A paleoenvironmental reconstruction of the cretaceous Willow Creek anticline dinosaur nesting locality : North Central Montana
by William Morris Bauer Gavin

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Science
Montana State University

Abstract:
The Willow Creek anticline dinosaur nesting locality is an important paleontological site in the Cretaceous (Canpanian) Two Medicine Formation. This study was done to place these finds in a paleoenvironmental setting developed by using stratigraphic columns and sedimentologic analysis.

The study area was divided into four subfacies which are part of lithofacies (d) of the southern Two Medicine Formation. The lower subfacies was deposited by anastomosing rivers with moderate aggradation rates which allowed moderate development of caliche layers. The climate was warm and semi arid. Rains came during summer when convective cells brought in moist air from the Cretaceous seaway. The rest of the year was dry. The study area was located in a rain shadow caused by the Cordilleran Mountains to the west.

The middle subfacies is comprised of the charophytiferous limestone middle subfacies and the calcareous mudstone middle subfacies. The charophytiferous subfacies is composed of lake-derived sediments from a shallow lake at the southern end of the study area. The calcareous subfacies was deposited by meandering streams with low aggradation rates which allowed extensive development of caliche horizons. High water tables and calcium carbonate-rich water allowed remarkable preservation of dinosaur eggs and embryos laid adjacent to the lake. The climate was the same as during the deposition of the lower subfacies.

The upper subfacies was deposited by anastomosing streams with a low aggradation rate which allowed extensive development of caliche layers. Climate remained the same as in the subfacies below.

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APPROVAL

of a thesis submitted by

William Morris Bauer Gavin

Thisthesis has been read by each member of the thesis committee and has been found to besatisfactoryregarding content,English usage,format,citations,bibliographic style,and consistency,and is ready for submission to the College of Graduate Studies.

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ABSTRACT

The Willow Creek anticline dinosaur nesting locality is an important paleontological site in the Cretaceous (Campanian) Two Medicine Formation. This study was done to place these finds in a paleoenvironmental setting developed by using stratigraphic columns and sedimentologic analysis.

The study area was divided into four subfacies which are part of lithofacies (d) of the southern Two Medicine Formation. The lower subfacies was deposited by anastomosing rivers with moderate aggradation rates which allowed moderate development of caliche layers. The climate was warm and semiarid. Rains came during summer when convective cells brought in moist air from the Cretaceous seaway. The rest of the year was dry. The study area was located in a rain shadow caused by the Cordilleran Mountains to the west.

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The upper subfacies was deposited by anastomosing streams with a low aggradation rate which allowed extensive development of caliche layers. Climate remained the same as in the subfacies below.

INTRODUCTION

Purpose

In 1978 a team of paleontologists from Princeton University discovered large deposits of dinosaur bones and eggs in Cretaceous Two Medicine Formation sediments in the Willow Creek anticline west of Choteau, Montana. Since the original discoveries, researchers from Princeton University and the Museum of the Rockies at Montana State University have continued to excavate the area. Their discoveries have led to significant new theories on dinosaur physiology and behavior. One of the shortcomings of these studies has been a lack of understanding of the environment in which these animals lived. This study is an attempt to eliminate such shortcomings by developing a detailed paleoenvironmental reconstruction of the research area by using measured stratigraphic sections, sedimentologic analysis and climatic modeling. By placing the paleontologic finds in the study area into an environmental and geographical context, this study will enhance the understanding of dinosaurs' ecology.

Location

The Two Medicine Formation crops out along the edge of the Northern Rocky Mountain Disturbed Belt in the United States to about 40 kilometers north of Helena, Montana (Figure 1). The Willow Creek anticline is located 19 kilometers west of Choteau, Montana, in

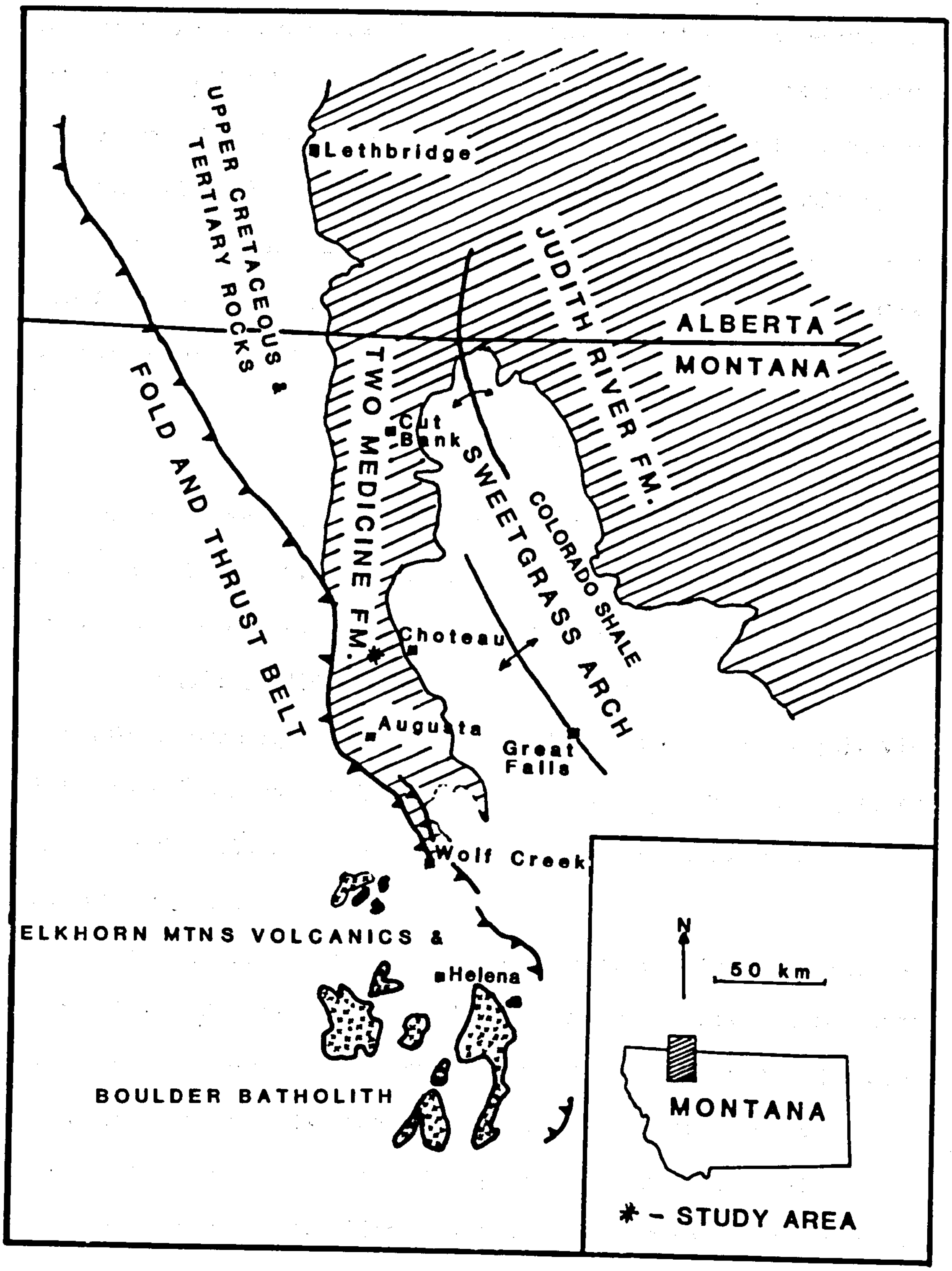

Figure 1. Index map showing general outcrop area of the Two Medicine Formation and related features (after Lorenz, 1981).

Teton County, north central Montana (Figure 2) and 16 kilometers east of the Disturbed Belt. The area emphasized in the study is roughly five square kilometers, comprising outcrops in and around the Willow Creek anticline, located in sections 19,20,29, and 30 of T.24 N., R.6 W. and sections 24 and 25 of T.24 N., R.7 W. Additional outcrops were studied near the main study area including Teton Buttes, Willow Creek and Pine Butte (Figure 3).

Previous Investigations

Upper Cretaceous strata of north-central Montana have been extensively studied over the past seventy years. Initial work on the Montana Group and descriptions of many of the units were accomplished by Stebinger (1914, 1916, 1917). Excellent papers dealing with Montana Group stratigraphy have been published by Cobban (1955), Viele and Harris (1965), and Gill and Cobban (1973). These investigations have been primarily concerned with the marine deposits of the Cretaceous seaway.

The Two Medicine Formation is included in the Upper Cretaceous Montana Group (Figure 4). At its base is the regressive marine Eagle Sandstone and at the top in most places are deposits of the Bearpaw Shale. The nonmarine Two Medicine Formation has received less attention than the rest of the Montana Group. After initial description by Stebinger, little work was done on the unit until the 1950's, when Cobban (1955) addressed the origin of the sediment in a paper on northwest Montana. Viele and Harris (1965) and Schmidt (1978) dealt with the Two Medicine near its southern limits and

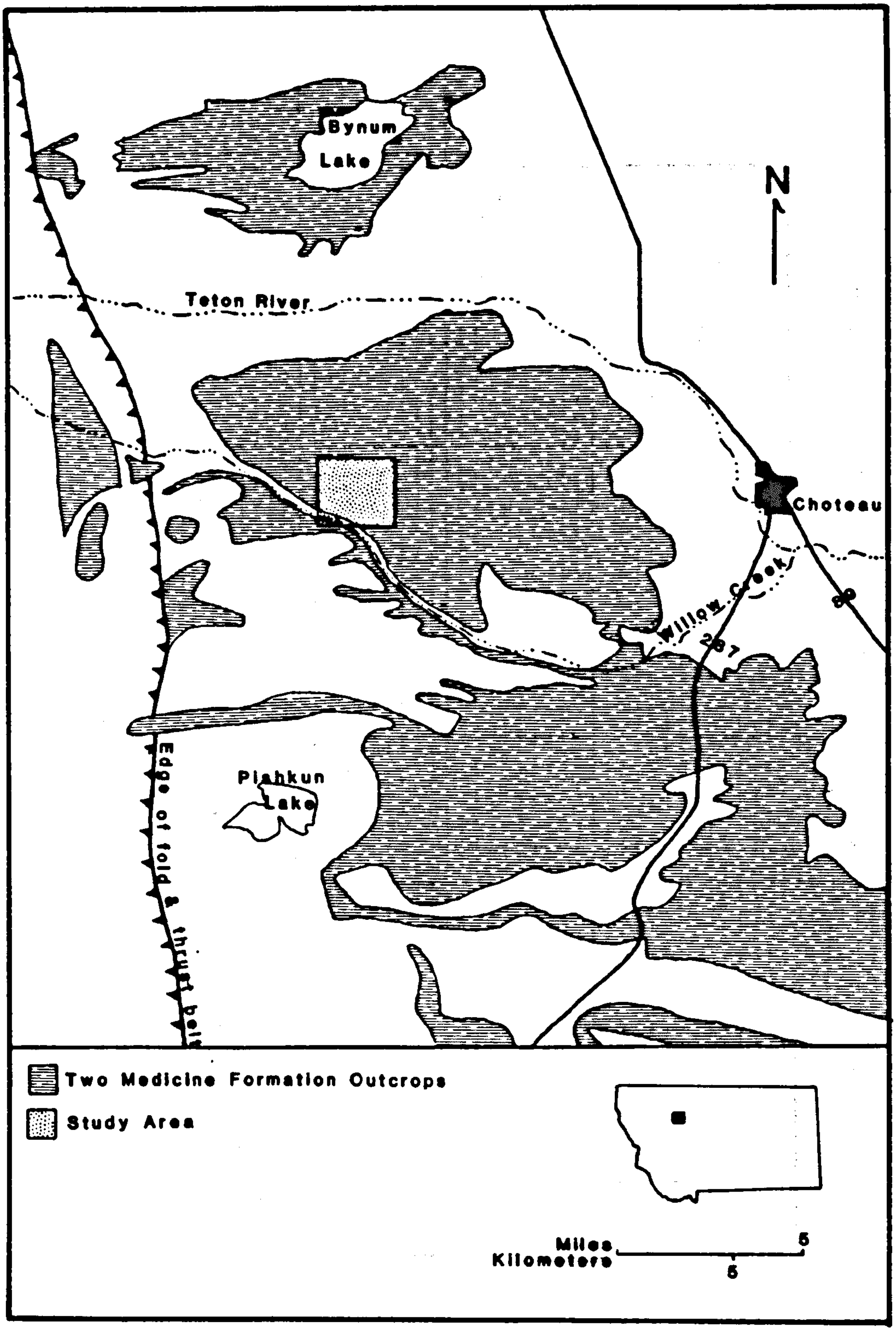

Figure 2. Two Medicine outcrops near Choteau, Montana, and the study area (after Mudge, 1979).

