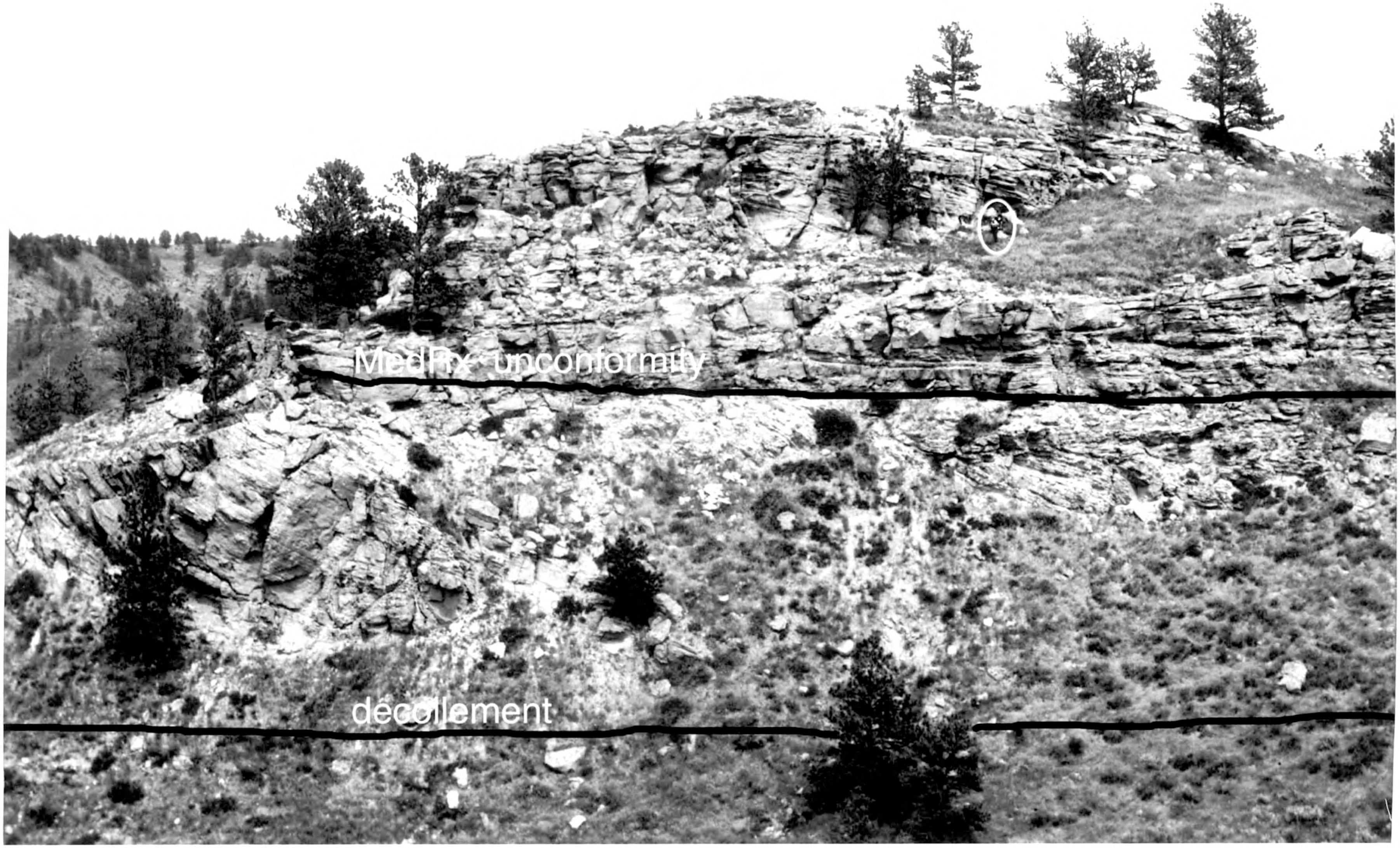


Figure 11. Outcrop view of the upper half of the Ekalaka Member as it appeared in 1991 (section B-5, figure 6). Flat-lying, thin sandstone beds that crop out at the lower left side of the photo, occur below *the surface of décollement (marked at the 60 meter level of figure 6 by a dashed line). Tilted blocks of facies association A lie between the décollement surface and the MedRx unconformity. Crossbedded wedges sets of sandstone are untilted above the unconformity. Scale is Susan Vuke (with her daughter, Emily, in a backpack).*

Figure 12. Facies association B, 1 kilometer north of Medicine Rocks State Park. This is the Medicine Rocks sandstone. The sandstone exhibits tidal bundle cross-stratification and "Skolithos" burrows. The measuring tape has been extended to 1 m. Details of bedding relationships where the tape measure appears are enlarged in figure 13.

Most of facies association B sandstones exhibit trough cross stratification. Additional sedimentary features have been observed locally, including limonitized, millimeter-thick mudstone draped on the foresets of trough cross-stratified sandstone bodies (see figures 12, 13a, b, c). The mud drapes are typically paired with double mud drapes separated by a centimeter or two of sandstone. In some cases, a thin sandstone, encased by double mud drapes, is cross laminated where the orientation of the cross laminae is opposite to the trend of the large-scale, trough cross-bedding. The double mud drapes are best preserved in the lower parts of the foresets. Where a double mud drape is traced up a foreset, it is typical, first for the upper, then the lower mud drape to pinch out (figure 13b). Mud drapes commonly pinch out where subtle, low-angle erosion or reactivation surfaces that are internal to the trough cross-stratified set, occur. Where mud drapes can be traced down the foreset into the trough, it is typical for them to become rippled. That is, at their toe, the trough cross-stratified foresets grade into rippled sandstone with mud drapes (figure 13c). Most ripple marks are asymmetrical and were produced by currents with paleoflow directions typically opposite or at high angles to those of the large-scale cross-bedding.

Double mud drapes occur repeatedly within trough cross-stratified sandstones and subdivide the sandstones into packages that are on the order of centimeters to decimeters thick (figure 13a). The packages are defined by the thickness of cross-stratified sandstone between adjacent sets of double mud drapes when viewed laterally in cross section. The thickness of the packages varies in a downstream direction in concert with the angles of cross-bedding dip. Where packages are thicker, the cross-bedding dips at slightly steeper angles (figure 13a), and conversely, where the packages are thinner, the cross-bedding dips at slightly gentler angles. Thus, there is a cyclicity to thickness and angle of dip of the cross-bedding when viewed laterally in a downstream direction.

"*Skolithos,*" the only trace fossil found, is scattered throughout facies association B and is concentrated densely in the ripple-bedded top of this facies, especially in the Medicine Rocks sandstone (figure 14). As was argued previously (Belt and others, 1997a), "*Skolithos*" is considered a brackish, not a freshwater, ichnogenus. That form occurs locally in the same bed with *Ophiomorpha* and *Diplocraterion,* which suggests that it was euryhaline (i.e., could tolerate a wide range of salinities including brackish and marine). The association of "*Skolithos*" with *Ophiomorpha* and *Diplocraterion* rules out a freshwater environment because the latter two ichnogenera are known from marine facies containing typical marine body fossils.

Depositional Interpretation

The sandstone bodies of facies association B are interpreted as tidally influenced, fluvial point-bar deposits. They were deposited in laterally migrating channels in a tidal-fluvial, inner-estuarine setting as described by Dalrymple and others (1992).

The single storey sandstone bodies of facies association B were produced by a single channel, whereas multistorey sandstone bodies resulted from multiple-channel migration at the same location during a period of net aggradation (Diemer and Belt, 1991). Intraformational conglomerates represent coarse-grained lag deposits that accumulated in the channel thalweg in part as a result of slumping of the cut bank (Bridge and Diemer, 1983). Superimposed sets of trough cross-stratification are the result of sinuous-crested bedforms that migrated down channel and accreted on the inner bank or point bar. The fining-upward sediment and the low dip angle of minor erosion surfaces that separate cosets of trough cross-stratification are a product of lateral accretion in a curved channel (Bridge and Diemer, 1983; de Mowbray, 1983). The absence of mud in clean, sandy deposits of facies association B resulted from efficient current winnowing.

The longhorn geometry in these particular multistorey sandstones is interpreted as the result of incision by a newly relocated, avulsed channel (Diemer and Belt, 1988) accompanied by an increase in accommodation space as base level rose. The incised, lower part of the longhorn was filled, in part, with the semi-consolidated sediment that was incised by the rivers, thus producing the intraformational conglomerates. After incision, the channel initially aggraded vertically. The upper part of the longhorn geometry resulted from the more widespread lateral migration of the channel as aggradation proceeded above the confines of the original valley walls.

The dominant paleocurrent direction to the east of these channels suggests that the longhorn channels were the result of rivers flowing into the Cannonball Sea, which was located in central North Dakota at the time (Belt and others, 1992; Belt and others, 1984).

The limonitized mud drapes on the foresets of facies association B are interpreted as subtidal, low-flow deposits formed in the inner estuary during the slack water periods between flood and ebb tides (van Straaten and Kuenen, 1957; Visser, 1980; Terwindt, 1981; Boersma and Terwindt, 1981a, b; Allen, 1982; van den Berg, 1982; Nio and others, 1983; de Mowbray and Visser, 1984; Diemer and Bridge, 1988; Yang and Nio, 1989; Nio and Yang, 1991). Depending on position within the estuary, either the flood or ebb tide could be the locally dominant flow (Dalrymple, 1984).

In the Ekalaka area, the dominant tidal direction in facies association B is interpreted to have been the east to southeast ebb tide, which was also the direction of fluvial flow determined from the crossbeds. The double mud drapes are interpreted as the slack water deposits formed on either side of the subordinate tide at a site, as described by Nio and Yang (1991). The double mud drapes are best preserved in the lower parts of the foresets because this location would have been best protected from the tidal currents. The double mud drapes pinch out on the upper parts of the foresets because this part

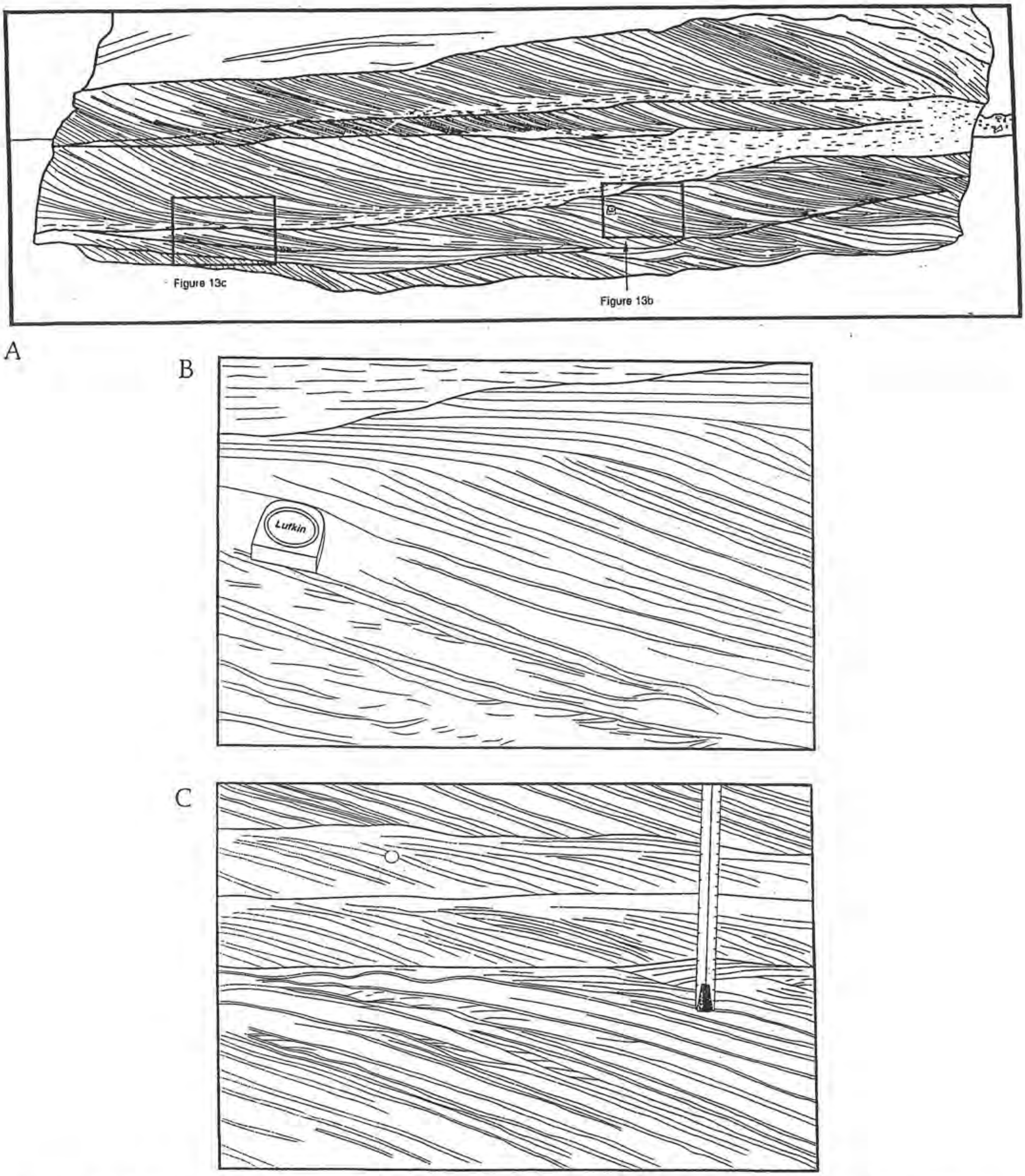


Figure 13. Line drawings of cross-stratified facies association B sandstone. Figure 13A is a tracing from the right side of figure 12 (note that the body of the tape measure has not been moved). Foresets and erosion surfaces separating cosets are indicated. Locations of figures 13B and 13C are outlined. Figure 13B is a close-up view of the trough cross-stratified sandstone with foresets draped by mud. Note double mud drapes on the lower parts of the foresets. The tape measure is 6 centimeters wide. Figure 13C is a close-up view of trough cross-stratified sandstone with the double mud drapes at the bases of the foresets that grade into mud-draped ripples. Note the opposed orientations of foresets and cross-laminae within the ripple forms. The tape measure scale is in centimeters and inches. The circle is a quarter (diameter 2.4 cm).

of the bedform would have extended higher into the flow and would, therefore, have been subjected to reworking. Reactivation surfaces locally record this reworking by the tidal currents. Ripples formed in the troughs are well preserved because of their relatively protected position. Some of the ripples may be counterflow ripples produced by the separation eddies during the dominant tide, but others were likely formed by the subordinate tide flowing in a direction opposite the dominant tide.

