THE STRATIGRAPHY AND ENVIRONMENTS OF DEPOSITION OF THE CRETACEOUS HELL CREEK FORMATION (RECONNAISSANCE) AND THE PALEOCENE LUDLOW FORMATION (DETAILED), SOUTHWESTERN NORTH DAKOTA

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ABSTRACT

The Cretaceous Hell Creek and Paleocene Ludlow Formations of southwestern North Dakota, with the exception of the included lignite beds and minor amounts of concretions and nodules, are almost exclusively clastic sediments and sedimentary rocks. Massive clays, clays alternating with silts and sands, sandstones filling channels and other depressions, sheet sandstones, and lignites are the dominant sediment and rock types present. These sediments and sedimentary rocks were mostly deposited in a continental environment and were largely alluvial, lacustrine or paludal in origin; though marginal marine deposition, in part, is indicated by the occurrence of brackish water faunas in portions of the upper Ludlow Formation.

With the possible exception of a persistent lignite near the base, persistent lignites are not present in the Hell Creek Formation.

Lignites, a few feet thick, and which occasionally exceed ten feet in thickness, are spaced out over intervals of a few tens of feet throughout the Ludlow Formation. The formation is cyclic in the sense that the lignite beds are repetitive, but the beds associated with the lignite indicate that the swamps were drowned (lacustrine clays) or were buried (alluvial sands or clay and coarser clastic alternations). No special cause is necessary for the cyclic sedimentation other than the vagaries of sediment supply and subsidence. Contrary to the common cliche that continental beds cannot be correlated, careful tracing through areas of good exposure has demonstrated that lignites, sandstones, and clays of the Ludlow Formation can be correlated for distances in excess of five miles.

The Ludlow can be subdivided into several informal units, typically coal-bounded, which can be traced laterally over large areas. This informal subdivision permits isolation of stratigraphic units for the study of local environments of deposition.

The lower contact of the Ludlow Formation is apparently coincident with the boundary of the Mesozoic and Cenozoic erathems and is defined by the occurrence of the first persistent lignite or lignite-zone. This zone consistently overlies the last dinosaur fossils, and, where floral collections have been carefully made, coincides with the initiation of the Tertiary flora.

The upper contact of the Ludlow Formation was taken as the top of a widespread white siliceous zone, which typically overlies a variable thickness of bleached and light colored sediments. This contact is higher than the contact used by Hares (1928) in this area but can be traced over large areas with confidence and effectively separates the gray sediments of the Ludlow from the yellows of the overlying Tongue River Formation.

Channel and depression fill sandstones of the Ludlow Formation have a relatively low permeability and a high organic content at the surface and, for this reason, are considered poor prospective uranium host rocks. The lighter colored yellow winnowed sheet sandstones of the Ludlow are more permeable and relatively free of organic matter. They are considered as possible host rocks for uranium occurring in association with an oxidation/reduction interface at shallow depths. The uranium potential is enhanced where the latter sandstones occur along paleodivides which have been overlain by the Oligocene White River Formation, or in local areas where the latter formation is still preserved. Light yellow winnowed sheet sandstones are rare in the Hell Creek Formation, and the chances for uranium prospects in this interval seem correspondingly reduced.

INTRODUCTION

General

The Ludlow Formation in southwestern North Dakota (fig. 1) has been little studied, apparently because of

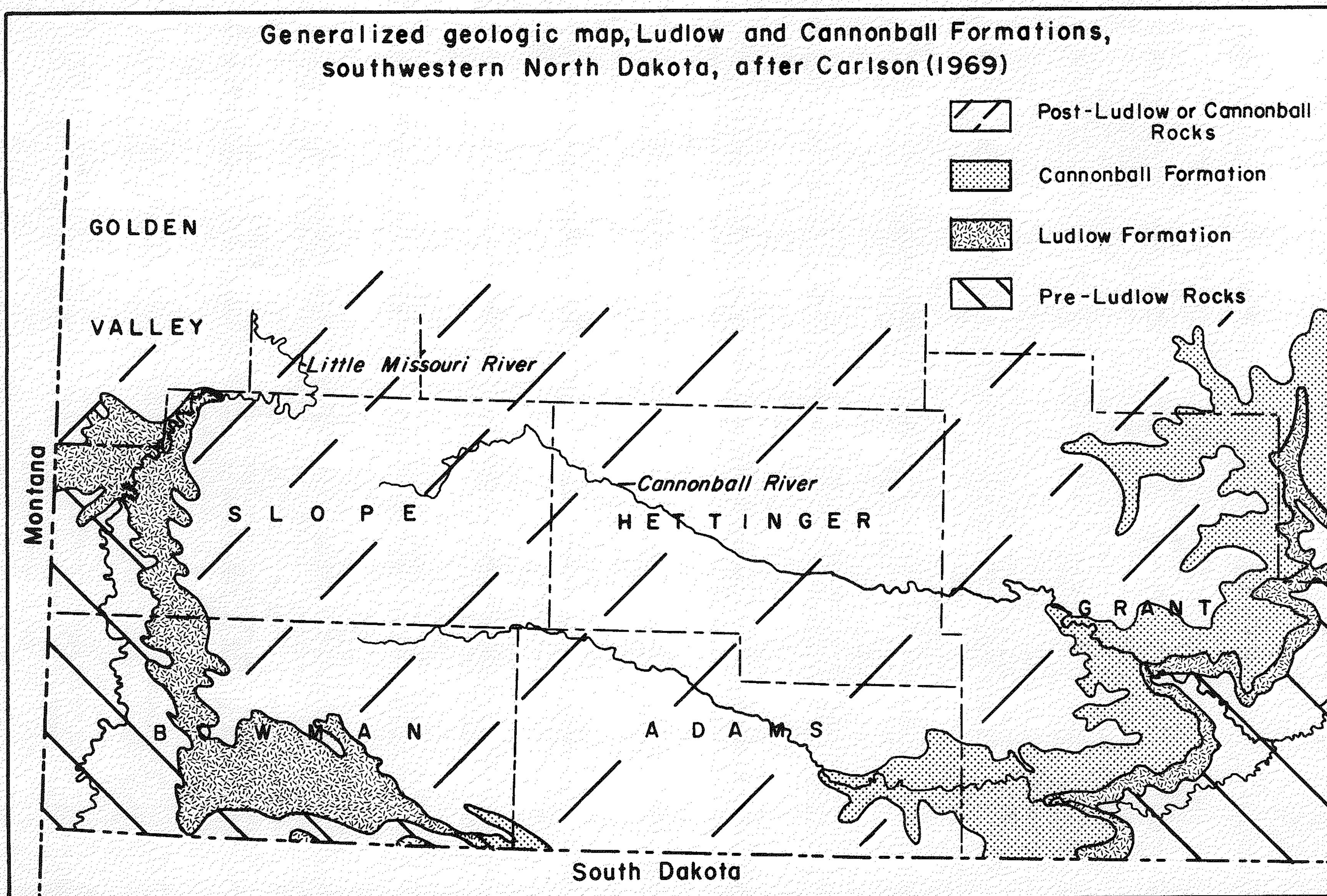

Figure 1. Generalized geologic map, Ludlow and Cannonball Formations, southwestern North Dakota.

its stratigraphic position between the underlying Hell Creek Formation and the overlying Tongue River Formation. The former has been studied because of its large and significant dinosaur fauna, and the latter was of interest because of its valuable lignite. Field work has demonstrated that the Ludlow has potentially economic deposits of coal (fig. 2). Because of the nature of its sedimentation, the Ludlow contains a number of different facies in the complex lateral relationship to the Cannonball Formation to the east.

Purpose

Study of the Ludlow Formation was undertaken initially to define the boundaries of this little known unit and to attempt to determine its environments of deposition. Coordinated within these broad goals, economic potential of lignite and groundwater was part of the study. Later in the program, this study was expanded to include the prospects for uranium occurrence in the Ludlow and in the underlying Hell Creek Formation. The study of the Hell Creek Formation has been largely reconnaissance as there have been other significant stratigraphic studies by earlier workers.

Previous Studies

Wilder (1902, p. 69), in discussing the Laramie Formation, included strata in this unit from the Yule area of North Dakota (a former Post Office on the Little Missouri River in sec 30, T136N, R104W) which are now included in the Ludlow Formation.

After he collected fossil floras and faunas in eastern Montana, Brown (1907) established the "Hell Creek beds." He noted, "But nowhere were beds of lignite observed in this member." In his diagrammatic stratigraphic section, figure 3, he shows a series of lignite-bearing beds between the "Hell Creek beds" and the "Fort Union?" and thus, by implication at this very early date, set apart some of the beds equivalent to the Tullock and Lebo Formations of Montana and Ludlow Formation of North Dakota.

Leonard (1907, p. 198) began the subdivision of the post-marine Cretaceous beds in the eastern Montana area with "Heretofore all the beds above the marine Pierre shale have been regarded as belonging to a single formation which carries the lignite and subbituminous coal beds of this field. These rocks have been called at various times, "Laramie" and "Fort Union" on the supposition that they composed a single formation." He continues, "at Glendive the rocks above the Pierre shale comprise two formations." He then set off the "dinosaur-bearing beds" (Hell Creek) using the lowest principal coal as the base of the overlying Fort Union. He failed to recognize the Fox Hills Formation underlying the Hell Creek in the Glendive, Montana, area, but did recognize it in the Hell Creek area. He anticipated the importance of the Hell Creek locality in "Perhaps the most favorable locality for the study of the dinosaur-bearing formation is the one already mentioned, in northwestern Dawson County in the valley of Hell Creek."

Leonard (1908, p. 44) rejected the broad term, "Laramie," and concluded "that the beds above the marine Cretaceous belong to the Fort Union formation." He found the "Fort Union rocks are readily separable into three members by a marked difference in character and appearance." These members consist of two somber units enclosing a lighter-colored unit. The lower of the above somber units includes both the Hell Creek Formation and the overlying Ludlow Formation of modern usage. He presented a measured section from Pretty Buttes, which includes the lower half of the Ludlow Formation (Leonard, 1908, p. 47, 48), and discussed the occurrence of fossil oyster shells (1908, p. 49) from 5 miles southwest of the then Yule post office, beds which are also now included in the Ludlow Formation. Leonard (1908, p. 77-80) further subdivided the Fort Union Formation into five coal groups; the lower or Yule group of coals was defined in measured sections in secs 16, 32, T135N, R105W, and includes most of the coals known in this area from the Ludlow Formation, as now used (fig. 2).

In the Livingston area of south-central Montana, Stone and Calvert (1910)

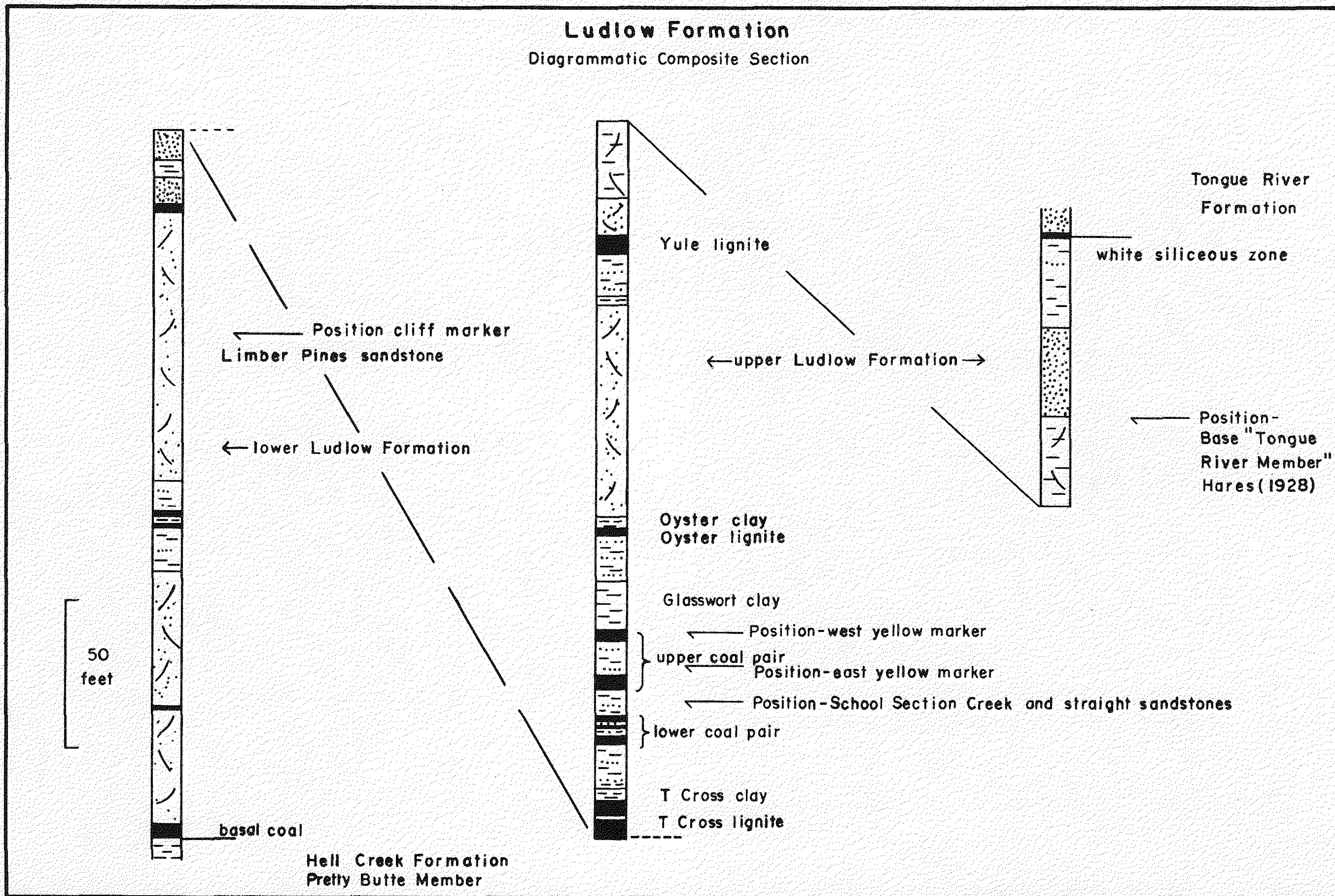

Figure 2. Ludlow Formation, diagrammatic composite section.

established the "Lebo andesitic member of the Fort Union formation," for the "upper, dark colored beds occurring between the Lance and the massive sandstone of the Fort Union of the section in the Musselshell valley." This terminology has been extended into North Dakota by later workers.

In a generalized discussion of the Pierre Shale and later beds in western North Dakota and eastern Montana, Leonard (1911) included beds below the Tongue River Formation and above the Fox Hills Formation in the "Lance formation." He notes their "dark and somber aspect in marked contrast to the overlying Fort Union" in the valley of the Little Missouri River. He described the general lack of coals in lower "Lance" and the abundance of thick coals in the upper portion in the vicinity of Yule, North Dakota.

Calvert (1912, p. 192-199) included the Hell Creek and Ludlow sediments in the "Lance formation." He noted that the highest horizon at which the bones of Ceratopsia were found was *above* the base of the lowest persistent coal which is now considered the base of Paleocene Epoch. This fossil site has been disputed by Brown (1962, p. 10) as a "mixup in locality citation or in fossil collections" because the inferred lowest lignite does not outcrop in the cited locality, and Brown concluded that this report of dinosaur remains above the lowest persistent coal was incorrect. Calvert did not attempt to subdivide the Fort Union Formation but realized that such recognition was based on color contrasts in the rocks, color contrasts which he found to be erratic in stratigraphic position (1912, p. 196, 197).

In a further discussion of the upper boundary of the Lance, Calvert (1912, p. 197) states "no attempt is made on the index map of the maps of the various areas treated in this report to differentiate the Lance formation from the overlying strata described in connection with the Fort Union formation." He continues, "the lowest persistent lignite bed was in the field arbitrarily considered to be the upper limit of the Lance, so that by reference to maps a general idea can be gained of the areal extent of that formation."

If, indeed, the other authors concerned with the eastern Montana coal fields (Bowen, 1912; Herald, 1912; Hance, 1912; Stebinger, 1912) did map the lowest persistent coal as the top of the Lance, except for terminology, their 1912 stratigraphic usage was essentially modern. One cannot substantiate this without extensive field checking, but such statements as "The Lance is the lowest lignite-bearing formation in the field" (Herald, 1912, p. 230) and study of the included maps, suggest that the lowest persistent lignite could be inferred to mean lowest lignite of potential economic interest (approximately 3 feet) or, particularly in covered areas, lowest clinker forming coal.

Modern terminology for the Dakotas began when the Ludlow was formally established as a distinct stratigraphic unit by Lloyd and Hares (1915, p. 528) as the "Ludlow lignitic member" of the "Lance formation." They set the type locality "in the vicinity of Ludlow, South Dakota." They described it as consisting of "350 feet of loosely consolidated buff and cream-colored calcareous sandstone with interbedded lignite." The presence of the lignite was considered the chief criteria for distinguishing it as a separate unit of the "Lance." These authors recognized the lateral equivalence of the Ludlow with their "Cannonball marine member" to the north and east of the type locality, in the Dakotas.

Winchester (and others, 1916) in a study of the lignites of northwestern South Dakota included the "Ludlow lignitic member" in the "Lance formation." They show it intertonguing to the east with the "Cannonball marine member." These authors (1916, p. 20) give a composite section of the "Ludlow lignitic member" measured in secs 32 and 36 of T22N, R5E, along the south margins of the North Cave Hills. This section apparently is the one used by Denson, Bachman, and Zeller (1959, p. 17) to more precisely locate the type section of the "Ludlow member" (see discussion below).

Rogers and Lee (1923) described the Tullock Creek coal field. They established the "Tullock member" of the "Lance formation" for "exposures in the valley of Tullock Creek" with a "base of coal bed A, the lowest in the Lance formation" and a top of sandstone "overlain by the soft beds of the Lebo shale member of the Fort Union." They thus extended the use of the term "Lebo shale member" from the type locality in south-central Montana eastward toward the Dakotas. Both terms have been introduced into North Dakota by later workers.

Thom and Dobbin (1924) summarized the stratigraphy of the Montana and Dakotas area from the "Pierre shale" upward through to the overlying "Wasatch formation." In their discussion they define the "Hell Creek member" as "typically exposed on Hell Creek, Garfield County, Montana," and wrote that this interval is equivalent to the "Hell Creek beds" and "lignite beds" of Brown (1907), occupying the interval between the Fox Hills sandstone and the yellow Tullock member of the Lance. By including the "lignite beds" of Brown in the definition of the "Hell Creek member" they included somber post-cretaceous Tullock equivalents below the yellow Tullock in the "Hell Creek member." They indicate that the Tullock member of the "Lance formation" of Rogers and Lee (1923) can be traced eastward from the type area to the Cedar Creek anticline of the Montana border and point out the equivalence of the "Tullock member" and the overlying "Lebo member" to the "Ludlow member" of the Dakotas.

In southeastern Montana in the Ekalaka lignite field, Bauer (1924) included the "Ludlow lignite member" in the Lance Formation. With regard to the lower contact he states "the same stratigraphic horizon being traced into the Little Beaver Valley that was mapped by C. F. Bowen in the Baker field as the base of the Fort Union. Subsequent work has shown that the lignite so mapped by Bowen lies at or near the base of the Lebo shale member of the Fort Union—that is, somewhat above the base of the type Ludlow as mapped by C. J. Hares in southwestern North Dakota." As in the coal fields farther to the north in Montana along the eastern border, the mapped Ludlow probably does not include that portion of the Ludlow below the T Cross coal which extends the Ludlow downward to the lowest persistent coal of Brown (1962), that is, to the Cretaceous-Paleocene contact.

Hares (1928, p. 14) continued to use the term "Lance formation" for the somber beds below the lighter rocks of the then "Tongue River member" of the "Fort Union formation." Along the Little Missouri River he divided the "Lance" into the underlying *Triceratops*-bearing beds of the "Hell Creek member" which are in turn overlain by the lignite bearing "Ludlow member." The term "Lance" has since been dropped, but otherwise these are essentially the usages of today when modified to fit the requirements of the stratigraphic code. Hares' maps and report of the Marmarth coal field is the only regional study of the Tertiary strata and economic deposits of southwestern North Dakota and is the base from which nearly all later published maps have been derived.