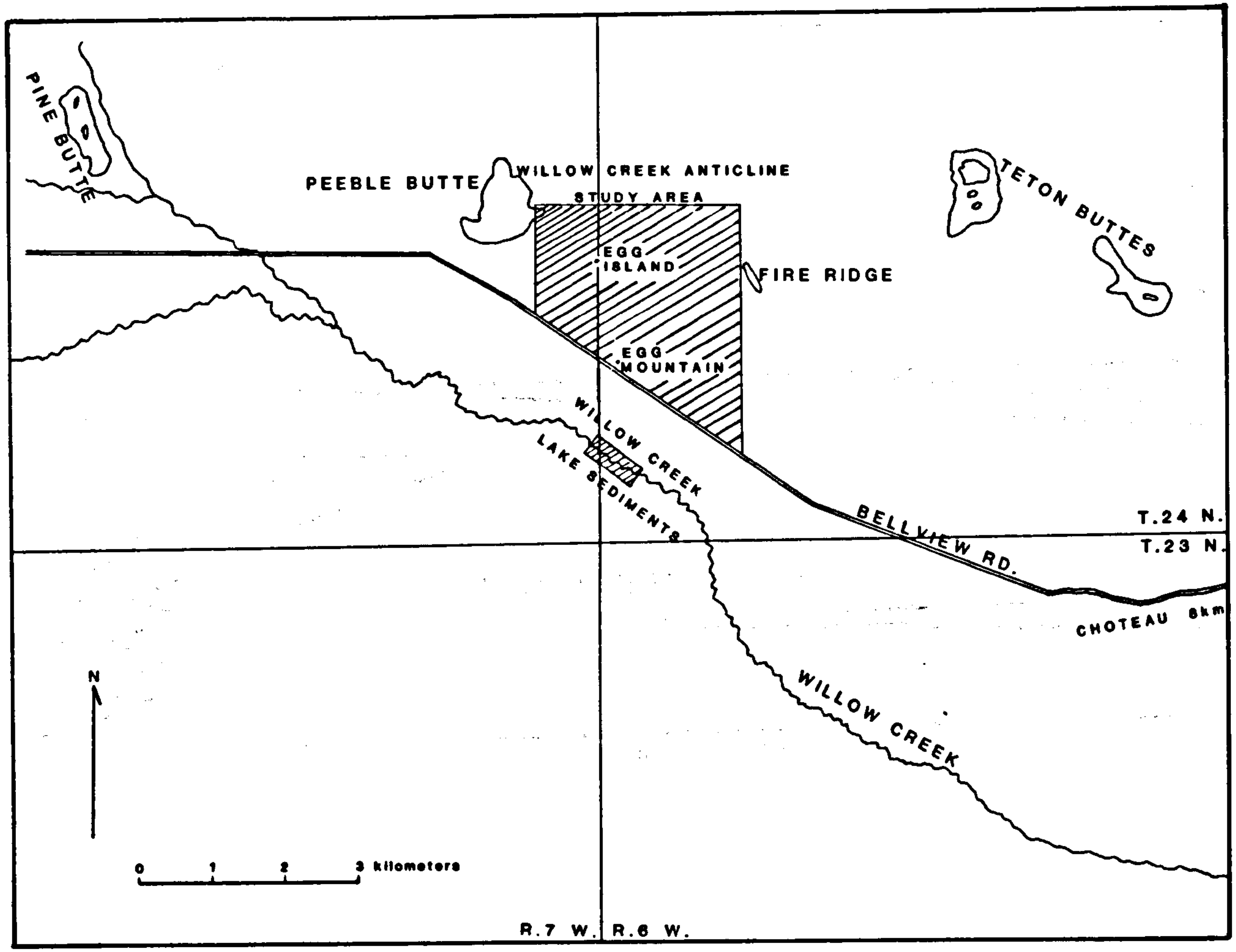

Figure 3. Map of study area and key geographic features.

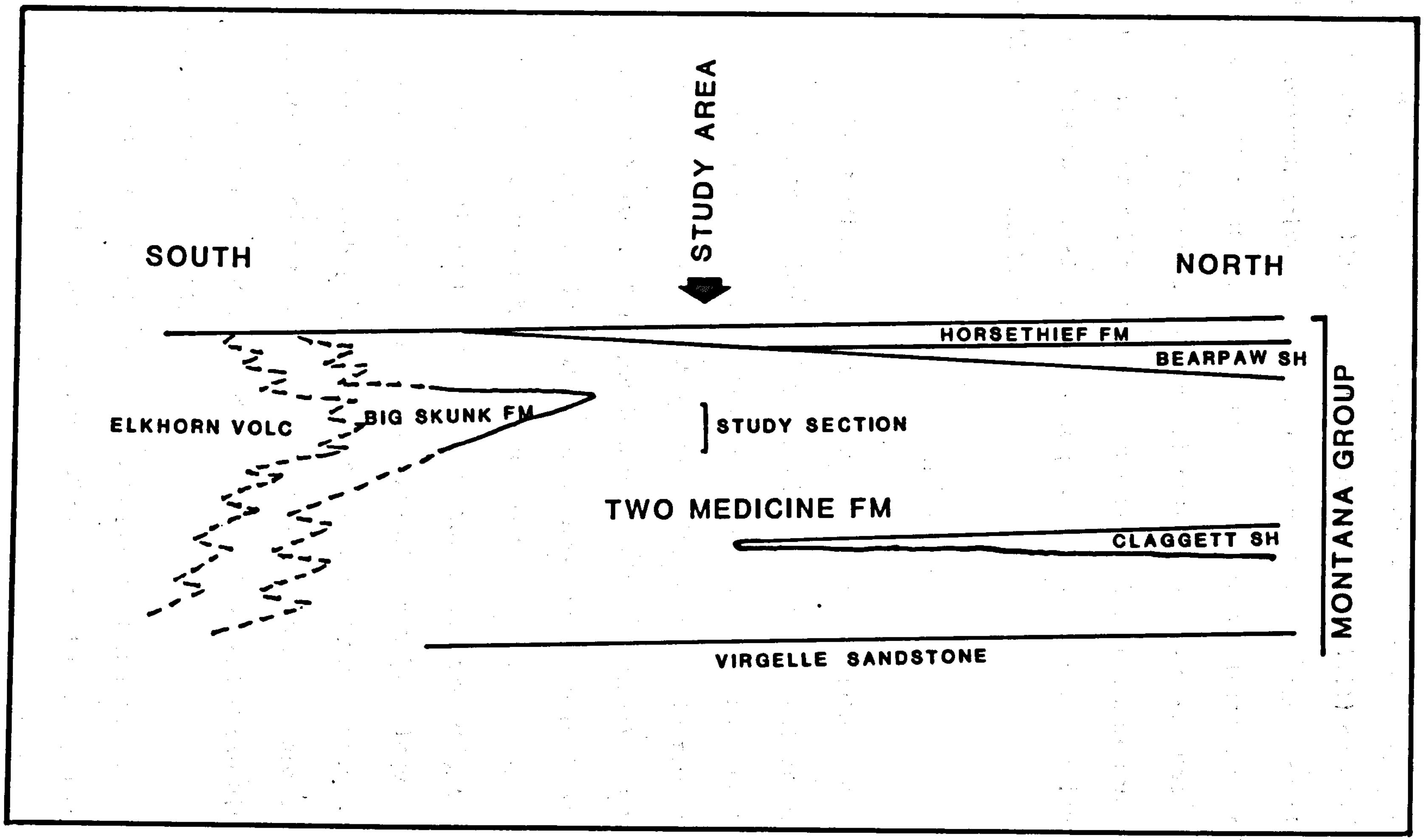

Figure 4. Generalized stratigraphic relations between the Two Medicine and adjacent formations, with the study area's location and stratigraphic level.

examined the stratigraphic relationship of the volcaniclastic member to its northern alluvial counterpart. Lorenz (1981) completed the first comprehensive study of the entire Two Medicine Formation, dealing with sedimentologic, stratigraphic, and tectonic aspects. Lorenz's thesis includes a general paleoenvironmental evaluation of the entire upper lithofacies of the Two Medicine Formation. To date, no one has addressed the specific paleoenvironmental setting for the Willow Creek anticline area.

Regional Geology

The Two Medicine Formation is a terrestrial molasse deposit shed into a foredeep in front of the Sevier thrust belts (Lorenz, 1981). The terrestrial deposits were bounded on the east and northeast by the Pierre-Niobrara seaway which extended discontinuously from Alaska to the Gulf of Mexico. This configuration with the highlands to the west accounts for an overall shift from upland facies to lowland facies and delta facies from southwest to northeast (Lorenz, 1981).

To the south in the Elkhorn Mountains, and probably to the west, there was intermittent volcanism which affected lithology and relief. The effects of this volcanism are progressively more pronounced to the south, to the point that the volcanoclastic sediments are considered a separate member of the Two Medicine Formation called the Big Skunk Member (Schmidt, 1978).

To the east, the Sweetgrass Arch affected the basin configuration. This arch, a zone of weakness dating from the Precambrian, was activated as a forebulge in front of the thrust sheets to the west during the late Cretaceous. It acted as a relative high and restricted sediment dispersal and transgressions by channelling both into a more northeast alignment (Lorenz, 1981). Mudge (pers. comm.) feels that movement on the arch after Two Medicine deposition was responsible for the series of folds that constitute the Willow Creek anticline today (Figure 5).

Lorenz (1981) divided the relatively complete section of Two Medicine strata near Choteau, Montana, into four lithofacies. He labeled those a-d from the bottom up (Figure 6). This section is approximately 660 meters thick and grades up into 30-60 meters of transitional deposits before being capped by the Horsethief Sandstone. The study area at Willow Creek anticline is located in the middle of the upper lithofacies (d) which begins approximately 250 meters above the Virgelle Sandstone and is approximately 395 meters thick. The sections studies herein begin 312 meters below the base of the Horsethief Sandstone and represent 76 meters of sediments. These deposits were laid down after the Claggett Transgression and are the remains of an alluvial apron that prograded eastward during the Campanian Stage, east of the thrust belt and volcanic highlands.

Procedure

Field work for this study was conducted during the summer of 1983. All operations were conducted out of a field camp run by the Museum of the Rockies at the Willow Creek anticline. First, a plane table map of the study area was surveyed at a scale of 1:4800. This allowed accurate location of measured sections and all paleontological

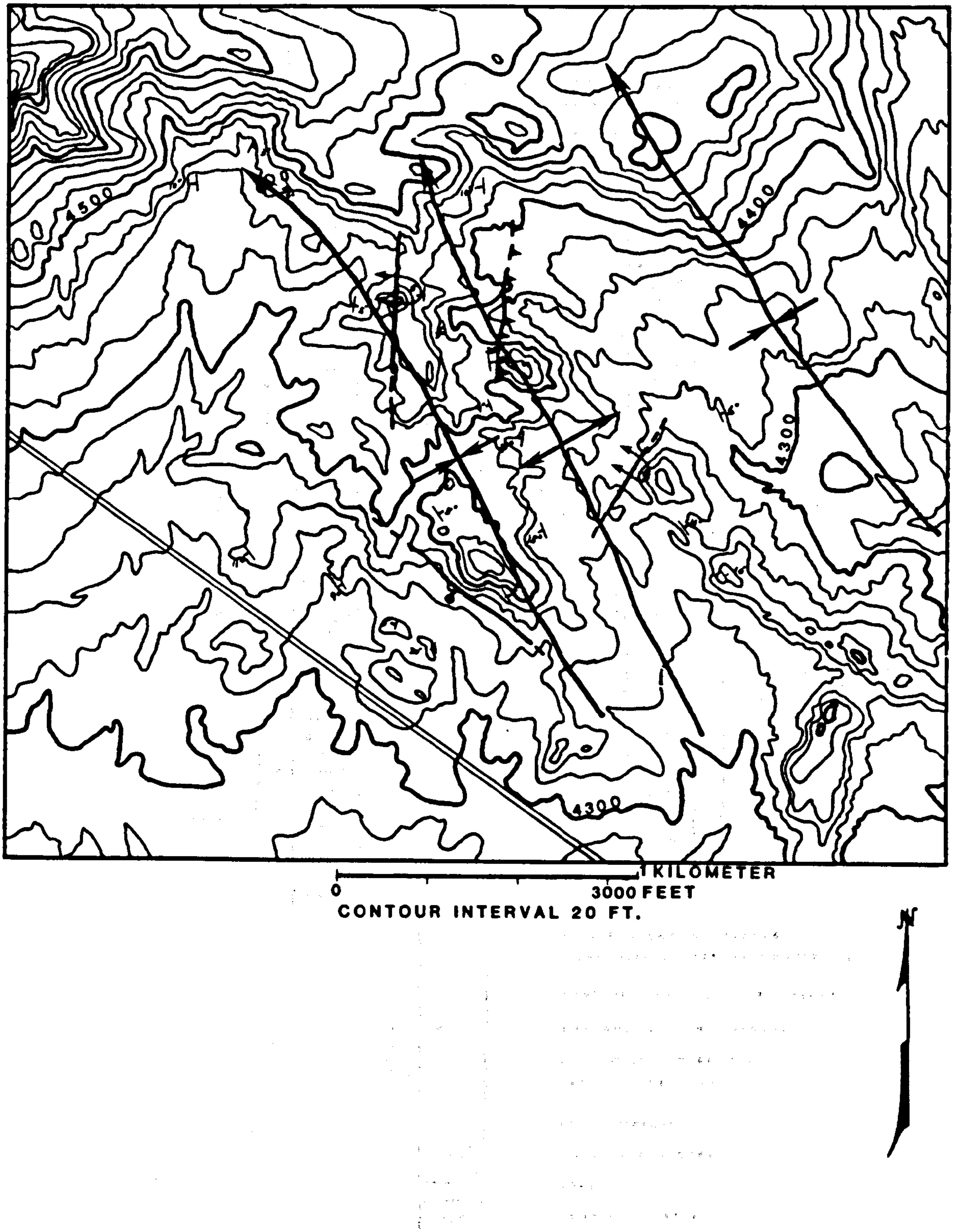

Figure 5. Structure map of the study area.