The packages of sediment that occur between adjacent sets of double mud drapes are interpreted as the cross-stratified sandstone deposited during dominant tidal flows. The variation in thickness of these packages is interpreted as a product of variation in the tidal flow related to neap-spring cyclicity in the tides. Likewise, the variation in the dip of the cross beds is interpreted as the product of stronger tidal flow during spring tides (steep foresets, well-developed separation eddy) alternating with weaker tidal flows during neap tides (gentler foresets, less well-developed separation eddy). These features are similar to those described by Visser (1980), Terwindt (1981), Boersma and Terwindt (1981a, b), Allen (1982), van den Berg (1982), Nio and others, (1983), de Mowbray and Visser (1984), Diemer and Bridge (1988), Yang and Nio (1989) and Nio and Yang (1991), and together include what is known as tidal-bundle cross-stratification.

An inner, more river-dominated estuarine setting, especially in the Medicine Rocks sandstone, is supported by the presence of only "*Skolithos*" (Bjerstedt, 1987; Belt and others, 1997a). These burrows are locally abundant (see figure 14) and produce a *piperock* appearance in the strata. In other cases, they may be responsible for the homogeneous appearance of facies association B sandstones. No other type of burrow was found, however, which suggests that few organisms were adapted to the prevailing conditions. Such low-diversity, but locally abundant, assemblages are characteristic of inner estuarine environments subjected to wide ranges in salinity (Dorjes and Howard, 1975; Howard and others, 1975). Thus, low diversity supports an inner-estuary depositional setting for the facies association B sandstones.

In summary, facies association B is interpreted as the product of deposition within an inner estuarine setting dominated by fluvial processes with active tidal influences, as described by Dalrymple and others (1992). These fluvial processes produced inner estuary channels that were slightly sinuous and migrated laterally, and deposited sand on their point bars. The channels avulsed occasionally leading to incision and longhorn channel-sandstone geometries. In general, the dominant tide in the system was the ebb as it was superimposed on the fluvial discharge of the region. Locally, however, the flood tide was dominant. Tidal features include double mud drapes, rippled troughs with paleoflows opposing those of the large-scale cross-stratification, 180° paleoflow divergence between storeys of multistoreyed sandstone bodies, consistent variation in thickness and angle of dip of packages of trough crossbedded sandstone (defined by bounding sets of double mud drapes), association with fine-grained, laminated, estuary-margin deposits (some of which occur as clasts within the intraformational conglomerates), and the presence of "*Skolithos*" in the tidal bundle cross-stratified sandstones.

Facies Association C

Description

Facies association C contains crossbedded sandstone bodies but also contains units of alternating thin beds of sandstone and mudstone, thin units of carbonaceous shale, coal beds less than 30 centimeters thick, and of sheet sandstone. This facies association is typified in section B-1 (figure 7). Where the sandstone bodies exceed 5 meters thick, those strata are considered facies association B.

The sandstone bodies are composed of fine-grained, moderately to poorly sorted sublitharenites and litharenites (Abell, 1993). Orthoquartzites are rare. Gravel-size intraformational intraclasts of mudrock, sandstone, iron-rich carbonate nodules, and coal typically occur above basal erosion surfaces.

Sandstone bodies in facies association C are not as thick as in facies association B. This facies association has two styles: shoestring geometry, which is commonly multistoreyed, and sheet geometry. In the shoestring bodies, trough cross-stratification in decimeter to meter thick sets is the dominant

Figure 14. Facies association B sandstone. The lower 30 centimeters show angular intraformational mud clasts in sandstone. The middle 75 centimeters are trough crossbedded, medium-grained sandstone. The upper 20 centimeters show current-rippled sandstone. The closely packed vertical tubes are identified as "Skolithos" burrows (Belt and others, 1997a). The upper part of the Jacob staff has been marked in the 30-cm segments. This outcrop occurs at the top of the Medicine Rocks Sandstone at the corner of Medicine Rocks Church road and Montana State Route 7.

sedimentary structure in the lower parts of storeys. Small-scale trough cross-lamination is typical in the upper parts of storeys where it is interbedded with centimeter to decimeter thick mudstone layers.

Major erosion surfaces at the bases of storeys (fourth-order surfaces of Miall, 1988; Diemer and Belt, 1991) have decimeters to meters of relief and define the lenticular shapes of the sandstone bodies. The lowermost erosion surface of a multi-storey sandstone body is a fifth-order bounding surface. The topmost storeys of multi-storey sandstone bodies are typically fully preserved, as are single-storey sandstone bodies. When viewed in the paleoflow direction, lateral accretion bedding can be observed extending from the base to the top of a storey. Paleoflow orientations from trough cross stratification are generally to the east. These observations are in agreement with the shoestring geometry of the sandstone bodies, which can be traced widely within areas of badland outcrop.

The sandstone-mudstone interbeds with carbonaceous shale and coal occur as centimeter to meter thick lenticular and sheetlike beds in stacks that are meters thick. The grain size in these stacks ranges from fine sand to mud. These sandstones have erosional bases and trough cross-stratified, horizontally laminated and cross-laminated bedsets that are centimeters to decimeters thick. The mudstones are generally massive and composed of kaolinite- and illite-dominated clay mineral assemblages. Fossil roots are typical in both the sandstone and mudstone. The carbonaceous shale is composed of dark-brown, organic-rich fissile mudstone. The organic matter includes plant stems and leaf fragments and constitutes at least 5 percent by weight of the mudstone. Centimeter to decimeter thick coal is interbedded with the carbonaceous shale locally.

The sheet sandstones are the more common geometry in facies association C. They consist of grayish-yellow to tan, fine to very fine-grained sandstone and siltstone in layers that are decimeters to a meter thick. Sheet sandstone units are cemented or replaced locally by calcium carbonate, resulting in discontinuous resistant ledges. These beds, whether replaced or not, are dominantly cross-laminated in centimeter to decimeter bedsets that typically become finer-grained upward. Certain beds may be rich in volcanic ash (figure 15). Preserved ripple forms and climbing ripple cross-lamination are typical. Massive to poorly laminated, bioturbated mudstone often drapes the fining-up sandstone units. Trace fossils in these sandstone beds include *Diplocraterion, Ophiomorpha, Thalassinoides, Planolites, Skolithos linearis,* and *"Skolithos"* (Belt and others, 1997a).

Depositional Interpretation

The shoestring sandstone bodies are interpreted as having been deposited by aggrading channels that migrated across an alluvial plain that lay along the margin of the Ekalaka Estuary. The laterally extensive, basal-erosion surfaces are products of lateral migration of the thalwegs. Intraformational breccias overlying those surfaces were derived from slumping of cutbanks. Trough cross stratification and cross lamination are products of dunes and current ripples that migrated down-channel, and the lateral accretion bedding records successive point bar surfaces formed during lateral migration (McDowell, 1960; Lane, 1960; Harms and others, 1963; Harms and Fahnestock, 1965; Singh, 1972; Singh and Kumar, 1974; Shelton and Noble, 1974).

The sandstone-mudstone interbeds containing carbonaceous shales and coals were deposited in a variety of overbank settings outside and along the margin of the estuary proper. These include levee, crevasse-splay and flood-basin environments. Thickness and composition variations may have resulted from proximity to source channels at the time of deposition. Individual fining-up bedsets record discrete flood events. Lenticular deposits formed in small (crevasse) channels, whereas, sheetlike deposits may have formed on levees adjacent to channels or on splay surfaces. Between flood events, the overbank deposits were vegetated and immature soils and carbonaceous shale accumulated in parts of the flood basins that received less clastic input. The thickest coal developed in even more distal parts of the flood basins where the rate of organic accumulation was much greater than the clastic supply; these were freshwater deposits. The thinner coals, overlain by sandy beds containing the estuarine ichnofauna, may have formed from brackish-tolerant flora that grew along the estuary margins. Depositional rates on this alluvial plain were low, and the rivers flowing across it contributed only a modest amount of fine sand to the estuary.

The sheet sandstones are interpreted as either splay deposits that formed in freshwater flood basins, or as estuarine-marine deposits if they contain brackish-water ichnofauna. The stacks of fine-grained, sheetlike bedsets with erosional bases suggest repeated flood events in a setting distant from the source channel. The combination of wave ripples and brackish trace fossils suggests superimposed marine episodes. In several instances, facies association C units that contain *in situ* rootlet beds, thin coals, and sandstone that contain freshwater megaplants and rare freshwater molluscs are interbedded with units that contain marine-based ichnofossils. This association indicates that brackish and freshwater conditions alternated in this depositional setting.

Megabreccia Deposits

Ten- to forty-meter thick intervals made up largely of megabreccia blocks occur within the Ekalaka Member in a 13-km by 14-km area, mostly north and northeast of the town of Ekalaka (figure 16). Twenty-eight sections that contain megabreccia were measured in the field by Albanese (1993), Clark (1993), and Kallweit (1993); these blocks are entirely composed of facies association A. The basal detachment surfaces to the megabreccia units are locally exposed (e.g., note decollement, figure 11).

The megabreccia intervals directly overlie either undeformed Ludlow Member (typically) or undeformed (largely facies association A and C) lower units of the Ekalaka Member (rarely). The megabreccia intervals are in turn overlain by undeformed upper Ekalaka units of facies association B near Ekalaka and, to the east, of facies association C.

Note in figure 9 that the megabreccia deposits are shown schematically as lenses. These are laterally equivalent to and interbedded with undeformed strata of facies associations A, B, and C, although details cannot be shown in the figure. Note that when the Ekalaka section contains units of undeformed facies association A or units of undeformed facies association B interbedded with deformed facies association A, these are also not shown on figure 9. See Cole (1993) for more information on each section.

Deformation in the interval of disrupted strata changes both vertically and horizontally, reflecting local variations in strain. The most commonly observed structures are small-scale, brittle to semi-brittle extensional faults that are typically traceable for a few tens of centimeters to a few meters and have separations of centimeters to decimeters. These faults are planar to subplanar, generally in one of two modes. The most common mode is in conjugate sets with sub-parallel strikes and dips ranging from 30° to 70°, averaging 52° (n = 201; Clark, 1993). The faults of each set may be equally abundant, or in any given outcrop one set may dominate. The other set may dominate in adjacent outcrops, however, and thus, while the extension direction can be determined (figure 17), neither relative displacement magnitude nor frequency of one set with respect to the other constrains the transport direction of the megabreccia blocks.

The other mode of faulting consists of fault planes that are inclined sub-parallel. The fault planes in turn truncate the bedding, which dips in the opposite direction. These faults indicate a definite transport direction for any given locality, but opposite transport directions are typically found in adjacent outcrops, indicating that they also record local adjustments in an extending mass.

Low-dipping faults of unknown but larger displacement (in some cases >100 meters) were observed in several areas and appear to bound blocks in which internal deformation was accommodated by the smaller-scale faults described above. Limited exposure in the Ekalaka region prevents tracing these larger faults to determine the geometry of the fault system, but it is possible to reconstruct a composite geometry by examining isolated pieces. Individual segments include: (1) extensional faults that flatten downward into a basal detachment at the top of the Ludlow Member (hanging wall down, strata dip

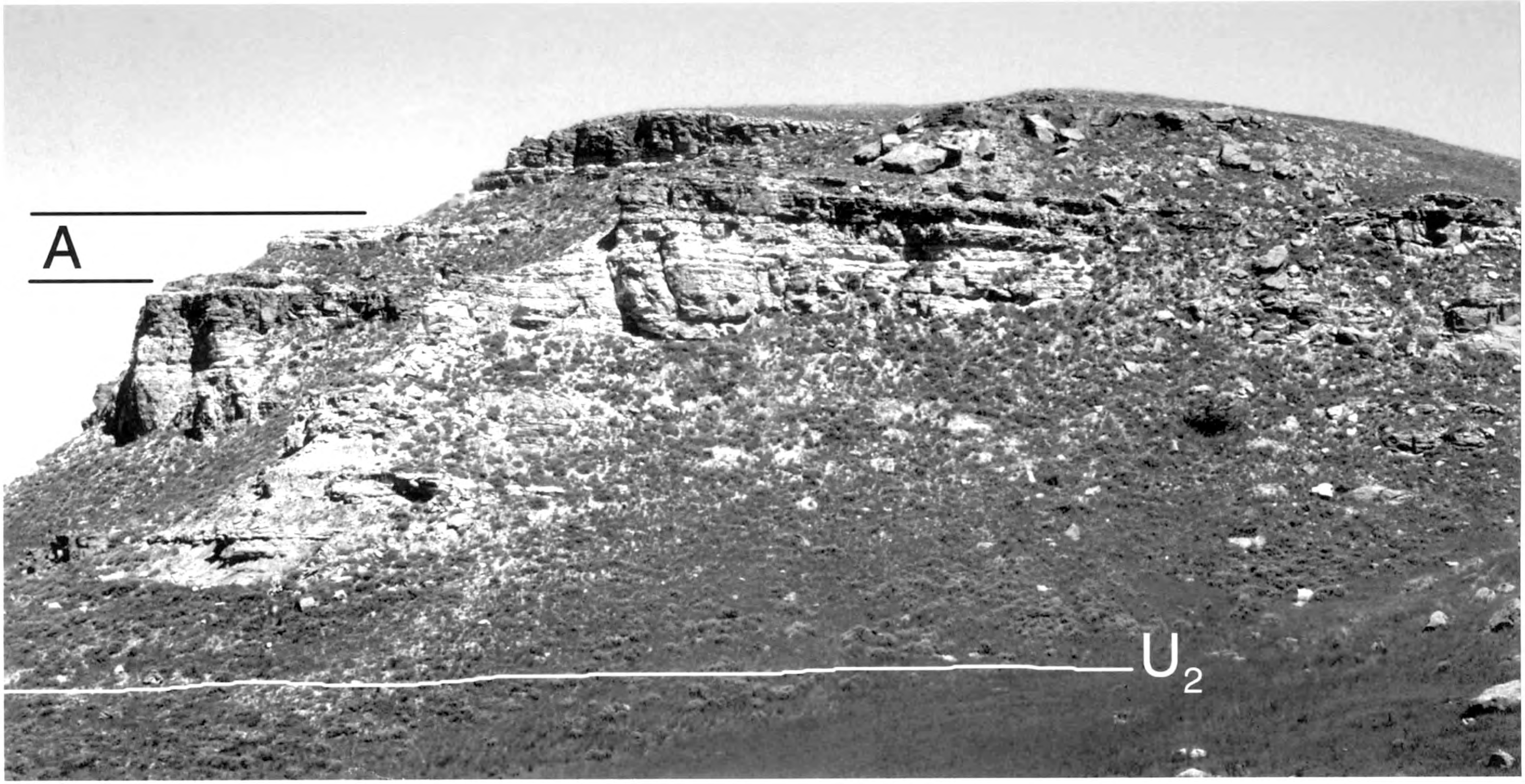


Figure 15. View of Ekalaka Member strata just west of the Radio Towers escarpment, town of Ekalaka (see figure 7). The U_2 line is an unconformity between the Ludlow Member (below) and the Ekalaka Member (above). Outcrops of Ludlow strata occur below the unconformity to the left of this view. Note the thick unit of light-colored volcanic-rich siltstone and fine-grained sandstone (A), which correlates (figure 9) 28 kilometers to the southeast to a unit of similar lithology near the base of section S-2 (figure 8).

toward the fault); (2) sub-horizontal faults or detachments at the top of the Ludlow Member that are overlain by horizontal or gently dipping Ekalaka Member strata containing numerous small-scale faults; (3) low-dipping faults with convex-upward curvature that appear to record a slumped sheet that overrode a smaller displaced fragment (a horse); (4) slightly tilted and faulted facies-association-A strata emplaced along shallow-dipping faults over more severely deformed, older facies-association-A strata; and (5) contractional (reverse dip) faults representing either the internal collapse of a slump sheet or a more rearward slump overriding a more forward one.