Dobbin (1929) used the term Tullock and Lebo in his Forsyth coal field study for the interval between the "Hell Creek member" and the "Tongue River member." He used the Wright coal bed as the base of the Tullock and the Big Dirty coal as the base of Lebo.

Pierce (1936) extended the use of the terms Tullock and Lebo eastward from the Tullock coal field (Rogers and Lee, 1932) to the Rosebud coal field just east of Forsyth, Montana, and suggests "that a lithologic distinction between the Lebo and the Tullock members cannot be carried eastward beyond the Rosebud coal field." His interpretation of the relationship between the major coals of eastern Montana is given in his plate 9. He placed the Big Dirty coal (Dobbin, 1929) at the base of the Lebo and correlated it with the C coal of the Miles City coal field.

Simpson (1937, p. 20) wrote "all of the strata generally referred to the Lance, often under the name of Tullock but not necessarily equivalent to the type Tullock, are in reality distinctly later than the typical Lance or the equivalent Hell Creek and both faunally and stratigraphically are more related to the overlying beds, that is, to the Fort Union."

Brown (1938) continued Simpson's resolution of the Mesozoic-Cenozoic boundary problem with his analysis "the strata overlying the Hell Creek formation and underlying the Wasatch constitute a recognizable, measurable and mappable unit carrying a distinctive flora and fauna differing significantly from those of the Hell Creek and Wasatch."

The first study restricted to the flora of the type Lance Formation was published by Dorf (1940, p. 213-236). He established that the flora of the type Lance is distinct from that of the Fort Union Formation and only the "flora of the non-dinosaur-bearing beds which have been generally regarded as upper Lance is of Fort Union aspect" (1940, p. 213). The upper Lance of this usage is equivalent to the present Tullock and Ludlow Formations. In his table 5, Dorf (1940, p. 230) raised the Fort Union Formation to group status. He extended the Fort Union downward to include all Paleocene beds, thereby effectively suppressing the name "Upper Lance." This resulted in the incorporation of these strata in the Tullock, Lebo, Ludlow, and Cannonball Formations at the base of the Fort Union Group. This usage of the Fort Union as a group has been adopted by the North Dakota Geological Survey. A similar extension of the Fort Union downward to include the Ludlow has been adopted by the U.S. Geological Survey, although the nomenclatorial rank is different, for the Fort Union is retained at the formation level and the other units are regarded as members.

Laird and Mitchell (1942, p. 16-18) mapped the thin Ludlow Formation along the Cannonball and Missouri Rivers in south-central North Dakota where the unit lies between the Hell Creek and Cannonball Formations. As elsewhere in the state, they found it separable from the Hell Creek by its lignite and lignitic shale content and also indicated that it intertongues with and replaces the Cannonball Formation to the west.

Brown (1948), in reviewing the correlation of the Sentinel Butte shale in western North Dakota, published, for the first time, that the pelecypod *Corbicula* occurs in a lower brackish tongue of the Cannonball Formation which extends westward from the type Cannonball Formation into the valley of the Little Missouri River. His figure 1 effectively illustrates this relationship and other regional stratigraphic relationships of western Dakotas and eastern Wyoming and Montana as known at that time. Brown (1952) briefly summarized the Tertiary strata of eastern Montana and the western Dakotas.

Kepferle and Culbertson (1955, p. 134) recognized the Ludlow as a member of the "Fort Union formation" in Slope and Bowman Counties, North Dakota. They used the term "Cannonball lignite bed" for the lowest persistent coal with which they marked the base of the Ludlow. They indicate that the Ludlow "is equivalent to the Tullock and Lebo shale members of the Fort Union formation in eastern Montana, and to the Cannonball formation with which it interfingers to the east." Using Hares (1928) measured sections, they calculated that 150 million short tons of lignite lie beneath less than 120 feet of overburden in a deposit of the T Cross lignite bed, a locally thick coal near the middle of the Ludlow Formation.

Forty-three years after the definition of the general type locality of the "Ludlow lignitic member" "in the vicinity of Ludlow, South Dakota" (Lloyd and Hares, 1915, p. 528), Denson, Bachman, and Zeller (1959, p. 17) state, "The Ludlow member of the Fort Union formation, named from the town of Ludlow in Harding County, S. Dak. is well exposed at its type locality along the south face of the North Cave Hills (Winchester and others, 1916, p. 20)." Accordingly, approximately the composite section along the south margin of the Cave Hills of Winchester and others (1916, p. 20) was set by these authors as a more specific type section for the Ludlow member. Additionally, in this study of the occurrence of uraniferous coals in the northwestern South Dakota and nearby areas, the authors show regional and stratigraphic relationships suggesting that the uranium was leached downward from the overlying White River and

Arikaree sediments and fixed in underlying coals where these coals are overlain by appropriate permeable horizons. Deposits of this type occur in the Ludlow Formation in states bordering North Dakota but occur higher in the stratigraphic section in North Dakota. Denson, Bachman, and Zeller (1959, p. 17) drew the base of the Ludlow member "where predominantly somber-colored shale of the Hell Creek is overlain by prominent yellow sandy strata characteristic of the Ludlow member of the Fort Union formation, and so marked in many places by a bed of lignite." The same authors (1959, p. 19, 43) describe a gray quartzite bed in the Tongue River member similar to that discussed by Hares (1928, p. 35-36) which is involved in later discussions of the top of the Ludlow Formation. They describe its normal occurrence as 10-20 feet below a persistent lignite bed which they refer to as the Harmon lignite bed.

Brown (1962), in a study of the Paleocene flora of the Rocky Mountains and High Plains, describes and discusses specimens taken from the Ludlow Formation. He further addressed himself to the nature of the Cretaceous-Paleocene boundary and summarized at some length the history and complexities of this problem. He concluded that the lowest persistent coal above the highest dinosaur remains is a significant boundary marker in this area. He also concluded that warm temperate to temperate climatic forms were mingled in Paleocene plant collections or that descendants of some Paleocene species have changed their environmental niches.

Frye (1969) extended the term Tullock Formation into southwestern North Dakota, assigning those beds below the T Cross coal of Hares (1928) and above the lowest persistent coal of Brown (1962) to this unit. He assigned the beds above the T Cross coal and below the Tongue River Formation to the Ludlow Formation and shows the Lebo Shale as a tongue near the top of the Ludlow.

In an unpublished master's thesis, Hickey (1973) followed Frye (1969) in using the term Tullock Formation for the beds below the T Cross coal of Hares (1928).

Cvancara (1966), in a study of the fauna of the Cannonball Formation, collected and described the oyster *Crassostrea glabra* (Meek and Hayden) and the clam *Corbicula* cf. *C. berthoudi* White from the Ludlow Formation from the general vicinity of Leonard's (1908) site and from Brown's (1948) locality. Leonard's (1908), Brown's (1962), and Cvancara's (1966) sites, along with some additional locations, were recollected and the fauna described by Van Alstine (1975). He expanded the known fauna and added foraminiferids to the list of known brackish water or marine forms which occur in tongues in the Ludlow Formation.

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HELL CREEK FORMATION

Stratigraphic Review

The Cretaceous Hell Creek Formation overlies the Cretaceous Fox Hills Formation and is overlain by the Paleocene Ludlow Formation (table 1).

The underlying Fox Hills Formation is a unit of tens of feet of light colored sandstone with some interbedded finer clastics. It has widespread lateral continuity and represents a marine transition facies

Table 1. Early and recent nomenclature of the Late Cretaceous and Paleocene, southwestern North Dakota.

Environment of Deposition	Nature of the Beds	Early Nomenclature (Leonard, 1911)	Present Nomenclature
Nonmarine	Somber beds mixed lithologies		Sentinel Butte Formation
		Fort Union Formation	
Nonmarine	Light beds mixed lithologies		Tongue River Formation
Mostly Nonmarine	persistent lignites	PALEOCENE	W Ludlow Formation | E Cannonball Formation
			Lowest persistent coal
Nonmarine	Somber beds mixed lithologies	Lance Formation	Dinosaurs
Nonmarine	local thin lignites	CRETACEOUS	Hell Creek Formation
Marine Transition	Light sandstones	Fox Hills Sandstone	Fox Hills Formation
Marine	Dark shale	Pierre Shale	Pierre Shale

from the underlying marine clays of the Pierre Formation to the overlying nonmarine Hell Creek Formation. The Fox Hills Formation contains sufficient invertebrate fossil material to be clearly dated as Cretaceous age.

The Hell Creek Formation is hundreds of feet thick and consists of somber carbonaceous clays and sandstones with occasional local lignitic zones. Internal lateral continuity is poor and few beds can be traced for distances in excess of a mile or more. The unit is nonmarine in western North Dakota but contains a thin marine tongue in south-central North Dakota along the Missouri River. Dinosaur fossils are the basis for a Cretaceous age of the Hell Creek Formation.

The Hell Creek Formation is overlain in central North Dakota by the marine Cannonball Formation and in western North Dakota by the mostly nonmarine Ludlow Formation. The Cannonball Formation consists of clays, siltstones, and sandstones which contain a Paleocene brackish and marine fauna. The Ludlow Formation, which is hundreds of feet thick, is similar to the Hell Creek Formation but is separable because of its general trend toward laterally persistent rock units and in its content of thick, widespread lignites. The Ludlow locally contains brackish tongues derived from the easterly and correlative Cannonball Formation but is mostly nonmarine. The Ludlow contains a Paleocene flora.

In brief, the Hell Creek Formation differs from the underlying Fox Hills Formation in the variability of its lithologies and from the overlying Cannonball and Ludlow Formations in its lack of lateral persistence of beds and the absence of significant lignite content.

The beds now referred to as the Hell Creek Formation have been referred to as the Great Lignite Group, Laramie, Lance and Fort Union "Formations" and variously assigned a Cretaceous, Paleocene, and Eocene age. Thom and Dobbin (1923, fig. 2, p. 484) introduced the term Hell Creek into North Dakota as the "Hell Creek member" of the Lance Formation in a regional cross sectional diagram. The usage of Hell Creek in North Dakota was firmly established by Hares (1928) with the publication of his study of the Marmarth coal field. Hares regarded the Hell Creek as the lower member of the Lance Formation. Brown (1938) raised the Hell Creek to formational status, the usage which has predominated since that time.

The Upper Cretaceous age of the Hell

Creek Formation is firmly established by the large dinosaur fauna which it contains. The existence of the Cretaceous and Paleocene boundary at its upper contact is generally accepted. The age of the Hell Creek Formation and the boundary problem with the overlying Ludlow Formation are discussed at some length in a following discussion of the Ludlow Formation and the reader is referred there for details.

Stratigraphic Nomenclature

The Hell Creek Formation is considered to have formational rank in essentially all modern papers and discussions. Early disagreements over upper and lower boundaries have been largely settled in the state of North Dakota.

Summary

The Hell Creek Formation and the overlying Ludlow Formation, as indicated in earlier and later discussions, are separable, above and beyond their floral and faunal differences, on the basis of the persistent lignites and the general overall lateral continuity of the Ludlow Formation. However, so far as could be seen in reconnaissance over the Hell Creek Formation, the individual lithologies of two units are highly similar, if not identical. Without prior knowledge of stratigraphic position, a small outcrop of Hell Creek sediments cannot be assigned unequivocally to that formation, for all lithologies, with the exception of thick persistent lignites and the possible exception of the light yellow, well-winnowed sandstones and the brackish fossil bearing beds, occur in both formations. This similarity is indicated in the early regional problems and local modern difficulties in separating the two units. Because of this similarity the discussions which follow, with the noted exceptions, apply equally well to both the Hell Creek and Ludlow Formations with regard to sediment type and probable modes of origin of these sediments. For details of stratigraphy of the Hell Creek Formation the reader is referred to Frye (1969).

As suggested in a later discussion of the uranium potential of the Ludlow Formation, the clay and organic rich sandstone of this unit, which is the overwhelmingly abundant sandstone type of the Hell Creek Formation, is probably not a good lithology for uranium prospecting because of the nearness to the surface of the oxidation/reduction interface. On this basis it seems probable that the Hell Creek Formation will not yield significant uranium production.

LUDLOW FORMATION

Stratigraphic Review

The Paleocene Ludlow Formation overlies the Cretaceous Hell Creek Formation and is overlain by the Paleocene Tongue River Formation (fig. 2, table 1).

The underlying Hell Creek Formation is a unit of hundreds of feet of somber lenticular gray sandstones and dark, organic-rich, swelling clays of nonmarine origin. Lateral continuity in beds is restricted and lignites are few, thin, and discontinuous. The unit is of undoubted Cretaceous age and contains abundant remains of ceratopsian dinosaurs.

The Ludlow Formation, hundreds of feet thick, is variable in aspect from somber to light, though the unit is generally somber in North Dakota. The rocks consist of light gray and light yellow to buff sandstones, dark organic rich clays, and lignites. Continuity in beds or zones of beds is well developed, and lignites are abundant, widespread, and locally thick. The Ludlow is dominantly nonmarine but locally contains tongues of brackish water sediment coextensive with the laterally correlative and marine Cannonball Formation. The Ludlow lacks dinosaur remains and contains a Paleocene flora.

The Tongue River Formation, also hundreds of feet thick, is light colored and generally contrasts sharply with the somber underlying and overlying formations. It consists of light gray and buff sandstones, light gray to yellow clays, and common persistent and thick lignites. The unit is nonmarine and contains a Paleocene flora.

In brief, the Ludlow differs from the underlying Hell Creek Formation in its content of lignites and tendency toward lateral continuity of beds and from the overlying Tongue River Formation by its somber aspect.

The beds now placed in the Ludlow Formation have been variously referred to as the Laramie, Lance, and Fort Union "Formations" and thus assigned a Cretaceous, Paleocene, or Eocene age. This complexity of nomenclature and age assignment arose because of the gross similarity of the rocks above the marine Cretaceous. This thick, monotonous sequence required a long period of study over a large area by many workers before criteria were established which effectively subdivided the strata according to color and lignite content (table 1).

Different age assignments arose because of an apparent disagreement between paleobiologic dates from vertebrate and floral studies. Vertebrate faunas showed the Mesozoic-Cenozoic contact to be located within the nonmarine section because of the faunal contrast which exists between lower dinosaur-bearing rocks and higher non-dinosaur and mammal-bearing rocks. Vertebrate workers early recognized the significance of this difference and associated the faunal change with the Mesozoic boundary and with the base of the lowest persistent coal in the northern High Plains. The existence of such a boundary was disputed by floral studies which apparently failed to show much change at this stratigraphic position. This lack of change was later shown to have been the result of the mixing of floral collections from below and above the contact which effectively blended the separate Cretaceous and Paleocene floras into a single entity. When the collections were properly unscrambled, with regard to their position with respect to the lowest persistent coal, the contrasts in the older and younger floras became apparent, and the floral and vertebrate fossil information came into agreement. Work since the forties has consistently shown the Mesozoic-Cenozoic contact in the Dakotas to lie at the base of the Ludlow Formation, that is, at the base of the lowest persistent coal in most areas.

The above changes are ably reviewed and summarized by Brown (1962) and are partially reconsidered in the following discussion of previous work.

Stratigraphic Nomenclature

Two usages, differing in stratigraphic rank, are common in this area at the present time for the rocks included in the Ludlow Formation. The older of the modern usages is that of the U.S. Geological Survey, which places the underlying beds of Cretaceous age in the Hell Creek Formation. The succeeding Paleocene Ludlow is then included in the Fort Union Formation as the lowest member, the Ludlow Member, which in turn is overlain by the Tongue River and Sentinel Butte Members. The North Dakota Geological Survey, however, as in Carlson and Anderson (1966, fig. 3), following Dorf (1940, p. 230, fig. 5), retains the Hell Creek as a formation and raises the Fort Union to group status, recognizing the Ludlow, Tongue River, and Sentinel Butte as formations. The latter usage is that followed by the author.

GENERAL DESCRIPTION AND ORIGIN OF SEDIMENTS

The sediments of the Ludlow Formation, with the exception of the organically derived lignites, are almost exclusively clastic sediments. Chemical precipitants occur as a relatively minor cement in clastic sediments or in scattered concretions and nodules of little volumetric importance.

For purposes of discussion the sediments will be divided into lignites, clays, silts, and sandstones with lesser subdivisions used for variations and gradations under these headings.

Sediment and Rock Nomenclature

With the exception of the concretionary and nodular masses which are commonly firmly lithified, the sediments and rocks of the Ludlow

Formation vary from unindurated to moderately lithified. Clays, other than lignitic shales, are nonfissile, modestly hard, breaking with a conchoidal fracture when dry and are weak and plastic when wet. Silts typically contain sufficient clay to have properties similar to those of the clays. Sands vary from loose masses, easily dug with a shovel, to tough, hard, almost rubbery outcrops which resist the pick. Because of their lack of coherence and fissility the sediments or rocks consisting of clay- or silt-size particles, except for lignitic shales, are referred to as clays and silts. The sediments and rocks of sand-size particles are referred to as sandstones. This choice reflects the typical state of lithification in the field.

Most of the clays of the Ludlow Formation swell when wet and this property dominates the appearance of sediments or rocks containing significant amounts of clay. Clay content in other rock types is indicated where the wetted, expanded clay produces swollen, rounded weathering surfaces which contract and fracture upon drying and tend to slough off in soft, rapidly disintegrating fragments. The distribution of clay in a sandstone is often strikingly apparent due to the differential swelling associated with variable clay content.

Silt is a common, admixed constituent of the clays. After weathering and slight washing, it accumulates as a lag deposit on clay surfaces and gives a misleading surface indication of abundance. Specimens which would be regarded as silts or silty clays from examination of the weathered surface show significantly less silt when viewed on freshly cut and wetted surfaces.

Color

Experience in boreholes and mines indicates that the Late Cretaceous and Paleocene deposits of North Dakota are almost exclusively various shades of gray in the subsurface. The buff and yellows of surface exposures are due to surface or near surface weathering or shallow groundwater alteration.

Because the major subdivisions of the rock of this age are based in surface studies on gross color change, major problems arise in use of surface terminology in the subsurface. Because of the difficulties in subsurface subdivision and a lack of economic impetus for doing so, little subsurface work has been done on the Paleocene rocks of North Dakota.

Color is discussed in more detail in later sections.

Lignites

The lignites of the Ludlow Formation vary from smuts to beds twelve feet in thickness in studied exposures and are reported to be up to twenty-four feet thick (Hares, 1928). The lignites are black except where clayey or shaley, and there brownish hues develop. The lignites are commonly layered within the seams in beds approximately an inch thick and are fractured by similarly spaced joints which break the coal up into small blocks. The coals are tough and may form rounded, protruding outcrops. Fractures conduct shallow groundwater, at least near the surface, and are reported as important aquifers at depth.

The lignites are woody and commonly contain flattened logs and trunks several feet in length. Stumps are uncommon in both the coal and the immediately underlying beds. In addition to the relatively well exposed woody coals, occasional residues of thin coals are seen along the outcrop which are a black to dull reddish brown extremely fine dust, apparently the result of surface weathering and slacking of a coal. It is possible these powdered coals represent a different coal type from the typical Ludlow coal which weathers to a debris dominated by granule and small pebble-size coal fragments.

The lignites contain iron sulphide nodules (marcasite, pryrite) up to six inches long and of highly variable shape, though spherical forms, approximately an inch in diameter, are most common. Sulphide nodules are more common near the boundaries of the coals and are fairly common in contiguous strata near the coal contact.

A few of the coals contain up to several-inch-thick extensive white beds of sediment of uncertain type. Some seem to be volcanic ash, but no microscope work was done to identify these materials.

Coals grade vertically and laterally into lignitic shales and carbonaceous clays. Lignitic shales are reddish brown clays laminated with coarse, flattened, and lignitized plant fragments, which commonly are more abundant than the clay fraction. The rock is fissile and the term shale is appropriate. This rock is apparently the "bone" or "bone coal" of earlier workers. The lignitic shales are rubbery and tough and commonly form rough slabby ledges.