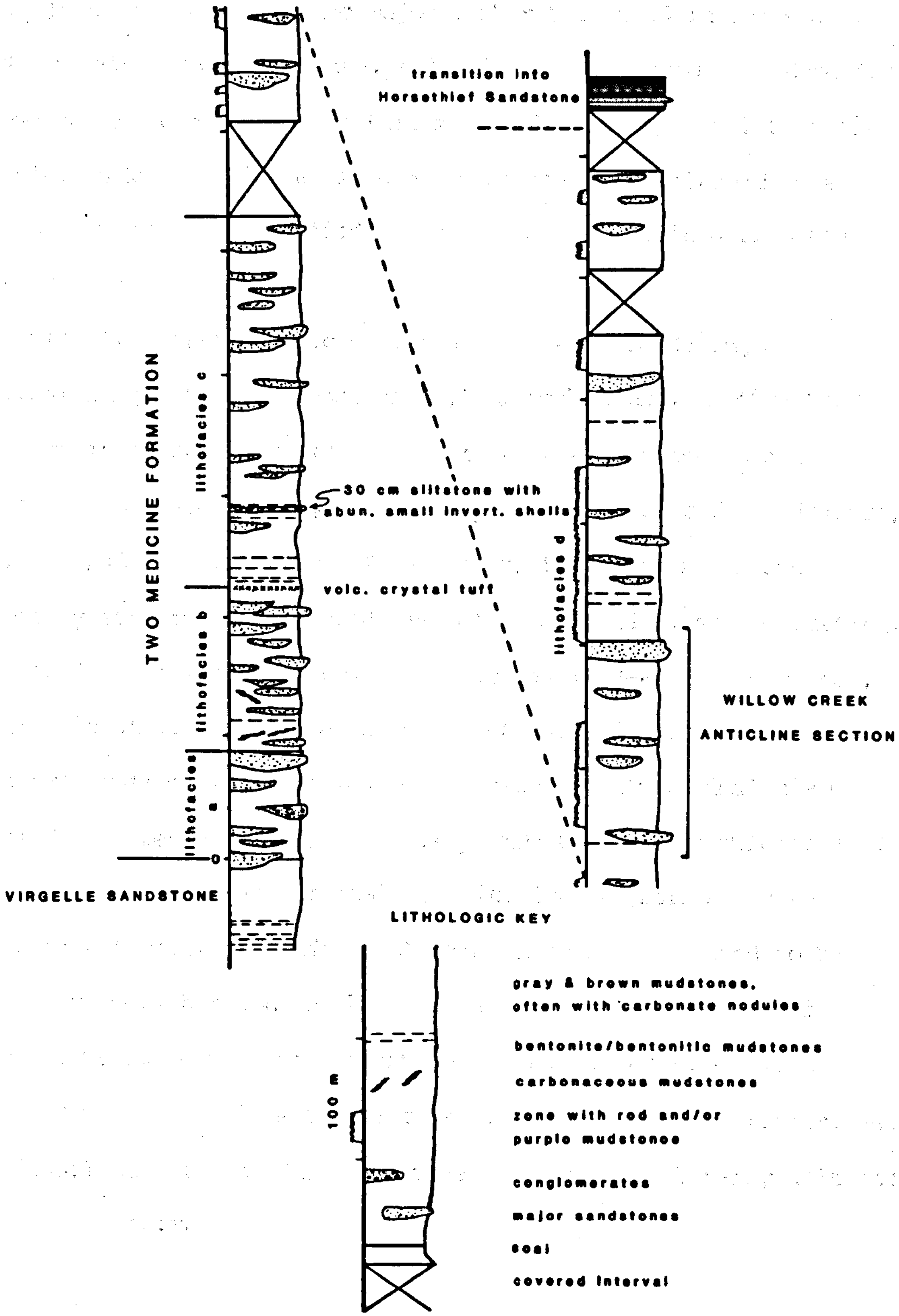

Figure 6. Composite stratigraphic column for the Two Medicine Formation near Choteau, Montana (after Lorenz and Gavin, 1984).

sites. This map also included major marker beds used in the study, structural elements in the area, and major channel sandstone deposits. Topography was superimposed on this map, using the appropriate section of the Bynum,Montana fifteen minute topographic map enlarged on a Saltzman projector and modified using elevations obtained from the plane table work.

Twenty-two stratigraphic sections were measured during and following the plane table work, using a Jacob's Staff. Sedimentary structures in channel sandstone deposits were also measured and described, and where possible, sandstones were measured for thickness, width, and paleocurrent data. In addition, the geometry of the sedimentary structures was noted, as well as the size, shape, sorting, and mineralogy of the sandstones. During the 1983-84 academic year, petrographic studies were conducted to determine diagenetic histories and classification of limestones and sandstones. Sieve analysis was performed on selected sandstones disaggregated with hydrochloric acid to determine sorting and vertical distribution of grain sizes to supplement petrographic studies. Calcareous rocks suspected to be derived from soil horizons or lacustrine deposits were collected during the field season and were slabbed and examined visually and with x-radiography to detect relict bedding, precipitation fronts, and trace fossil structures. This was done using a medical x-ray unit and 3M Rare Earth film.

RESULTS

The study area is divided into four subfacies based on their lithological and petrologic characteristics. These four subfacies comprise approximately one-fourth of Lorenz's lithofacies (d). These subfacies are:

- the lower subfacies
- the middle subfacies, composed of two laterally equivalent subfacies which are designated the charophytiferous limestone middle subfacies and calcareous mudstone middle subfacies
- the upper subfacies (Figure 7).

Lower Subfacies

The lower subfacies comprises only about one-fourth of the entire section which is exposed at the anticline. Most of it is covered by alluvium or does not crop out due to structural complications but there are indications that it comprises a large part of the section. The main areas where it crops out include the central portion of the anticline and to the north near Fire Ridge (Figure 8 and Plate 1). No base was defined for this unit due to the lack of lower exposures.

In the lower subfacies, there are two distinct sandstone body morphologies. These are termed major and minor sandstone bodies with the major sandstone bodies apparently being derived from the main channel system.

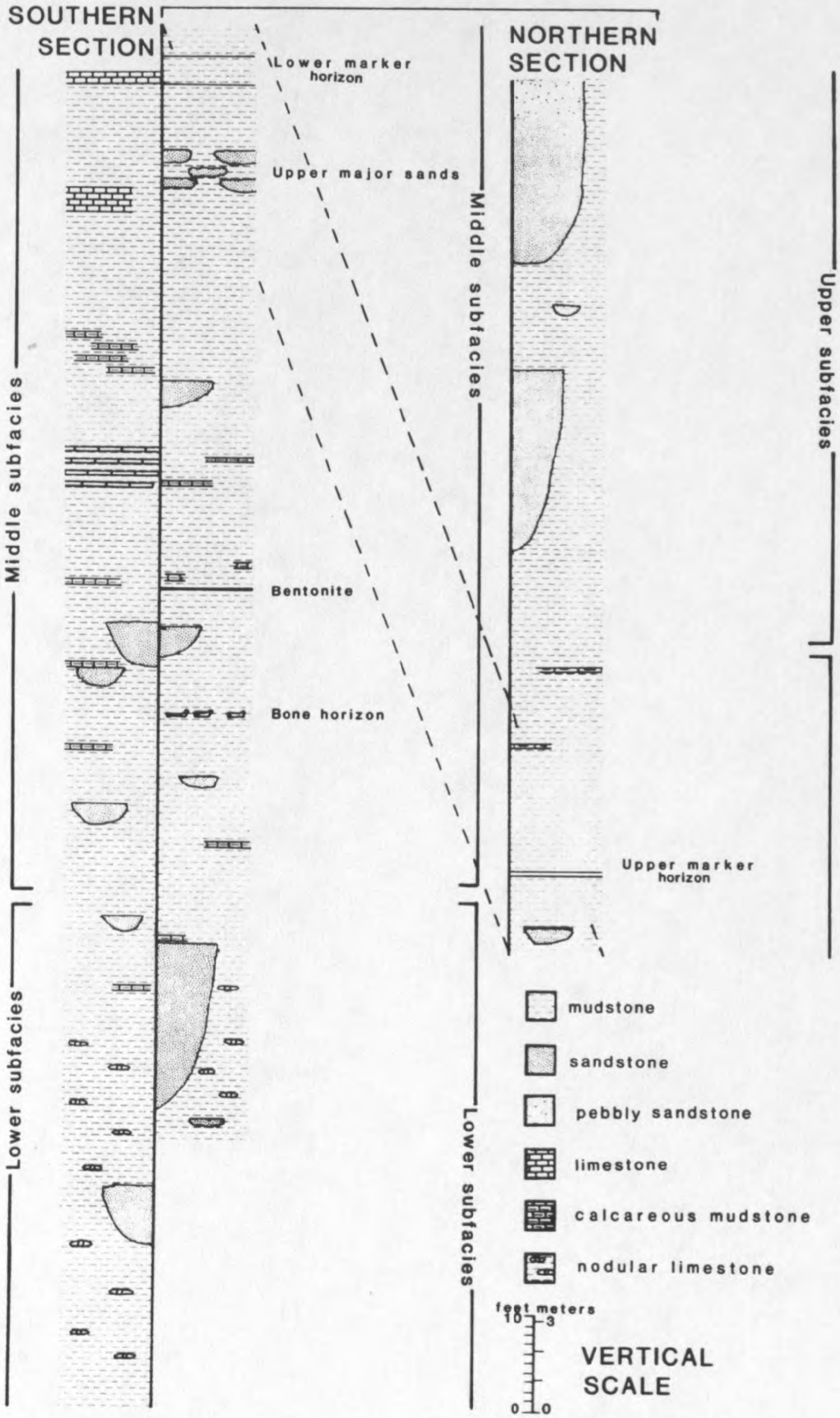

Figure 7. Composite stratigraphic columns for the Willow Creek anticline study area (dashed lines denote continuation of northern section).

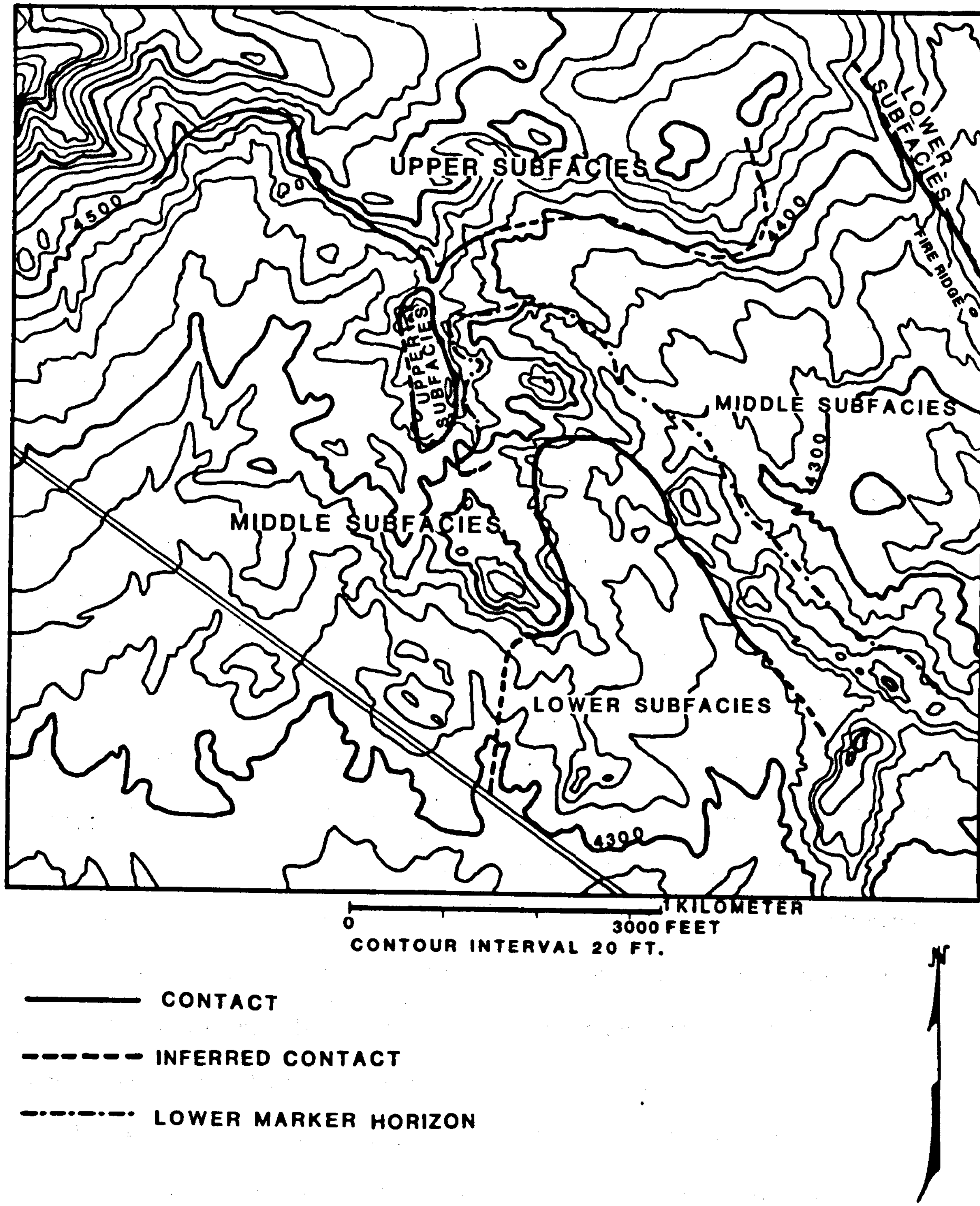

Figure 8. Map of the subfacies outcrops in the study area. No attempt is made to separate the two middle subfacies.