These observations give an overall picture of extensive, recurring slumps, with basal detachment above the expanding smectite clays of the Ludlow Member or within similar behaving shaly units of facies association A of the Ekalaka Member. Higher-level slides occasionally moved over previously slumped strata and may have produced the small-scale plastic deformation seen within some megabreccia blocks.

The possible extension directions throughout an area of slumping are generally well constrained. The direction of motion, however, can only be defined relatively (figure 17). The normal faults give consistent extension axes, but no features provide displacement vectors. The only possible exception to this is at the site of measured sections JR-1 & 2 and L-23 (figure 4; cf. sections in Cole, 1993), where normal faults on a variety of scales, and in one substantially faulted anticline, suggest movement toward the south at 197° (Kallweit, 1993). This movement is toward a thick (>20 meters) southeast-flowing fluvial channel (facies association B) that eroded as the fault blocks disintegrated during coeval stream activity (figure 18). The extension directions shown on figure 17 are variable, but nearly north - south orientations dominate. The systematic orientation of extension direction can be attributed to a regional west-to-east orientation of channels and their poorly supported channel banks, or to regional tectonic stresses (e.g., upwarping along the northwest axis of the Miles City Arch), or to both causes.

Facies-association-B crossbedded sandstones occur at various levels interbedded with megabreccia; this can be seen at the JR-1 & 2 and the L-23 localities (figure 4). These sandstones contain shredded angular clasts of granule- to boulder-size sandstone (figure 18; *cf.* Blair and McPherson, 1999) of facies association A. Estuarine sedimentation, slumps, and fluvial flow must have been coeval to produce discrete deposits of each type in that area.

The erosive relationship between crossbedded sandstone and underlying megabreccia blocks is best photographed (figure 11) from the outcrops of section B-5 (see figure 6 for log). The relationship here is an angular unconformity, defined as the MedRx unconformity. The facies association B crossbedded sandstones at the top of the section above the MedRx contain many rounded clasts that were derived from erosion of the underlying megabreccia blocks.

Modern Analog

The Turnagain Heights landslide, triggered by the 1964 Good Friday Alaska earthquake (Voight, 1970; Hansen, 1965; Seed and Wilson, 1967; Wilson, 1967), provides a reasonable analog model for the slump deposits in the Ekalaka Member. In that case glacial outwash sediments slid on the highly sensitive Bootlegger Cove clay and produced similar effects as those that resulted when the Ekalaka Member slid on the smectite-rich Ludlow Member. In both cases, deformation was mainly by brittle and semi-brittle faulting rather than by liquefaction. From this analog we can make useful extrapolations concerning the geometry and dimensions of the systems in which the Ekalaka Member slumping occurred.

At Turnagain Heights, the slump was slightly over 0.5 kilometers parallel to displacement (slump width) and up to 2 kilometers normal to movement direction (slump length). During the slide, width expanded while length remained constant. That is, the slumped strata, with an original cross-sectional width of up to 0.25 kilometer, was extended by 100 percent to 0.5 kilometer, and as a result, its original average thickness was thinned during slumping by 50 percent.

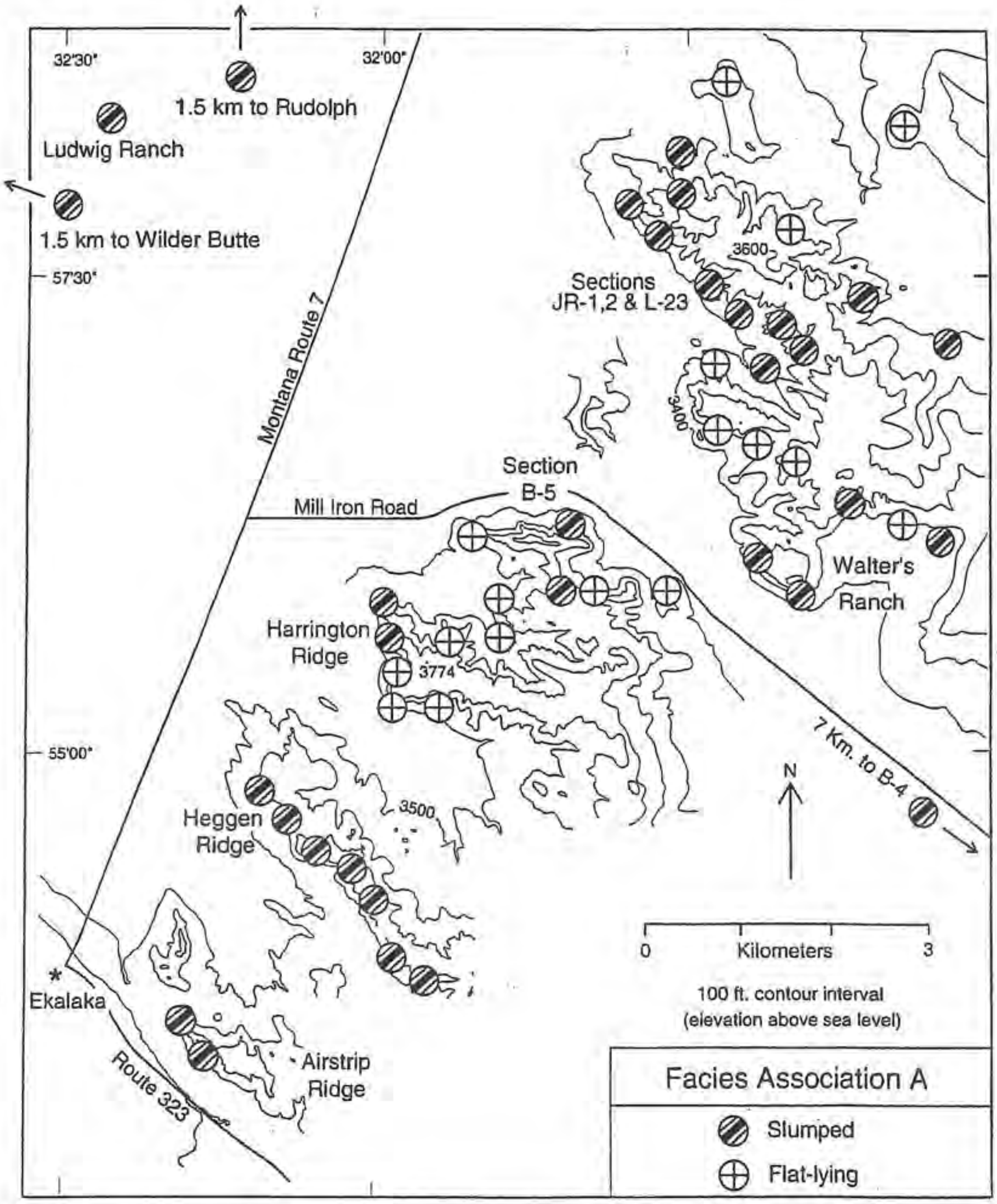


Figure 16. The map distribution of megabreccia slump blocks within facies association A and of undisturbed facies association A. Compare with the sections shown in figure 9. This is the only part of the area shown in figure 4 that has slumped blocks within facies association A. After Clark (1993).

The area of Ekalaka slump deposits, where the displacements occurred, is at least 13 kilometers parallel to the extension direction (its northerly extent is not exposed) and is 14 kilometers perpendicular to the extension direction. The thickness of deformed facies association A intervals averages 20 meters, and is as much as 40 meters thick. Forty meters is also the maximum thickness of undeformed facies association A, measured by Cole (1993) at one locality. Using the Turnagain Heights landslide as an analog, these observations suggest that the Ekalaka slump deposits, before deformation, may have been on average up to 80 meters thick and could have become 50 percent thinned during the slumping events.

There are several important implications of these observations: (1) the parts of the estuary receiving the slumps must have been at least 1 kilometer wide, otherwise the slumps would have run into the opposite side of the estuary to result in pileup features that would have been obvious in the field; (2)

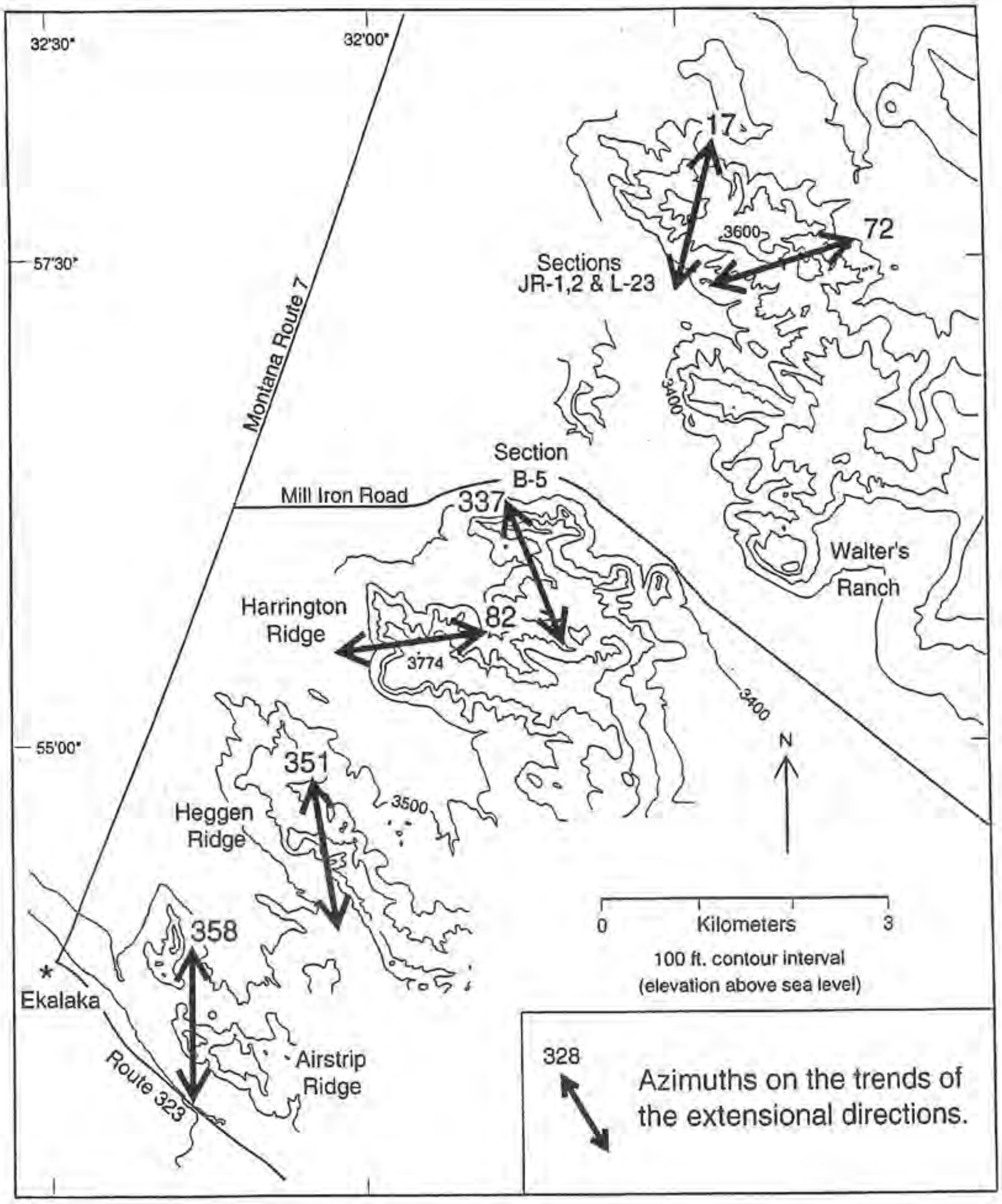


Figure 17. Extension directions and their azimuths, based on 3-D strain analysis of faults within megabreccia blocks of facies association A. Data from six study sites were grouped, and the results summarized (Clark, 1993; additional data in Albanese, 1993). Hundreds of readings were analyzed from the six areas shown on this map.

those layers of facies association A involved in slumping may have been as much as 80 meters thick; (3) one or several channels at least 40 meters deep were needed for slumping to occur; (4) although the slumps moved in a north-south direction, the deeper part of the Ekalaka Estuary in that region had a northwest-southeast trend (figure 19); and (5) the type and scale of the deformation indicate that the trigger for the slumps was very likely seismic in origin, which may account for the movement oblique to the axis of the estuary.