The term carbonaceous clay was used for clay-dominant sediment which contains significant amounts of readily visible, relatively fine carbonaceous plant fragments. The color is highly variable, grading from black flecks of lignitic plant remains on dull white clays to organic flecked nearly black clays. Because of their high clay content the carbonaceous clays weather to smooth, rounded, poorly vegetated slopes.

The coal, lignitic clay and carbonaceous clay suite represents the gradation from organic-dominant to clay-dominant sedimentation as the environment changed from swamp to sheltered lacustrine or lagoonal conditions.

A coal swamp forms in an area where the water table and the surface are nearly coincident. If this relationship persists, that is, the water table rises or the substrate sinks at the rate at which organic matter accumulates so as to maintain proper coincidence, large quantities of organic matter may be deposited and ultimately a thick coal may result.

If no change takes place in the level between the water table and the coal swamp the process is self limiting, for the accumulation of the organic debris gradually raises the swamp above the optimum water table and surface coincidence to a level at which further rise inhibits growth. The swamp may persist with production equal to losses through weathering and erosion. A coal swamp under these conditions could exist for a long period of time without producing significant preserved organic deposits.

A coal swamp may be terminated by a rising groundwater table due to an excessive subsidence rate of the substrate or to a rise of water table with which the upward growth of the swamp cannot keep up. The swamp drowns and organic debris is overlain by the quiet water deposits of a lake, lagoon, or bay.

A coal swamp may be partly or completely destroyed by erosion. A coal swamp may also be terminated by an influx of sediments, alluvial or marine transition, which effectively lowers the water table by raising the surface and the swamp is buried.

Drowning of swamps in Ludlow time was common, for lignites are frequently overlain by a sequence of strata which grades from lignitic shale through carbonaceous clay to massive clay. Any of the units may be missing, but one or more of the organic rich transition units is usually present. The reverse sequence is common at the base of lignites and reflects the gradual shoaling of quiet, deeper water followed by the establishment of the swamp community.

Burial of swamps was also common. Lignites are frequently overlain by lignitic sands or more commonly by banded sequences of alternating coarse and fine clastics reflecting the encroachment of levee and point bar deposits upon the swamp areas. The lignitic sands are probably crevasse splay deposits or deposits of streams draining the swamps.

The preceding discussions of coal swamps have ignored the potential for lateral migration inherent in the swamp environment. Changes in distance between the water table and surface of the ground may laterally displace swamp environments. If such changes take place at a rate slow enough for swamp development to keep pace, the margins of the swamp or the overall swamp may migrate laterally (the expression, migrate laterally, is used to avoid the specific connotations of such terms as transgressive and regressive, though either term might be correct for a given situation). Correspondingly, the deposits of such an environmental shift may be time transgressive; however, within our ability to discriminate time, most individual coals in the Ludlow are essentially synchronous throughout their distribution. An exception to this statement might be the T Cross lignite and its correlatives, which are thick, widespread, and, at least in part, overlain by brackish water deposits. This may indicate the coal is associated with a marine transgression.

Lignites are ordinarily considered to represent an essentially flat horizon at the time of deposition. This simplification ignores the fact that the water table to some degree follows the topography and also ignores the possibility that the organic deposit can create a lens in the surface of the water table. An organic deposit tends to pull the water table up as it grows upward, partly by capillarity and partly by retaining discharge in the "organic dammed" central part of the swamp. The first effect was not important in the Ludlow deposits because of the probable low relief of the site of deposition as shown by the accompanying widespread lacustrine and overbank sediments. The latter may account for some of the relatively abrupt local thickening of lignites, but evidence for differential subsidence is so ubiquitous throughout the Ludlow that this cause is more probable for the rapid changes in coal thickness.

Clays

The clays of the Ludlow Formation can be divided into two basic types, the massive clays, which are nearly pure clays thick enough to be regarded as separate sediment bodies, and the remaining clays, which are intimately associated with other sediments.

The massive clays occur in all shades of gray, being darker with increasing organic content. Scraped surfaces expose clays with a rare slight green tinge which disappears during weathering. The darker gray clays commonly develop a bluish tinge when weathered. These clays are extremely fine, typically free of silt and other clastics. A wetted knife cut surface, when examined through the lens, shows minute lamination and other extremely delicate structures. The massive clays vary rapidly in thickness laterally and commonly grade vertically into carbonaceous clays and lignitic shales. Exposure to weathering and erosion yields smooth, rounded slopes with reduced vegetation. When dry, a crumbly surface of angular irregular flakes, generally less than a half inch in greatest dimension, locally referred to as "popcorn," develops.

These massive clays are almost certainly of lacustrine origin and were deposited in the quiet waters of flood basin lakes or are the brackish to marine deposits of quiet bays and lagoons.

Clay Alternations

Clay is combined with silt and sand in a coarse and fine alternation which is the dominant sediment type of the Ludlow Formation. Fresh, scraped surfaces and natural exposures show the alternations to occur on all scales from less than inch to feet in thickness, though most fall on a scale of inches. The alternations consist of a light colored lower silt or sand, which may be plane-bedded or cross-laminated, and which grades rapidly or abruptly into the overlying darker and thinner clay cap. Either the coarse clastic or the clay portion of the alternation may be the thickest portion, and many outcrops show a systematic thickening of the clay portion upward or conversely of the coarser portion upward through the exposure, so that overall thicknesses of the preceding alternations may be clay or silt and sand-dominant and vary from one to the other both vertically and laterally.

In a stratigraphic unit in which the sand portion of the alternation is proportionally dominant and about four inches or more thick, banded or striped beds may result. Because of the large amount of sand present the unit tends to form the smooth, bare slopes typical of a badlands sandstone. The sand portion is light gray with the thin clays, either gray or yellow gray to buff, and the bedding and coloration are nearly parallel across the breadth of a typical outcrop.

With increasing clay content the alternations typically have a loose, dark, swollen, clayey surface which obscures the underlying dual lithology; the banding is not displayed and the sediment appears to be all clay. Fresh natural exposures, which are uncommon, or trenching of the outcrop are necessary to show the alternation of coarser clastic and clay where clay is the dominant component.

In many units the alternations thin and the clay content increases upward and the coarser clastic fraction changes from sand to silt. These fining upward units, for the most part, represent alluvial point bar deposits; the fining and thinning upward reflecting the gradual migration of the point bar from the site concerned.

In other units the alternations thicken and coarsen upward, and the unit changes from clay-dominant to sand- or silt-dominant. This change, at least in many outcrops, reflects the migration of a levee crest toward the depositional site. Such an interpretation seems reasonable for the units where the alternations near the top are less than a foot or two thick and the coarser clastic portion remains coarse silt or fine sand. In some units, however, the upper part becomes a medium grained sand in excess of several feet thick and is relatively free of both clay and lignite fragments. In these units the presence of lacustrine or marine winnowing processes is suspected, and the coarsening upward may represent the classic lacustrine or marine transgressive cycle.

The coarse-fine alternation reflects an episodic sedimentation in the area of accumulation, each episode of which must have been relatively large scale, attested to by the thickness of the alternations and the relative coarseness of the coarser fraction. Periodic flooding of overbank and marine transition areas seems a reasonable cause for the cyclical nature of these sediments.

One puzzling aspect of the alternations is the remarkable preservation of minute sedimentary structures. If the interpretation is correct that the alternations are largely overbank deposits, then one would expect bioturbation by plants to be prevalent, indeed, pervasive. One does see lignitized root systems and some mixing of sediment types in mottled sections. In many scraped surface sections, however, the details of sedimentary structures are preserved, at least to the hand lens level of resolution, which suggest an absence or at least minimal disturbance by root systems or animal bioturbation. Perhaps sediment accumulation rates were so high in these areas that the level of root disturbance was moved upward by successive flood deposits before extensive bioturbation could occur.

In the banded beds the clays are typically various shades of darker gray, the silts are generally yellow or buff, and the sands are yellow to buff or gray white. In the case of the thicker sands, the yellow or buff color is most commonly associated with the coarsening upward unit, while the gray-white sands are associated with the fining upward unit. Here, as in larger sand bodies discussed later, color seems to reflect permeability, yellow and buff coloration being associated with more winnowed and permeable sands which have transmitted larger amounts of oxidizing surface water.

Clay Drapes and Drape Dips

Beds with primary dips which are relatively steep are common in the Ludlow Formation. Most steep primary dips are found in silts and coarser clastics and are constructional in origin, having formed during deposition. Associated with these steep primary dips in coarser clastics are similar dips in associated clays which are largely the result of drape. Drape occurs on many different scales and corresponds to the scales of the various underlying deposits. Perhaps the most common coincidence of primary dips and drapes occurs in crosslaminae and crossbedding and is associated with the avalanche or lee slope of ripples, megaripples, sand waves, dunes, or bars, etc.

A more complex, larger scale primary dip surface is associated with lateral accretion involving the varying sedimentary processes on meander points. In this case the primary dip is the result of the periodic migration laterally (progradation) of a complex of varied processes which produce a channelward dipping, doubly tapering body of sediment with sigmoid boundaries which fines upward toward the point and away from the channel. As in the earlier case, clay drapes may be deposited and assume a dip conforming to this underlying constructional surface.

Another primary dipping surface inherits its geometry from an erosional rather than a constructional surface. The younger sediment drapes more or less uniformly over the underlying eroded surface and reflects its form.

These dips in clays deposited on constructional or erosional surfaces are hereafter referred to as drape dips and are formed by the accumulation of finer clastics which are deposited during the waning phase of a once higher energy regime. The waning phase is incapable of modifying to any extent the underlying surface and, as its competence decreases, the underlying surface is buried under fine sediment. Drape dips are common on all scales, but they are especially striking in the Ludlow Formation in the form of sweeping crossbeds consisting of clay beds crossing horizontal intervals of many feet with dip components in excess of ten degrees. Traced laterally, some of these dipping clays can be shown to be resting on sloping channel banks. The slope component of the channel bank matches the dip component of the overlying beds. The primary dip surface merely reflects the underlying surface slope.

Drape dips of the type described can persist through numerous thin clay beds which show little tendency to thicken downslope. This behavior probably reflects the gelling property of these clays which accumulate by the settling of a late stage very fine suspended load, which gels to form a compact and firm bed parallel to the surface of deposition. The resulting steep primary dip surfaces do not reflect the high energy environment typical of crossbeds but rather are a product of a subsequent low energy environment.

Silts

The silts of the Ludlow Formation are relegated to an apparently natural accessory position by their occurrence as part of the clay and coarser clastic alternations, previously described, or because they occur as an admixture in clays and sandstones. Although accessory, the silts are an important part of the bulk of both the clay alternations and the coarser sand fractions and probably do not receive the attention they deserve.

Sandstones

The sandstones of the Ludlow Formation are separable readily on outcrop characteristics into two basic types. These are the somber clayey sandstones which form gray rilled badlands and the light yellow winnowed sandstones which form cliffs or sandy vegetated slopes.

The somber clayey sandstones are characterized by changing upward and laterally into clays at both abrupt and grading contacts. The surfaces of change are typically complex, the two sediment types being intricately associated, with wedges and lenses of one intimately intermixing with the other. Most commonly the individual beds of this sandstone, when seen in an appropriately oriented section, are gently dipping tapered lenses, the tips of which dip more gently than the main portion. Upper and lower contacts are sigmoid. The upper feathering edge is typically a clay or is clay rich, and the lateral juxtaposition of these clay edges produces a clay cap for the underlying sandstone which falsely looks like a single clay unit. These lenses represent lateral accretion in a complex and rapidly varying environment of deposition. Within the sandstones many of the common bedding and sedimentary structures such as cross lamination and crossbedding are locally well developed.

Geometrically, the somber clayey sandstones have a long dimension and are relatively thick in proportion to the least dimension. Some fill relatively narrow troughs, but others are relatively broad though still with a pronounced elongation.

Contacts with underlying beds tend to be abrupt. The upper parts of most of these sandstones grade to clays through the earlier discussed tapered upper clayey ends of the accretion units. Lateral contacts are in part abrupt and part gradational into alternations of clay and gray sandstone.

These somber clayey sandstones typically are inset into older stratigraphic units in eroded channels or fill depressions in which the underlying beds "sag under" the thickened sandstone bodies if one uses an overlying lignite as a level datum.

The somber clayey sandstones contain scattered vertebrate and invertebrate fossils, all apparently fresh water inhabitants. The recognizable flora is largely leaves and is erratically distributed through these sandstones. Abundant fragmented lignitic material is disseminated through the body of the rock and locally it occurs as laminae and thin beds.

Rough, very large carbonate concretions are common in these sandstones as are dark, brownish-red metallic ironstones. The outcrop of the somber sandstones are commonly littered with pavements and lag gravels of concretions and nodules.

The light yellow winnowed sandstones are characterized by a low clay content and typically do not have closely associated clays or clay beds in the form of included wedges, or lenses. The sands are commonly massive, and though lateral accretion can be demonstrated, the evidence for this mode of accumulation does not pervade the rock. Within the sandstone many of the common bedding and sedimentary structures can be found, but cross lamination is persistent and especially well developed near the top of these sand bodies.

Geometrically, the light yellow winnowed sandstones tend to be sheet-like and are relatively thin compared to their other dimensions, although one occurrence is known in the Ludlow Formation which is linear. Their contacts are parallel to underlying and overlying beds.

Contacts with underlying and overlying beds tend to be abrupt. Lateral contacts are either abruptly truncated or gradational into alternations of clay and yellow sandstone.

Vertebrate and invertebrate fossils are scarce in these sandstones. Plant fossils, particularly leaf impressions, are fairly common in areas of carbonate concretions.

Smooth carbonate concretions are fairly common toward the top of some light yellow winnowed sandstones where they form protective ledges for the underlying rocks. Ironstones are poorly developed.

The most obvious difference between the two sandstone types in the Ludlow Formation is the color contrast. However, as seen in the preceding discussion, the sandstones are fundamentally different; their present distinction must have resulted from different primary modes of deposition and from different secondary responses to weathering and erosion.

The geometry, bed forms, sedimentary structures, complex internal relations between clays and sandstones, the fining upward, and the fresh water fauna indicate with some degree of certainty that the somber clayey sandstones are alluvial stream deposits. Part are point bar deposits associated with intensely meandering streams, while others are fills in gradually abandoned channels. The relatively high clay content of these sandstones has restricted penetration of weathering phenomenon by limiting water flow, and the abundant organic material has overwhelmed the potential for oxidation, and surface and subsurface properties are similar.

The origin of the light yellow winnowed sandstones is less certain. Their most striking property is their relative lack of fine clastic sediments in a section rich in clays. This winnowing of the finer clastic sediments is suggestive of levee crest deposits but may reflect marine or lacustrine margin wave processes or perhaps winnowing associated with tidal ebb and flow. The high permeability and the low organic content of these rocks has permitted some penetration of weathering.

Concretions and Nodules

The concretions and nodules of the Ludlow Formation can be classified in two general categories, carbonate concretions and ironstone nodules.

Carbonate concretions in the Ludlow Formation can be further subdivided on the basis of color and surface texture. The most common and abundant of the concretions are the rough surfaced concretions which are grayish in overall tone and variably hued from grayish white to dull yellow and vary in shape from nearly spherical to elongate log-like bodies. Surface textures vary from a small-scale roughness with less than a fraction of an inch between individual low relief surface points to sharp and hackly surfaces with splinters measured in inches.

The rough-surfaced concretions may be massive and structureless or preserve sedimentary structures like those of the enclosing matrix. Preservation of pre-concretion structures is especially striking when crossbedding can be traced from the overlying matrix through the concretion into the underlying matrix.

As pointed out by Jacob (1973), for younger formations the long dimension of linear concretions commonly parallels the dip direction of the cross strata, and the lengths of the concretion can be used, with discretion, as paleocurrent direction indicators.

Contact between the irregular concretionary masses and the matrix is typically abrupt, but some specimens show gradational contacts.

Rough-surfaced concretions occur in groups and fields adjacent to concretion-free areas in the same sandstone body. Although I have no quantitative data to substantiate this observation, it is my impression that the concretions occupy what was earlier the most permeable part of the sandstone. The concretion-forming process has substantially reduced this permeability locally by filling and replacement of the matrix with carbonate.

The concretions are mechanically strong, resist chemical weathering, and commonly occur as caps on pedestal rocks where the concretions form a cover for a pillar of underlying, protected, less resistant sandstone.

Smooth concretions of the second subdivision occur only in the upper part of the Ludlow Formation as weathered buff to yellow lenses and discontinuous beds of carbonate a foot or more in thickness with a few feet to a few tens of feet of exposure along the outcrop parallel to the bedding. The rock is probably dolomite or dolomitic, for it effervesces weakly in dilute hydrochloric acid. It is dull gray when fresh, finely crystalline and without apparent porosity, being compact and well indurated. It is one of the few materials in the Ludlow Formation for which the term rock is fully appropriate.

The smooth concretions are commonly broken by fractures which are normal to bedding in thin concretions or are subradial in lenticular concretions. The fracture surfaces are shallowly conchoidal.

The smooth concretions resist weathering, and the fractured lenticular masses are conspicuous where developed. Small talus slopes of sharp edged angular blocks, derived from the typically developed nearly radial fracture pattern, coat the slopes below many concretions of this type.

The origin of the smooth concretions is problematic. The smaller ovoid bodies appear to crosscut the bedding and hence are probably secondary. Some of the more flattened bed-like concretions represent cementation of the upper part of a sandstone, and the preserved cross lamination clearly demonstrates their secondary nature. Some concretions occur as discontinuous "near beds," recurring laterally at approximately the same stratigraphic horizon and these may represent primary fresh water carbonate deposits. Extended field and laboratory studies will be needed to resolve the relationship of these bodies to the enclosing rocks.

Metallic gun blue to nearly black ironstone nodules which may weather with dull reddish brown to buff surfaces are very common in the gray channel fill sandstones of the Ludlow Formation. The nodules range from small isolated spheres, less than an inch in diameter, through complex larger irregular rounded forms to thin beds which extend along the outcrop for many tens of feet. The small isolated nodules may be so common as to form treacherous lag gravels on slopes, and the ironstone beds are occasionally persistent and resistant enough to make a cap on which small local erosion surfaces form. Surfaces of the nodules are variably and complexly patterned with "alligator skin" like plates and depressions being common.

Among the more unusual of the ironstone nodules are those where iron-bearing compounds have replaced clay pebbles and cobbles in some of the gray clayey sandstones. The earlier clay clasts now occur as brown rounded ironstone nodules in an apparently unaltered matrix or within an iron-enriched matrix. In the former case of the unaltered matrix the nodules appear to have been reworked clasts of early formed nodules, and such exposures were taken as evidence that the ironstone nodules were formed in Ludlow time and incorporated in the channel fills as large particles. However, exposures along the banks of Horse Creek, in sec 13, T135N, R106W, show the ironstone nodules to be ironstone replacements of clay clasts in the sandstone and clearly indicate that the iron replacement occurred after channel filling. In these outcrops all degrees of ironstone replacement occur, varying through the range from slight discoloration to total iron oxide replacement of clasts. Alteration is less complete in the matrix, for the high silica content of the matrix has apparently inhibited the development of the more complete replacement stages within the matrix. Most alteration takes place in clasts in the pebble- and cobble-size range, but occasional clay boulders are partially affected.

While the above outcrops do not necessitate that all rounded ironstones in channel fills in the Ludlow Formation represent later replacement of clay clasts, they do raise serious questions about simply assuming the clasts were reworked as ironstone nodules formed early in the history of the unit.

Iron sulfide nodules are common in some of the lignites and in coarser clastics, marginal to lignites. The nodules are marcasite or pyrite, up to six inches in maximum length, and of highly variable shape, though subspherical forms, about one inch in diameter, coated with small crystals, are most common. When fresh, the nodules are brassy to bronzy and greenish yellow with a metallic luster. Most have weathered sufficiently to have a dull gray color and a submetallic luster. Further weathering oxidizes the formerly heavy and resistant nodules to a soft core of powdery gypsum surrounded by a red and buff rim of clayey iron oxides. The red color, associated with the weathering, locally forms small bright red spots and rims which are almost scarlet and which contrast sharply with the generally subdued colors of the Ludlow Formation.