Minor Sandstone Bodies - The minor sandstone bodies are tabular to slightly lenticular, 0.5 to 1.2 meters thick, and up to 43 meters wide. The average width is 15 meters. In most of these sandstone bodies, cross-stratification is impossible to observe due to their extremely friable nature. However, in some sandstones, small-scale trough cross-bedding is visible but diminishes in size, grading into ripple cross-lamination towards the edges and the top of the sandstone bodies. Associated with this decrease in sedimentary structure size is a corresponding decrease in grain size with the top of the sandstone often grading into siltstone or alternating layers of siltstone and very fine-grained sandstones. Sandstone body tops almost always contain burrows and root tubules, some of which have ferric staining and cementation around their perimeters. Sandstone bodies are surrounded by siltstone and mudstone and their bases rest on channels that show evidence of erosion.

The sandstone is gray to gray-green in outcrop and salt and pepper in hand sample. Petrographic study of these sandstones shows 30 to 40 percent calcium carbonate cement and abundant quartz and chert with minor percentages of feldspar and mica. These are classed as chert-arenites and sub-chert-arenites. Grain size is medium to very fine sand and grains range from subangular to angular.

Major Sandstone Bodies - This type of sandstone body is considerably thicker than the minor sandstone bodies (6 to 10.5 meters). Only three outcrops of the major sandstone body morphology occur in the anticline and in no instance is a complete cross-sectional view available due to erosion and structural complications. Measurements taken at several locations along the bases of some of the major sandstone bodies indicate that the sandstone bodies are approximately 30 meters wide. Width-to-thickness ratios are estimated at 3 to 4. All three outcrops occur at the same stratigraphic level and appear either to have been derived from the same channel or branches of the same channel system, based on their morphology and sandstone composition. The major sandstone bodies have abrupt lateral contacts with adjacent red and purple siltstone (Figure 9). There is some minor interfingering along these contacts but it is limited to 1.5 to 3.0 meters in lateral extent. Rounded fist-sized pebbles of siltstone--probably chunks of bank cave that were incorporated into the sandstones before they could be completely disaggregated--occur irregularly throughout the sandstones. The bases of the sandstone bodies are slightly concave and irregular with ripup clasts and a coarser sandstone that contains white to buff rounded clay clasts and tuffaceous volcanic fragments 1 millimeter to 1 centimeter in diameter. The sandstone's friable nature makes it hard to determine the type of cross-bedding, but trough cross-bedding has been observed. Similarly, this friable nature also makes determination of paleocurrent direction impossible.

Major sandstone bodies are composed internally of stacks of fining upwards sequences. The base of any single sequence is composed of medium- to fine-grained sandstone with claystone clasts and tuffaceous volcanic fragments. This base is usually well-cemented with calcium carbonate and weathers into brownish resistant lenses within the sandstone bodies. The top of each sequence is composed of

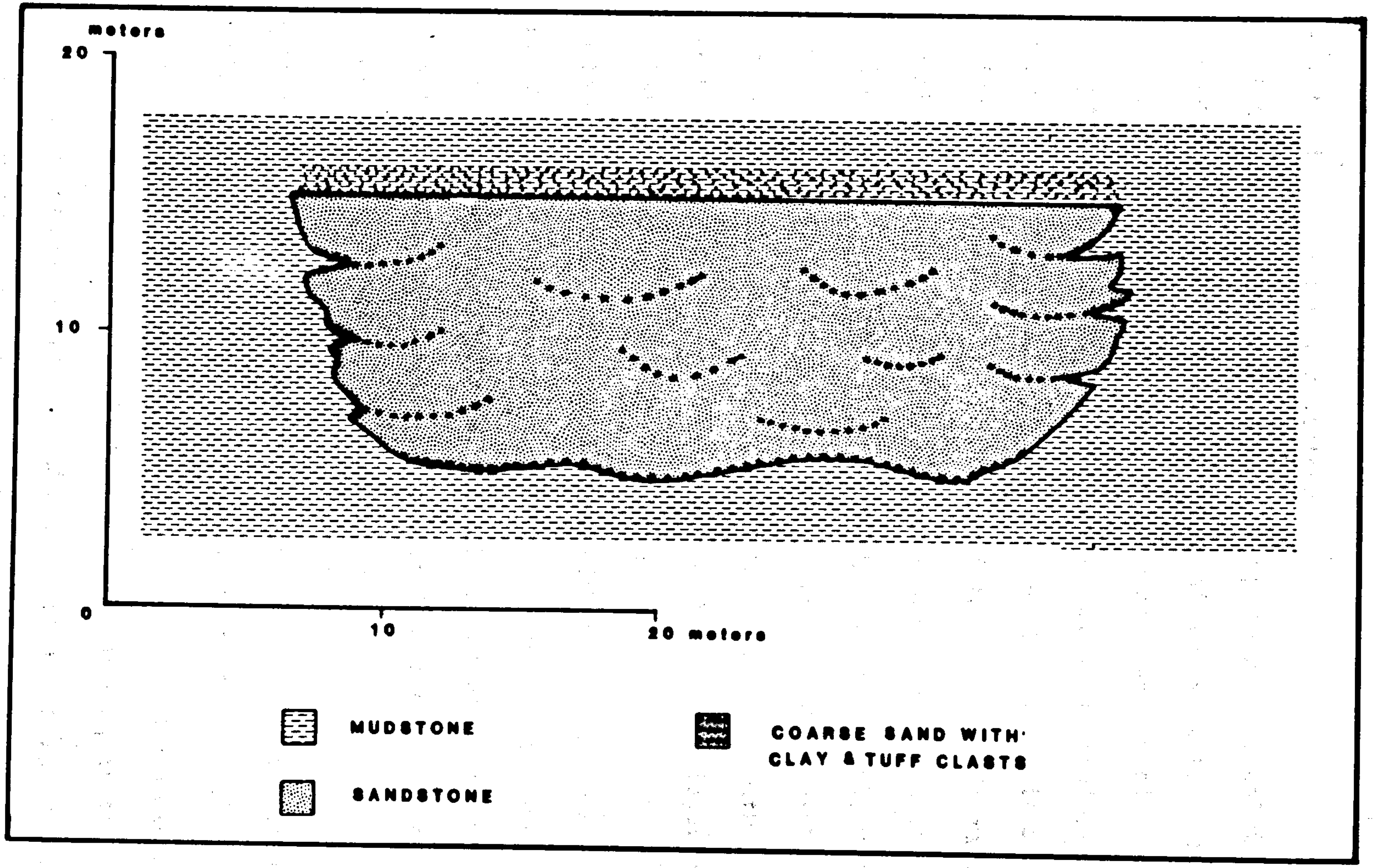

Figure 9. Cross section of typical lower subfacies major sandstone body.

very fine-grained sandstone. In sections at the edge of the sandstone body, the tops grade into siltstone.

Petrographic analysis shows a lower percentage of calcium carbonate cement (49 percent) and a much higher percentage of feldspar than the minor sandstone bodies. These sandstones are classified as feldspathic litharenites. All sandstone grains are angular to subrounded. Of the disaggregated sandstone, 20 percent is silt-size or finer, giving a sand-to-silt ratio of 4. Sand-to-silt ratios, determined from percentages of sandstone in measured sections within the lower subfacies, are much lower, .92, and are probably more representative of the area. The top of these major sandstone bodies is composed of fine to very fine sand which alternates with sandy siltstones in layers 15 to 30 centimeters thick. This layering continues for about 1.5 meters. The sandstone occasionally shows ripple cross-lamination and is riddled with burrows and root tubules. In some instances, ripples in some of the mudstones appear squashed and deformed by the overlying sand, indicating that they were still wet and plastic at the time of the new influx of sand. No desiccation cracks are noted in any of these sediments.

Calcareous Mudstones - The calcareous mudstones in this facies occur as fist-sized nodules in irregular layers that are 5 to 10 centimeters thick and spaced about .3 meters apart. The nodules are pitted and irregular with a rust-colored rough surface. In many instances, the nodules branch down vertically and seem to follow old root traces. When slabbed, these nodules reveal they are composed of smaller nodules 10 to 20 millimeters in diameter. The nodules are almost pure micrite with no silt or sand inclusions within the component nodules. Small inclusions of mudstone occur between nodules. Bone fragments found in this subfacies often have calcareous mudstone nodules growing around them.

Siltstone - Siltstone and mudstone within this subfacies are usually red, orange, purple or yellow and occasionally gray and green. The purple mudstone usually occurs around the edges of channel sandstones. No grain-size analysis was done on any of these fine-grained sediments but almost all have various concentrations of silt or sand-sized material in them. Fifty-two percent of strata encountered in stratigraphic sections measured in the lower subfacies are mudstone. However this may not be representative of the total amount of mudstone in the lower subfacies due to the limited area exposed in the anticline.

The top of this subfacies is located where the calcareous mudstones change from small nodules to thick continuous layers. The major sandstone body morphology changes from thick, laterally confined sandstone bodies to thinner, more laterally extensive sandstone bodies. The siltstone and claystone change in color from red and orange to green and gray. This top is approximately 300 meters below the base of the Horsethief Sandstone.

The carbonate and sandstone morphologies grade upward into the two overlying middle subfacies. These are termed the calcareous mudstone middle subfacies and the charophytiferous limestone middle subfacies. In the transition from the lower to the middle subfacies, the mudstone gradually changes from red and orange to gray and green.

Middle Subfacies

The middle subfacies is divided into two subfacies defined by the presence of either a charophytiferous limestone or calcareous mudstone. The charophytiferous limestone middle subfacies includes thinly laminated mudstones and laterally persistent mudstone beds. The calcareous mudstone middle subfacies is defined as those siltstones containing sandstones and calcareous mudstone layers. Total thickness of the middle subfacies is 40 meters (Figure 7) with the top being approximately 256 meters below the Horsethief Sandstone. The upper contact of the middle subfacies is gradational and is placed at a point 7 meters above a key marker horizon, composed of cemented volcanic ash, which is termed the upper marker horizon.

Calcareous Mudstone Middle Subfacies - This subfacies becomes more predominant in the north part of the study area. However, there is considerable interfingering of both charophytiferous limestone middle subfacies and calcareous mudstone middle subfacies, both north-south and east-west (Plate 2, 3).

Minor Sandstone Bodies - The smaller sandstone lenses are much like those in the lower subfacies, usually 0.6 to 1.2 meters thick and up to 30 meters wide. They average about 15 meters. Bedding in these sandstones is often obscured due to their friable nature but trough cross-bedding is visible in the middle of the sandstone bodies and ripple cross lamination is visible at the top and sides. The top usually grades into siltstone and is always heavily bioturbated with burrows and root traces. These upper areas are usually more resistant and often weather to a brown color. Sandstone bodies are lensoidal in shape and the base is concave upward.

Petrographic studies of these sandstones show they are medium-grained to very fine-grained and angular to subrounded. In most samples, quartz is the primary constituent with varying amounts of chert and feldspar, and minor amounts of mica and heavy minerals. These are classified as sublitharenites and chert-arenites. In some samples, volcanic rock fragments make up the major part of the rock, making these volcanic-arenites. In most cases these sandstones are moderately sorted and are immature to submature.

Major Sandstone Bodies - The second sandstone morphology is thicker and more laterally extensive with high width-to-thickness ratios. There are two stratigraphic locations for these sandstones (lower and upper). The base of the lower sandstones occurs approximately 7.5 to 9 meters above the lower subfacies and about 1.8 meters below a bentonite bed that occurs in the middle subfacies.

These lower sandstone bodies are poorly to moderately indurated and are greenish gray in fresh hand sample and yellowish brown in weathered outcrop. Sandstones are broadly lenticular with relatively indistinct lateral contacts. The top of the sandstone grades up into alternating layers of siltstone and fine sandstone which is riddled with root tubules and burrows. They are fine- to coarse-grained with calcite cement and are composed of abundant volcanic rock fragments with lesser amounts of quartz and chert, making these a volcanic-arenite.

Sedimentary structures are difficult to distinguish but appear to be exclusively trough cross-bedding. The relative lack of observable sedimentary structures make it impossible to collect paleocurrent data for these sandstones. However, work by Hooker (pers. comm.) on bone orientation in a bone horizon located just above these sandstones has determined a paleocurrent orientation of N 40-50 $^{\circ}$ E. This probably closely corresponds with the sandstone channel axis orientation.

The upper group of sandstones is located about 15 meters below the top of the middle subfacies. The two major outcrops of this upper sandstone are definitely linked together and form a continuous channel that crosses the study area from west to east.

These sandstone bodies have very large width-to-thickness ratios. The thickness reaches 2.4 meters but averages about 1.8 meters. An exposure of this sandstone on the west side of the study area is almost 200 meters wide while 1.5 kilometers to the southeast, an equivalent outcrop is estimated to be 70 meters wide. The western sandstone body forms one continuous outcrop while the sandstone bodies to the southeast are composed of a series of sandstones which appear to be caused by lateral avulsion. The only sedimentary structure observed was trough cross-bedding. No epsilon cross-stratification was observed in any of these sandstones.

The base of the sandstone bodies rests on pebble lags composed of rounded siltstone clasts averaging 15 millimeters but ranging up to 8 centimeters in diameter. These basal lags occasionally contain isolated dinosaur bones which usually appear to be weathered. Throughout all of the sandstone bodies there is an abundance of rounded mudstone clasts which are presumed to be from bank cave. The lateral contacts show considerable interfingering with adjacent mudstone. The tops are usually abruptly overlaid by siltstone. There is little or no indication of bioturbation at the top or within the sandstone except for some isolated root traces which parallel the top of sandstone.