S-Fold Locality

Unusually deformed Ekalaka strata occur at the S-fold locality (figures 4, 19). At that locality, thin sandstone beds and thin units of mudstone and carbonaceous shale of facies association C are exposed within several acres. These strata are folded into an anticline and a syncline, and they are truncated

Figure 18. Units of sandstone with angular fragments derived from megabreccia blocks are interbedded with normal crossbedded channel sandstones. Normal crossbedded sandstone units contain no angular megabreccia fragments. This facies is coeval with tilted megabreccia blocks. The angular fragments are of facies association A and consist of fine-grained, planar-bedded sand with a high concentration of volcanic ash. Exposure is 3 meters in height. Locality is at JR-1, 2 (figure 4).

above by the MedRx erosion surface (figure 20). Thus, folded lower Ekalaka Member strata are unconformably overlain by flat-lying Medicine Rocks sandstone of facies association B. The folded lower Ekalaka strata in turn overlie flat-lying smectite-rich Ludlow mudstone with a detachment fault. Rip-up clasts at the base of the Medicine Rock sandstone have the same lithologies as are found in the folded Ekalaka strata.

Undeformed, flat-lying Medicine Rocks sandstones directly overlie undeformed Ekalaka strata in some places, deformed Ekalaka strata in other places, and elsewhere the Medicine Rocks sandstone lies directly above Ludlow strata. The unconformity directly below the Medicine Rocks sandstone, the MedRx unconformity, is shown on figure 5 at a position 38 meters above base of section B-3A as well as on both cross section A-A' and B-B', figure 9. Near the type section (B-3, figures 5, 9), faulted and folded Ludlow strata, deformed prior to the deposition of the Medicine Rocks sandstone (facies association B) may represent the initiation of uplift that produced the U_2 unconformity below the Ludlow Member and above Ekalaka Member.

Folding at the S-fold locality resulted from plastic deformation quite unlike the brittle megabreccia block deformation within the main body of the Ekalaka Member. Two explanations seem possible. One is that the folding resulted from local compression because of a collision of a rearward slump block with a more forward slump block. The forward slump block had ceased movement before material at the rear of the slump had stopped. Unfortunately, no slump blocks are found in the region around the S-fold (see figure 19, region of diagonal slash pattern).

A second explanation entails a larger tectonic cause, such as a second uplift, younger than U_2, along the Miles City Arch, which might have caused a slump folding at the S-fold locality and subsequent uplift to produce the MedRx unconformity. The limited exposure in the Ekalaka area seems to preclude resolving this issue.

Definition of the Ekalaka Member

The Ekalaka Member of the Fort Union Formation is here designated as a formal lithostratigraphic unit. The name of the member is derived from the town of Ekalaka, the community surrounded by the member and nearest the type section. The type section is located on the western side of Medicine Rocks State Park (section B-3; figures 4, 5) 18 kilometers (11 miles) north of Ekalaka on Route 7.

Lithology

The Ekalaka Member is subdivided into three facies associations, defined earlier. Facies associations A and B contain more than 80 percent sandstone, and facies association C consists of about 50 percent sandstone. Taken as a whole, the Ekalaka Member has a higher percentage of sandstone than most other members of the Fort Union Formation in western North Dakota and eastern Montana. The exceptions are the Tongue River Member in the Powder River Basin, along the Wyoming border (Flores, 1981) and facies assigned to the Cannonball Member at Cave Hills, South Dakota (Cvancara and Hoganson, 1993). In addition, the Ekalaka Member contains fewer and thinner coal beds than other Fort Union members, with the exception of the marine Cannonball Member, which contains no coal beds. The Ekalaka Member contains several siliciclastic units that have a high volcanic ash concentration. Ash-rich siliciclastic sandstone units are as thick as 5 meters in facies association C, and as thick as 10 meters in facies association A. The ash in facies association A is typically altered to microspherules of analcime. Although Hare (1959) originally discovered analcime in strata now assigned to the Ekalaka Member, Jason Hicks (unpubl. 1995) recognized the significance of ash-rich Ekalaka Member sandstones as marker beds for correlation and as ideal rock for magnetic reversal stratigraphy. Ash-rich sandstones (figure 15) have a distinctive very pale green color, and those occurring in the lower part of the member can be correlated from the north rimrock at the town of Ekalaka to the Snow Creek area, 30 kilometers to the southeast (figure 9).

Six different trace fossils are found in the Ekalaka Member (Belt and others, 1997a): *Ophiomorpha, Skolithos linearis, Diplocraterion, Thalassinoides, Planolites,* and *"Skolithos."* All but *"Skolithos"* are of marine to brackish-water origin. Beds bearing these inchnotaxa alternate with beds of obvious fluvial origin indicating an autogenic interaction of fresh and marine conditions in a brackish-water setting (Belt and others, 1997a). We see no evidence of allogenically driven marine incursions into a depositional succession of alluvial deposits.

Some units contain only *"Skolithos,"* which if found alone might suggest the lack of any marine connection. However, because of the typical association of *"Skolithos"* with *Skolithos linearis* in the study area, the latter being a definite marine/brackish indicator (H.A. Curran, Smith College, personal communication, 1999), the units containing only *"Skolithos"* are interpreted to indicate low-salinity brackish-water with a connection to the sea. *"Skolithos"* and *Skolithos linearis* have been found together in the same bed in upper Ludlow Member channelbelt deposits in the Cave Hills area and in the eastern part of the Ekalaka area (Belt and others, 1997a). The river flow was sufficiently weak that it allowed a marine salt wedge to form in the channel.

The upper Ludlow and upper Ekalaka strata (the latter being chiefly the Medicine Rocks sandstone) showed minimal marine influence, chiefly in the channel deposits that either lay the farthest up into the estuary or as permanent salt wedges within rivers that fed into an estuary. Of the six ichnotaxa found in the lower Ekalaka Member, only four (*Ophiomorpha, Diplocraterion, Thalassinoides,* and *Planolites*) so far have not been found in the upper Ludlow Member in the Ekalaka area, in the Cave Hills area, or in the Medicine Rocks sandstone. In contrast to the upper Ludlow, no trace fossil burrows have yet been found in the lower Ludlow, either in the Ekalaka area or in outcrops 30 kilometers southwest in the direction of the Powder River (Belt and others, 1997a, 1997b). Thus the lower Ekalaka Member in the study area differs from the upper Ludlow Member not only on the basis of lithology but also on the basis of a higher diversity of ichnotaxa.

The only brackish and marine body fossils found so far in the Tongue River Member beds have been identified North of the study area. These are the brackish-water mollusc, *Corbula,* and the marine diatom, *Coscinodiscus.* As many as six beds in the lower 85 meters of Tongue River strata contain the following nine ichnotaxa, *Teichichnus, Skolithos linearis, "Skolithos," Diplocraterion, Planolites, Monocraterion, Ophiomorpha, Arenicolites,* and *Thalassinoides,* in eastern Montana and western North Dakota (Tibert and others, 2000). In the Ekalaka area, only *Skolithos linearis* has been found in the lower Tongue River Member in the Snow Creek area (figure 8). Thus trace fossils can be used in the Ekalaka area for distinguishing Ekalaka strata from Tongue River strata because the Tongue River Member contains only one marine trace fossil and the Ekalaka Member contains six.

In summary, the Ekalaka Member can be recognized throughout most of its geographic region on the basis of (a) its distinctive sand-dominated lithology (including megabreccia blocks), (b) absence of regionally correlatable coal beds, (c) key marker beds (volcanic ash beds and ash-rich siliciclastic beds, silcrete horizons at the top), (d) bounding unconformities (U_2 and U_3), and (e) diversity of ichnotaxa in the lower Ekalaka Member relative to the upper Ludlow and lower Tongue River in the Ekalaka area.

The use of characteristic lithologies, fossils, and unconformities associated with the Ekalaka Member conform to the criteria from the American Commission on Stratigraphic Nomenclature (Code of Stratigraphic Nomenclature, 1983) for establishing a new stratigraphic unit. Because the bounding unconformities for the Ekalaka Member were previously unrecognized, they are described below in detail.

Contacts: The Physical Evidence for Bounding Unconformities

Previous workers have not reported unconformities within Paleocene strata in either the Williston Basin or the Montana portion of the Powder River Basin (Bergantino, 1980; Belt and others, 1984; Luft,

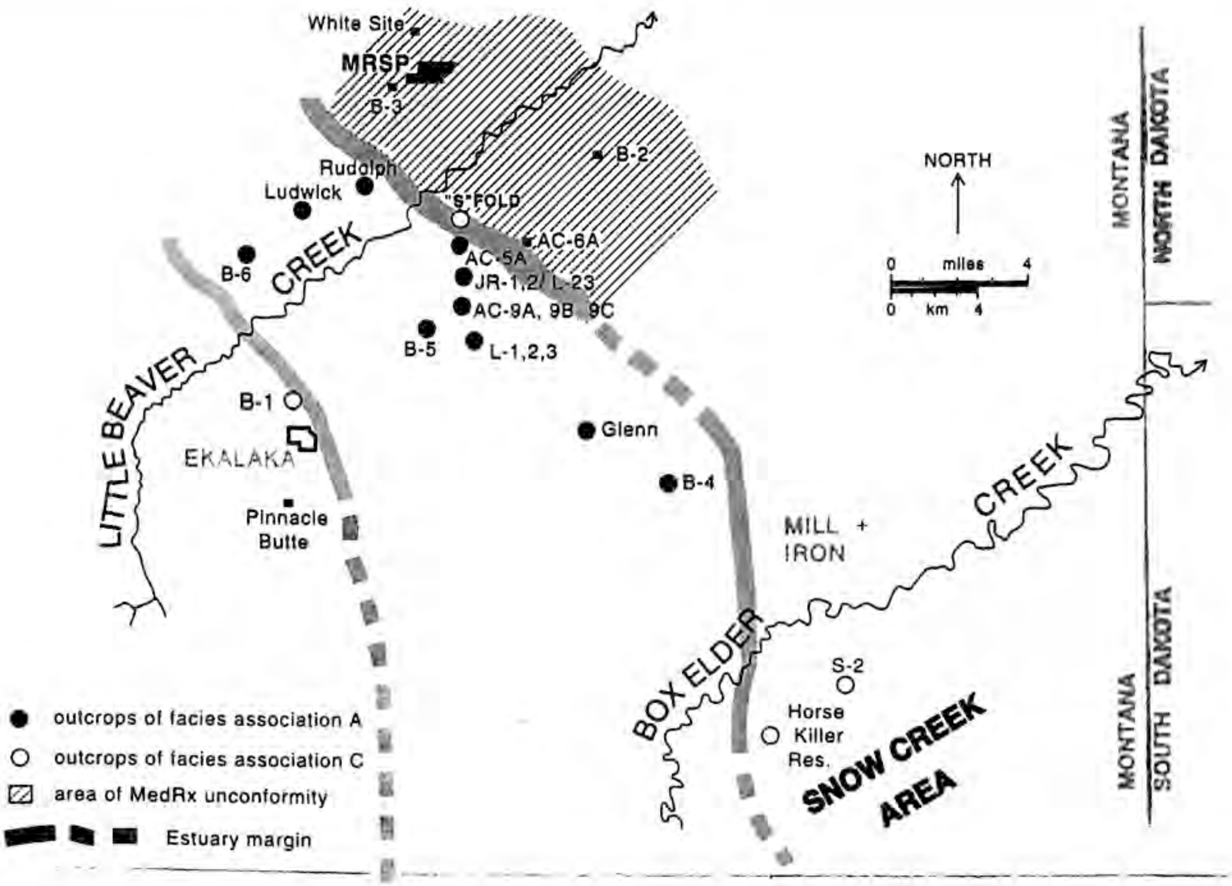


Figure 19. Outline of estuarine deposits of the Ekalaka Member facies association A. The region indicated by diagonal lines is overlain by an undeformed, erosively based facies association B sandstone body. This sandstone body truncates deformed facies association A deposits (e.g., S-fold locality, figure 4) and Ludlow Member deposits. The erosion surface defines a local unconformity, the Medicine Rocks (MedRx) unconformity.

1986a, b; Luft and Meier, 1986; Flores and Bader, 1999; Flores and Keighin, 1999) because of the paucity of detailed biostratigraphic evidence in the Williston Basin.

The physical evidence for the unconformities bounding the Ekalaka Member is explained in this section of the report. In the next section, biostratigraphic and chronostratigraphic evidence are used to verify the existence of a time gap or hiatus in the record, as was done by Belt and others (1997b) for a pre-Hell Creek unconformity, the U_1.

Several types of physical field evidence suggest a cessation of sedimentation in the stratigraphic record at the base and at the top of the Ekalaka Member. One or more of the following indicators suggest the presence of an unconformity: (1) mature paleosols *in situ* within the older strata immediately below the contact; (2) a marked change in lithofacies at the contact; (3) a mappable discordance with the overlying unit resting on successively different stratigraphic horizons; (4) biostratigraphic or chronostratigraphic information indicating a large gap in geologic time.

The Lower Contact

All or part of the Ludlow Member as well as the upper Hell Creek Formation is missing below the Ekalaka Member near the Miles City Arch. This unconformity disappears eastward and southeastward from the study area, and it is likely to be absent in South Dakota (figure 21).