In various localities, especially on dark clays near lignites, rosettes, fans, blades, swallowtails, and various rhombic-shaped fragments of transparent gypsum, up to a foot in length, litter the surface. These gypsum occurrences are distributed through the Ludlow Formation but seem to be especially common near the oyster-bearing upper brackish tongue. Gypsum, in the baked zones over burned lignites, at some localities, has been converted to dull white and opaque anhydrite. The field occurrence suggests the gypsum results from the oxidation of disseminated iron sulfides in the dark clays by oxygen rich, very shallow groundwater.

Channel fill sandstones locally contain areas of a few square feet to a few square yards with scattered dull white rosettes up to an inch or more in diameter. The rosettes fit the description of analcite rosettes (Denson, Bachman, and Zeller, 1959), but no further analysis has been made.

Jarosite, a hydrated, iron-potassium sulphate, sometimes forms bright yellow sulphur-like coats along fracture zones in dark clays. This mineral, identified by X-ray diffraction, is especially abundant in the dark clays of the oyster-bearing upper brackish tongue where it can be found in nearly every outcrop. It occurs locally elsewhere in the section but is not common. The occurrence in the field suggests it is a near-surface oxidation product.

Replacement of wood by silica and iron oxide is a common form of petrifaction in the Ludlow Formation. Silicification is the more abundant of the two processes and results in two differing kinds of fossil wood. The most common silicified wood consists of dull, nearly white to yellowish gray chert like silica, which has more or less completely replaced the original wood with minimal preservation of detailed internal structure, although growth rings and surface textures may be preserved. The bulbous base of trunks is most commonly preserved, but flattened logs are fairly abundant. Much less commonly the silica is glassy (opaline?) and the preservation seems to be more detailed.

Silicification is scattered lithologically, stratigraphically, and areally throughout the exposures. The base, or near the base, of lignites is a common zone for silicified stumps, but none are known to extend far enough to form useful markers.

Some logs are replaced by dull reddish brown iron oxide. Internal details of the wood are obliterated, at least at the hand lens scale, although knots and other coarser features may be preserved. Replacement of wood by iron oxides seems to be restricted to channel sandstones.

Silicification and replacement by iron oxides of wood materials may occur in close proximity in the same outcrop. Both of the silicification types and the iron oxide type occur in relative abundance within a few tens of feet of one another in sec 8, T135N, R106W.

Clinker

Zones of variably altered baked clay, silt, and sandstone overlie the burned coal seams of the Ludlow Formation. This material is locally called scoria, a name established by usage, although technically incorrect. Others have referred to the material as porcellanite or clinker. The term "clinker" is used here because it is brief and is more technically correct than the term "scoria."

In clinker zones the primary color of the overlying material has been reddened or yellowed where the alteration is slight and changed to brick red or black where the heat and oxidation have been intense. Increase in induration varies from slightly enhanced to flint hardness and locally, melting and relithification have occurred. The outcrops are invariably shattered and treacherous where more than a few feet of the material overlying the coals has been modified. The shattering effect results from the intersection of well-developed and closely-spaced sets of fractures parallel to the bedding and a more prominent irregularly planar set of perpendicular fractures. The fractures probably result from the expansion and contraction of the heated and cooled sediment, and a change in volume is probably due more to loss of water content than to simple heat expansion and contraction.

As might be expected, clays are most altered and sandstones least modified at any given level of heating. Primary bedding and sedimentary structures are commonly enhanced and beautifully displayed in slightly modified beds but disappear completely in intensely altered areas. Lignite fragments and other fossils are preserved as molds and impressions.

Carbonate concretions in a heated area are calcined and bleached, leaving a light gray to white powdery mass in the form of the concretion which stands out sharply from the enclosing reddish mass.

Ironstone concretions darken and redden. Rare specimens develop a minute columnar jointing perpendicular to the long dimension of the concretion and in which the individual columns are a fraction of an inch in greatest width.

Clinker is common in the area of outcrops of the Ludlow Formation but covers large areas only where it forms butte caps or holds up erosion surfaces as the result of the burning of the T Cross or Yule coals. Other clinkers are typically localized.

Field occurrences indicate that thick coals and reasonably high relief are required for extensive clinker deposits, but almost any coal, even those less than a foot thick, can produce a local clinker.

In addition to the alteration of the overlying beds, the burning of a coal produces a burn ash or residue consisting of the incombustibles in the coal bed. In some locations the ash, referred to here as burn ash to reduce the confusion with volcanic ash, is commonly a white, loosely compacted, almost fluffy layer of small white particles. In other localities the coal burn residue is a dull gray scoriaceous mass of fused glass. The two forms probably reflect the variability in the incombustibles in the coal and in the nature of the burning process, but definitive relationships were not established.

Recognition of burn ash and glassy burn residues in clinker areas is important in indicating the number and stratigraphic position of preburn coals. Casual observation suggests a foot of burned coal produces somewhat less than an inch of burn ash, but perhaps the most generous conclusion that one should draw is that a thick burn ash results from the burning of a thick coal.

In light of experiments where uraniferous lignites were burned to concentrate uranium minerals, the natural burn ashes and glasses are potential uranium sites, though to my knowledge none have been prospected or mined.

Fossils

Neither vertebrate nor invertebrate fossils are common in the Ludlow Formation. Occasional shells of the snail genus *Campeloma* are scattered through the formation in clay-rich sediments. At two localities, the NE¼ sec 17, T135N, R105W, and SE¼ sec 3, T136N, R104W, snail and clam shells were deposited in coquinoid masses. The first locality is associated with deposits at the margins of the School Section Creek channel and the latter is associated with a channel sandstone near the top of the Ludlow. In both cases the shells are in bar or windrow-like accumulations of nearly pure shells bordered at the same stratigraphic level by areas of more scattered specimens. Snail shells dominate the accumulations, but unionid clam shells are fairly common. The snail shells are dull white and locally cemented into more or less white concretionary masses by calcium carbonate. Less common are concretionary shell masses cemented by dull red iron oxides. Local lenses and thin beds of a shell hash sandstone and conglomerate are also associated with the shell accumulations.

A persistent, four- to six-inch, dark clay, which can be traced from the SW¼ sec 36, T136N, R105W, Golden Valley County, North Dakota, three miles southwest to the NE¼ sec 15, T135N, R105W, Slope County, North Dakota, contains fairly abundant snail shells throughout this distance which are associated with ostracodes. A few snail specimens have been collected from immediately over and underlying beds.

The fresh water fauna of the Ludlow Formation has not been collected or described by a modern worker.

Pods and lenses of oysters from one to two feet thick occur in the upper Ludlow Formation in dark carbonaceous clays. The oyster pods were first reported by Leonard (1908, p. 49), and knowledge of their distribution was expanded by Hares (1928). Brown (1948) reported the genus *Corbicula* from just above the base of the upper Ludlow Formation. From these same sites Cvancara (1966) collected and described the fauna which has been more recently collected and expanded to include foraminiferids by Van Alstine (1975). These faunas are important in establishing the existence of brackish water sedimentation within the Ludlow.

Vertebrate fossils are confined to channel and depression fill sandstones and are mostly fragments. Isolated turtle plates, bones, and partial specimens are the most common but still rare vertebrate remains. *Champsosaurus* bones and fragments and the polished plates of ganoid fishes occur sporadically. Vertebrate remains tend to occur in patches or pockets, and in these locales fragments and isolated bones are fairly common over an area of a few square feet of outcrop.

Lignitized plant fragments are abundant throughout the Ludlow Formation. Plant fragments are typically somewhat larger than matrix particles, probably reflecting the lesser density of the plant materials. Larger plant fossils are mostly leaves, which are fairly common and occur in almost every sediment and rock type. They are locally abundant and well preserved as impressions (molds) coated with lignitic films which delineate the more organic rich portions, such as the veins. Clinker zones, in which alteration has not been too intense, are commonly good sites for collecting plant fossils.

Cyclic Sedimentation

Assuming appropriate climatic conditions exist for the development of the swamp community, a coal swamp can form or migrate into areas where the water table and the sediment surface are essentially coincident. For the fresh water environment, emergence lowers the level of coincidence, and the swamp or swamp margins migrate down the slope. Submergence raises the level of coincidence, and the swamp or swamp margins migrate up the slope. In the former case new swamps form or existing swamps migrate laterally onto formerly submerged areas, and in the latter case new swamps form or existing swamps migrate laterally onto formerly exposed areas. As a result, swamps can rest on any fresh water sediment, either formerly submerged lacustrine deposits or formerly exposed alluvial deposits.

Once in existence at a given site a coal swamp may persist with or without the accumulation of large amounts of organic debris.

A swamp may be terminated by an influx of water. The coincidence of the water surface and the sediment surface is lost; the sediment surface is lowered and the swamp drowns.

A coal swamp may be partially or completely destroyed by erosion.

A coal swamp may be terminated by an influx of sediment. The coincidence of the water table and the sediment is lost; the sediment surface is raised and the swamp is buried by clastic sediment.

The preceding brief statements suggest that a coal swamp, once formed at a given site may persist; with or without forming a significant coal deposit, may drown; may be partially or completely eroded; may be buried; or may migrate from the site. Migration merely defers the other cases. Drowning, partial erosion, and burial are the causes for differing sediment types overlying a coal.

If a swamp drowns, lacustrine deposits overlie the coal; if it is partially eroded, channel fill or crevasse splay deposits overlie the coal; and, if it is buried, it is overlain by point bar or levee deposits.

All of the inferred relationships can be seen in the sediments underlying and overlying the lignites of the Ludlow Formation.

The Ludlow Formation along the Little Missouri River contains approximately twenty coals on the order of a foot or more in thickness which are typically separated by twenty to thirty feet of clastic sediments. Although the coals of the Ludlow Formation are repetitive, the formation is only rudely cyclical. The thin alternations of clay and coarser clastics, typical of overbank sediment, are the dominant sediment type, and, by virtue of this abundance, coals are most frequently buried and overlain by overbank sediment. No special cause is necessary for this repeated relationship other than a supply of sediment, in excess of the subsidence rate, which is sporadically supplied to any given depositional site by the vagaries of alluvial deposition. Where overbank sedimentation was delayed, subsidence leads to thick coal deposits or to coals overlain by lake deposits. No special cyclic causes seem to be necessary to explain the coals and related beds other than the interaction of subsidence and sediment supply.

The preceding discussion was concerned only with fresh water deposits. The occurrence of oyster-bearing clays in the Ludlow Formation indicates clearly the existence of the marine transition environment along the Little Missouri River in Ludlow time. The addition of the many environments of deposition associated with the marine transition zone greatly complicates the interpretation of the sedimentary environment. If a swamp drowned, the invading water may not have been fresh, but could have been brackish or marine. In addition to the lacustrine environment, such environments as interdistributary bay, lagoon, estuarine, etc., must be considered. Correspondingly, if the swamp was buried, such transition deposits as beach, barrier island, cheniers, etc., may be present.

Except for the *Corbicula* and oyster-bearing tongues, fossils are rare and by their absence of little help in determining past salinities. The overall lack of fossils, other than fresh water types in beds other than the above tongues, suggests that the finer-grained sediments are dominantly of fresh water origin.

For the coarser clastics, the channel and depression fill sandstones contain fresh water invertebrates. The sheet sandstones of the yellow marker type are, with one exception, faunally unfossiliferous.

CONTACTS AND SUBDIVISION OF THE LUDLOW FORMATION

General

The Ludlow Formation, along the Little Missouri River, may be subdivided into various thin units which are useful, at least for descriptive purposes. On a larger scale the formation can be subdivided, using the base of the T Cross coal as a dividing horizon, into a lower Ludlow Formation and an upper Ludlow Formation. Such a division separates the lower section, with numerous, thin, typically noneconomic coals, from the overlying beds which contain thick, potentially economic coals. So divided, the upper Ludlow contains the known brackish water sediments of the Ludlow. This two-fold subdivision of the Ludlow is possible and practical because of the persistence in the area of outcrop of the thick T Cross coal or the clinker and burn ash derived from it.

Informally named units of special interest within the lower Ludlow Formation are the basal coal or coal zone and the channel sandstones, especially the Limber Pines sandstone and the cliff marker section.

Informally named units of interest in the upper Ludlow Formation are the T Cross lignite and its overlying brackish clay tongue, the School Section Creek sandstone, the straight sandstone, the west yellow marker, the glasswort clay, the oyster coal and its overlying brackish water sediments, the beach section, and the white siliceous bed.

These subdivisions are described in stratigraphic order from oldest to youngest in the following paragraphs.

Lower Contact

The lower contact of the Ludlow Formation with the underlying Hell Creek Formation is placed at the base of the lowermost persistent coal in this portion of the stratigraphic column. The coal may be reduced laterally to a smut, lignitic shale, or carbonaceous clay, but with good exposures its continuity with laterally equivalent coal can be confirmed. This arbitrary choice of contact marks a more fundamental change in rock character than just the occurrence of a coal would suggest. Below the coal, the gray sandstones and gray clays of the Hell Creek form a large-scale mix of rock types, lacking widespread lateral continuity. The generalized lack of lateral stratigraphic persistence in the Hell Creek contrasts with the lateral continuity of beds and groups of beds of the Ludlow which can be seen by eye and confirmed by field tracing. The preceding statement concerning the variability of the Hell Creek Formation is contradicted to some degree by the sediments immediately underlying the contact. This unit, established as the Pretty Butte Member of the Hell Creek Formation by Frye (1969, p. 38), has, as its top, a persistent uppermost gray to blue gray swelling clay zone (bentonite). With experience one finds this persistent uppermost part of the Hell Creek Formation to be as useful a stratigraphic tool as the overlying coal bed.

In the Little Missouri River area Hares (1928), in his regional study of the Marmarth coal field, also used the lowest persistent coal as the base of his "Ludlow member" of the "Lance formation." He referred to this lowest persistent coal as the Cannonball coal (Hares, 1928, fig. 1), presumably named for exposures on Cannonball Creek (1928, p. 48), which joins the Little Missouri River from the west and which should not be confused with the more easterly and larger Cannonball River. Kepferle and Culbertson (1955, p. 134) continued the use of the term Cannonball coal, but this nomenclature should be discontinued because of the similarity to and chances of confusion with the Cannonball Formation.

The importance of this coal zone as a marker for the boundary between the Paleocene Ludlow Formation and the underlying Cretaceous Hell Creek

Formation was apparently first published by Calvert (1912, p. 196, 197) for relationships in the vicinity of Glendive, Montana, northwest of this study area. However, the general difference between the underlying nonlignitic and dinosaur-bearing beds and the overlying non-dinosaur-bearing and lignitic beds was understood by other and earlier workers. This base has been utilized by later workers and advocated by Brown (1962, p. 11), who states "Calvert's basal coal zone, as proved at all localities east of the present Continental Divide and north of the Colorado-Wyoming line to the Canadian border, can, with a little experience be detected readily and mapped satisfactorily." Brown, in an expanded statement concerning this contact, uses the lowest persistent coal as the marker for Cretaceous-Paleocene boundary. This generalization applies to the area of the Little Missouri River, for dinosaur fragments can be collected, at scattered but fairly numerous localities, to within several feet of the lowest persistent coal. None have been collected from above this coal where the vertebrate fauna instead consists of bony fish plates, turtle bones, and fragmental skeletons of *Champsosaurus*.

Like most stratigraphic generalizations, the use of the contact between the Pretty Butte Member and the lowest persistent coal to mark the contact of the Hell Creek and Ludlow Formations breaks down locally because of minor erosional unconformities and facies changes.

Minor erosional unconformities alter the normal contact where channels slightly younger than lowest persistent coal were eroded through this coal zone and into portions of the underlying Pretty Butte Member and were then back filled with clastics so that Ludlow channel sands rest directly on some part of the Pretty Butte Member. This situation can be viewed in SE¼ sec 28, T135N, R106W, just northeast of the crossing of Cottonwood Creek by the west Marmarth road. Similar channel contacts are known at other localities.

Facies changes in the Pretty Butte Member and in the lower persistent coal zone bring uncharacteristic sediments into contact. The uppermost clay of the Pretty Butte Member grades laterally and downward into a light gray silt and sandstone along sigmoid bedding surfaces, which suggests that the clay and its underlying sand are facies equivalents resulting from point bar deposition along shallow high sinuosity streams. Scattered lapses in this sedimentation pattern place sediments other than the typical gray bentonites under the lowest persistent coal. Again lateral tracing demonstrates a return to the typical circumstance in relatively short distances.

As suggested earlier, the basal coal, though typically a coal, changes along the outcrop from thick to thin lignite, through smuts, to lignitic shale and carbonaceous clay. In areas of good exposure, reasonable care will detect such changes. In areas of poor exposure, movement of the contact upward to the next higher coal probably results unless the Pretty Butte Member can be identified. It is possible that in regional studies the contact may be a series of such steps, though this possibility is minimized by the common occurrence of dinosaur-bearing beds within a few feet of the coal zone.

Frye (1969, p. 25) emphasized that more than one criteria is needed to separate Paleocene beds from the underlying Cretaceous. For reconnaissance purposes in southwestern North Dakota, one of the easiest approaches to finding the base of the Ludlow Formation is to look for the lowest yellow coloration. At many locations the beds immediately overlying the lowest persistent coal, or its equivalents, are light yellow friable sandstone and siltstone beds. With one exception, I know of no occurrence of the light yellow coloration in the upper Hell Creek Formation in this area. This lowest yellow zone was pointed out to me by Frye and hence was carried in my field notes as the Frye marker.

In south-central North Dakota, where the Ludlow Formation is in close lateral and vertical contact with the overlying marine Cannonball Formation, the abundance of lignitic material and the lack of bentonites serves to separate it from the underlying Hell Creek Formation and the overlying Cannonball Formation.

Basal Coal or Basal Coal Zone

Early in the study of the Ludlow Formation, the basal part of the unit was observed over a large area to consist of a thin lower coal, overlain by a light yellow to buff clastic section, followed by a second coal. Later study showed the two coals to merge and form a single, commonly clinker-forming coal, up to seven feet thick. This lower coal, or where split, lower coal zone, overlies the Pretty Butte Member of the Hell Creek Formation and forms the lowest unit of the Ludlow.

The sediments which form the split for the basal coal may exceed ten feet in thickness and range from a nearly pure, very friable, light yellow, fine-grained sandstone and siltstone through sections of similar sandstone and siltstone interbedded with various amounts of light gray clay to sections dominated by dull gray clay. All rock types include variable amounts of lignitic material. Color closely follows the dominant lithology. Sandy sections are light yellow buff or light gray, grading toward darker grays with increasing clay content. As indicated earlier this facies forms a striking color contrast at or very near the base of the Ludlow Formation, where developed as a sandy light yellow phase.

The basal coal zone was studied by Hickey (1973). He concluded that the beds between the lignites were levee, well drained swamp, lacustrine and crevasse splay deposits which intertongued with coal swamp deposits.

Measured sections of the basal coal zone are shown in plate 1. A thick unsplit lignite occurs along a northeast-southwest trend between the three easterly measured sections of line A-B and the westernmost section of line C-D (from SE¼ sec 10, T13N, R106W, to SE¼ sec 25, T135N, R106W) as shown on plate 1. This coal grades to the northwest into a lignitic shale and intertongues with a lignitic sandstone probably derived from swamp margin stream. The coal is split to the southeast by a section of interbedded silts and clays. The silts and clays are indistinctly interlayered so that scraped surfaces show a mottled mixture of light gray clay and dull yellow silt with an overall yellowish gray cast. The mottling appears to be due to bioturbation of an original cyclically interlayered clay and silt. Definite burrows are lacking and the mixing is seen as vaguely bounded lenses of clay and silt which are suggestive of root disturbance rather than burrowing. These sediments probably represent flood plain deposits and were put down in well drained swamp or lower levee position.