This upper group is moderately to well indurated and very resistant, forming pronounced ledges in the study area. In hand sample and outcrop, the sandstones are gray-green with a salt and pepper appearance. These sandstones usually fine upwards throughout the entire sandstone body but considerable size variation occurs at any given point. The base ranges from coarse to very fine-grained. The middle is coarse to very fine-grained, and the top is medium to very fine-grained. The sandstones range from volcanic arenites to feldspathic litharenites with abundant volcanic rock fragments. Up to 60 percent of the sandstone may have been silisic volcanic glass. The sandstone has been partially cemented by silica from devitrification of the glass. The devitrification process has also left an abundance of clay in the matrix. There is also some minor calcareous cement. In these sandstones there is an abundance of heavy minerals (mostly magnetite) which are often concentrated at the base of individual beds. Grains are angular to subrounded. Many of the subrounded grains are probably the result of authigenic alteration of formerly angular grains.

Paleocurrent data for these sandstones were obtained by measuring the orientation of axis and limbs of the trough cross-bedding (Figure 10). The results for the western outcrop are V_0 = 38.00 degrees with a consistency ratio of .91 where a ratio of 1 represents perfectly preferred orientation and 0 represents totally random orientations. The results for the eastern outcrop are V_0 = 77.65 degrees and a consistency ratio of .83.

Calcareous Mudstones - The calcareous mudstones in this subfacies are thicker and form more laterally extensive layers than those in the lower subfacies. They range in thickness from 10 centimeters to 1 meter and extend laterally up to several hundreds of meters. Usually they are discontinuous and no single bed can be traced far enough to use it as a marker. The carbonates around nesting sites are more discontinuous than in other areas. They are very limited laterally and seem to occur through a greater vertical area.

Calcareous mudstones are often fractured or jointed due to the folding associated with the area. Where large surfaces of the mudstones are exposed, they form a series of elongate bread loaf-like ridges 1 to 3 meters long with vertical fractures through them, forming "slices" 5 to 10 centimeters thick. The layers are less closely spaced than those in the lower subfacies, varying from 1 to 3 meters, but there is very little consistency in spacing through any given section. These layers are usually the same color as the surrounding clay and mudstone (reddish-brown and gray-green).

Polished slabs of these limey mudstones show rounded clasts of the host mudstone floating in a matrix of very calcareous mudstone.

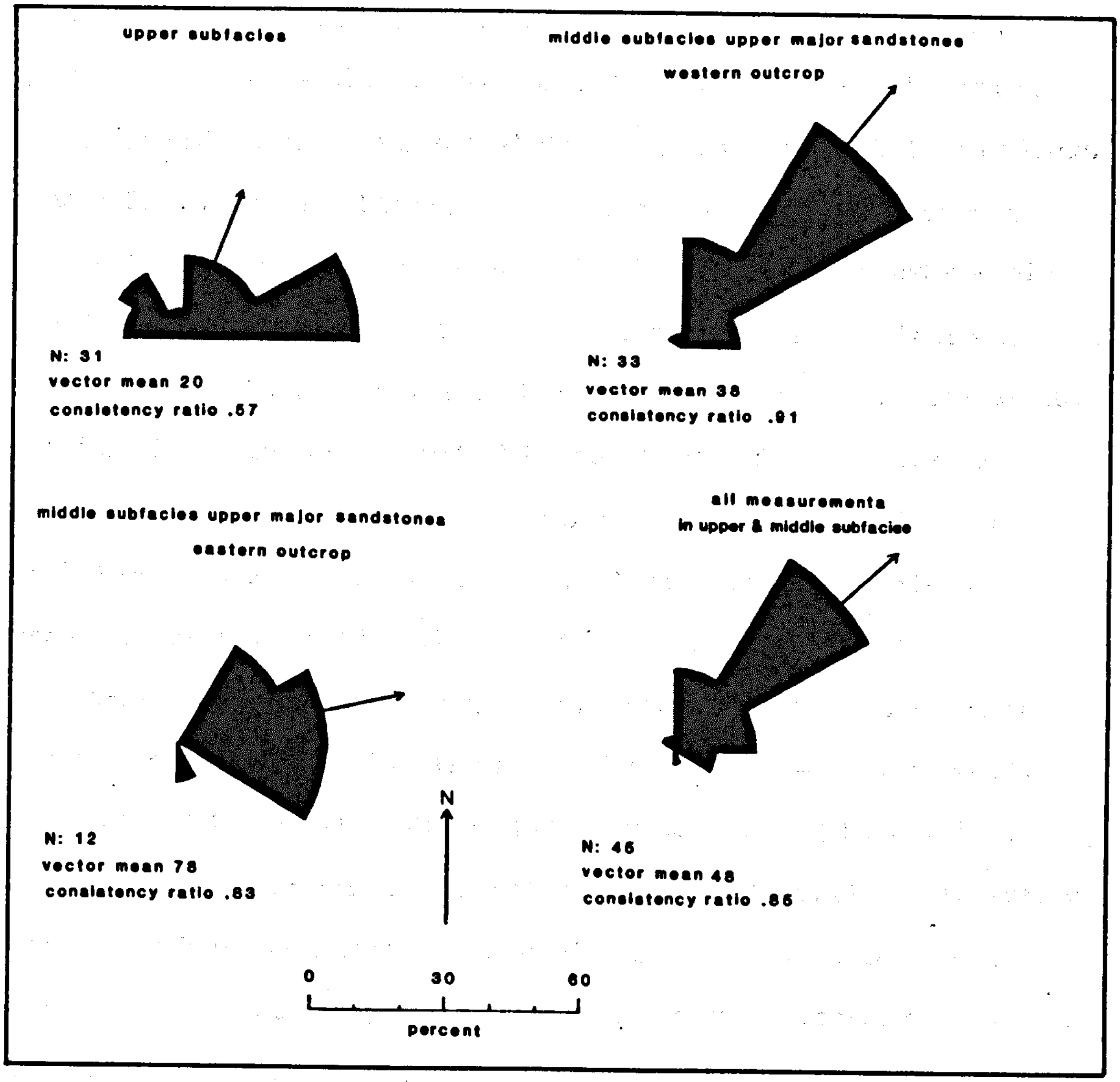

Figure 10. Rose diagrams of paleocurrent data gathered in the study area.

These clasts range in size from microscopic to 1.5 centimeters in diameter and are usually rounded to subrounded (Figure 11). Often there are undulatory veins of calcite that run subparallel to bedding, spaced from 2 to 15 millimeters apart but averaging 5 millimeters.

Thin sections exhibit the same fabric as the slabs and contain rounded to subrounded clasts of mudstone floating in a calcareous matrix. Many clasts can be seen being forced apart by the calcareous matrix, displaying an "exploded" fabric. Most of the calcareous mudstones contain abundant sand and silt grains with little or no grain-to-grain contact. The ratio of clastic grains to calcium carbonate varies considerably but appears to average about 1.

X-rays of slabs show no internal bedding or lamination and the mudstone clasts show only faintly. Pedotubules show up very well, being opaque to x-rays. This is probably due to some hematitic lining of the tubules. In thin section these are usually filled with sparry calcite with no hematitic staining although there must be enough hematite to affect x-rays. In some cases, these calcareous mudstones are riddled with pedotubules which branch and taper, appearing to be root systems (Figure 12). The top and often the bottom do not contain these tubules, indicating some deposition after roots could no longer penetrate this layer. In many cases, it appears that these opaque tubules have subsequently been invaded by the calcium carbonate matrix and are being forced apart.

Since several of these calcareous layers are unique and important to later discussions, they will be described in detail here. The first of these is a calcareous mudstone about 30 to 60 centimeters

Figure 11. Photograph of a slab of the calcareous layer showing rounded clasts of host mudstones and veins of sparry calcite.

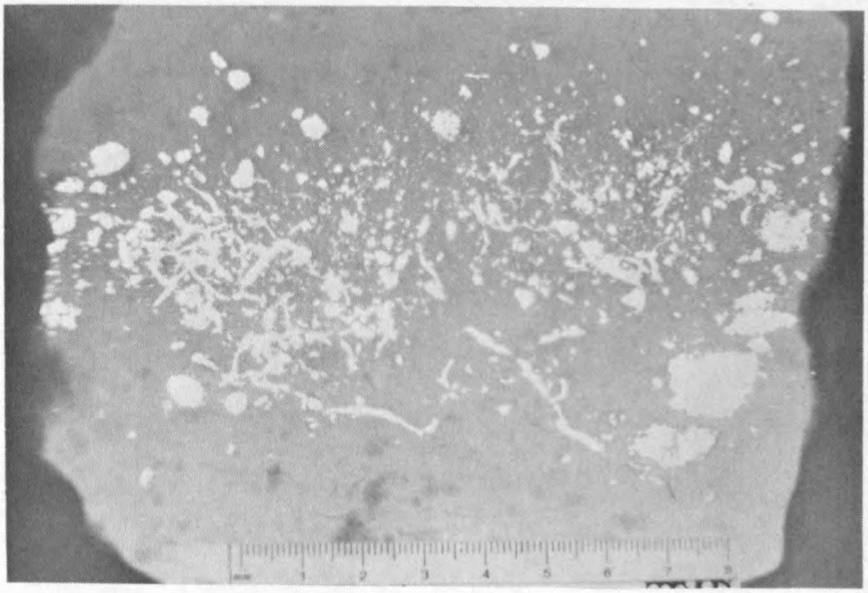

Figure 12. X-ray of slab of calcareous layer showing root tubules in middle and undisturbed bottom and top.

thick, which underlies the lower major sandstone described above. This calcareous layer has developed a mini-karst-like surface of pits and tunnels averaging 10 centimeters in diameter but varying considerably in size. The sandstone overlying the calcareous mudstone has filled this karst-like surface and in many instances has incorporated pebbles of the calcareous layer and siltstone into a basal lag. Another calcareous layer occurs at the base of a bed containing an extensive deposit of dinosaur bones which occurs 9 meters above the base of the middle subfacies. This layer is from 10 to 30 centimeters thick and is not typical of the calcareous mudstone layers mentioned above. It is very resistant and calcareous but still retains its sedimentary fabric of laminations. There is none of the typical clasts of matrix or exploded clasts found in the other calcareous layers. Bones in the overlying layer rest upon and in some case appear to have been slightly pressed into the underlying layer. This would indicate that this layer was still slightly unconsolidated and probably not cemented at the time of bone horizon emplacement. The calcium carbonate must have been deposited after the overlying sediments accumulated. This will be expanded upon in the discussion section.

Another unique calcareous layer occurs about 1.5 meters above the bentonite beds. At this level an initial calcareous layer appears to have been replaced by silica and was subsequently broken up and forced apart by another calcareous layer. Angular blocks of the greenish to white siliceous layer float in the new carbonate matrix (Figure 13). These blocks range from 2 millimeters up to 2.5 centimeters. The amount of silica replacement varies. In other areas at approximately the same stratigraphic level, nodules of chert have grown in the calcareous matrix. These are usually red to pink. They seem to have filled voids or other fillings in the calcareous layer and in many cases seem to be following old root tubules. Bones associated with this horizon also have been replaced by jasper, the only place in the study area where this occurred.

Figure 13. Photograph of block of calcareous layer with chert inclusions.

Siltstone - The siltstone and shale of the calcareous mudstone middle subfacies are primarily gray-green and reddish purple with some orange and pink. However, the gray and green colors probably characterize 50 to 60 percent of the subfacies. The colors are laterally very inconsistent and usually can only be traced for a few hundred meters. The sand-to-silt ratio for the middle subfacies is .20 based on measured sections, considerably lower than for the lower subfacies.

While most of the sediments in the calcareous mudstone middle subfacies are devoid of any carbonaceous material, there are some isolated carbonaceous siltstone lenses. Distinct plant remains do not occur, but the mudstone has abundant small lignitic flakes. These lenses are not laterally extensive, usually only 15 to 30 meters wide and 30 to 60 centimeters thick, and only occur in two places on the anticline.

One bentonite bed occurs in the middle subfacies, as mentioned earlier. This bed is located approximately 11 to 12 meters above the lower subfacies. It is usually only a few centimeters thick and does not blanket the area, but instead seems to be restricted to topographic lows at the time of deposition. It was not possible to derive an age date from the volcanic ash due to the extensive alteration. The distance between this bentonite and the underlying bone horizon varies up to 2.4 meters, reflecting minor topographic relief within this interval.

In addition to the main bentonite layer, much of the mudstone just above and adjacent to it are bentonitic. This gives the mudstone a crusty, crumbly texture on weathered surfaces.

Fossils - Plant remains found in the study area occur in silicic to calcareous nodules 15 to 30 centimeters in diameter. These are very resistant and blackish-gray in color. None were found in place so it could not be determined if these came from any specific stratigraphic level. Thin sections of these show fragmentary crushed plant remains that are very well preserved. No whole plant parts have been found in the nodules for identification.

The only invertebrate remains found in the calcareous mudstone middle subfacies are two types of gastropods. Most of these are found in red siltstone near the contact between the lower and middle subfacies, and in gray-green siltstone interfingering with lake sediments. The shells are less than 2 centimeters, medium to high spired, and have little or no ornamentation. No identification of these has been made. A mudstone directly beneath a laminated siltstone layer contains hundreds of snail opercula.

Vertebrate remains are found scattered throughout this subfacies. In addition to the extensive bone bed that extends through much of the area, isolated and partially articulated bones are frequently found. Isolated and grouped clutches of hadrosaur eggs have been found in this subfacies.

Charophytiferous Limestone Middle Subfacies - The deposits of this subfacies interfinger extensively with those of the calcareous mudstone middle subfacies. This interfingering extends across much of the study area with the charophytiferous limestone middle subfacies being more common to the south.