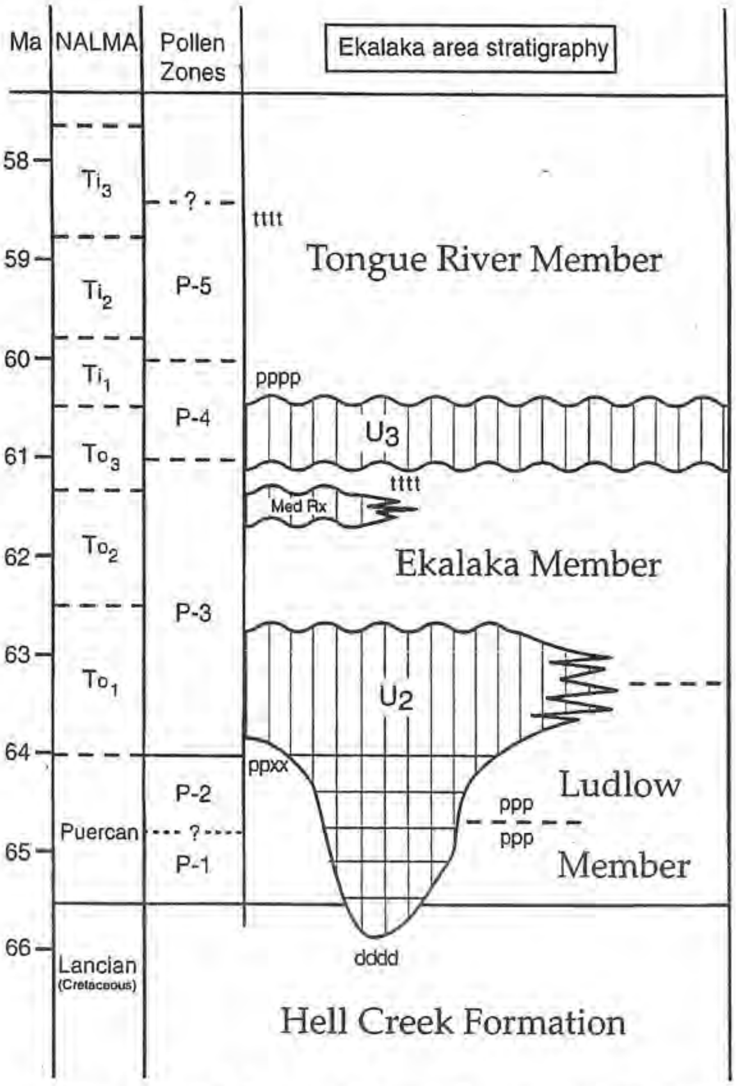


Figure 20. Time stratigraphic column showing Hell Creek, Ludlow, Ekalaka, and Tongue River strata in the study area and their correlation to the Pollen Zones of Nichols (1999b), Mammal Ages (NALMA), and radiometric dates. To represents Torrejonian; Ti represents Tiffanian. Vertical ruled regions are non-depositional hiatuses in the stratigraphic record for the unconformities U_2 and U_3; the cross-ruled region represents the pre-Ekalaka strata missing due to erosion along the Miles City Arch. tttt represents the stratigraphic position of mammal teeth; pppp represents the position of pollen; dddd represents dinosaur bones; ppxx represents pollen date from coal and radiometric date on volcanic ash from the same coal bed. The ash date is 64.03 ± 0.19 Ma. U_2, MedRx, and U_3 are unconformities (see text for explanation). Correlation of NALMA with radiometric ages modified from Hartman and Kihn (1996).

A regional angular relationship is recognized between the Ekalaka Member and the underlying strata in the study area (figure 3). To date, no incised paleovalley fill deposits (channeled estuarine deposits *sensu* Devine, 1991) or mature paleosols have been recognized at or directly below the U_2 contact, but a marked facies change does occur.

Where the contact separates flat-lying Ludlow from overlying chaotic Ekalaka megabreccia blocks, it is a detachment plane. The megabreccia is always facies-association-A lithology, so undeformed, flat-lying strata of that lithology may also overly a detachment plane. In individual exposures, the lower contact may be difficult to identify as an unconformity (U_2).

Where facies association C occurs at the base of the Ekalaka Member, it is a completely autochthonous succession (e.g., figure 7), or a partially autochthonous succession with megabreccia higher in the section (figure 11). Where autochthonous facies association C occurs above smectite-rich *somber*-colored mudrock, the lithologic differences between Ludlow and Ekalaka strata are obvious, but a hiatus can only be verified by combining the regional structural relationships with biostratigraphic dating. This will be discussed below.

At the following measured sections: B-3, AC-5A, B-2, B-1, B-5, and S-2 (figure 9), there is a significant lithologic change at the Ludlow-Ekalaka contact but no megabreccia. The Ludlow consists of smectite-rich dark- to medium-gray mudstone and coal beds. The basal units of the Ekalaka Member above the contact with the Ludlow are typically facies association C, although facies association A or B may occur. Where the basal facies association C is present, it typically consists of thin, burrowed sandstone with interbeds of light-gray shale and thin coal beds (see figures 6, 7).

Despite the above-mentioned local difficulties, the regional structural relation strongly suggest an unconformity at the Ludlow-Ekalaka contact. In the southern part of the study area, at Horse Killer Reservoir (figure 4) and from there southeast 6.4 kilometers (4 miles) to the Speelmon Creek area, as well as south 16 kilometers (10 miles) to the Belltower area, the lower contact of the Ekalaka Member lies unconformably on the middle part of the Hell Creek Formation. The Hell Creek Formation was identified not only by its distinctive lithology (see Belt and others, 1997b) but also by the presence of dinosaur bones (Marshall Lambert, pers. communication, 1993) and by Late Cretaceous pollen (Doug Nichols, pers. communication, 1996). The Ekalaka Member was identified by its lithology and the presence of burrows *Skolithos linearis* and *Diplocraterion*. Unfortunately, pollen samples from the Ekalaka strata in this area were barren. The basal Ekalaka consists of flat-lying facies association C beds. There is no megabreccia or even any undeformed facies association A in this area or anywhere south or southeast of the rimrock hills around the town of Ekalaka. For these reasons, we consider Ekalaka strata autochtonous throughout this southern area, which includes outcrops from Humboldt Hills to the Belltower Buttes area.

The regional discordance between Ekalaka Member and underlying units indicates that Ludlow strata were broadly warped and variously eroded prior to the deposition of Ekalaka strata. In this southern part of the study area, pre-Ekalaka erosion removed (a) all Ludlow strata (which had a maximum estimated thickness of 137 meters based on the closest complete exposures), and (b) all of the upper part of the Hell Creek Formation (estimated thickness of 55 meters; Belt and others, 1997b). Northwest of the Horse Killer Reservoir, the thickness of Ludlow strata increases to about 130 meters measured in a well that was drilled near Rattlesnake Butte (see figure 4).

The Upper Contact

The upper contact of the Ekalaka Member is also identified as an unconformity (U_3). This unconformity has a much wider geographic distribution than U_2, extending from the Little Missouri River (figure 2) to the Miles City area (figure 2; Diemer and others, 1996; unpublished work in progress), and is found in the Ekalaka and Cave Hills area (this report). Erosive downcutting has been seen at the base of the Tongue River Member all along the section shown in figure 2. Paleovalleys incised 15 to 23 meters into the silcrete at the top of the Lebo Member were found at Miles City, the Pine Hills (Locate), and in the Terry badlands in Montana as well as 10 meters into the top of the Ludlow Member along the Little Missouri River in North Dakota. Identifying the U_3 unconformity north of Ekalaka relies on the correlation of mature paleosols and on new biostratigraphic age data, all of which are still being analyzed.

The upper contact of the Ekalaka Member is exposed in widely scattered areas in the study area (figure 3). This contact is characterized by widespread mature paleosols (locally silcretes) developed within the uppermost strata of the Ekalaka Member directly below the Tongue River Member. Silcretes of this maturity take hundreds of thousands of years to form (Greg Retallack, personal communication, 1997).

The interval containing mature paleosols, including silcretes with fossil roots and rootlets, occurs at the top of the Ekalaka Member. It is not exposed in the type section, but it crops out in section B-2

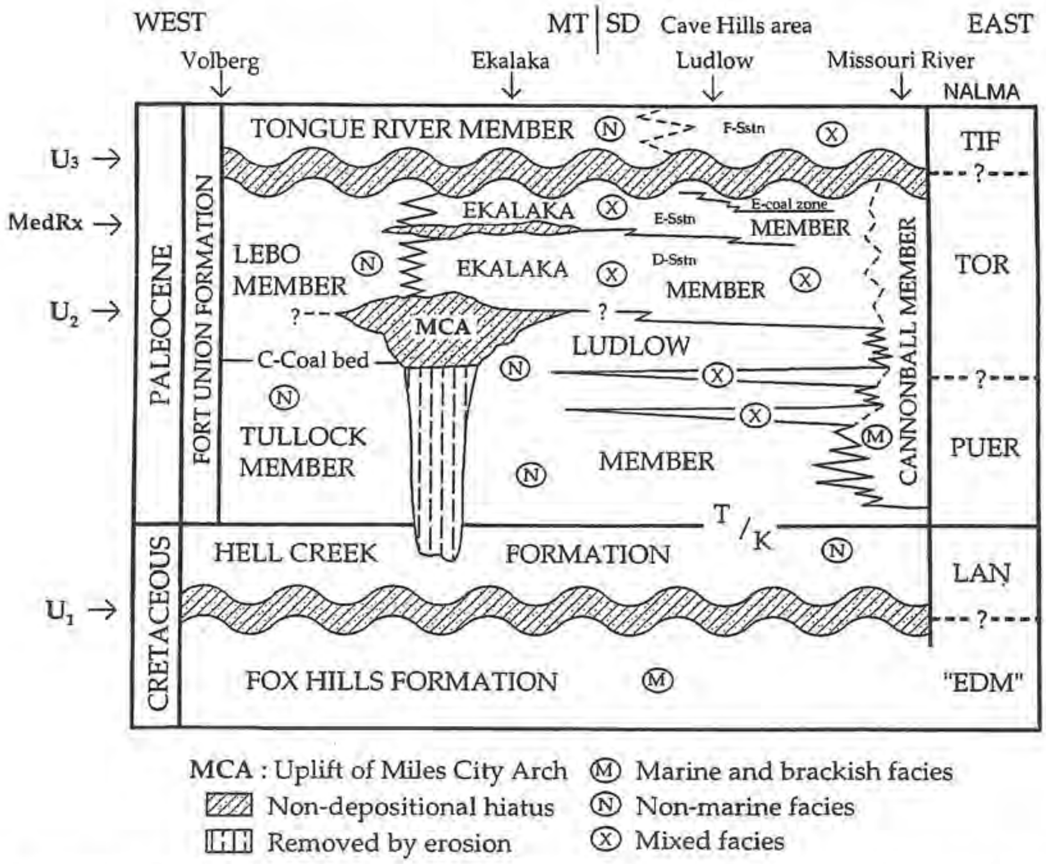


Figure 21. Correlation of Late Cretaceous and Paleocene strata from near Volberg, Montana to the Cave Hills, South Dakota. The positions of the U_1, U_2, MedRx, and U_3 unconformities and regionally extensive C-coal bed are shown. Because the Ekalaka Member rests on Hell Creek Formation in the southern part of the Humboldt Hills, an estimated erosional hiatus is distinguished from a non-depositional hiatus in the area of the Miles City Arch. Marine tongues in the lower Ludlow Member are indicated where specific ichnogenera are found in sheet sandstones in the South Cave Hills and near Mill Iron, Montana (Belt and others, 1997a). T/K represents the Tertiary–Cretaceous boundary. "EDM" is the "Edmontonian" land mammal age.

(figures 4, 9) and in sections L-1, 2, 3 on figures 4 and 19. Silcretes believed to be at the same stratigraphic position also are found in the Snow Creek area at section S-2 (figures 4, 9). Throughout the study area, silcrete beds vary from 30 centimeters to 1.5 meters thick, and may occur as a single bed or as several beds within a thicker unit of bleached strata.

The upper Ekalaka silcrete probably correlates with the Rhame Bed (Wehrfritz, 1978; Christensen, 1984) in eastern Montana as far west as Miles City ; it occurs at the top of the Ludlow Member in southwestern North Dakota (figure 2). The Rhame was referred to as "white marker bed" by Belt and others (1984). The Rhame bed is a horizon up to 5 meters thick composed of gray silcrete, and bleached sand, silt, and clay that is rarely lithified. The silcrete is usually less than 1 meter thick, but at Rhame, North Dakota, it is 3 meters thick. Pollen samples from zones P-2, P-3, and P-4 need to be collected and analyzed from many outcrops in southeastern Montana to verify this correlation.

A photograph of the Rhame Bed in North Dakota is shown by Flores and others (1999) in their figure WF-5. At that locality, a 30 centimeters thick silcrete bed occurs within 5 meters of bleached siliciclastic strata (Belt and Diemer, unpublished 1996 notes, section B-100). The white strata in their photograph occurs along the Little Missouri River in the upper Ludlow Member below the Harmon and Hansen coal beds of the lower Tongue River Member.

Biostratigraphic and Chronostratigraphic Evidence for Unconformities and for Uplifts of the Black Hills

Background

Fossil pollen, mammal teeth, and dinosaur bones have been collected from Paleocene and Late Cretaceous strata in the Ekalaka area. These support the physical evidence that a time gap occurred at the U_2 and U_3 levels because the strata above and below them have been assigned to specific pollen zones and North American Land Mammal Ages (NALMA). The only chronostratigraphic evidence from the study area consists of one radiometric date. All biostratigraphic and chronostratigraphic information collected has been keyed to specific horizons in measured sections.

Figure 20 shows a composite time-stratigraphic section for the study area. Note the time gaps for the unconformities that bound the Ekalaka Member as well as the MedRx unconformity, which lies within that member. Note also the stratigraphic position within each rock unit where fossil pollen, mammal teeth, and dinosaur bones were obtained. Only a few of the 45 pollen samples are shown in figures 6, 7, and 8. Douglas J. Nichols (U.S. Geological Survey, Denver, unpublished written reports to the Montana Bureau of Mines, 1989-1997) and Donald W. Englehardt (Earth Sciences and Resources Institute, Columbia, SC, 1998-1999) analyzed pollen samples from the Ekalaka area and assigned them to specific pollen zones. The mammal teeth were dated by Hare (1959), Krause (1987), and Strait and Krause (1988). The dinosaur bones were collected and identified by Marshall Lambert of the Carter County Museum, Ekalaka, Montana.

The absolute dates shown in figure 20 for the boundaries of North American Land Mammal Ages (NALMA) are based on a chart published by Hartman and Kihm (1996). The absolute dates for the boundaries of the pollen zones are based on data published by Nichols (1998), but with one correction. That correction is based on a $^{40}Ar/^{39}Ar$ date from a volcanic ash bed (J. F. Hicks, collector, oral communication, 1995; J. D. Obradovich, analyst, written communication, 1995) contained in a coal bed in the Ludlow Member, 4.5 meters below the base of the Ekalaka Member (Cole, 1993, Section 5A, p. 106; cf. Vuke and Belt, 1995).

Nichols (1998) reports an absolute age of 64.4 Ma for the boundary between pollen zones P-2 and P-3. However, our Ludlow ash sample (section AC-5A) came from a coal that was dated as P-2 pollen zone by Nichols (pers. communication, 1996). It yielded a radiometric date of 64.03 ± 0.19 Ma (figure 20). Thus, the boundary between the P-2 and P-3 zones is closer to 64.0 Ma than to the 64.4 Ma reported by Nichols (1988).

An additional adjustment needs to be made to the age of the base of the P-1 zone. The base of the Paleocene (which is the base of the P-1 pollen zone) has recently been corrected to 66.5 ± 0.1 Ma (Obradovich and Hicks, 1999).

The most reliable absolute ages in the entire sequence in the study area are the K/T boundary and the boundary between pollen zone P-2 and P-3. The least reliable is the 60 Ma age for the boundary between P-4 and P-5. We accept Nichols' (1998) estimate of 61 Ma for the boundary between pollen zones P-3 and P-4.