An abrupt change occurs in the thickness of the light yellow sand rich portion of the split (sec. E, pl. 1). The two sections measured are approximately 200 yards apart and over this distance an already surface-erosionally-thinned eight feet of sandstone thins to less than a foot. The sandstone is soft, very friable and typically winnowed free of clay and minute lignite fragments, except where thin or in local patches where it may become shaly and lignitic. Internal structure, where preserved, consists of small-scale crossbedding and cross lamination. The latter seems more common near the top of this unit. The rapid thinning, erratic occurrence of the sandstone, internal structures, and the association with swamp and probable overbank sediment suggest the sandstones are levee deposits.

Clay Plugs

Overlying channel fill sandstones in a few areas in the lower Ludlow Formation, typically closely associated with the lower coal zone, are very dull black to bluish black swelling clay beds less than ten feet thick. These clay layers are particularly striking because they cap buttes or form shoulders, the black color of which contrasts sharply with the underlying gray white channel sandstones. The clays are swollen and fragmented into a "popcorn" surface when dry and form a stiff slurry when wet. These clays occasionally flow and slide down underlying slopes, leaving a dark trail. Unweathered specimens of these beds are nearly pure black clay containing very fine disseminated organic matter. Scattered, dull white, silicified stumps, up to four feet in diameter, which commonly display cone-in-cone structure, occur along the tops of the outcrops. An area of several acres is covered with a clay of this type in sec 14, T135N, R106W, Slope County, North Dakota.

The bulk of the above clays probably represent lacustrine deposits which formed after the abandonment of a partially filled alluvial channel. The purity of the clays and their high organic content suggests that these probable cutoff meander or oxbow deposits were nearly completely surrounded by swamps which inhibited any influx of coarser clastics. The stumps suggest the gradual encroachment of swamp conditions in the late stages of the clay fill. These deposits are almost certainly remnants of ancient clay plugs.

Cliff Marker Sandstone

A bright yellow sandstone several tens of feet thick forms a sheer cliff along the west side of the Little Missouri River just north of the mouth of Cannonball Creek in sec 29, T135N, R105W, Slope County, North Dakota. This sandstone will hereafter be informally referred to as the cliff marker sandstone.

The cliff marker sandstone can be traced westward along both sides of Cannonball Creek for at least four miles up from the mouth. In these exposures it forms a persistent light yellow marker which can reasonably be inferred to have extended over a minimum area of at least ten to twelve square miles. Although it has one of the larger exposure belts of the light yellow winnowed sandstones, outcrops are typically poorly exposed and the unit was not studied in detail. Observations indicate it has the features common to the later described west yellow marker sandstone and the straight sandstone.

Stratigraphic sections involving the cliff marker sandstone are illustrated in plate 2.

Limber Pines Sandstone

Strikingly developed in the Ludlow Formation are gray, typically local sand bodies, which vary rapidly in thickness and in their relationship to surrounding beds. One such sandstone body strikes north-south through the west half of secs 30 and 31, T135N, R105W, into the west half of sec 6, T134N, R105W; an area south of Cannonball Creek and about one mile west of its junction with the Little Missouri River. This body will be referred to informally as the Limber Pines channel or sandstone because of the occurrence of these trees, which are rare in North Dakota, along the topographic high present in the sandstone area. This is a typical and well exposed area and will be used for the basic description.

The Limber Pines sandstone is an elongate mass of variably shaded gray, massive to crossbedded clayey and lignitic sandstone. As shown in cross section F-G, plate 3, the sand body is inset in older beds. The base of the channel, as seen along the east margin in the SE¼ sec 31, T135N, R106W, is a series of steps, with remnants of the eroded coals forming resistant flat benches, above relatively abrupt rises or banks cut in other lithologic types. The base of the channel, at least at this locality, is not a simple flattened trough but is a more complex, stepped profile formed by the lignite-supported platforms. This resistance of lignites to erosion is a common observation in this section, for many channels are bottomed at the upper margin of a lignite. This resistance of lignites to erosion probably reflects the toughness of the mat produced by the intertwining trunks and branches of the well preserved woody swamp deposits. Even today, where unslaked due to limited exposure to the atmosphere, many lignites resist erosion and form waterfall ledges and segments of rapids in actively deepening arroyos.

In secs 30 and 31, T135N, R105W, the top of the Limber Pines sandstone is a gradation up through a few feet to a few tens of feet of gray clay to a lignite or alternatively through a lignitic shale to a lignite. The lignite is about a foot thick over the sandstone body but can be traced to the north where it thickens to nearly six feet (pl. 3). To the south, the coal is absent and sandstone is overlain directly by another sand unit.

The Limber Pines sandstone extends

north to W½ sec 19, T135N, R105W, where it is exposed along the divide between Cannonball and Horse Creeks. Because of the valley of Cannonball Creek, these exposures are isolated from the main body of the Limber Pines sandstone by a distance of about a mile. However, correlation with the main body is reasonable as these outcrops are intercepted by the projection of the strike of the long dimension of the main body, and the stratigraphic position of the top of this sandstone is similarly related to the overlying coals. The northern outcrop is atypical, showing a division of the sandstone into two parts by a relatively persistent clayey and lignitic shale zone at about the middle. It is possible that only the upper part of the exposure is equivalent to the Limber Pines sandstone and that the lower part represents an earlier unrelated channel fill. Exposures do not permit the tracing of the middle shaly zone laterally to test for its confinement to the channel. If the shaly zone is confined to the channel it clearly indicates that the two sandstones are episodes in the fill of a single channel. Tentatively, only the upper sandstone body is considered to be equivalent to the Limber Pines sandstone.

Exposures along the bottom of Horse Creek, in the W½ sec 13, T135N, R106W, northwest of the above outcrops, contain a gray sandstone section of uncertain stratigraphic position which is very similar and may be correlative with the Limber Pines sandstone. These outcrops are notable for their content of large, partly concretionary, clay cobbles and boulders. Clasts commonly are rounded, in part fractured and have previously joined fragments in close proximity. Particles range in size from several inches to as much as five feet in largest exposed dimension. The particles commonly "float" in a matrix of light gray sandstone and are variably separated by intervals of inches to feet. Clasts tend to be concentrated in large irregular patches and streaks. Occasional irregular patches of the outcrop have a chaotic assemblage of clay clasts of widely varying size, shape, and distribution. The clay and lignitic shale fragments swell on exposure and form a soft fluffy surface which weakly contrasts with the more smoothly faced but slightly swollen surface of the similarly colored enclosing sandstone. Occasional clasts have sloughed from the outcrop leaving cobble- and boulder-shaped holes in the sandstone. The sandstone matrix in the areas of cobble and boulder concentrations has a higher content of clay which swells and softens the sandstones in these areas.

Similar clay cobble and boulder concentrations occur in sandstones near the mouth of Horse Creek and in other scattered occurrences elsewhere in the lower Ludlow Formation. Though it could not be demonstrated on the outcrop, the heterogeneous and large size of particles, the poor sorting and chaotic texture, and the higher clay content of the adjoining matrix, make it seem probable that the cobble and boulder areas are channel fill deposits located at the toe or slightly downstream from a site of bank caving and slumping, possibly on the outside of a meander. The alteration of some of these cobbles and boulders to concretions was discussed earlier under concretions and nodules.

The Limber Pines sandstone is a fine- to medium, rarely coarse-grained sandstone with an overall light to medium gray color at a distance and a black and white, salt and pepper appearance up close. Under the hand lens this sandstone is poorly sorted and has a complex mineralogy. It is reasonably indurated, tough and only partly friable. The cement is apparently clay or a minor amount of silica. Sufficient carbonate to effervesce in weak acid is not usually present and hence is probably not an important cementing agent outside of areas modified by concretions. The softened, swollen, and slick surfaces of the sandstone which develop after a rain suggest that a swelling clay is the important binding agent.

Sedimentary structures within the Limber Pines sandstone vary greatly in scale and expression. Much of the sand appears massive and, except for widely spaced bedding, is without visible smaller structure on the outcrop. Scattered outcrops, however, show cross lamination, crossbedding on a scale of several feet, and very large-scale crossbedding on a scale of tens of feet. Such features are commonly outlined by thin dark lignitic sand layers deposited in moments of less agitated water when the low-density lignite fragments could come to rest.

Some of the very large-scale crossbedding surfaces are convex upward with a steep upper slope and a lower slope which tails off gently toward the lower contact. The sand body between the bedding surfaces grades upward into clays and the change from sand to sandy clay varies rapidly in position from one wedge or sigmoid bed to the next. These beds almost certainly represent individual lateral accretion units within a point bar deposit in a large stream transporting mainly sand.

This sandstone unit commonly weathers to smooth, steep faces and the outcrop is characteristically rounded and without sharp corners. Occasionally, fluting with sharp small scale ridges and numerous intervening narrow rill channels develops in a typical badlands format and covers a surface of steeply sloping outcrop. More common, in lower slope areas, is an intensely dissected surface of dendritic patterned rills with broadly rounded or nearly flat divides. Local groupings or fields of concretions of extremely variable sizes and shapes are common throughout the Limber Pines sandstone (see an earlier discussion of concretions and nodules for details).

The greater than ninety-foot depth of the channel, the large-scale crossbedding, the clay boulder deposits, and the relatively coarse poorly sorted nature of the Limber Pines sandstone suggest it represents the deposits of a major stream. Dip components for the larger-scale crossbedding and the map projections of the channel margins suggest a southerly flow in a near north-south channel.

T Cross Coal and Clay

The thickest and apparently most widespread coal of the Ludlow Formation is the T Cross coal. This coal takes its name from the old T Cross ranch which was located in sec 20, T133N, R105W, Slope County, North Dakota. Hares (1928, p. 87) reports the coal is "twenty-four feet thick at the T Cross mine in sec 10, in the bank of Bacon Creek." This is the greatest reported thickness of this coal, which more typically is about ten feet thick. The T Cross is commonly split by one or more lignitic shale zones into two or three relatively clean seams.

Burning of the T Cross coal at the outcrop has produced some of the thickest and most persistent clinker and burn ash zones in the Ludlow Formation. Many of the flat topped ridges and buttes along the Little Missouri River are held up by this clinker and in grassy low relief areas the T Cross can usually be located by its thick clinker.

The bed overlying the T Cross is consistently three to six feet thick and very dark brown, to nearly black very fine carbonaceous clay which weathers brown or occasionally with a purplish hue. The clay is commonly nearly fissile and is also broken by closely spaced vertical fractures which are commonly lined with powdered layers or massive films of jarosite up to a quarter of an inch thick. The clay is nonswelling and this property sets it off, along with a stratigraphically higher and similar oyster-bearing clay, from most of clay and clay rich zones of the Ludlow.

The lower foot of the clay contains a few molds of flattened clams and snails which are persistent in small numbers at this horizon. The fossils are more readily located when these beds have been baked, as the fossils then occur as reddened films in impressions on the brick-like fired clay. Van Alstine (1975, p. 25) reports brackish water bivalves and foraminiferids from the base of this clay section. He did not report the gastropods.

The combination of the relatively thick T Cross coal and the overlying nonswelling clay produces an extremely useful horizon marker in the study of the Ludlow Formation.

The T Cross lignites extend across southwestern North Dakota into South Dakota where it correlates with the Giannonatti bed of northwestern South Dakota (Hares, 1928, p. 47). To the west, Hares (1928, p. 25) concludes the "T Cross bed is undoubtedly the 'lowest persistent lignite' bed mapped in eastern Montana." Though the T Cross lignite can be correlated into Montana, and indeed may be the "lowest persistent lignite" mapped in the eastern coal field studies, it is not the coal or coal zone at the Hell Creek Formation and Ludlow Formation boundary, that is, the lowest persistent coal of Brown (1962), but occurs one hundred to two hundred or more feet higher in the section. This same general conclusion was reached by Bauer (1924, p. 242-243) in a discussion of the base of the "Ludlow lignitic member" in the eastern Montana coal fields.

Economic studies of the T Cross coal were updated with the publication of an estimation of shippable coal in the vicinity of the old T Cross mine by Kepferle and Culbertson (1955, p. 74, 75).

The relatively great average thickness and the widespread areal distribution of the T Cross coal indicate the existence in middle Ludlow time of a persistent and large swamp in southwestern North Dakota, eastern Montana, and northwestern South Dakota. If one uses a four to one compaction ratio (Ting, 1974, p. 21, 24), in excess of one hundred feet of peat must have accumulated in the T Cross mine area of sec 20, T130N, R104W, Slope County, North Dakota, and between twenty-five and fifty feet was typical over much of the remaining area. Interruption of swamp conditions locally by drowning and the initiation of lacustrine conditions is indicated by the carbonaceous clay and lignitic shales which form scattered splits in the coal. The overlying brackish water fossil-bearing clay beds suggest the final destruction of the T Cross coal swamp by the incursion of quiet water marginal marine conditions in the form of lagoons or bays. This brackish environment gave way in time to fresh water and alluvial conditions, for the sediments overlying the clay above the T Cross bed are typical of those of the remaining Ludlow. Van Alstine (1975, p. 21) reports fresh water fossils from this interval.

A fresh water swamp succeeded by a brackish environment as a result of a partial marine incursion raises the possibility that the T Cross lignite is time transgressive, being younger to the east and older to the west. However reasonable this may be in concept, and probably correct in detail, I know of no data, other than the general paleogeographic setting and the stratigraphic sequence, to indicate that the T Cross bed is not essentially time synchronous, within our present ability to discriminate geologic time, in this part of the geologic record.

School Section Creek Sandstone

The earlier described Limber Pines sandstone is especially striking because of its large size and clearly inset nature. Its features are typical of a broad range of such channels and channel fills, from a few feet to many tens of feet thick, which are common throughout the Ludlow Formation and which are especially well developed in the lower Ludlow.

The Limber Pines sandstone occupies a clearly eroded and inset channel, as do many of the sandstones in the Ludlow Formation. Sandstones also occur which occupy depressions which are not, or are only partially of erosional origin. Such a depression and channel fill occurs in sec 8, T135N, R106W, which will be referred to informally, as the School Section channel and sandstone because of its good exposure along the creek known locally as School Section Creek.

The School Section sandstone is underlain and overlain by pairs of coals which can be traced laterally with confidence (see pls. 4-6). These paired coals are separated by less than two feet of section at one location along the south line of sec 10, T135N, R106W. Traced westward into sec 8, T135N, R106W, a distance of less than one and one half miles, these coal pairs are separated by over seventy feet of sandstones and channel fill deposits. Most of the visible School Section channel fill deposits rest directly on or within a few feet of the underlying marker coal pair. At one location seventeen feet of post-lower-coal pair and pre-channel deposits are preserved, indicative of some pre-channel fill and its later erosion, but most of the channel fill occupies a depression of non-erosional origin.

This increased interval between marker beds along the axis of channels, when compared with lateral thicknesses over correlative intervals, is a common phenomenon. Some of the difference in thickness is due to differential compaction between channel fill and laterally equivalent beds with a high clay content but, as in the above example, lateral compaction probably cannot account for all of the interval difference. Differential compaction of beds beneath the channel fills may be involved, for the underlying Hell Creek and Pierre Formations contain many thick clay units. Development of a surface depression by differential compaction in underlying beds and the occupation of this depression by a stream, with or without erosion of possible earlier partial depression fill, would account for most of the features seen. Most of the depressions probably developed slowly and where shallow filled with overbank, swamp or lake deposits rather than channel associated deposits.

Channel fills in largely non-erosional depressions are unexpected, for common experience and our nomenclature indicate channel fill deposits should fill eroded depressions. Streams can occupy and fill pre-existing depressions of non-erosional origin, and the Ludlow Formation contains many alluvial fills of this type.

The non-erosional, or only partially erosional, channels used by streams may be the result of differential compaction, but at least two other reasonable coexisting or alternative processes may be involved. The Ludlow Formation along the Little Missouri River in North Dakota lies northeast of the Cedar Creek anticline, a structure active during late Mesozoic and early Cenozoic time. Structural deformation of a minor type might be involved in depression development. Also, this same area is underlain by Paleozoic and Mesozoic salt beds of considerable thickness, and depressions due to salt solution, preserved by thick fills, are known from beds removed short distances stratigraphically and areally from the Ludlow exposures. Similar solution depressions may explain some Ludlow depressions.

Stratigraphic sections involving the School Section Creek sandstone are illustrated on plate 5.

Straight Sandstone

The sandstone body, hereafter informally referred to as the straight sandstone, is variably exposed in secs 4 and 10, T135N, R105W. Excellent exposures of the sandstone occur in a "straight" cliff outcrop along the west side of the Little Missouri River in SW¼ sec 10. In the latter outcrop the sandstone misleadingly appears to be a thick sheet sandstone because the strike of the outcrop approximates the strike of the long dimension of this trough-shaped sandstone body. Closer examination demonstrates that the straight sandstone fills a depression between the same paired coals which contain the School Section Creek sandstone (pl. 5). The two bodies are laterally separated by an area in which the paired coals are vertically removed from one another by only a few feet of sediments. West of this thin interval the School Section Creek sandstone fills a depression, while to the east a similar depression is occupied by the straight sandstone. The west margin of the straight sandstone is the thin interval between the paired coals; the eastern margin is a rapid thinning of the sandstone between the overlying coal pair and an underlying clay-rich section. The overlying coal tends to thin and disappear over the upper part of the straight sandstone in the northern outcrops. The resulting geometry is an elongate body up to 400 yards wide, 50 feet thick, and in excess of two miles in length. The lateral margins are relatively sharply tapered wedges, and the top is flat to slightly convex upward while the base is broadly trough shaped. Contacts with underlying and overlying beds are abrupt.

In spite of their equivalent stratigraphic position and close geographic proximity the two sandstone bodies are not alike. The earlier described School Section Creek sandstone is a typical gray clayey depression fill sandstone. The straight sandstone, except for its linear and channeled character, has the color and physical properties of the sheet sandstones.

It is relatively clay free, commonly cross laminated and crossbedded on several scales, with the crossbedding giving way upward to cross lamination. The upper part is characterized by carbonate cementation which locally yields elongate concretionary masses.

The well winnowed sands of the straight sandstone suggest a levee or possibly a marine or lacustrine margin related origin for this rock body. If the straight sandstone is a levee deposit it has an unusual geometry. The trough shape of the body, its abrupt contacts with underlying and overlying sediments and its internal structure suggests depression and eroded channel filling by alluvial processes. A tidal inlet channel provides a possible origin for this sandstone which would explain the combined properties. The sand is winnowed and the gross features developed with the ebb and flow of the tides. The assignment of the straight sandstone to a tidal channel is probably too specific an interpretation, but strandline as well as alluvial processes may have been involved in its origin.

West Yellow Marker

Bright yellow sandstones are conspicuous along the exposed upper slopes of many of the escarpments developed in the Ludlow Formation. The light coloration contrasts markedly with the more somber hues of the lignitic and clay-rich portions of the formation, and these sandstones form useful marker beds. An easily accessible sandstone of this type is exposed along the divides between the tributaries of School Section Creek in secs 7, 8, and 17, T135N, R105W, Slope County, North Dakota. This sand body will be referred to informally as the west yellow marker and will be used for the basic description of this lithologic type.

The west yellow marker is a sheetlike body of bright yellow sandstone up to twenty feet in thickness, which lies over a lignite or lignitic shale zone, and in localities where the overlying beds have not been removed by Quaternary erosion, is overlain by a dark clay or carbonaceous clay. The contact with underlying and overlying units is abrupt. The lower contact may be an erosive contact, for at some localities an otherwise persistent coal is missing, although the lignitic shales and carbonaceous clays associated with this coal are still present. If erosion preceded deposition of the marker it was of limited depth and areal extent.

The west yellow marker sandstone is a very fine to fine and occasionally medium-grained rock. In a formation otherwise characterized by poor sorting, the marker is surprisingly free of both clay and lignitic materials. It is so soft and friable that it is commonly excavated by bank swallows and wasps for nesting sites. Locally, near the top, the sandstone is firmly cemented by smooth carbonate concretions.