The lowest deposits of the charophytiferous limestone middle subfacies occur 11.5 meters above the lower subfacies, just north of Egg Mountain. The highest deposits are 7 meters below the base of the upper subfacies. The highest of these deposits is the upper marker horizon which is composed of a green volcaniclastic silica-cemented deposit. The maximum thickness of this subfacies in the main study area is 22 meters which encompasses most of the middle subfacies.

Limestone - The charophytiferous limestone is the main lithology used to distinguish the presence of this subfacies. These limestones are gray to gray-green and composed almost completely of micrite. In thin section they often contain charophyte gyrogonites and other fragments of the plant. Three types of gyrogonites have been found. One is spherical with very thick walls and an almost smooth surface (Figure 14). A second is slightly oblate with nine convex ridges per side (Figure 15). This could possibly be a member of the genus _Clavator_. The third has seven concave grooves per side and is relatively rare (Figure 16). None of these gyrogonites has been positively identified other than being charophytes. The _Clavator_ genus identification is based on descriptions from Peck (1957).

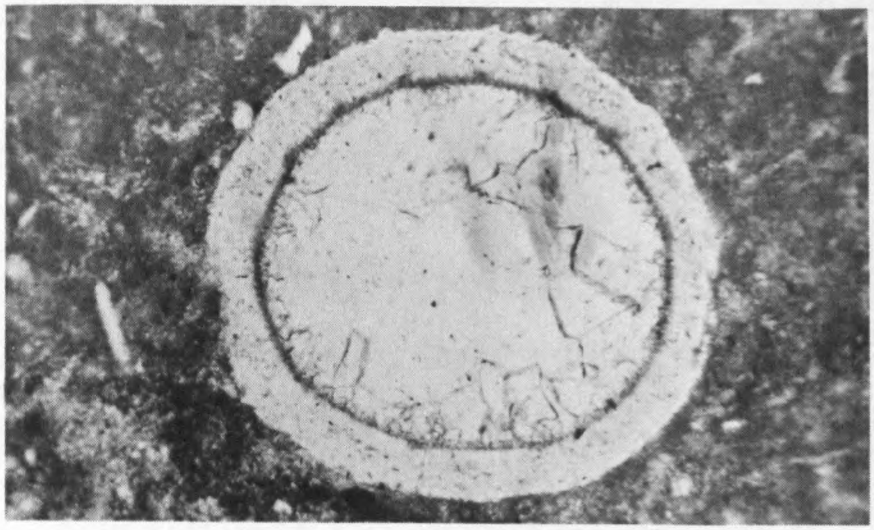

Figure 14. Photomicrograph of thick, smooth-walled charophyte gyrogonite (100x, approximately 1.5mm across field of view).

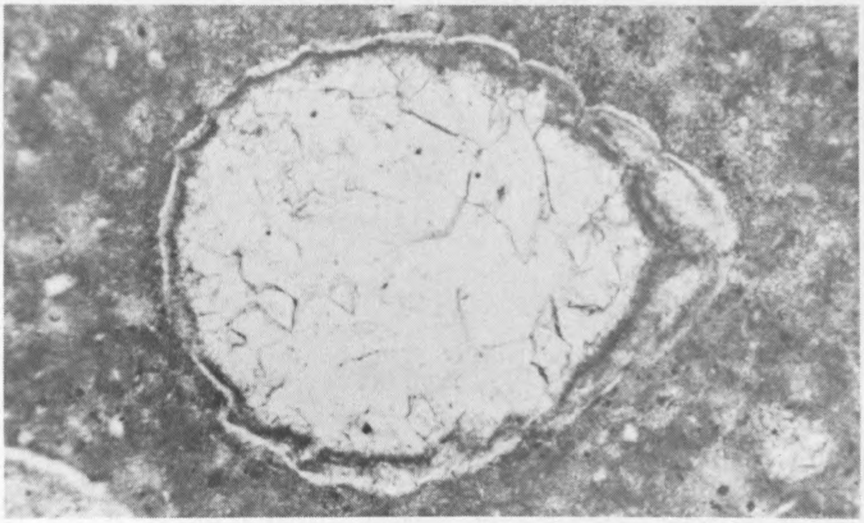

Figure 15. Photomicrograph of charophyte gyrogonite with nine convex ridges per side, possibly genus Clavator (100x, approximately 1.5mm across field of view).

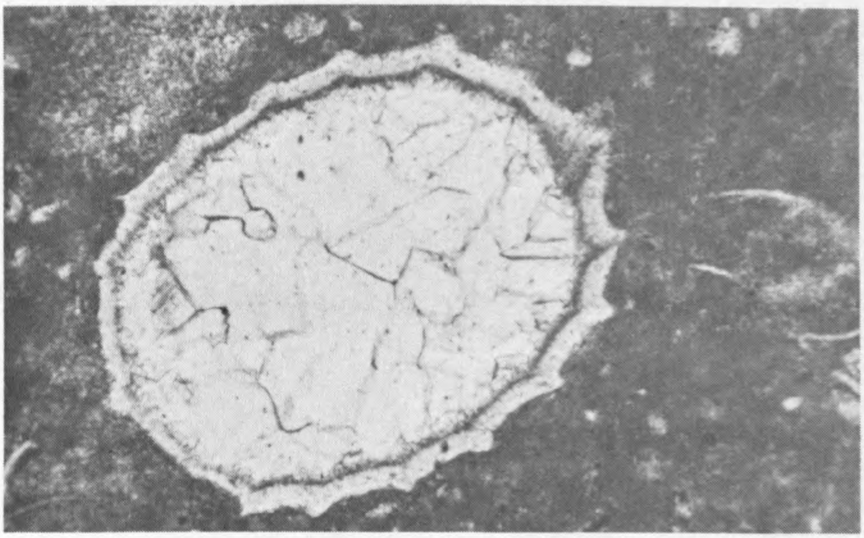

Figure 16. Photomicrograph of charophyte gyrogonite with seven concave grooves per side (100x, approximately 1.5mm across field of view).

In thin section all of the limestones contain sand and silt grains. The percentage of clastic sediments ranges up to 10 percent in some samples but is usually less than 1 percent. The grains are as large as 0.35 millimeters but most are very fine sand to silt-size. The grains' composition reflects that of sandstone bodies in the area with abundant angular to subangular quartz, chert and feldspar, with minor amounts of mica and opaque minerals. Most limestones also have various amounts of sparry calcite fillings in elongate hollows which appear to be rhyzoliths.

In outcrop the limestones are usually 15 centimeters thick and alternate with gray silty shale 30 centimeters thick in sequences from 1.5 to 3 meters thick. The limestones are usually very fractured and crumble into thumb-size pieces when hand samples are extracted.

Mudstone - Criteria used to recognize mudstones of the charophytiferous limestone middle subfacies are:

- thin, even horizontal bedding and lamination
- symmetrical ripple marks
- shrinkage cracks
- continuity of beds
- presence of stromatolites

Most of the clastic material is gray but some is purple and green. Thicknesses vary considerably. In the anticline the clastic material is usually associated with limestones and averages 30 centimeters in sequences up to 3 meters thick. South of the study area along the Willow Creek there is a relatively uninterrupted sequence of charophytiferous limestone middle subfacies clastic sediments 5-10 meters thick, with no limestone deposition. These strata are mostly silty shale and sandy siltstone about 30 to 45 centimeters thick.

Two clastic horizons are very extensive and are used as marker horizons on which to correlate measured sections. The lower marker horizon is a sequence of thinly laminated siltstone, mottled green and purple, located 10.3 meters below the upper subfacies. This sequence is about 30 centimeters thick but varies from 8 to 90 centimeters. It extends across much of the study area including outcrops along Willow Creek. It is missing in the northwestern part of the study area. The siltstone is noncalcareous in general and has varying amounts of sand. It is penetrated at the top with abundant rhyzoliths and burrows and the top surface often shows desiccation cracks. In one area where this layer is covered by a sandstone, the top surface contains current crescents caused by the sand flowing around a mudball imbedded in the underlying surface.

The upper marker horizon is 6.7 meters below the base of the upper subfacies. It is an olive green siltstone that is very well indurated and very resistant. It is about 10 to 15 centimeters thick and rests on top of 0.3 to 1.2 meters of red and green laminated siltstone. In thin section the matrix seems to be a siliceous clay with the sand and silt grains floating in it with very little grain-to-grain contact. The grains are primarily angular quartz, feldspar and chert with some rare glass and heavy minerals. The grains appear to have been derived from pyroclastic material which has been altered into a resistant layer rather than altering to bentonite. This horizon also represents the uppermost extent of the charophytiferous limestone middle subfacies.

Fossils - The charophytiferous limestone middle subfacies is important because of its association with many of the outstanding paleontological finds in this area. There are two major hypsilophodont nesting localities which occur in the middle subfacies. Egg Mountain (Plate 1) has yielded 14 clutches of eggs as well as juvenile bones, an embryo, and mammal remains during intensive quarrying. A second locality called Egg Island (Plate 1) was found in 1983 and appears to be the same type of deposit as Egg Mountain. This site has yielded two egg clutches and 16 embryos. Both of these localities are situated in sediments adjacent to charophytiferous limestone middle subfacies but not at the same stratigraphic level as each other. These nesting localities are thought to have been contemporaneous with deposition of this middle subfacies.

A relatively complete, remarkably preserved pterosaur was found in charophytiferous limestones very close to Egg Mountain. The hollow, fragile bones of these animals are usually found crushed due to overburden pressure exerted before complete fossilization (Horner, pers. comm.), but in this case, the bones had been permineralized by calcium carbonate in still water, allowing the skeleton to be preserved intact.

The only other fossils commonly found in the charophytiferous limestone middle subfacies are located along the Willow Creek outcrop. Here stromatolites are found in some of the siltstone layers. These appear in the rock as series of concentric circles of brown to black carbonaceous material along bedding surfaces of the siltstone. These were identified as stromatolites by Albert Fischer of Princeton University. There are also isolated steinkerns of Unio, a freshwater bivalve.

Upper Subfacies

Like the lower subfacies, the upper subfacies has limited exposure in the study area. Due to the northwesterly plunge of the anticline, the upper subfacies crops out only in the northwestern part of the study area (Figure 8 and Plate 1). In many respects, this subfacies is much like the calcareous mudstone middle subfacies it overlies. The main criterion used for distinguishing it from the underlying subfacies is a difference in sandstone body morphology and the lack of charophytiferous limestone. The base is approximately 160 meters below the Horsethief Sandstone and no top is defined due to limited exposure in the study area. One stratigraphic section (section 16) which has been measured at the western edge of the study area (Plate 1) ran well above the top of all other sections in the area. The cross section shows a marked upward decrease in the number of calcareous layers, but no attempt has been made to place an upper boundary on the subfacies based on this finding.

The sandstones of this subfacies change back to a morphology resembling that of the lower subfacies. Once again, there are two sandstone body types—minor and major.

Minor Sandstone Bodies - The minor sandstone bodies are rare in the upper subfacies but similar to those of the lower subfacies. These sandstone bodies are planar to slightly lenticular sandstones up to 2 meters thick. Widths range up to 84 meters but average 15 to 30 meters. One of these sandstones located at the top of section 11 (Plate 1) is unique to the study area. It goes from small trough cross-bedding at the base with no evidence of scour, to large-scale trough cross-bedding, to horizontal planar beds, to trough cross-bedding, decreasing to ripple cross laminations at the top with heavy bioturbation. Current lineation along the planar beds give an orientation of N 75° E. The channel is 84 meters across and 2 meters at its thickest.

Major Sandstone Bodies - The width-to-thickness ratio of the larger sandstone bodies shifts back to that of the sandstone bodies in the lower subfacies. Complete channels are rare but two that have been measured give ratios of 6.7 and 4.8, with widths of 49 meters and 30 meters and thicknesses of 7.3 meters and 6.4 meters. The sandstones become much more common in this subfacies as opposed to the middle, giving sand/silt ratios of .56 based on measured sections.

The bases of these sandstones often show some evidence of having cut into underlying sediments. Many times there is a basal lag of claystone clasts as well as argillite, quartzite pebbles, and bones. The bones are usually fragmentary and show evidence of weathering and transport. The base is usually concave. The top grades up into finer sandstone which alternates with siltstone, all of which are bioturbated. Lateral contacts have very little interfingering with the adjacent siltstone. The sandstones are usually light green to gray-green and are poorly to moderately indurated. The sandstones are composed of numerous fining upward sequences, which in some channels begin with lenses of pebbly sandstone.

Trough cross-bedding is the dominant sedimentary structure in these sandstones. The typical trough size is 2 meters wide and 20 centimeters high. Paleocurrent data has been obtained from the troughs of the sandstone at the top of section 12. This was done by measuring the orientations of the axes and limbs of the troughs (Figure 10). An average axis orientation derived from plotting the poles for right and left limbs of the troughs is 83 degrees. The vector mean for all measurements is 20.48 degrees with a consistency ratio of .57.

Thin section examination of the sandstones shows most are cemented with calcium carbonate. Some sandstones, however, show considerable silica cement with some associated clay in addition to the calcite. The silica seems to have precipitated subsequent to the calcite.