Age Constraints on the Unconformities

The Ekalaka strata overlying the U_2 unconformity have been dated as old as pollen zone P-3 (unpublished data, D. J. Nichols, U.S.G.S., written communication, 1989-997). Strata below the U_2 vary in age from Early Paleocene pollen zone P-2 (Ludlow Member, but likely not the youngest strata from that member) to Late Cretaceous (<u>middle</u> Hell Creek Formation).

The youngest fossils from the strata directly underlying the U_2 unconformity are of two different ages: (1) Late Cretaceous pollen and dinosaur bones were found in the Hell Creek Formation directly below the Ekalaka Member at Horse Killer Reservoir (figure 4), at Speelmon Creek 6.4 kilometers (4 miles) southeast of the reservoir, and near Belltower 16 kilometers (10 miles) south of the reservoir, and (2) P-2 pollen dates have been obtained from the youngest Ludlow strata that lie below the Ekalaka Member north and east of the town of Ekalaka. Recall that the Ludlow was broadly warped prior to the deposition Ekalaka strata. Hence Ludlow strata have different ages in different places. On the other hand, analysis of basal Ludlow pollen (Nichols, op. cit.) indicates a P-1 pollen age, and two pollen samples from a 10-meter high butte 11.75 miles northwest of the crossroads at Mill Iron (figure 4; T. 1 N., R. 60 E., NE 1/4, SW 1/4, section 10), pinpoint the position of the P-1/P-2 boundary.

Thus in the Ekalaka area, the Ludlow strata exposed seem to be confined to the Puercan mammal age zone (i.e., pollen zones P-1 and P-2), whereas the Ludlow in the Little Missouri River area of North Dakota includes not only the Puercan but also the Torrejonian mammal age zones (i.e., pollen zones P-1 through P-3, Nichols, 1999b). The Ludlow in the Ekalaka area seems to be equivalent in age to all of the Tullock Member in the Miles City to Locate, Montana study area (Belt and others, 1992).

The oldest strata above the U_2 unconformity from the base of the Ekalaka Member at section B-5 (figure 6) and B-1 (figure 7) lie within the P-3 zone.

The MedRx unconformity is constrained above by mammal teeth (Hare, 1959; Krause, 1987) found at the base of the Medicine Rocks sandstone in Medicine Rocks State Park (figure 5). These mammal teeth have been dated as Torrejonian 3 (To_3), the accepted NALMA designation for the age of that horizon (Archibald and others, 1987). The Ekalaka strata below the MedRx unconformity in the type section yielded no fossils.

The oldest strata above the U_3 unconformity are in the Tongue River Member at the White Site (figure 4; section B-3B, figure 5). Pollen samples from two closely spaced thin coals (shown as a single coal on figure 5) were dated as pollen zones "P-3 &/or 4" by Nichols (poster session accompanying the abstract of Warwick and others, 1998, but not recorded in that abstract). An age of P-3 is unlikely because of the Tiffanian 3 (Ti_3) age that was implied by Strait and Krause (1988) for the mammal teeth that were collected 25 meters above the two coals. We suggest, therefore, that the age of these coals is more likely pollen zone P-4 than any older zone.

Strait and Krause (1988) verified that the mammal teeth found at the top of the White Site butte 25 m above the two coals are "not Tiffanian 2 (Ti_2) but younger than Tiffanian 2." These teeth were previously thought to be Ti_2 (Archibald and others, 1987). The revised age was the result of research by Strait that was unfortunately not completed (Krause, pers. communication, 1998). Hence, we assume that the correct NALMA designation ought to be: "Ti_3 (or younger)" for the mammal bones found at the top of the White Site butte (the top of section B-3B).

Note in figure 20 that pollen zone P-3 (Torrejonian) spans an interval 3 Ma long and that a combined P-1 and P-2 (Puercan) spans and interval 1.5 Ma long. The least reliable dates shown in figure 20 result from the lack of a more precise absolute age for the boundary between P-4 and P-5. The evidence to date suggests that this boundary is younger than 60 Ma, and may even lie within the Ti_2 mammal age zone. On figure 20, we have assigned 1 Ma for the deposition of the lower part of the Ekalaka Member. Most likely it was considerably less.

Note also in figure 20 that we distinguish the erosional hiatus from the non-depositional hiatus. The erosion of strata accompanying the uplift (erosional hiatus) has increased the apparent time gap. However, the time represented by nondeposition ought to be confined to the early Torrejonian.

Initial Uplift of the Bighorn Mountains and the Black Hills

Neither the Bighorn Mountains nor the Black Hills are thought to have been positive topographic features during the Late Cretaceous (Lillegraven and Ostresh, 1988, figure 4). The paleogeographic maps of Lillegraven and Ostresh (1988, figure 4; 1990, figure 4) show Campanian through Maastrichtian shorelines in a sequence of Western Interior Basin maps, with no evidence of uplifts in the regions where either the Bighorn or the Black Hills Mountains are today.

The best and most recent evidence for the time of initial Bighorn uplifting is based on (U-Th)/He ages, and it suggests uplift at about the K/T boundary (Crowley and others, 1999). This conclusion is consistent with data (Connor, 1992; Belt and others, 1997b, figure 15) from paleodrainage directions. During Lancian time, Late Cretaceous rivers, in the region of the present Bighorn Basin, flowed eastward toward the area that was to become the Bighorn Mountains. Obviously, no mountains could have existed in the Bighorn area at that time. In addition to paleodrainage directions, strata in the western Powder River Basin thicken during the Puercan and the Torrejonian but not earlier (Lewis and Hotchkiss, 1981). Thus all the currently available data seem to agree.

The timing of the initial Black Hills uplift has likewise been debated. Flores and Ethridge (1985) suggested an early Paleocene (Early Puercan) age for the uplift of the Black Hills on the basis of bimodal north-south paleocurrent directions in the Tullock Member of the Powder River Basin. More recently, however, Perry and Flores (1997) argued that the initial uplift of the Black Hills occurred during late Paleocene time, which was more consistent with their model of northeast-moving sequential Laramide deformation. Lisenbee and DeWitt (1993) believe the appearance of the smectite-rich Lebo Member heralded the Black Hills uplift. Lebo sediment, they argue, resulted from the initial stripping of the ash-rich, Late Cretaceous Pierre Shale. They and Lillegraven (1993) considered that the initial Black Hills uplift occurred somewhere between 63 to 65 Ma with an average age of about 64 Ma or middle Paleocene age (Torrejonian).

If one uses the appearance of Lebo facies for determining the initial uplift of the Black Hills, then a problem arises because the Lebo Member in southeastern Montana is apparently older than strata identified as Lebo in the Powder River Basin of Wyoming. Flores and Nichols (1999, figure IN-4) date the basal Lebo Member in the central and southwestern part of the Powder River Basin as Pollen Zone P-3 (lower Torrejonian mammal age). Near Terry, Montana, however, upper Lebo Member has been dated (unpubl. palynology by Don W. Englehardt, 1998) as Pollen Zone P-2 (late Puercan). At Signal Butte, Miles City, Montana, Engelhardt (unpublished data) has dated upper Lebo as Pollen Zone P-3 (Torrejonian), but at present we are unsure whether it is early, middle or late Torrejonian. Work in progress (Tim Kroeger, Bemidji State University, Bemidji, MN) attempts to determine where the P-2 / P-3 boundary lies at Signal Butte.

Belt and others (1992, figure 21; 1997b, figure 15) use regional changes in the directions of trunk paleodrainages for timing of the initial Black Hills uplift. Paleodrainage directions rather than the appearance of smectite-rich strata should be a more reliable indicator of a Black Hills uplift event because smectite-rich strata are typical throughout all Hell Creek, Tullock, Lebo, and Ludlow strata in the Williston and Powder River Basins. The appearance of the Lebo Member does not herald the uplift of the Black Hills; smectite had been derived from western Wyoming and western Montana since Late Cretaceous time.

We argue that during Lancian and Puercan time, the southeastward flow of paleodrainages in eastern Montana could not have persisted if the Black Hills had been a feature with any significant topographic relief. Note the change in direction of trunk paleodrainages, from a direction toward the southeast during Late Cretaceous through Puercan time, to a direction toward the northeast during early Torrejonian time (Belt and others, 1992, compare figures 24 & 25). This change was initiated by the uplift of the Black Hills, and it is recorded at the base of the Lebo Member at the time of C-coal deposition. It is also recorded at the base of Ludlow Member (facies B, *in* Belt and others, 1984) at the time of Oyster coal deposition. This paleodrainage direction change is found throughout eastern Montana and western North Dakota (Belt, 1993). Flores and Ethridge (1985) indicated an Early Paleocene uplift of the Black Hills based on paleocurrent data from the Tullock Member in the Powder River Basin. Our conclusion is consistent with theirs considering that the late Tullock Member in the southwestern Powder River Basin is equivalent to the lower Lebo Member of southeastern Montana, as mentioned above.

Correlation of Facies within the Ekalaka Member

We have established that the bounding contacts of the Ekalaka Member are unconformities that can be correlated widely if not regionally. Furthermore, pollen and mammal teeth have dated significant parts of the Ekalaka, Ludlow, and Tongue River members in the study area. In this section we examine the facies patterns within the Ekalaka Member as a means of distinguishing it from the Ludlow or Tongue River Members, and as a basis for interpreting the depositional environments.

The correlation of facies associations A, B, and C is shown in figure 9. Cross-section A–A′ extends from the type section that lies just west of the Medicine Rocks State Park (figures 4, 9) through four other sections that extend 16 kilometers southeast and east of the park. Cross-section B–B′ extends from the town of Ekalaka to the Snow Creek area (figure 4).

Silcrete beds and ash-rich siliclastic beds are the most important of the many types of marker horizons that help correlate the three facies associations within the Ekalaka Member; they are useful in correlating the small thin outcrop patches of lower Tongue River Member as well. The unconformities themselves are an additional means for correlating the facies within the Ekalaka Member as well as the members above and below it.

Well-defined intervals of volcanic ash in siliciclastics were identified by Jason Hicks (personal communication, 1995) who recognized unabraded, inclusion-free euhedral feldspars. In outcrop, the high percentage of ash gives the strata a distinctive color that allows easy recognition. High-ash siliciclastic intervals used for correlation occur in sections B-1 and S-2 near the base of the Ekalaka Member (B–B′, figure 9). One also occurs near and at the top of the exposed Tongue River Member in sections B-3 and B-2 (A–A′, figure 9).

Silcrete beds that occur at the top of the Ekalaka Member crop out in three localities in the study area. All three of them are shown in figure 9 as (#) symbols. Note that one of the silcretes (the box at the top of figure 6; figure 9, A–A′) was correlated a short distance into section B-5. Another silcrete lies in section S-2 (B–B′; note between 65 and 70 m in figure 8). The third occurrence is in section B-2 (figure 9, A–A′; locality B-2, figure 4); note the # symbols just below the U_3 unconformity. These lie at the top of the Medicine Rocks sandstone.

Cross-section B–B′ (figure 9) shows the correlation of Ekalaka Member facies from the town of Ekalaka into the Snow Creek area (figure 4). The U_3 bounding unconformity has been removed by Holocene erosion except in section S-2 and in the surrounding area (figure 3). Here the U_3 is recognized by abundant *Skolithos linearis* in sandstones directly above multiple silcrete horizons (see top of section S-2, figure 8). The silcretes are in the upper Ekalaka Member, and the beds with burrows above the silcretes are in the lower Tongue River Member.

The U_2 and the MedRx unconformities are more apparent in the B–B′ cross-section than in A–A′, although they are obvious at the S-fold section in cross-section A–A′. The MedRx unconformity is identified in section B-4, but it is not found in section S-2 (figure 9). A MedRx angular unconformity occurs between the megabreccia blocks and the overlying facies association B in section B-5 (figure 6). Rip-up sandstone clasts derived from the megabreccia blocks occur at the base of the facies association B in this section. The U_2, on the other hand is found in each of the sections in A–A′; where there is a thick unit of volcanic ash and siliciclastic sediment a few meters above the base of the Ekalaka Member (sections B-1 and S-2).

Summary of Ekalaka Facies Changes

In the northern part of the study area (figure 9, cross-section A–A′), facies association A is a thin (< 5 m), unbrecciated unit. In this northern region, either this facies did not slide or slid only a small distance on the smectite-rich Ludlow mudstones. Regardless of whether it slid or not, it was not otherwise disturbed, with the exception of section AC-5A in which facies association A is brecciated. South of section AC-5A, and in cross-section B-B' (figure 9), facies association A forms jumbled megabreccia blocks with vertically measured intervals reaching 20 meters in most places, but 40 meters in one place (sections JR-1,2 and sections L-l through L-23, the logs of which are in Cole, 1993). Cross-section B-B' (figure 9) shows intervals of megabreccia blocks of facies association A that are not at the same stratigraphic position in the various measured sections. They are, therefore, not correlated and were likely deposited at different times. Interbedded units of megabreccia and undisturbed crossbedded sandstone indicate that there were several slumping events between which current-bedded sand was deposited.

Facies association B in both cross sections B-B' and A-A' lies above the MedRx unconformity and in each area can be correlated with the Medicine Rocks sandstone (Hare, 1959; type section at Medicine Rocks State Park, figure 4). It was not found in Snow Creek area section S-2, but may occur in the surrounding Humbolt Hills.

Facies association C is most typical in cross-section B-B' (figure 9) south of cross-section A-A'; it is found only at the S-fold locality (figure 4) in cross-section A-A'. Facies association C is best exposed in sections B-1 (figure 7) and S-2 (figure 8). In the Snow Creek area, outcrops of the Ekalaka Member are dominated by facies association C, whereas that facies forms less than 50 percent of the Ekalaka Member to the northwest near the town of Ekalaka. The Ekalaka Member seems sandier and thicker southeast of the fault along Box Elder Creek (figure 3). Although the most recent fault movement clearly cuts across Ekalaka strata, it may have been active during the U_2 uplift or during deposition of the Ekalaka Member.

The Ekalaka Member pinches out north and northwest of Medicine Rocks State Park and the type section. Note also at the northwestern corner of the geologic map of the Ekalaka area (figure 3) that the Tongue River Member (Tftr) rests directly on the Ludlow Member (Tfld), with no intervening Ekalaka Member (Tfe). The Ekalaka Member appears abruptly in the region of the Medicine Rocks State Park and 7 kilometers to the southwest of the park.