Sedimentary structures are locally evident, but the west yellow marker is commonly massive and without apparent internal structure on both natural and in trenched exposures. Locally, especially near the top, the sandstone is cross laminated. Associated ripples are symmetrical to the unaided eye, with subparallel crests spaced from four inches to a foot apart, and are about an inch in height. Linguloid or crescentic ripples occur but are not as common as parallel ripples.

Locally the sandstone is crossbedded on several scales. Rare, except for local concentrations, are planar crossbeds, one to two feet thick. Less common are planar or gently sigmoid sweeps which extend the full thickness of the sandstone from the top to the base with apparent dips of fifteen degrees or less.

No vertebrate fossils were seen though plant fossils are fairly common in concretionary portions of these sandstones.

The west yellow marker forms soft vegetated slopes or steep bare faces where capped by more durable beds. The rilled, bare, concretion-littered badland slopes characteristic of the channel fill sandstones are not found associated with this unit.

The west yellow marker is eroded or retreats into the subsurface to the south and west. To the east, along a nearly north-south trending time through secs 8 and 17, T135N, R105W, the west yellow marker abruptly thins to nothing or abruptly thins from over ten feet to less than three feet in thickness and changes from its typical aspect to a cross laminated sandy clay.

Other sheet sandstones of the yellow marker type are present from the basal coal zone upward through the Ludlow Formation. They reach thicknesses greater than fifty feet and can be traced along the outcrop for distances in excess of four miles.

The yellow marker sandstone, where seen along the outcrop, is rather uniform in thickness, but some of the other sheet sands show local thickenings.

Typically the contact with the under and overlying bed is abrupt; however, similar sandstones cap coarsening upward sequences where they represent the uppermost part of a sand-clay alternation sequence which is thickening and becoming sand dominant upward. These sands may have a different origin than the sheet sandstones, although the appearance and sedimentary structures are very similar.

Stratigraphic sections involving the west yellow marker are illustrated in plate 6.

Glasswort Clay

A relatively widespread clay unit is exposed along the higher ground marginal to School Section Creek in the NW¼ of T135N, R105W. The clay severely restricts plant growth and, at least locally, the outcrop is populated almost exclusively by the small salt tolerant plants known as glassworts. This clay will hereafter be informally referred to as the glasswort clay (pl. 7).

The glasswort clay is approximately twenty feet thick as exposed along the south facing escarpment extending for approximately two miles parallel to the south margins of secs 9, 10, T135N, R105W. It is very dark gray to black clay with some areas lightened by a bluish white surface cast similar to those developed on some phosphatic shales. It forms dark, smooth, barren slopes or shoulders. The clay is sticky and plastic when wet and dries to a rough granular "popcorn." Below the swollen upper surface the dry clay is massive and structureless although fragmented into small tough blocks by closely spaced fractures. Locally the clay contains, in addition to finely disseminated organic matter, isolated fragments of lignitized wood. The clay thins to nothing to the northeast and is lost in the remaining directions to the subsurface or is eroded. Many sections are nearly pure clay but a two-inch seam of lignite and thicker lignitic shales and carbonaceous clays are included as well as a foot of alternating clay and sand.

The clay overlies the west yellow marker or the upper of the pair of coals which overlies the School Section Creek and straight sandstones. It is overlain by various sediment types all of which are associated with clay and coarser clastic alternations.

The glasswort clay is a quiet water subaqueous deposit, probably lacustrine in origin, although no fossils have been found which clearly separate it from brackish or marine quiet water environments. Except for the western outcrops, where it rests on the west yellow marker or its mottled sand and clay facies, the clay rests on a coal, and the probable lacustrine environment ensued through swamp drowning. The lower part of the clay to the west probably intertongues with the west yellow marker through a laterally intervening alternation of clay and coarser clastics which are partially disrupted by bioturbation.

Locally the lake shallowed and small swamps formed lignitic shales and a thin lignite seam before the lake reoccupied the area.

The lake ultimately succumbed to burial. The overlying sediments are alternations of clay and coarser clastics typical of overbank deposits.

In summary, the glasswort clay is probably the deposit formed in a moderate sized alluvial plain lake in a depression produced after swamp drowning and which was remote from sites of deposition of coarser clastics. The lake basin was eventually filled by stream flood plain deposits.

The clay deposits of the glasswort type are closely related to clay plugs, although the latter term is here restricted to channel fill deposits which are clearly inset into older strata or overlie coarser channel fill deposits and have limited areal extent.

Oyster Clay and Lignite

Approximately 150 feet stratigraphically above the T Cross coal, at about the middle of the upper Ludlow Formation, occurs a persistent one-foot- to three-foot-thick lignite bed overlain by a dark clay which contains small oyster banks and pods. This lignite and clay zone will be hereafter informally referred to as the oyster lignite or oyster clay.

The oyster clay varies from five to over twenty feet in thickness. This variation in thickness is due, in part, to an erosional unconformity at its top and, in part, due to lateral changes to other lithologies. The clay is a rich dark brown to nearly black and sparkles with small flecks of mica. The clay is organic rich throughout with the organic matter disseminated in the clay as minute particles. The clay weathers to a dark dull reddish brown, smooth, nonswollen outcrops which occasionally have a purplish hue. The base of the clay tends to form a rounded ledge over the underlying coal, and this lower several feet of section is commonly cut by fractures lined with powdery films and layers of jarosite up to a quarter of an inch thick.

Oyster pods are typically about a foot thick and spread along the outcrop for about three feet, though oyster lenses up to about two feet thick and in excess of ten feet in horizontal width were seen. The cores of the masses of weakly consolidated and poorly preserved oyster pods are apparently in growth position. Pods are commonly surrounded by a scattering of isolated reworked specimens and occasional isolated single specimens occur. The westernmost oysters occur in a pod, in which the matrix is a reddish ironstone, and a compact concretionary mass results. Approximately ten feet above the base of the clay a six-inch to one-foot, very dark black carbonaceous clay zone, which looks like a coal on the outcrop, occurs over much of the area of exposure. The oyster pods occur from immediately overlying the oyster coal and throughout the ten feet of section underlying the previously mentioned thin very dark clay zone. Over this interval no horizon seems to be preferred. The oysters have been identified by Cvancara (1966, p. 320) as *Crassostrea glabra* (Meek and Hayden).

So far as can be ascertained, the oyster coal and the overlying clay are conformable, the lignite grading up through a few inches of gradually increasing clay content into the overlying carbonaceous clay (pl. 8). The upper contact of the oyster clay is in many locations an unconformity on which relief measured in feet can be demonstrated. The overlying beds are alternations of clay and coarser clastics and, though typically parallel to the underlying clay, primary dips of up to ten degrees occur in some outcrops.

The oyster clay, like the underlying and similar T Cross clay, was deposited in an incursion of quiet brackish waters over an earlier coal swamp site. The general lack of coarser clastics over much of the area of the oyster clay suggests a protected lagoonal or bay environment remote from both active streams and shoreline processes.

In an outcrop along the west side of the Little Missouri River in the E½ sec 1, T135N, R105W, Slope County, North Dakota, the oyster clay gives way upward to a beach deposit. Here one sees the invasion of the quiet water area by active, probably marine, shoreline processes.

Beach Sandstone

The previously discussed gray inset channel and depression fill sandstones are almost certainly of alluvial origin. The origin of the sheet sandstones such as the west yellow marker is less certain. The two sandstone types are different in many properties which must reflect a genetic difference as well as a different response to post depositional effects, particularly weathering. The differences are compared and contrasted below.

The bright yellow color of the sheet sandstones contrasts with the light to somber grays of the channel sandstones.

The yellow coloration of the former probably reflects a relative abundance of oxidized iron minerals due to rapid weathering by oxidizing surface and near surface waters. The good primary sorting of these sandstones gives these rocks a high permeability for transmitting oxidizing waters, and the low included organic content has a limited capability for inhibiting oxidation.

As implied in the preceding paragraph the sheet sandstones are relatively free of clay and organic matter which are common in the channel sandstones. This comparatively good sorting and the associated abundance of cross lamination and parallel crested symmetrical ripples suggests wave tossed water is associated with the development of the sheet sandstones.

The smaller scale cross stratification of the sheet sandstones is not obviously different from that of the channel sandstones. One exception to this general statement is the occurrence of a gently dipping parallel bedded and laminated sandstone in the E½ sec 1, T135N, R105W, Slope County, North Dakota. The lower portion of these beds grades into an underlying bioturbated sandy clay section which in turn overlies a dark clay containing pods of oysters. The upper part of these beds contains the burrows of the trace fossil *Ophiomorpha*. This section is almost certainly a beach deposit, and the gently dipping "crossbeds" represent beach face deposits.

In the channel sandstones, some of the "crossbedding" is due to preservation of sigmoid thicknesses of lateral accretion units formed during point bar migration and growth. The growth units fine upward to clay drape and overbank deposits. Similarly shaped crossbedding occurs in the sheet sandstones, but the growth increments consist of sand; the finer clastics are not present. These sigmoid sand units represent lateral accretion under conditions in which the finer clastics sediments were not deposited.

Fragments of pearly mollusks, possibly unionids, found at one locality, were the only vertebrate or invertebrate fossils recovered in the sheet sandstones, although both vertebrates and invertebrates occur in the channel sandstones. Plant fossils are uncommon, but not rare, in both sandstone types.

The sheet sandstones contain less clay and lignitic material and are typically more intensely winnowed and better sorted than the channel fill deposits. They are thin, widespread, generally sheetlike, though locally thickened and contain a variety of internal sedimentary structures, none of which precisely defines a sedimentary environment. Overall they seem to be levee and marine or lacustrine marginal deposits which, with the exception of the earlier mentioned beach deposit, are not attributable by me to any more specific site of sedimentation.

Stratigraphic sections illustrating the beach sandstone are shown on plate 8.

Williams Creek Sandstone

Most of the internal features of the School Section Creek sandstone are repeated at various stratigraphic horizons in the upper Ludlow Formation. Particularly striking exposures of this lithology occur in secs 15, 16, 21, 22, T136N, R105W, Golden Valley County, North Dakota, along the well developed badlands of the north tributaries to Williams Creek. This section lies above the Yule lignite, near the top of the Ludlow Formation. In field notes this area was referred to as the Williams Creek complex because of the intricate relationships between the clays and sandstones and the complex and varied kinds of crossbedding and other bedding forms. This complexity of relationships results from the reworking of the sediments by meandering streams which leave behind a trail of interwoven channel fill and point bar deposits usefully summarized by calling them meander swath deposits.

Other meander swath deposits occur over the oyster lignite and clay, along the divide between Deer Creek and Bull Run Creek in sec 33, T136N, R105W, and also in section 36 of this same township. The latter locality is probably continuous with the meander swath deposits which truncated the earlier described beach sandstone in sec 1, T135N, R105W, south across the county line in Slope County. This locality is notable for the occurrence of reworked clay boulders in some of the clayey sandstones and indicates clearly the incursion of alluvial processes into an area of quiet brackish water deposits (oyster clay) which is overlain by marine or brackish margin deposits (beach sand).

The meander swath facies occurs just below the, to be described, white siliceous bed along the North Dakota and Montana border in sec 29, T136N, R106W, Golden Valley County, North Dakota. The relationship of these somber beds to the contact between the Ludlow and Tongue River Formations is discussed later.

White Siliceous Bed

Scattered along the outcrop at what appears to be approximately the same stratigraphic horizon at the top of the Ludlow Formation is an inches- to several-foot-thick loose pebble rubble or an indurated bed of dull white siliceous rock hereafter referred to informally as the white siliceous bed. Though typically white on fresh fracture the bed commonly has a slight buff or yellowish surface tinge due to a thin coat of iron oxides. Occasional specimens, freshly dug from below the surface, are dark gray to black with disseminated organic matter. This rock is aphanitic to fine grained and consists of quartz as determined by X-ray diffraction analysis. The individual fragments or portions of a bed are cut by numerous tubular to flattened holes, and the surface is scored by abundant bladelike and fibrous impressions, apparently molds of plant material. In addition to this coarse porosity, the matrix of the rock may have an intergranular porosity and be finely porous like chalk or may be intensely cemented and be compact and nonporous.

The white siliceous bed is commonly overlain by a lignite or lignitic shale and in turn overlies a variety of sediment types which are commonly bleached white. The bleached zone may extend to depths of several tens of feet below the bed into underlying sediments. Locally associated with the bleached zone are subtle green and lavender colors, both of which are absent from weathered surfaces of the main body of the Ludlow and the overlying Tongue River Formation.

Where the white siliceous bed is developed in a continuous layer, more than a few inches thick, it resists erosion and holds up surfaces and caps buttes and benches. It forms an excellent stratigraphic marker because of these topographic characteristics and the commonly associated white coloration of the underlying bleached zone. Where developed as a thin discontinuous nodular bed the white siliceous bed is reduced to a white pebble and cobble rubble protecting shoulders on the underlying rocks.

The white siliceous bed is not continuous but occurs in variable sized patches on surfaces and as pebble lines along outcrops. The bleached zone with which it is associated is correspondingly erratic, being locally thick and prominent and then diminishing abruptly laterally to negligible thickness.

The erratic distribution, the bleaching, the association of the bleaching with many different rock types, and the subtle colors unique to the horizon suggest the white siliceous bed is associated with an unconformity.

At two locations, along the tributaries of Horse Creek, west of the Little Missouri River, stratigraphically well below the typical level, small surface exposures of rocks of the white siliceous type a few inches thick cover a few tens of square feet. These outcrops demonstrate the rock type is not unique to the upper horizon of the Ludlow, but field work certainly indicates that occurrences below the top of the Ludlow are rare. Similar beds are reported from the Tongue River, Sentinel Butte, and Golden Valley Formations (Hares, 1928; Brown, 1948).

Hares (1928, p. 34-36) discussed the white siliceous material under the heading siliceous beds, though he commonly referred to them as quartzites in the text. He noted their distribution from Montana through North Dakota in to South Dakota. He commented (p. 48) that the lowest coal of the Tongue River Formation, bed H, in T134N, R105W, "is about 60 feet above the Lance Formation and rests upon the quartzitic layer." He thus placed the contact between the Ludlow and Tongue River Formations, of this report, sixty feet below the white siliceous bed in this township.

Though laterally erratic, the white siliceous bed occurs over an area of many townships at approximately the same stratigraphic position. It commonly overlies a whitened or otherwise pastel colored zone which is distributed through a thickness of up to tens of feet in many different sediment types from clays through sandstones. These features suggest the bed and the underlying discolored zone are associated with a surface of unconformity, and it is possible that this bed and others like it in the section represent paleosol remnants. The siliceous bed is commonly overlain by a lignite or lignitic shale and seems to be consistently associated with lignites. This observation does not contradict the earlier paleosol concept, for lignites could be reasonably expected to form during the subsidence of an area after the planation and soil formation associated with an unconformity. In this sense, the relationship is fortuitous, and such an element of circumstance is supported by the general lack of siliceous zones underlying most lignites. This concept of the siliceous bed being related to an unconformity is based on field study, as laboratory work has been confined to X-ray diffraction studies of a few specimens.

Brown (1948, p. 1269) states, "The megascopic fossilized plant debris in these beds includes chiefly roots and stumps. As such, if silicifying conditions have been favorable, the top or bottom of every incipient coal seam might have been a likely possibility for the development of such a bed." He uses this reasoning to account for the occurrence of siliceous beds at a number of stratigraphic horizons in the Fort Union Group. I am suggesting that the silicifying conditions are related to unconformities and are relatively uncommon and incidentally associated with lignites.

Upper Contact

The basal contact of the Ludlow Formation which has been the subject, directly or indirectly through the discussion of correlative units, of considerable dispute and a large literature. The upper contact of the Ludlow has received little attention in North Dakota. It has generally been placed at the change from the somber grays of the Ludlow to the light yellow colors of the Tongue River Formation. Because the contact occurs below what are ordinarily considered the economically useful lignites, and perhaps also because it is only a member boundary within the Fort Union Formation, if one follows the nomenclature of the U.S. Geological Survey, the contact has been generalized and the color change has been a satisfactory criterion.

Examined more closely, this definition of the contact is troublesome. Light yellow coloration occurs from the basal coal zone upward throughout the Ludlow Formation in beds of few feet to sections in excess of fifty feet in thickness. The general observation that the Ludlow is somber-colored is applicable to only parts of the Ludlow, because large areas of the outcrop of this unit, hundreds of feet stratigraphically below any reasonable upper contact, are very light yellow. Choosing the upper contact for the Ludlow then becomes a question of which yellow zone is the lowest zone to be assigned to the Tongue River Formation.

Along the Little Missouri River this problem can be resolved, at least for this area, by using the white siliceous bed, and the probable unconformity associated with it, as the top of the Ludlow Formation. Use of the white siliceous bed as a boundary marker is essentially the same as using the top of the highest somber gray swelling clays and thus in a sense is change in emphasis from "lowest yellow" to "highest gray." If it were not for the white siliceous bed and the associated bleached zone, this choice would be arbitrary, but my experience suggests that the combination of "highest gray and white siliceous" is a useful and consistent approach to an upper contact between the

Ludlow and Tongue River.

If I am correct that the white siliceous bed is associated with an unconformity, then this choice of boundary probably has regional significance.

Hares (1928, p. 24), in the only detailed study of the Little Missouri River area, used for the "base of the Fort Union formation," that is, the base of the Tongue River Formation of modern usage, the "channel conglomeratic light-yellow and somewhat massive sandstone" and infers this same characteristic occurs at the contact where the Tongue River Formation rests on the Cannonball Formation in the "Cannonball River Country." Later in this paper (1928, p. 48) he indicates that his coal H rests on the white siliceous bed and is as much as sixty feet above the Ludlow and Tongue River contacts. Use of the white siliceous bed as the upper contact would thus raise the contact in the Marmarth coal field. Extension of this usage to the south into the Cave Hills and other boundary buttes and mesas along the North Dakota and South Dakota border would eliminate most of mapped Tongue River Formation in these areas by including it in the Ludlow Formation.

Change to a specific marker horizon like the white siliceous bed for the upper contact of the Ludlow Formation in the area of the Little Missouri River seems reasonable, but its extension southward remains tentative until more regional studies can be made.

Stratigraphic sections illustrating the white siliceous bed are shown on plate 10.

URANIUM POTENTIAL

Sands and sandstone with varying degrees of induration and permeability are abundant in the Ludlow Formation. All are somewhat localized, though lateral and vertical contacts between sand bodies probably create extensive groundwater flow paths in many areas. The sands and sandstone increase in permeability and horizontal extent from west to east across Montana and the Dakotas as the change from alluvial dominant to marine dominant sites of deposition is traversed.

Sands and sandstones contain variable amounts of organic material. Organic content decreases from west to east as the changes take place from alluvial dominant to marine dominant sedimentary processes.

Sand and sandstones are never far removed laterally or vertically from organic rich sediments which range from nearly pure deposits like the lignites to the abundant organic fragments distributed through all clastic sediments and rocks.

With the preceding summary in mind, if uranium is transported from the source by oxygenated groundwater and then deposited where reducing conditions develop as the result of reactions with organic matter, then certain generalizations can be drawn about uranium prospecting in the sand bodies of the Ludlow Formation. These are:

1. The gray, relatively impermeable and organic rich sandstones, inset in channels, filling depressions or occurring as point bar deposits, are probably not good prospecting sites. These sandstones have not, as shown by their surface organic content and dull gray colors, transmitted sufficient water to eliminate the organic matter at the outcrop and no well-developed oxidizing/reducing interface can be expected at depth. With the low permeability and relatively high organic material available, the flow system has had insufficient time, in the face of relatively rapid erosion rates, to develop a subsurface interface. The oxidation/reduction interface is essentially the modern erosion surface.
2. The light yellow, permeable and low organic content, more nearly sheetlike sandstone bodies, whatever their origin, have transmitted sufficient oxidizing water to have the potential for a uranium-bearing oxidation/reduction interface at shallow depth. Lignite mining and well samples have consistently indicated that the yellow surface coloration, taken here to indicate oxidation, does not penetrate great distances from the outcrop. The oxidation/reduction interface should be present in the subsurface relatively near the outcrop, varying in position with the water and hydrostatic head available, permeability, amount of organic matter

and oxidizable minerals, and length of time the flow system has been operative.