Sand size analysis has been done on an entire sandstone body as well as single fining upward sequences. Samples have been taken from the base, the middle, and the eroded top for grain size analysis on the entire sandstone body, located at the top of section 12 (Plate 1). All three samples are unimodal with the modes being 1.75 ϕ for the lower, 2.5 ϕ for the middle, and 2.75 ϕ for the upper sample: an overall fining upward sequence. Within a single fining upward sequence, the sands have a bimodal grain size distribution with one peak at -2.0 ϕ and one peak at 1.75 ϕ. Grain size varies considerably in the sandstone bodies of this subfacies, ranging from pebbles up to 2.5 centimeters to silt-size material. The gravel-size material is partly composed of clay pebbles of contemporary origin with the sand and resistant quartzites and low-grade metamorphic mudstones. Sand-size grains are mostly quartz, feldspar, chert and volcanic rock fragments with minor amounts of mica and heavy minerals. In most instances the grains are angular to subangular. The feldspar grains in many of the coarser grained sands are often almost euhedral. Most of these sandstones are classified as feldspathic litharenites or lithic arkoses due to the abundance of feldspar and chert.

Calcareous Mudstone - The calcareous mudstone of the upper subfacies is similar to that of the calcareous mudstone middle subfacies. In a few instances layers contain sand and pebble grains floating in a micritic matrix relatively free of clay and silt. No calcareous layers developed in sandstones in any of the lower subfacies.

Mudstone - The siltstone and mudstone of this subfacies are identical in color and frequency to those of the calcareous mudstone middle subfacies. However, the sand/silt ratio is about the same as that of the lower subfacies, or .89. Very few fossils have been found in this subfacies, due in part to its limited exposure in the area. Eggshell fragments and isolated bones are common but no egg clutches or extensive bone beds have been found.

DISCUSSION OF SANDSTONES

Morphological Classifications

The sandstones found in the study area were almost certainly deposited in a fluvial environment based on the presence of terrestrial fossils, lack of marine fossils, their highly oxidized nature and the known paleogeography of the area. The morphology of the streams that deposited these sandstones must fall into one of four morphologies commonly accepted which are:

- anastomosing
- meandering
- braided
- straight

These are defined according to two parameters--braiding and sinuosity (Table 1) (Rust, 1978). Characteristics of these morphologies will be described to aid with the discussion of the streams which deposited the various sandstones in the study area.

The anastomosed model of channel geometry has only recently been defined as a separate morphology by Smith (1976), Smith and Smith (1980), and Smith and Putnam (1980). Due to the relative newness of this concept and the dearth of descriptions of ancient examples, considerable time will be spent describing the anastomosed morphology and reviewing the literature concerned with modern examples of anastomosis.

Table 1. Classification of channel morphologies (after Rust, 1978, pg.194).

	Channel Classification	
	Single-channel (Braiding parameter<1)	Multi-channel (Braiding parameter>1)
Low-sinuosity (<1.5)	Straight	Braided
High-sinuosity	Meandering	Anastomosing

$$\text{Sinuosity} = \frac{\text{thalweg length}}{\text{valley length}}$$

$$\text{Braiding index} = \frac{2(\text{sum of islands and bars in a reach})}{\text{length of reach measured midway between banks}}$$

Anastomosing Streams - Smith and Putnam (1980) note that the term 'anastomosing' was originally used to describe portions of the upper Green River of Wyoming by M. R. Jackson (1834) and A.C. Peale (1879) (as cited in Smith and Putnam, 1980). After that time the term appears to have become synonymous with 'braided' until Smith recognized it as a separate morphology with distinct physical conditions distinguishing it from both meandering and braided streams--both of which had previously been considered to be the main morphological styles. Smith (1983) describes anastomosed channels as "rapidly aggrading, stable, multiple, interconnected, low-gradient, low-sinuosity, laterally confined sand or gravel bed channels."

Smith and Putnam (1980) state that the reason for a shift to an anastomosed morphology is due either to a rising local base level downstream or relative subsidence of the anastomosing section relative to downstream areas. A key factor in stabilizing channel banks and limiting horizontal migration of channels to allow for a typical anastomosing pattern is the presence of abundant vegetation along the banks of the channels. Their roots act as riprap protecting the banks from erosion while helping to trap silt and clay to aggrade the banks into levees (Smith, 1976).

In his classification of alluvial channels, Schumm (1968b) groups anastomosing systems into the suspended load channel type. Within the tripartite classification there is a further subdivision based on channel stability into stable, depositing, and eroding. Smith's anastomosing channel morphology would fall into Schumm's depositing category due to the aggradation taking place in response to the increase in relative base level. While Smith does not directly address it, the anastomosing morphology of multiple interconnected channels would seem to be an attempt by the river (holding other factors constant) to continue to move the same amount of material at a lower gradient by increasing the effective width-to-depth ratio.

Given Schumm's equation (1968b),

$$Q_s \propto \frac{w, l, s}{d, P}$$

(where Q_s is the ratio of bed load to total sediment load, w is width, l is meander wavelength, s is gradient, d is depth and P is sinuosity), if Q_s is held constant, and gradient is decreased then width-to-depth ratio may increase as may meander wavelength. Sinuosity will decrease. This description fits Smith's definition of anastomosing streams well. It should be noted that Smith uses the term 'stable' in his definition. This refers to bank stability and lack of horizontal migration and not to overall stability of the river system.

In a comparison of meandering to anastomosing channels Smith (1983) notes that a meandering stream will have high sinuosity, as compared to an anastomosing stream which has medium to low sinuosity. Aggradation rates for meandering streams are low, while anastomosing streams have a medium to high aggradation rate. Meander belts are wide for meandering streams and are confined or absent for anastomosing streams. These conclusions are in accord with what we expect based on Schumm's equation for a system experiencing a change in base level with load held constant.

One important facet of anastomosing rivers that Schumm's classification does not address is the effect of vegetation on the river's morphology. In two of his papers (1968a, b) he dwells at length on the effects of vegetation in the drainage basin upon the sand/silt ratio and thus, indirectly, on morphology. However, he never addresses the actual effect of bank vegetation upon morphology. The effect of vegetation on anastomosed rivers is very important in that it stabilizes the banks, helps to create and preserve levees and thus stops the channel from migrating laterally. The vegetation has the same effect as an increase in fines in the sediment load. An increase in fines would stabilize banks and prevent the lateral migration of channels due to the fine-grained material's resistance to erosion, as shown by Hjulstrom's curve. In the case of a change of base level for a meandering stream, vegetation would prevent an increase in the single channel's width and instead would force vertical accretion and an increase in effective width-to-depth ratio by creating new channels from breaches in the forming levees. This process creates an anastomosing morphology.

All of Smith's studies of anastomosing channels were conducted on rivers located in temperate, well vegetated areas in western Canada. Rust (1981) and Rust and Legun (1983) have studied anastomosing reaches in arid climates in central Australia. In these areas, overall vegetation is sparse but there is a concentration along levees bordering anastomosing sections due to the concentration of water there. Rust and Legun note that in the channels they studied there is no indication of lateral migration features and thus anastomosing channels must shift by avulsion, if and when they do shift. This conclusion was implied in Smith's papers but never directly stated.

Rust and Legun (1983) note several differences between the arid and temperate rivers. The channel density in the arid area was much lower, covering only 3 percent of the alluvial plain. In temperate areas, they may cover from 15 to 20 percent (Smith and Smith, 1980). In temperate areas, organic accumulation is quite common and extensive, while in the arid environment very little organic matter accumulates due to rapid oxidation. Rust (1981) notes that duricrusts of calcrete, silcrete and ferricrete are common in overbank mud units.

Smith and Putnam (1980) note six sediment facies in alluvial plains containing anastomosed channels. Three are wetland facies termed peat bog, backswamp, and floodpond, which are all low-lying areas bounded by the channel levees and subject to frequent flooding and standing water. The levees bordering the channels, the channels themselves, and crevasse splays are the other three facies. The first three facies are essentially the same and are separated based on organic content of the sediments. They all occupy the same position within the system and could probably be considered one facies. They are characterized by silt and clay-sized sediment in laminae with variable amounts of organic matter. The laminated nature of the sediment can be rapidly disrupted by bioturbation and homogeneous sediments may result. As noted by Rust, arid zone anastomosing fluvial systems would have very little organic matter due to the original lack of it and its rapid oxidation in a dry climate.

Levee facies are composed of sandy silts with abundant roots. In arid zones, Rust notes, many of the roots are replaced with rhizoconcretions and duricrusts of calcrete often occur in the levees as well as other overbank areas.

The channel sands are composed of sand and gravel in stacks of fining upward sequences. Main channel fill is thought to be mainly composed of trough cross-strata while the less active channel fill is composed of planar cross-strata with some trough cross-strata. Epsilon cross-beds are rare or absent due to the lack of lateral migration. Crevasse splays are thin sheets of sand and in some instances can take the form of small channel systems radiating from the crevasse.

Ancient deposits - Criteria used to distinguish deposits of ancient anastomosed fluvial systems are still rather sketchy and to date only two examples have been studied in detail. Galloway (1979) gives general characteristics for a suspended load channel, given the physical parameters of modern examples listed by Schumm. Criteria listed by Galloway include:

- Dominant channel-fill sediment ranging from very fine sand to silt and clay, rarely with very coarse sediment
- A highly lenticular sandstone body geometry in cross section
- Vertically stacked channel-fill units encased in fine grained floodbasin deposits
- Sequences that may or may not fine upward, depending on the range of grain sizes available.

In their study, Smith and Putnam (1980) give the most extensive list of criteria to be used in distinguishing ancient anastomosed systems. Criteria listed are:

- low width-to-depth ratios (commonly less than 10)
- a high percentage of silt and clay outside of channels
- little or no indication of lateral migration
- multistory channel deposits
- no epsilon cross-beds
- multiple interconnected channels
- splays and avulsions
- the presence of coal
- the presence of freshwater organisms

The ability to determine the presence of multiple interconnected channels is rare. However, in their study, Smith and Putnam were able to use closely spaced oil and gas well data to determine a map view of the system. They note that there is no single feature which is unique to anastomosed systems.

It should be noted that lower delta facies contain many of the same characteristics as anastomosing systems and therefore an understanding of the overall depositional setting and the presence or absence of marine fossils is important. In connection with overall geologic setting, Smith and Putnam (1980) note that the most likely settings in which anastomosis occurs are intermontane valleys and basins, foreland plains with subsiding depositional basins, and some intracratonic basins with fluctuating sea level or subsidence.

Rust and Legun (1983) and Legun and Rust (1982) studied anastomosed channels in an arid region. The sandstone bodies they studied were divided into two types. One type is lenticular and is composed of medium-grained, trough cross-stratified sandstone. The other type is a sandstone sheet several meters thick composed of fine to very fine-grained ripple cross-laminated sandstone. The first type probably represents major channels and the second type represents splay deposits. The sandstone bodies are small in volume compared to the surrounding mudstone and very seldom show any lateral accretion bedding. In addition, they noted that in arid regions coal would be rare and duricrusts would be common in an anastomosed system.

Meandering Streams - Meandering morphologies are characteristic of the mixed or suspended load type of river according to Schumm's classification and have high sinuosity and low braiding parameters. This morphology was the first to be extensively studied and was the basis for the first facies model of alluvial sedimentation to be developed (Allen, 1963b). This facies model, called the fining upward point bar model, has been extensively reviewed and was long considered the classic model of all fluvial systems—especially of meandering streams. Recent work, however, has shown that the fining upward model only occurs in idealized situations at one very limited point along a point bar. In fact, meandering streams are very unlikely to be recognized by this model.

Jackson (1978) identified five facies models of meandering streams based on the dominant grain size being transported (Table 2). The characteristics Jackson gives for these streams are for modern

Table 2. Facies models and their characteristics for meandering streams as defined by Jackson (1978, p. 562-563) based on the dominant grain size being transported.

#1: Muddy fine-grained streams (lack rock gravel)

1. Channel shows small width-depth ratio, commonly a very high sinuosity, and an erratic cross-sectional profile. Steep point-bar slopes often exceed 20o.

2. Transitional and fully developed textural zones in coarse member usually not recognizable. Upward fining of coarse member common but not ubiquitous.

3. Fine member equals or exceeds coarse member in thickness, but its mud need not be "overbank," even in part. Locally abundant intraformational mud chips in coarse member. Bed material usually is of medium-sand size or finer.

4. ECS possible in point-bar deposits of gently curved bends and likely consists of thin laminae of fine sand and silt. Prominent natural levees and channel-fill mud deposits expected. Scroll bars and chutes absent.

#2: Sand-bed streams with modest thickness of fine member

1. Channel shows variable width-depth ratio, prominent point bars of modest transverse slope, the usual asymmetrical triangular cross section in bends, and substantial scour-and-fill during major floods.

2. Upward fining of coarse member common but not ubiquitous. Generally poor development of transitional and full developed textural zones.

3. Fine member is thinner than, but comparably thick to, coarse member; its mud is largely "overbank."

4. ECS likely in coarse member and can dip steeply in small streams. Prominent natural levees and channel-fill mud deposits common. Scroll bars and chutes can be both common and prominent.

5. Rates of channel migration uniformly large; both chute and neck cutoffs expected.

6. Chutes, chute cutoffs, and major scouring surfaces (which truncate any ECS) predominate in ephemeral streams.

Table 2.—Continued

#3: Sand-bed streams lacking mud and rock gravel

1. Channel displays larger width-depth ratio than muddier meandering streams of comparable channel size and the normal asymmetrical triangular cross section.

2. Good development of transitional and full developed flow and textural zones in each bend. Textural zonation becomes subtle in streams with a narrow size range of sand. Coarse member can contain all sand sizes or only a narrow size range, depending upon provenance.

3. Natural levees, channel-fill mud deposits, and inner accretionary banks are minor to absent entirely. No riffles (in the textural sense). Scroll bars can be common.

#4: Graveliferous sand-bed streams

1. Deposits usually contain comparatively little mud, especially "overbank" mud. Some streams (e.g., S. Esk) are virtually mud free. Predominance of coarse sands and fine gravel in coarse member.