Correlation with Cave Hills, South Dakota

We have shown that the Ekalaka Member can be mapped from the Ekalaka, Montana area to the South Dakota border (figure 3). In this section of the report we make a case that this member likely extends farther east into the Cave Hills area of northwestern South Dakota. Here it was originally mapped as Tongue River Member (Pipiringos and others, 1965). More recently, all but the upper units (i.e. F-Sandstones) were redesignated to the Cannonball Member (Cvancara and Hoganson, 1993) because of the presence of marine-vertebrate skeletal remains and of marine ichnofossils. We argue below that their Cannonball designation for the D- and E-Sandstone units should more properly be Ekalaka Member.

The type section of the Ludlow Member is located in the southern part of the North Cave Hills where the Ludlow is a medium- to light-gray (*somber*), smectite-rich shale with a few light-gray to yellowish gray sandstone beds. The sandstone beds have either a thin sheet or a lenticular and thick shoestring geometry. The Ludlow contains numerous beds of coal; the basal coal contains the K/T boundary ash and coincidentally also marks the contact between the Hell Creek and Fort Union Formations. Some of the thin sheet sandstone beds contain marine ichnotaxa (Belt and others, 1997a).

In the Ekalaka area, the Ludlow Member more closely resembles its type section in the North Cave Hills of South Dakota (Lloyd and Hares, 1915; Goodrum, 1983; Best, 1987) than it does the Ludlow facies found in the Little Missouri River (Belt and others, 1984). The total thickness of the Ludlow varies considerably regionally. In the Ekalaka area, total Ludlow thickness is 137+ meters (recall it was thinned by the early Paleocene U_2 erosion), and yet it is only 128 meters thick in the type section of the North

Cave Hills where there is no unconformity. In the Little Missouri River area, where it is 180 meters thick, the Ludlow is much sandier than in the type section or in southeastern Montana (Belt and others, 1984), and so compactional differences between mud and sand may account for part of the thickness discrepancy.

In the North Cave Hills, Ludlow lithology contrasts markedly with the overlying massive cliffs of yellowish gray sandstone, the D-Sandstone and E-Sandstone units (figures 22, 23) that may represent Ekalaka Member strata. They are definitely not the same facies as the Cannonball Member of central North Dakota that contains much more shale and little sandstone (Lloyd, 1914; Cvancara, 1976; A. M. Cvancara, personal communication, 1997).

The precipitous cliffs of the Cave Hills area (Flores and Keighin, 1999, see their figure WS-11) of northwestern South Dakota consist of very thick, massive-bedded, medium-grained sandstone units with barrier island and estuarine features. The D- and E-Sandstones (figure 22) contain marine ichnotaxa that include *Skolithos linearis, Ophiomorpha,* and *Diplocraterion* (Goodrum, 1983; Best, 1987; Belt and Diemer, unpublished notes, 1992). Goodrum (1983) was the first to mention specific marine ichnotaxa in these strata and to interpret the D-Sandstone as a beach-shoreface depositional environment.

There is also an interval, 30 meters thick, of chaotic megabreccia blocks that Dane (1978) called "Problem Beds" (figures 22, 23 lower part). These were shown by Dane (1978, plate I) as two deeply incised units. Jack Redden (South Dakota School of Mines & Technology, pers. comm., 1992) considered them to represent slump blocks. Similar slump deposits have been reported by Galloway (1990) from paleovalleys Cenozoic deposits of the Gulf Coastal Plain. We therefore correlate the U_3 unconformity to the top of the E-Coal zone (figure 22).

The E-Sandstones (figure 22), like the Ekalaka beds, contain abundant spherules of analcime, indicative of altered volcanic ash. Finally, the upper 5 meters of the E-Sandstone unit contains typical facies-association-A rhythmic beds that are found in the Ekalaka Member in the Ekalaka area. These rhythmic beds consist of decimeter thick plane-bed and ripple-bedded, fine-grained sand, riddled with *Skolithos linearis* (figure 24).

In addition to similarity in lithology, an argument also can be made that the U_3 unconformity is found in the North Cave Hills area and separates the F-Sandstone units (figure 23) from the underlying D-Sandstone and E-Sandstone and E-Coal Zone beds. However, the U_2 unconformity is probably not present in the Cave Hills area.

The U_2 unconformity seems to be confined to a region adjacent to the Miles City Arch; it likely resulted from the tectonic uplift of the Black Hills because the Miles City Arch is co-axial with the northwestern curve of that basement-cored uplift (Lisenbee, 1985, see tectonic sketch map), and the paleodrainages shifted from southeast to northeast after the U_2 event (Belt and others, 1992). Hence, if the U_2 is present in the Cave Hills area, it would have to be established on the basis of fossil dates, and it would be represented by the change from Ludlow facies into the Ekalaka sandstone facies.

The correlation of the U_3 unconformity into the Cave Hills area seems reasonable. This conclusion is based on the presence of a thick, mature paleosol (silcrete) at the top of the E-coal zone (figures 22, 25) that may correlate with silcrete beds at the top of the Ekalaka Member in the study area, the presence of deep paleovalley deposits (with slumped strata) of the F-Sandstone units that formed subsequent to the silcrete, and the presence of marine ichnotaxa in the D-Sandstone beds that lie above smectite-rich gray mudstones and coals in the type section of the Ludlow Member.,

Despite its thickly bedded, cliff-forming sandstone (figure 23) that is similar to D- and E-Sandstone units, we consider the F-Sandstone unit to be part of the Tongue River Member where the U_3 separates the E-Coal Zone from the F-Sandstone unit. Belt and Diemer (unpublished notes, 1992) found *S. linearis* and *Ophiomorpha* in the F-Sandstone unit, which is consistent with marine ichnotaxa in the lower 60 to 85 meters of the Tongue River Member from Signal Butte at Miles City, Montana, to the big bend in the Little Missouri River of western North Dakota (Diemer and others, 1996).

The Ekalaka Estuary

Dalrymple and others (1992) define an estuary as the seaward part of a drowned valley system. As such it is a narrow, confined depositional system that contains sediment influenced by tide, wave, and fluvial processes. An interdistributary bay between active distributaries on a delta does not qualify as an estuary even though brackish-water fauna can be abundant in that environment. However a depositional system can still be classified as an estuary when there is lateral confining by an uplifted structure on at least one side of it (cf. Tessier and Gyot, 1989; Richards, 1994), even though a drowned river valley system was not proposed in either of these cases. The classification of estuaries by Dalrymple and others, (1992) emphasizes input variables, such as tides, waves, and river flow. In this section, we examine these influences on the various facies of the Ekalaka Member.

It is unlikely that the Ekalaka Estuary resulted from a drowned river system, but rather it was a trough that lay between a tectonically positive area and a delta. The Miles City Arch formed the southwestern margin of a trough that became the Ekalaka Estuary. This estuary lay between the arch and the delta farther northeast. In figure 26, note the position of the Ekalaka Estuary south of the Marmarth Delta (the name first used by Warwick and others, 1997).

Because the Marmarth Delta bounded the Ekalaka Estuary to the northeast, it is important to examine why the Ekalaka Estuary was not immediately filled by crevasse lobes. The answer might lie in strong northeast progradational direction of the Marmarth Delta (Belt and others, 1984). Such a progradational trend may have bypassed the region south of it, much like processes today in the Mississippi Delta. On that delta, Lake Pontchartrain and Lake Maurepas lie north and northwest of the city of New Orleans. The southeast progradational trend of the birdsfoot delta region bypasses these lakes, with lobe-switching and avulsion activity restricted to the birdsfoot region 100 kilometers (65 miles) southeast of the city. The two bodies of water near New Orleans have not filled with fluvial deposits from the modern Mississippi River. The water in those "lakes" is at times fresh and at other times brackish to marine.

The Ekalaka Estuary likely was sinuous, perhaps with an east-west orientation in the western part, but it ultimately opened to the southeast into the Cannonball sea proper (figures 19, 26). The northwest-southeast paleoflow directions within facies association B (Medicine Rocks sandstone) support the interpretation that in its final phase, the inner estuarine tidally influenced fluvial deposits flowed toward the southeast. Most paleocurrent indicators within beds of facies association A are in slumped blocks and hence are not reliable paleoflow indicators.

Dalrymple and others (1992) indicate that the degree to which sediment input into an estuary is derived from the open sea *versus* from the river at the head of the estuary will strongly influence the facies developed within the estuary. These variable sources of sediment can cause small deltas, with associated marshes, to form at the head as well as along the margins of an estuary These estuary-margin deposits are probably Ekalaka facies association C, which contains thin, impure coal beds.

The Ekalaka Member can be divided into two units: (a) the pre-MedRx unit, which is primarily facies association A with some facies association C and B; and (b) the post-MedRx unit, which is largely facies association B, with some facies association C but with no facies association A.

The pre-MedRx unit likely formed in the upper part of an estuary with well-developed tidal activity in the deeper parts and small deltas with marsh deposits along the margin. Water was sufficiently deep in the central part of the estuary (figure 19) to allow shallower-water deposits of cross-laminated sandstone (facies association A) to slump down into that deeper part, perhaps in response to contemporaneous earthquakes. These earthquakes may have occurred at the same time as the earthquakes that slumped the megabreccia blocks into the estuary in the Ekalaka area. The alternation

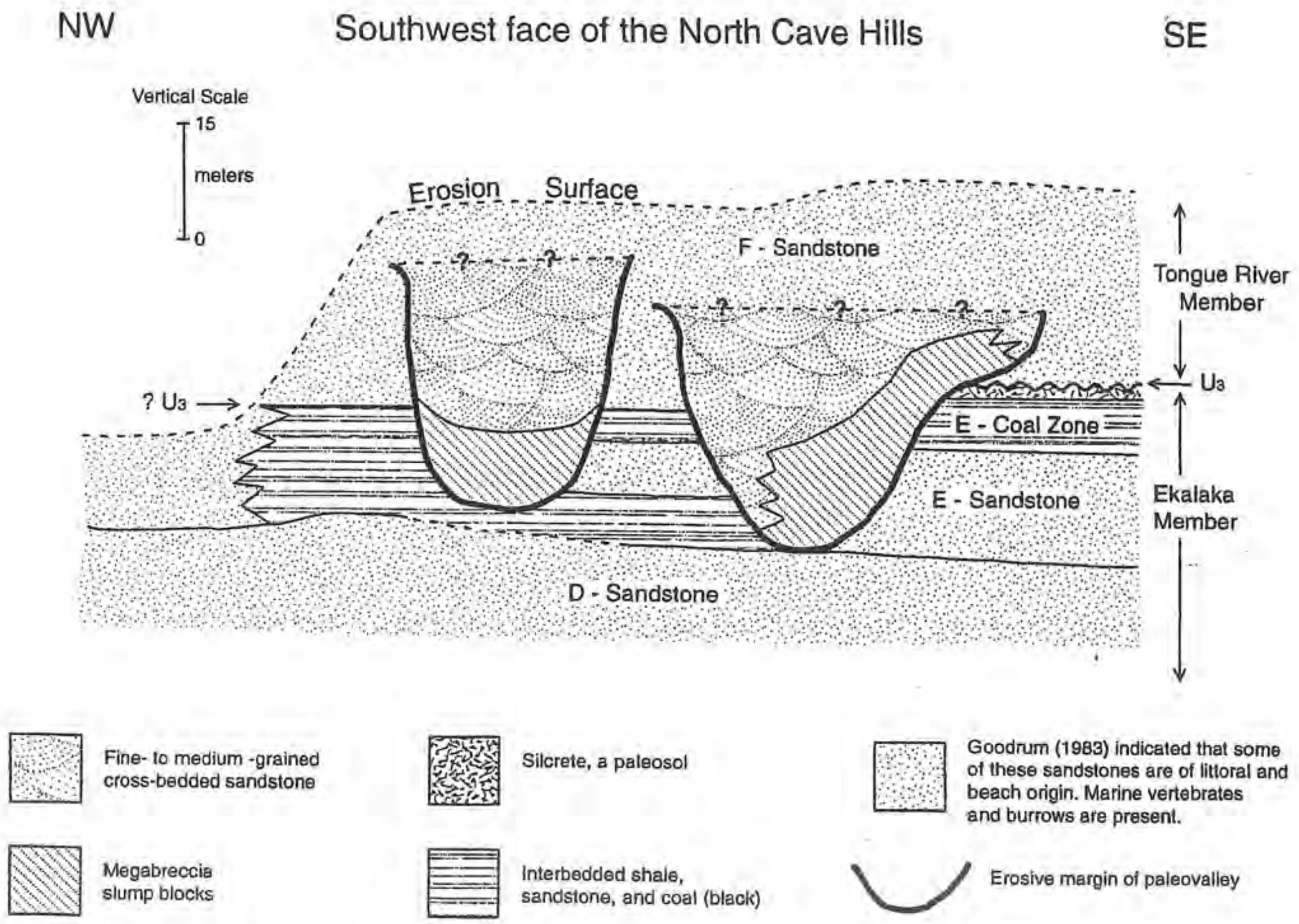


Figure 22. Cross section adapted from Dane (1978) showing the possible position of the U_3 unconformity in the North Cave Hills, South Dakota. The D and E sandstones are correlated with the Ekalaka Member, whereas the F sandstone (and associated coal beds) is considered part of the Tongue River Member. Note the silcrete at the top of the E coal zone below the U_3 unconformity. This silcrete is cut out by the erosion surface at the base of the F-Sandstone. The 30-meters deep cuts are paleovalley fills with syndepositional slump beds ("problem beds" of Dane, 1978).

of marine and nonmarine deposits within facies association C suggests an alluvial plain setting with channels that were subjected to repeated drowning and marine incursion.

Facies association B deposited above the MedRx unconformity, developed in an active fluvial environment with cyclic saline water intrusion from tidal activity. This facies is typified by the Medicine Rocks sandstone and is interpreted as a tidally influenced fluvial facies. Other facies association B lithologies are interpreted as fluvial deposits with less tidal influence.

Goodrum (1983) and Best (1987) are correct in interpreting the Cave Hills D- and E- Bed sandstones as beach and shoreface deposits. We suggest these deposits were formed as barrier islands that originated by spit extension from the Marmarth Delta and from there extended to the south across the mouth of the Ekalaka Estuary. Hence, the barrier island sands caused partial constriction at the mouth of the Ekalaka Estuary, which influenced tidal activity and therefore salinity within the estuary.