3. Studies of the uraniferous coals in the Dakotas suggest the uranium source is in the volcanic rocks of the Oligocene White River Formation, once extensive over the area, but now largely restricted to erosional outliers. This present geographic limitation of available source and the implied shallowness of penetration of the oxidation/reduction interface severely limits prospecting sites to areas near where the White River Formation crops out or to areas where this stratigraphic unit has been removed in relatively recent geologic time. Available data suggest that the modern divides are probably the areas in closest stratigraphic proximity to relatively recently eroded White River Formation. Divides which probably brought this unit into past contact with the Ludlow Formation are the divide between the Little Missouri River and Beaver Creek along the Montana-North Dakota border and the area southeasterly from the Medicine Pole Hills along the various forks of the Grand River in Bowman County, North Dakota. These areas should be considered prospective Ludlow uranium sites.

The earlier rejection of channel filling sands in the Ludlow Formation is an apparent rejection of known extensive uranium occurrence in channel fill deposits. This rejection of *Ludlow* channel fills as too fine grained and poorly sorted to have conducted sufficient water to have an oxidizing/reducing interface at depth, in the face of a rapid erosion rate, is not a categorical rejection of channel fills as uranium sites.

The suggestion that the sheet, or sheetlike sands, may be potential uranium sites is somewhat tempered by the lack of an apparent reason for "localized" flow system in these sheets. Geologic circumstances suggest that uranium deposits result from the reaction of the prolonged flow of large volumes of extremely dilute fluids by or through a chemical interface. Channelization accomodates large volumes of fluid while minimizing the area of the reaction interface and thus tends to result in a concentrated deposit. Localization of flow within the sheet sands is not demonstratable with the data available, though it probably occurs.

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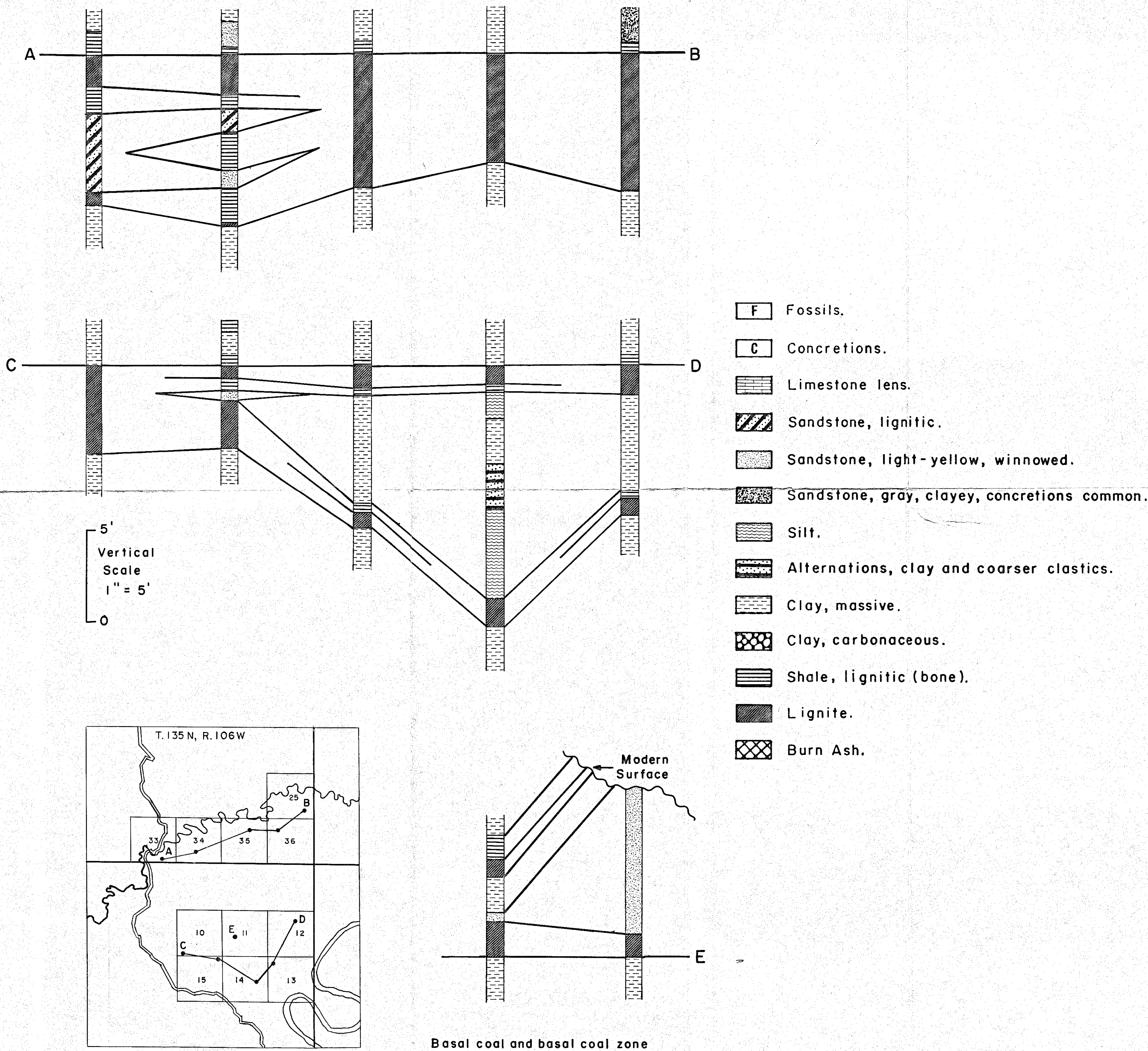
Plate I



Basal coal and basal coal zone
lower Ludlow Formation

Plate 2

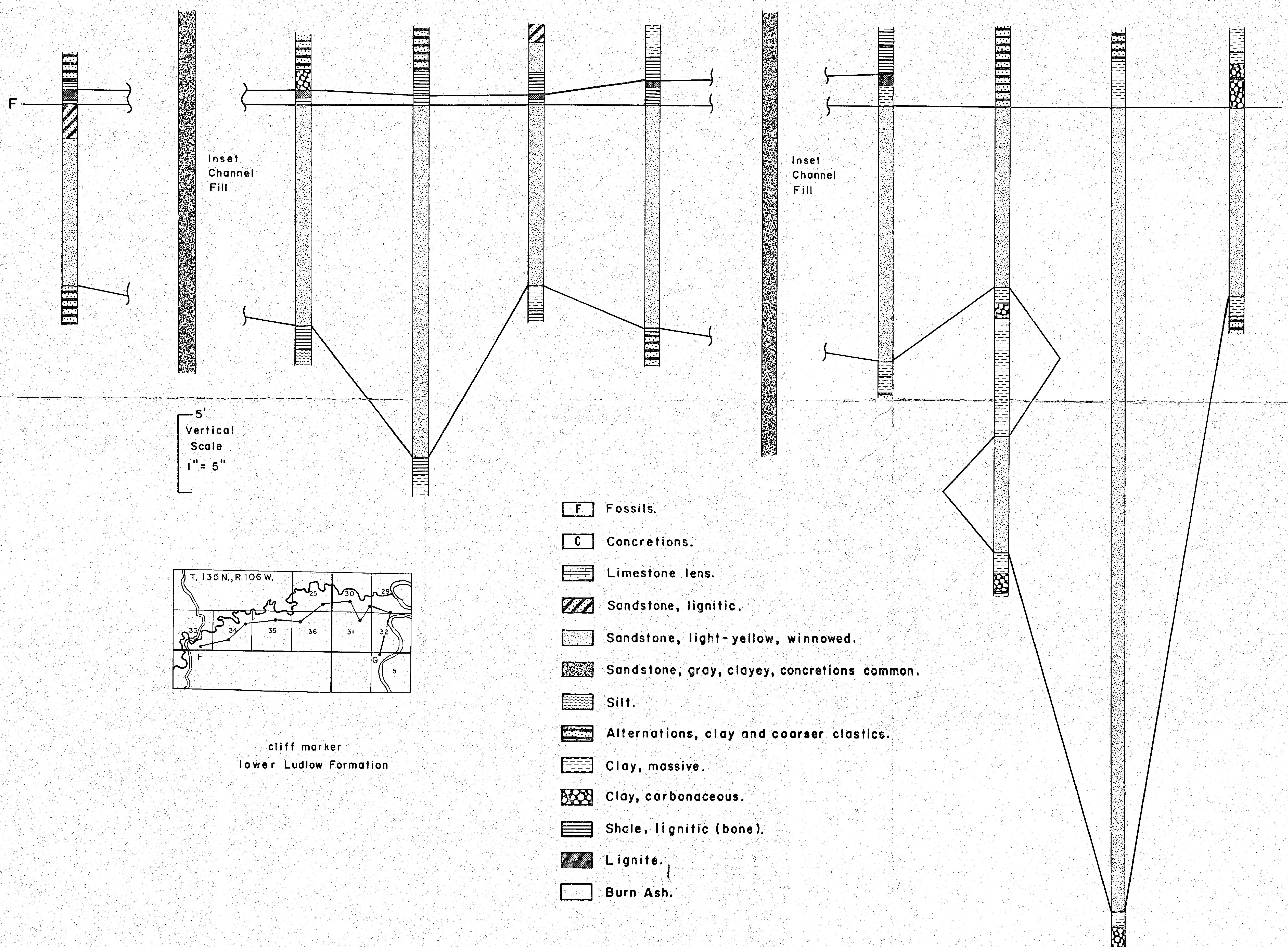
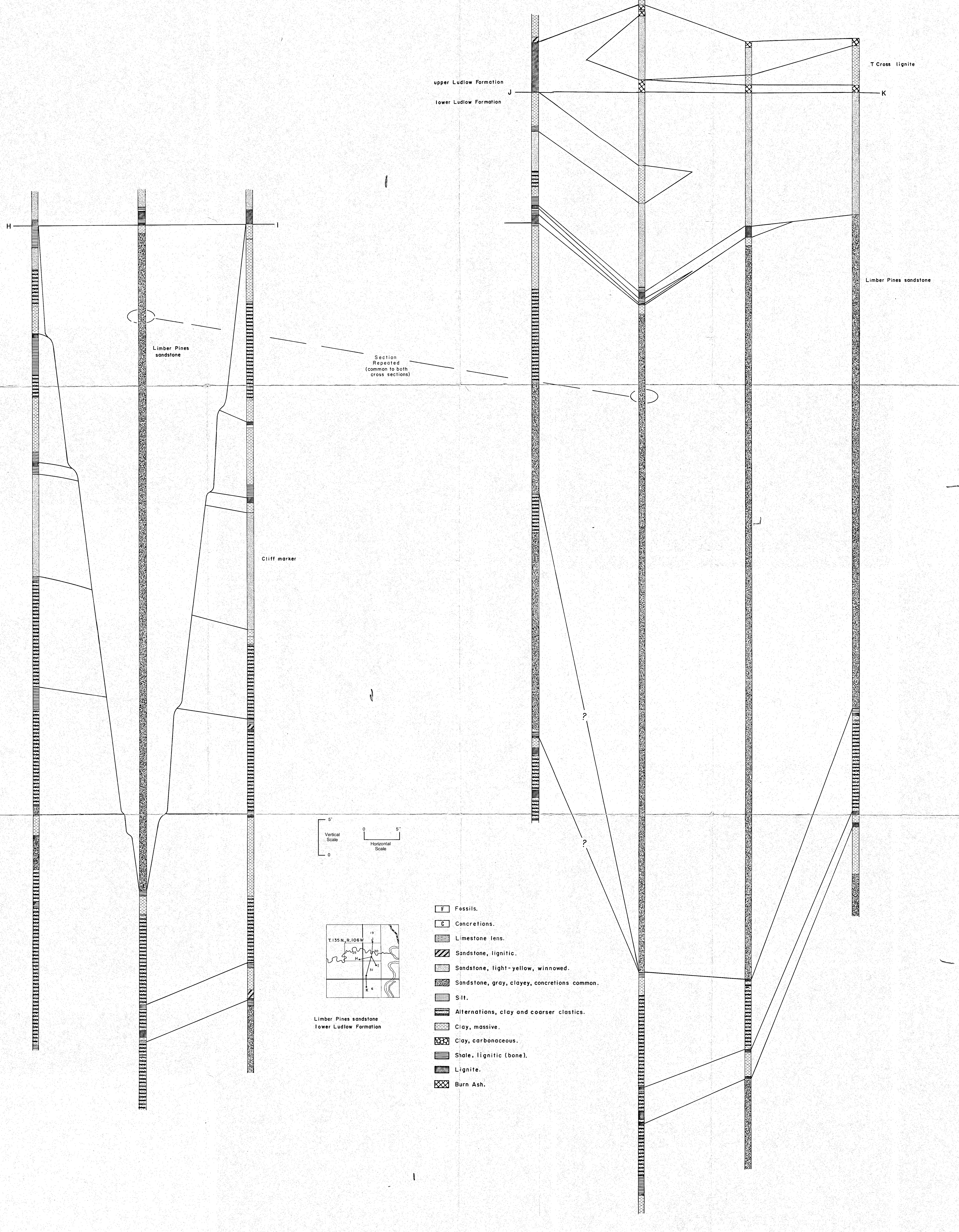
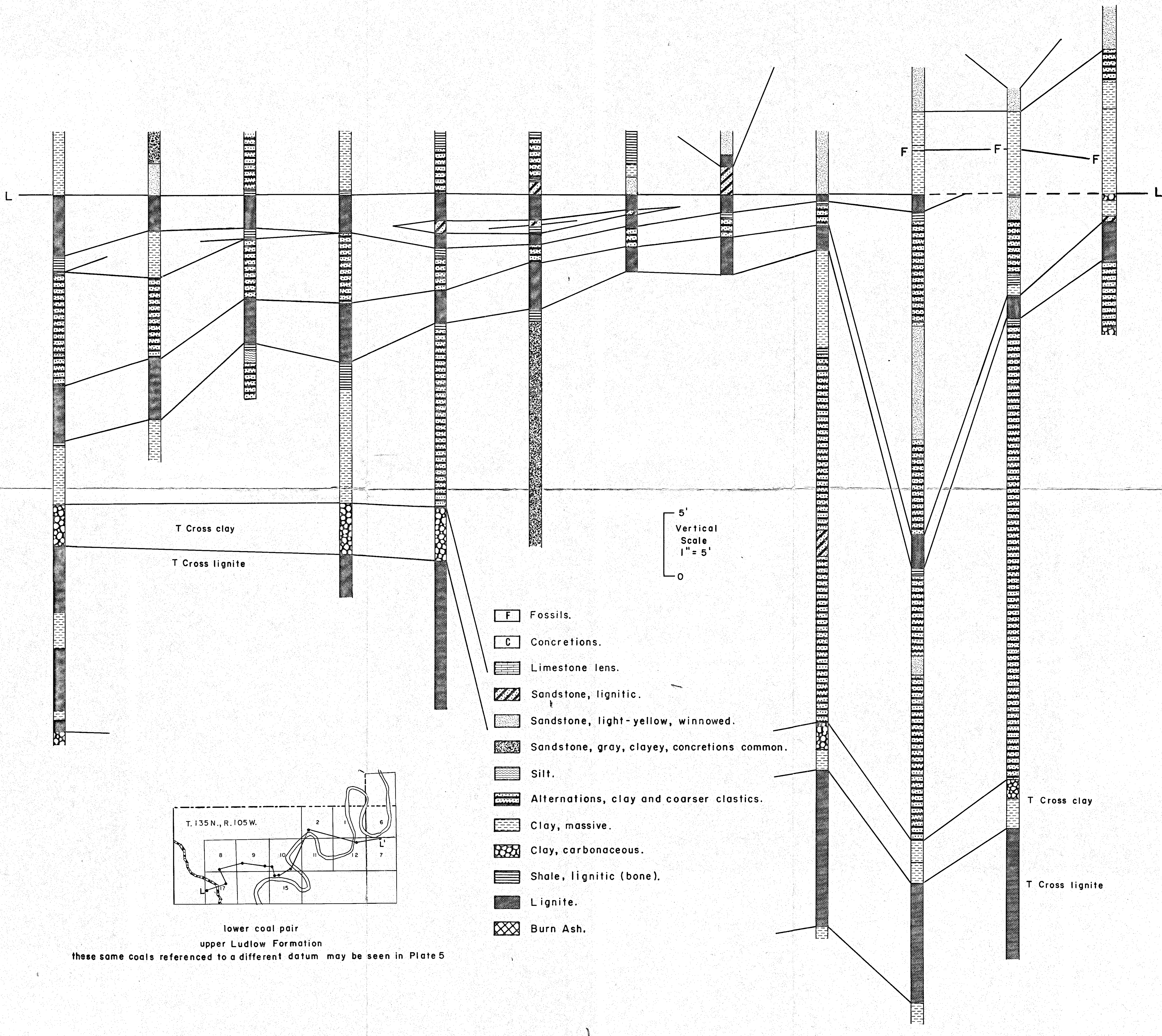

F
G
Inset
Channel
Fill
Inset
Channel
Fill
5'
Vertical
Scale
1" = 5'
T. 135 N., R. 106 W.
25
30
29
33
34
35
36
31
32
F
G
5
cliff marker
lower Ludlow Formation
F Fossils.
C Concretions.
Limestone lens.
Sandstone, lignitic.
Sandstone, light-yellow, winnowed.
Sandstone, gray, clayey, concretions common.
Silt.
Alternations, clay and coarser clastics.
Clay, massive.
Clay, carbonaceous.
Shale, lignitic (bone).
Lignite.
Burn Ash.

Plate 3



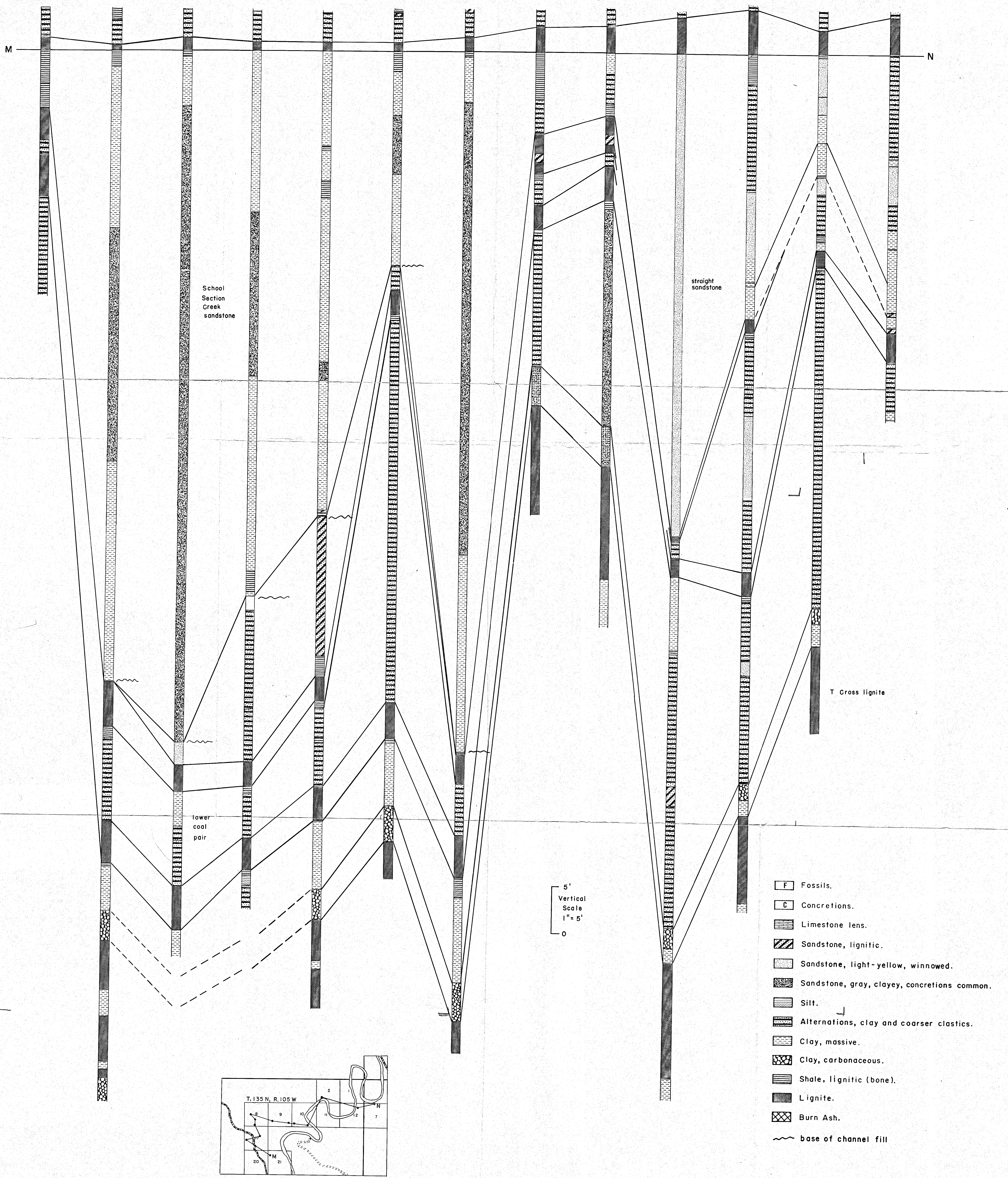
upper Ludlow Formation
J
K
lower Ludlow Formation
T Cross lignite
Limber Pines sandstone
H
I
Limber Pines sandstone
Section Repeated (common to both cross sections)
Cliff marker
?
?
5'
Vertical Scale
0
0
5'
Horizontal Scale
T.135N., R.106W.
Limber Pines sandstone
lower Ludlow Formation
F Fossils.
C Concretions.
Limestone lens.
Sandstone, lignitic.
Sandstone, light-yellow, winnowed.
Sandstone, gray, clayey, concretions common.
Silt.
Alternations, clay and coarser clastics.
Clay, massive.
Clay, carbonaceous.
Shale, lignitic (bone).
Lignite.
Burn Ash.

Plate 4



lower coal pair
upper Ludlow Formation
these same coals referenced to a different datum may be seen in Plate 5

Plate 5



Interval between the lower and the upper coal pairs
Includes the School Section Creek sandstone and the straight sandstone

Plate 6

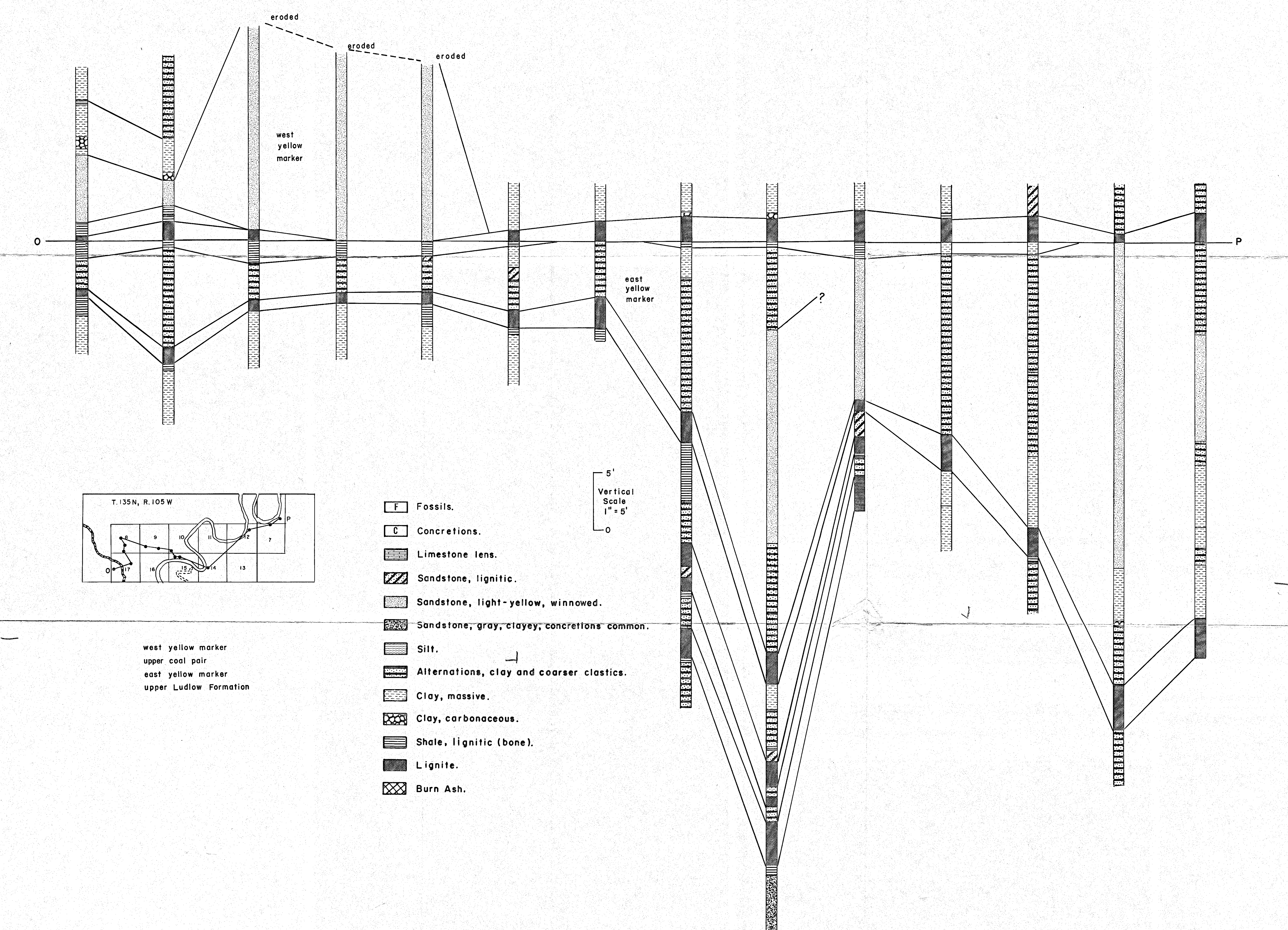
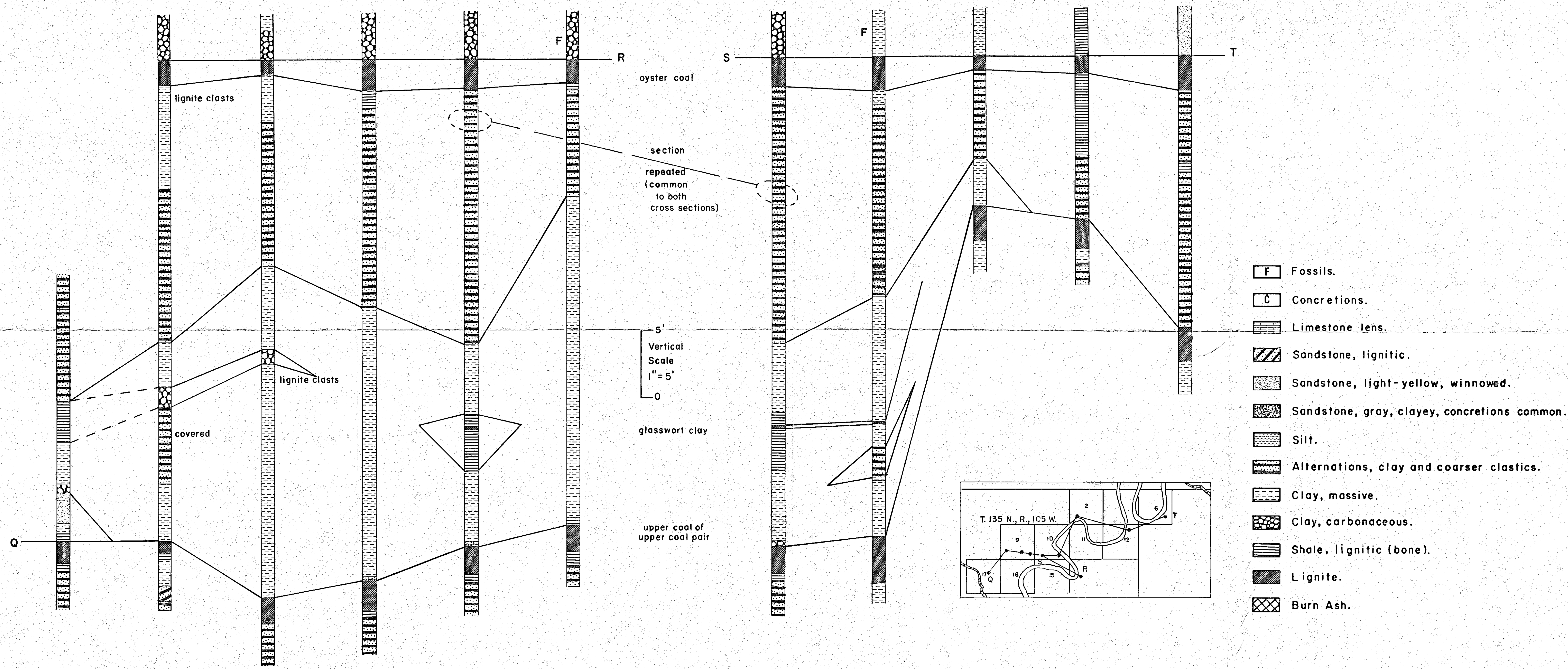

eroded
eroded
eroded
west yellow marker
east yellow marker
?
O
P
5'
Vertical Scale 1" = 5'
0
T. 135 N, R. 105 W
F Fossils.
C Concretions.
Limestone lens.
Sandstone, lignitic.
Sandstone, light-yellow, winnowed.
Sandstone, gray, clayey, concretions common.
Silt.
Alternations, clay and coarser clastics.
Clay, massive.
Clay, carbonaceous.
Shale, lignitic (bone).
Lignite.
Burn Ash.
west yellow marker
upper coal pair
east yellow marker
upper Ludlow Formation

Plate 7

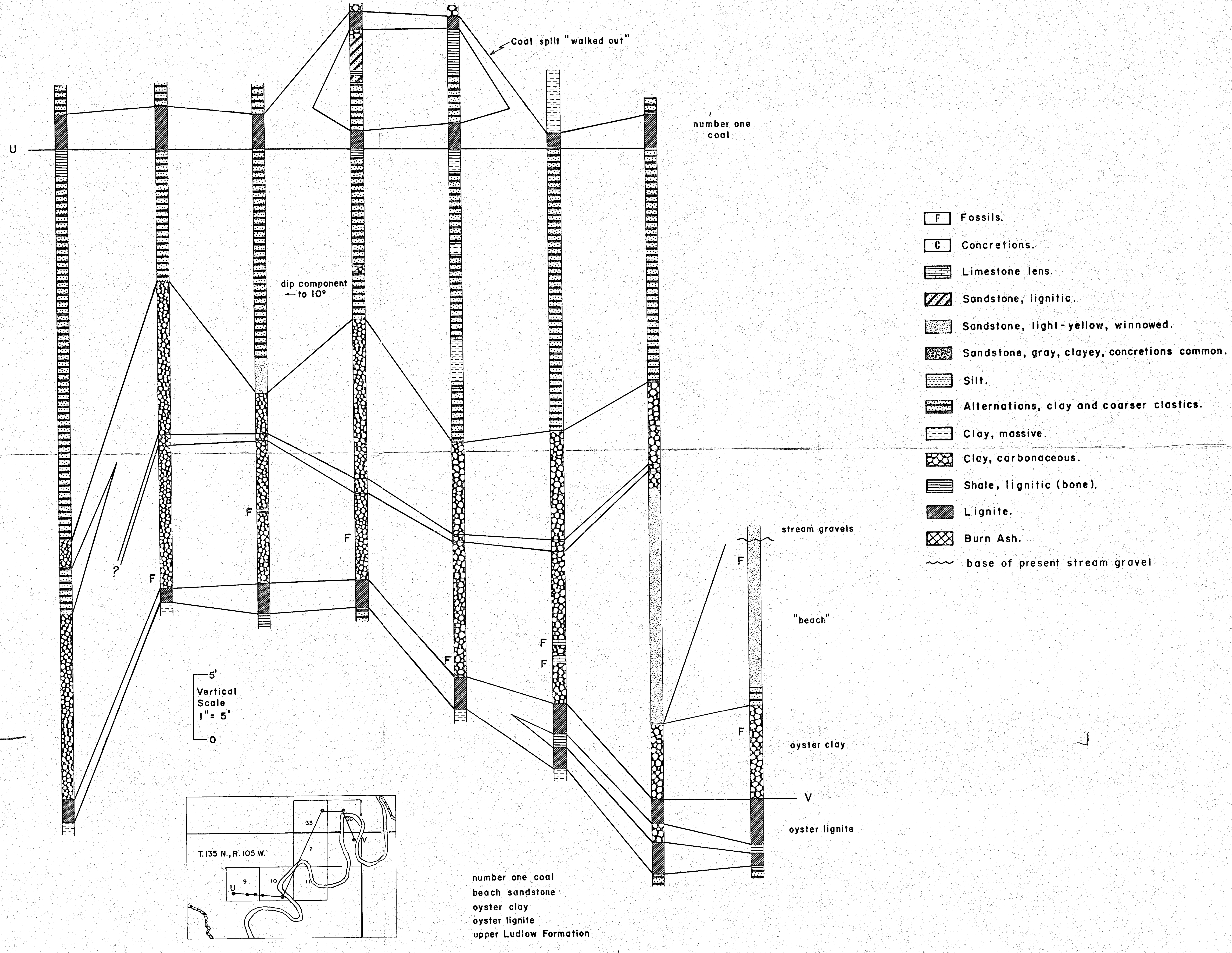


interval-upper coal pair to oyster coal

glasswort clay

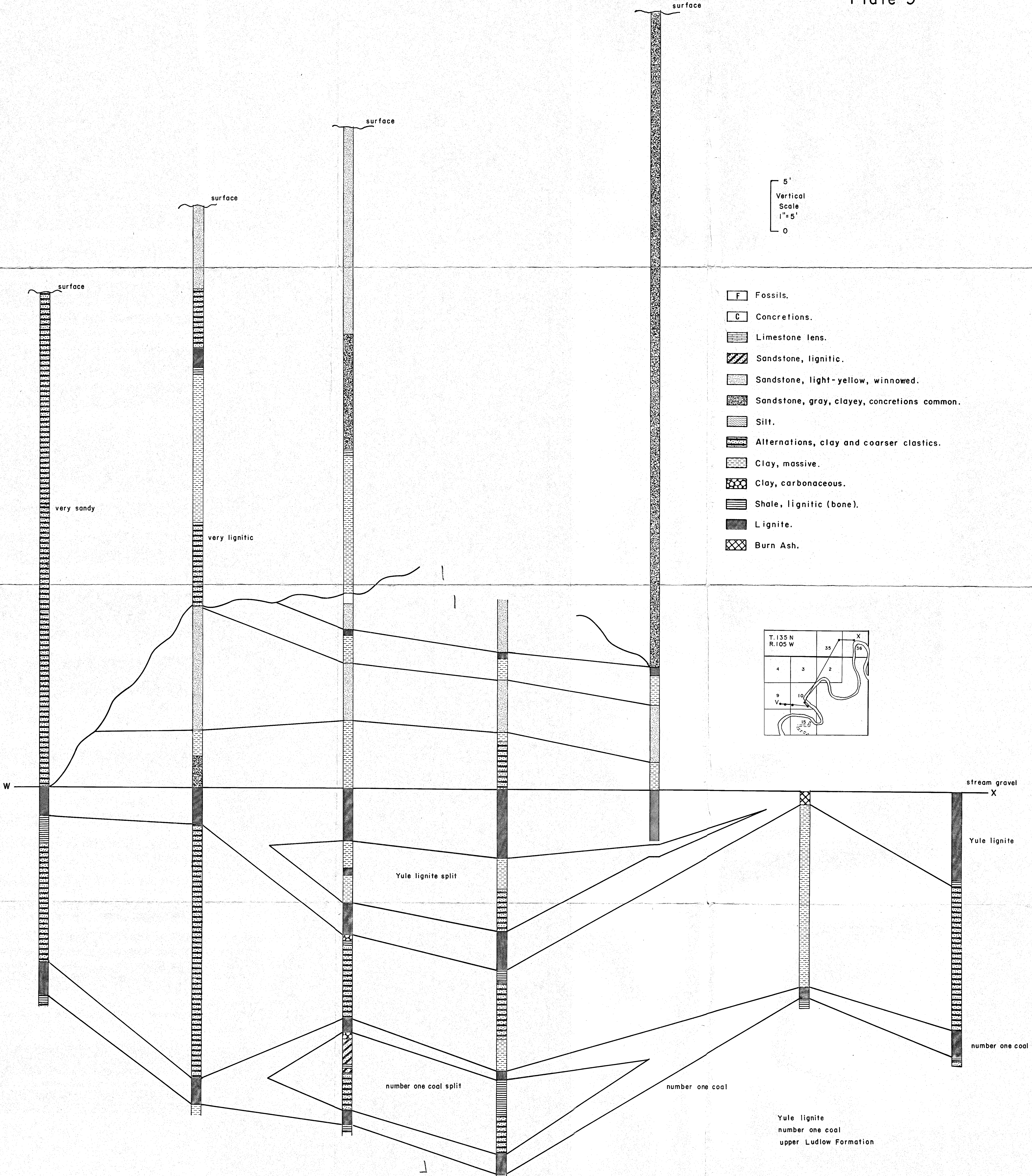
upper Ludlow Formation

Plate 8



Coal split "walked out"
number one coal
U
V
dip component
← to 10°
?
F
stream gravels
"beach"
oyster clay
oyster lignite
5'
Vertical Scale
1" = 5'
0
T. 135 N., R. 105 W.
35
36
2
9
10
11
U
V
number one coal
beach sandstone
oyster clay
oyster lignite
upper Ludlow Formation
F Fossils.
C Concretions.
Limestone lens.
Sandstone, lignitic.
Sandstone, light-yellow, winnowed.
Sandstone, gray, clayey, concretions common.
Silt.
Alternations, clay and coarser clastics.
Clay, massive.
Clay, carbonaceous.
Shale, lignitic (bone).
Lignite.
Burn Ash.
base of present stream gravel

Plate 9



surface
surface
surface
surface
5'
Vertical
Scale
1"=5'
0
F Fossils.
C Concretions.
Limestone lens.
Sandstone, lignitic.
Sandstone, light-yellow, winnowed.
Sandstone, gray, clayey, concretions common.
Silt.
Alternations, clay and coarser clastics.
Clay, massive.
Clay, carbonaceous.
Shale, lignitic (bone).
Lignite.
Burn Ash.
very sandy
very lignitic
T.135 N
R.105 W
W
X
stream gravel
Yule lignite
Yule lignite split
number one coal split
number one coal
number one coal
Yule lignite
number one coal
upper Ludlow Formation

Plate 10


burn ash, H lignite of Hares (1928)
Tongue River Formation
white siliceous marker
4"-6" thick
Top Ludlow Formation
this report
underlying rocks bleached
white or colors lightened
base
of
bleached
zone
surface
concretionary ledges
concretionary ledges
surface
base of "Tongue River member"
or top of "Ludlow lignitic
member" of Hares (1928)
5'
Vertical
Scale
1" = 5'
0
F
Fossils.
C
Concretions.
Limestone lens.
Sandstone, lignitic.
Sandstone, light-yellow, winnowed.
Sandstone, gray, clayey, concretions common.
Silt.
Alternations, clay and coarser clastics.
Clay, massive.
Clay, carbonaceous.
Shale, lignitic (bone).
Lignite.
Burn Ash.
Y
22
23
T. 136 N.,
R. 105 W.
32
Z
5
Y
Z
Yule lignite
upper Ludlow Formation above the Yule lignite