The nondeposition and possible erosion at the time of the U_3 unconformity recorded a drop in sea level. This sea level change could have resulted from either (a) a tectonic uplift that involved the entire western Williston Basin accompanied by further uplift of the Black Hills, or (b) a basin-wide base level change that in turn was either a drop in sea level within the Western Interior Basin or a global drop in sea level.

Figure 23. West side of the North Cave Hills, South Dakota. The lower part of the cliff shows tilted megabreccia blocks of F-Sandstone. These are overlain in the upper part of the cliff by flat-lying crossbedded F-Sandstone. The tilted blocks have been interpreted (Jack Redden, personal communication, 1992) as having slumped during the deposition of the early phases of the F-Sandstone. We interpret this slumping to be associated with deep channel cutting during the time of erosion associated with the U_3 *unconformity (see figure 22 for geometric relationships).*

Conclusions

(1) The Ekalaka Member is proposed as a new member of Fort Union Formation. The type section lies within and adjacent to the Medicine Rocks State Park, 18 kilometers (11 miles) northeast of the town of Ekalaka, Carter County, Montana.

(2) Within the study area, the Ekalaka Member is lithologically distinct from the underlying Ludlow Member and from the overlying Tongue River Member. In addition, the new member is lithologically distinct from the Lebo, Tullock, and Cannonball Members, which occur outside of the study area.

The Ekalaka Member is dominated by fine- to medium-grained sandstone with a lesser percentage of mudstone and a very small amount of coal in thin beds. The Tullock, Lebo, and Ludlow Members are dominated by mudstone with a lesser percentage of sandstone. The Lebo and Ludlow Members have many thick coal beds; the Tullock has a few thick coal beds; and the Cannonball has no coal beds. The Tongue River Member is approximately half sandstone and half mudstone and contains many regionally extensive, thick coal deposits.

(3) The Ekalaka Member in the study area contains five different types of trace fossils. *Ophiomorpha, Skolithos linearis, Diplocraterion, Thalassinoides, Planolites* and *"Skolithos."* These support an estuarine interpretation because all but *"Skolithos"* has been described from marine strata and none is reported from nonmarine strata. The occurrence of *"Skolithos"* in the same bed as *S. linearis* and *Ophiomorpha* (Belt and others, 1997a) is evidence that *"Skolithos"* tolerated brackish marine water. There is a higher diversity of trace fossils in the Ekalaka Member in the study area than is found in either the upper Ludlow Member (2 genera) or in the lower Tongue River Member (1 genus).

(4) The Ekalaka Member is bounded by unconformities. The basal U_2 is limited to the vicinity of the Miles City Arch. The upper U_3 can be traced from the Ekalaka area into the Miles City area and eastward to the Little Missouri River area. It also may be present in the Cave Hills area of northwestern South Dakota.

(5) The Ekalaka Member is subdivided into three facies associations:

(a) Facies association A consists of cross-laminated and flat-bedded, fine-grained sandstone that was locally bioturbated by marine organisms that inhabited a brackish-water setting. This facies association is interpreted as shallow sand bar and tidal-flat deposits from the upper part of the Ekalaka Estuary. Part of facies association A was deformed and today appears as megabreccia blocks. These blocks slid into the deepest part of the Ekalaka Estuary, possibly triggered by earthquakes.

(b) Facies association B consists of locally bioturbated, tidal-bundle, cross-stratified sandstones in sandstone bodies up to 22 meters thick. Double mud drapes and reversed paleoflow indicators document an ebb-dominated, inner estuary setting for the deposition of facies association B. The dominant unit of this facies association is the Medicine Rocks sandstone, which is interpreted as an tidally influenced fluvial deposit.

(c) Facies association C consists of interbedded sandstone, mudstone, and thin coal that were locally bioturbated by marine organisms. This facies association is interpreted as having formed along the margin of the Ekalaka Estuary where alluvial plain deposits and swamps dominated.

These facies resulted from varying influences of estuarine and fluvial processes. Facies association A resulted from inner estuary sand flats that show tidal rhythms. Facies association B resulted mainly from fluvial processes, but there was also some tidal influence. Facies association C was primarily deposited on an alluvial plain adjacent to an estuary and shows mixed terrestrial and estuarine influences.

(6) Ekalaka facies in the study area are probably the same age as D-Sandstone and E-Sandstone units in the Cave Hills area. Evidence for this correlation is based on the following characteristics found in

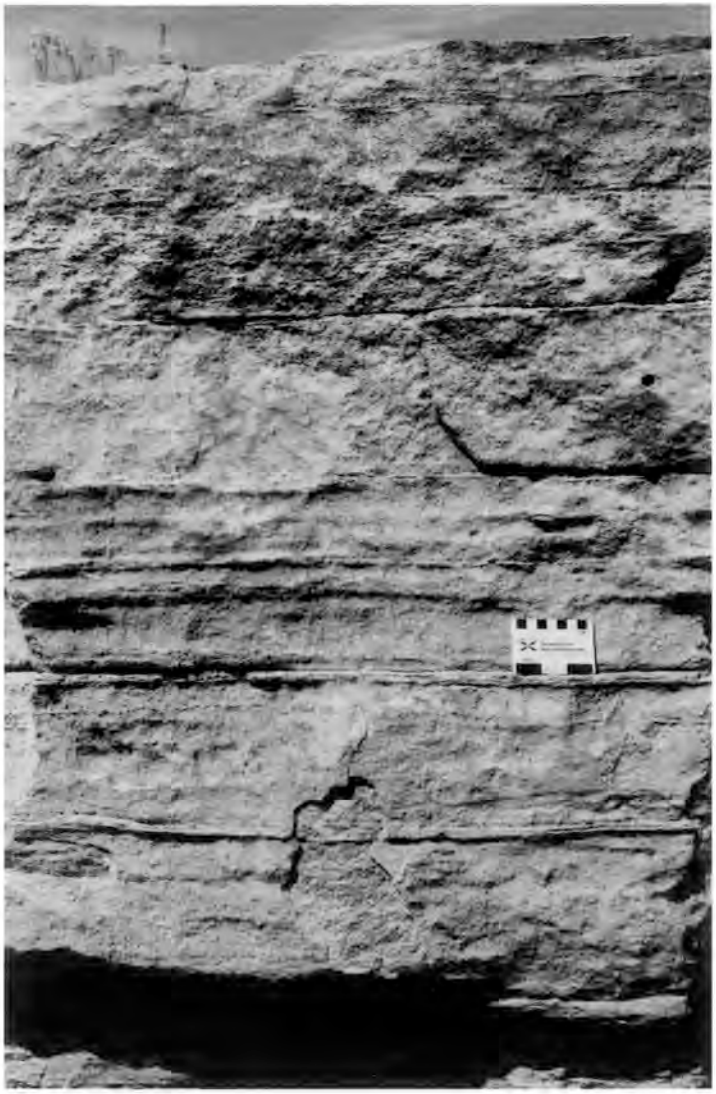


Figure 24. Lodgepole coal mine, Riley Pass, North Cave Hills, South Dakota. Facies association A here consists of rhythmically bedded fine-grained planar and rippled sandstone with Skolithos linearis *burrows. The thin, more-resistant layers are higher in volcanic ash. Large (1 to 2 mm) analcime spherules give this outcrop a rough granular appearance. The exposure occurs at the top of the E-Sandstone just below the E-Coal zone (see figure 22).*

both areas: (a) facies association A, (b) analcime spherules, (c) a mature paleosol with silcrete at the top of the section, and (d) megabreccia blocks that resulted from slumps. We correlate the U_3 unconformity from the Ekalaka area to the North Cave Hills and suggest that records of earthquakes and volcanic activity are found in both areas.

(7) The Ekalaka Estuary was situated between the Marmarth Delta (Ludlow Member, facies B, Belt and others, 1984) to the northeast of the Ekalaka study area and the Black Hills uplift to the south. The mouth of this estuary was partly restricted by barrier island sands (the D-Bed and E-Bed sandstones, Cave Hills, SD) that spread by longshore drift to the south.

(8) The initial uplift of the Black Hills is inferred from the regional shift in paleodrainage directions recorded near the base of the Lebo Member (C-coal zone) in the Miles City coal field (Belt and others, 1992), and at the base of the Ludlow Member, facies B (Oyster coal bed) in the Little Missouri River area,

Figure 25. Silcrete (the lightest-colored bed) at the top of the E-coal zone in the Lodgepole coal mine, Riley Pass, North Cave Hills, South Dakota. The silcrete forms the top of the zone of bleached strata, which overlie the coal deposits in the mine. F-Sandstone beds lie above the silcrete. This unit is believed to correlate with the silcrete below the U_3 contact in the Ekalaka area.

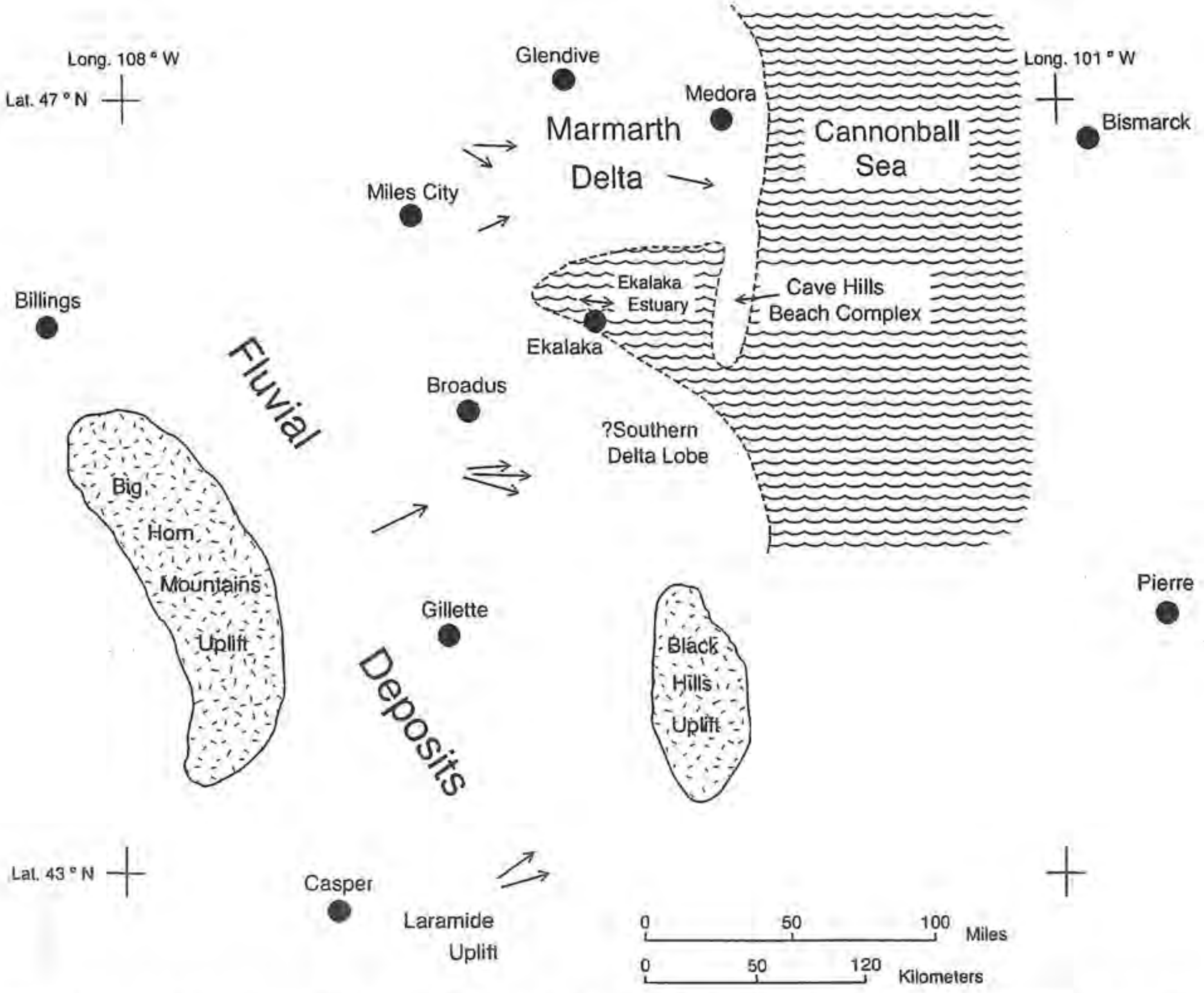


Figure 26. Regional paleogeography during deposition of the lower Ekalaka Member (this is largely facies association A and excludes the Medicine Rocks sandstone above the MedRx unconformity). Note that the upper Ludlow Marmarth Delta (Ludlow Facies B of Belt and others, 1984) lies in southwestern North Dakota, whereas a barrier island (or spit extending from the edge of the delta) lies in northwestern South Dakota (Goodrum, 1983). The laterally equivalent Lebo Member is entirely of fluvial origin to the west of the northern delta (Belt and others, 1992). Paleocurrent directions south of Broadus are based on data shown in Brown (1993, figure 3) for the Late Tullock which should be the same age as Lebo in southeastern Montana (Flores and Nichols, 1999, figure IN-4). To the south of the Ekalaka Estuary, we postulate another delta lobe. Thus, the Ekalaka Estuary probably lay between two delta lobes. The Black Hills Uplift, farther south, was likely a source of sediment at this time.

North Dakota (Belt and others, 1984). It is also inferred by the local U_2 unconformity that represents the initial uplift of the Miles City Arch and Black Hills. The youngest Ludlow strata beneath the U_2A have been dated in the P-2 pollen zone of late Puercan age.

(9) The late Puercan uplift was followed by marine (estuarine) transgression that deposited the Ekalaka Member in the vicinity of Ekalaka from 62.5 Ma until about 60.5 Ma, or essentially the entire Torrejonian.

(10) Following Ekalaka deposition, a regional unconformity (U_3) was produced throughout the western Williston Basin. Upper strata of the Ekalaka Member show well-developed paleosols representing weathering during a post-Ekalaka hiatus. Subsequent to the development of these soils, Tongue River paleovalleys (Little Missouri River, North Dakota and Locate, Montana) incised into the paleosols and cut down as much as 20

meters into Ekalaka strata. The event that produced the U_3 unconformity resulted from a relative base level fall at about 61 Ma. This regional erosion may have resulted from a regional tectonic upwarping of the western Williston Basin, or from a eustatic sea level drop, or a combination of both.

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