2. Prominent development and preservation of transitional and fully developed textural and flow zones for each bend, in much the same manner of the lower Wabash River. Textural zonation enhanced by the large size range in coarse member and the regular bed topography around bends. Prominent point bars.

3. Riffles (in the textural sense), ECS in coarse member, natural levees, and major scouring surfaces are rare to absent entirely. Scroll bars and channel-fill mud deposits are common, but latter comprise a comparatively minor volume of alluvial fill.

4. Levee-like, accretionary deposits of inner bank can be prominent (local thickness as much as 1/3 of total vertical sequence) in upstream portion of each bend and can show ECS.

#5: Streams with coarse gravel and little sand

1. Substantial channel sinuosity, commonly about 1.8. Bends tend not to be tightly curved but can be very long. Highly erratic bed topography arises from presence of prominent gravel riffles (with armoring) in crossings and in bends.

Table 2.—Continued

2. Bed-material transport limited to high flows, in contrast to finer-grained streams. Suspended loads can be very high in muddy streams susceptible to flash floods.

3. Fair development of transitional and full developed textural zones often is obscured by spectacular pool-and-riffle sequences.

4. Fine member is highly variable in thickness (along a bend and from river to river in a small region) and consists largely of levee-like alternations of sand and silt. This levee-like deposit resembles well in morphology and structure the inner accretionary bank of Bluck (1971). Little true "overbank" mud.

5. Flow-regime bedforms, ECS in coarse member, major scouring surfaces, and scroll bars are rare to absent entirely, largely owing to paucity of sand.

examples and he states that even these characteristics are derived from limited observations, especially #1 and #2. Distinguishing these types of streams in ancient deposits would be very difficult. However, it does show the variability in characteristics that can occur in a meandering stream and points out that many of the common criteria used to distinguish braided from meandering stream deposits in the rock record may be invalid. Jackson lists four criteria he deems useful in identifying old meander deposits:

- substantial mud content in the coarse member
- thick fine member
- asymmetric channel-fills with much mud
- exhumed meander belts with many intersecting sets of highly curved accretionary topography.

The presence of epsilon cross-stratification, a criteria commonly used in the past to identify meandering deposits, would not occur in most of the models Jackson has proposed, although its presence would still strongly suggest a meandering morphology for models #1 and #2.

Other criteria often used to determine meandering streams in the past such as lack of large clasts, presence of scroll bars, large dispersion of current indicators, and lateral continuity of sands, would not be valid in most of the models Jackson describes.

<u>Braided Streams</u> - Two other morphologies have been described in the literature for streams and rivers in addition to the two discussed above. These are braided and straight channeled types. Braided rivers are primarily bedload dominated and usually have steep gradients and non-cohesive banks. The width-to-depth ratio is usually

greater than 40 and may exceed 300 (Miall, 1982). Six types of braided rivers have been described (Miall, 1978), and only three of these are sand dominated and thus possibly related to the study area. These three are the South Saskatchewan, Platte, and Bijou Creek types. The Platte type system is dominated by linguoid bars and sand waves and as a result the major lithofacies found in ancient deposits is composed of solitary or grouped planar cross-beds (Miall, 1982). The Bijou Creek type is an ephemeral river with occasional flash floods. The critical lithofacies in this type is composed of horizontal laminations with parting or streaming lineation from planar bed flow during floods (Miall, 1982).

The South Saskatchewan type of braided river is the only one that bears any resemblance to deposits in the study area. In this system, eight facies have been defined (Cant and Walker, 1976). The first is an erosional surface with a coarse sandstone with clay pebble interclasts. Two facies are trough cross-bedded sandstones deposited in the deeper channels. Two facies are composed of planar cross-stratified sandstones deposited in shallower channels. The remaining facies are derived from planar and ripple-related features that are found on bar tops during flood stage.

Straight Streams - Straight channels are very rare in modern drainages and primarily occur in deltas (Miall, 1982). No discussion of ancient deposits has been found by the author.

Interpretation of Sandstone Bodies

Table 3 shows a summary of criteria listed in the literature which are commonly used to distinguish the three main stream morphologies. The absence of large clasts in any of the sandstone studied in the area has effectively ruled out the possibility of these sandstone bodies being deposited in gravel-dominated braided rivers or gravelly meandering rivers. For this reason, all of the criteria listed are for fluvial systems that primarily carry sand and finer material.

Lower Subfacies - The main physical characteristics of these sandstones are shown in Tables 3 and 4. A braided origin for the major sandstone bodies of the lower subfacies is ruled out because of the following criteria:

- low width-to-thickness ratio of the sandstone bodies
- the high percentage of silt and clay outside of the channels
- the lack of indications of lateral migration
- abundant splay deposits
- lenticular sandstone body geometry
- stacks of fining upward sequences
- abrupt lateral contacts

Table 3. Criteria for recognition of depositing stream morphology from sand bodies and associated sediments, with characteristics for major sands in the lower subfacies (from Smith and Putnam, 1980; Jackson, 1978; Walker and Cant, 1979; and Miall, 1982).

Criterion	Sandy braided (S. Saskatchewan)	Meandering	Anastomosing	Lower subfacies	Middle subfacies	Upper subfacies
Width/thickness ratio	>40 often >300	<40	<10	3.8-2.9	45-129	4.8-6.7
% silt/clay outside of channels	low	high	high	high	high	high
Epsilon cross-beds	absent	common	rare	absent	absent	absent
Multi-story channel deposits	common	rare	common	common	absent	common
Lateral migration	common	common	rare	absent	present	absent
Splays and avulsions	absent	uncommon	common	common	common	uncommon
Aggradation rate	high	low	medium	medium	low	low

Table 3.—Continued

Criterion	Sandy braided (S.Saskatchewan)	Meandering	Anastomosing	Lower subfacies	Middle subfacies	Upper subfacies
Planar cross-bedding	common	uncommon	rare	absent	absent	absent
Horizontal laminations	common	uncommon	rare	absent	absent	absent
Lenticular sand body geometry	absent	rare	common	common	present	common
Fining upward sequences	rare	common	common	common	common	common
Abrupt lateral contacts	absent	rare	common	common	absent	common

Table 4. Additional characteristics noted in the major sand bodies of the study area which are not commonly used to distinguish the type of channel system that deposited the sand.

	Lower subfacies	Middle subfacies	Upper subfacies
Predominantly trough cross-bedding	yes	yes	yes
% of clastics, silt size or finer	20	–––	4.9
Overall sand/silt ratio	.9	.2	.9
Erosional basal contact	?	yes	yes
Basal lag	?	yes	yes
Clasts of bank cave in sands	yes	yes	yes
Interfingering of lateral contacts	little	much	little
Overall sand body fines upwards	?	yes	yes
Paleocurrent dispersion	?	low	moderate
Top grades into interlayered sands and silts	yes	no	yes

A meandering origin for these sandstone bodies is ruled out because of the following criteria:

- ubiquitousness of multistory channel deposits
- lack of any indication of lateral migration
- high amount of associated splay deposits
- lack of planar cross-bedding in main channel deposits
- well-defined lenticular sandstone bodies
- width-to-thickness ratio is much lower than would be expected in a meandering system

An anastomosing origin for the sandstone bodies of the lower subfacies appears to be the mostly likely. Width-to-thickness ratios are extremely low, similar to those commonly found in modern examples. Sand/silt ratios are high for this subfacies, especially for nonchannel deposits. Indications of lateral migration were totally absent, including epsilon cross-beds. Multistory channel deposits were common among the large sandstone bodies and these bodies were commonly concave upwards at the base and lenticular in shape although the complete cross sectional views were never exposed. Fining upward sequences were common in each unit of the multistory deposits. Planar cross-bedding and horizontal laminations were totally absent. The thin tabular to slightly lenticular sandstones associated with the thicker sandstone bodies are interpreted to be splay deposits. They are commonly perpendicular to the perceived direction of main channel sandstones. Showing an upward decrease in grain size and scale of current derived structure, they are heavily bioturbated at the top and grade into fine-grained overbank deposits. All of these characteristics are common in splay deposits (Reineck and Singh, 1980, Collinson, 1978, Coleman, 1969). Splay deposits are very common in anastomosing river systems and less common in meandering river systems.

<u>Calcareous</u> <u>Mudstone</u> <u>Middle</u> <u>Subfacies</u> - The major sandstone bodies found in this subfacies occur at two levels within the subfacies. There are some variations between the sandstones in the two levels but for the most part their morphology seems to be similar. The main physical characteristics are shown in Tables 3 and 4.

A braided origin for the calcareous mudstone middle subfacies sandstones is ruled out for the following reasons:

- high percentage of silt and clay in the facies
- absence of multistory channel deposits
- presence of deposits interpreted as splays
- low aggradation rate
- absence of planar bedding and horizontal laminations
- some sandstones show a lenticular sandstone body geometry
- fining up sequence
- indications of avulsion
- little dispersion in paleocurrent measurements

The case for ruling out a braided origin is not as clear cut as for the lower subfacies. The sandstones' extremely high width-to-thickness ratio is common for braided streams. However, it is felt that the sandstone body giving the extremely high ratio of 129 does not represent a single channel, but a channel which has migrated laterally. This same channel at a location to the southeast yields a ratio of 45 at the low end of the range expected for a braided stream. The lack of epsilon cross-bedding in the sandstone body thought to have migrated laterally is not unusual and Collinson (1978) notes that epsilon cross-bedding is not commonly found in lateral migration deposits or point bars except in cases of "temporal fluctuation in conditions as well as the spatial variation implicit in the point bar model." Lateral migration is common in braided rivers. However, it is also common in meandering streams.

An anastomosing origin for these sandstones is ruled out for the following reasons:

- moderate to high width-to-thickness ratios
- absence of multistory channel deposits
- presence of indications of lateral migration
- the low aggradation rate

Again in this instance the case for ruling out an anastomosing origin for these sandstones is not clear cut. The presence of high percentages of silt and clay, splays and avulsions, and a fining upward sequence could all be used to argue in favor of an anastomosing origin. However, these are all characteristics shared in common with meandering streams. The fining upward sequence occurs for the unit as a whole and does not repeat itself in several stacked units—a criteria common in the lower subfacies deposits. The overall geometry for these sandstones is also much different from what would normally be expected for anastomosing deposits. Many of the lower sandstones in the calcareous mudstone middle subfacies have very broadly concave upward bases, but these are unlike those found in the lower subfacies and are not present in the upper sandstones of the calcareous mudstone middle subfacies. The most compelling argument against an anastomosing origin for these sandstones is the presence of indications of lateral migration, a phenomenon expected to be very rare in anastomosed derived sediments. The very broad sandstones previously mentioned would almost certainly have had to be derived from lateral migration. In the sandstones the presence of large numbers of rounded mud clasts, thought to be derived from bank cave, indicates that considerable bank erosion took place, in keeping with the idea of lateral migration.

Sandstones in this calcareous mudstone middle subfacies are thought to have been deposited by a meandering stream system for the following reasons:

- width-to-thickness ratios for some channels are near the upper limit expected for meandering streams
- high percentage of silt and clay
- lack of multistory channel deposits
- presence of indication of lateral migration
- low aggradation rate
- overall fining upward sequence of sandstone body

The width-to-thickness ratios for sandstones other than the one thought to be migrating laterally are close to the upper end expected for meandering systems. The high percentage of silt and clay in the subfacies would provide the necessary bank cohesiveness needed in a meandering morphology. The lack of vertical stacking in these deposits indicates that channel movement occurred laterally, but without the preservation of epsilon cross-bedding. The overall fining upward of the sandstones throughout the sandstone bodies is expected in meandering streams. Its lack of a corresponding decrease in the scale of the sedimentary structures, while part of the classic point bar model (Allen, 1963b), is not unusual and may indicate a neck cutoff (Walker and Cant, 1979). This is supported by the abrupt transition at the top of these sandstones to siltstones. The considerable interfingering of these sandstones at the edges of the point bar with siltstones may be the only remains of the epsilon cross-stratification, and is distinct from the sandstone bodies of the lower subfacies which are interpreted to be derived from anastomosing streams.

Presence of thin sandstones thought to be splay deposits indicates that the stream system was building levees and breaching them periodically. Most of those sandstones show a fining upward profile, indicating that they were primarily deposited near the crevasse where initial downcutting took place and sandstone was deposited during waning flow.

Paleocurrent data for these upper sandstone bodies of this subfacies give a consistency ratio of .85 which is extremely high for what would normally be expected for a meandering stream. One explanation of this is that both outcrops where the measurements were taken were deposited on approximately the same parts of the adjacent meanders. If this is true, a meander wavelength for this channel could be approximately 1300 meters which is consistent with its width-to-thickness ratio. The meander wavelength and width-to-thickness ratio of these deposits are comparable to the South Fork White River at White River, Nebraska, based on data compiled from alluvium in the midwestern United States (Schumm, 1968a). The South Fork White River has a mean annual discharge of 3.85 m^3/s, bankfull discharge of 25.77 m^3/s, and mean annual flood of 65.13 m^3/s. No sand/silt analysis has been done on the sandstones found in the upper sandstone bodies due to their resistance to disaggregation. A sand/silt analysis would be a very important component in substantiating a comparison between the channels that deposited the upper sandstone bodies and the South Fork White River.

Upper Subfacies - As noted in the results section of this paper, the exposures of the upper subfacies are limited and major sandstone bodies showing complete cross sections are limited. These bodies are interpreted to have been deposited by an anastomosing stream. The main physical characteristics of the major sandstone bodies are shown in Tables 3 and 4.

The presence of pebble-size clasts in some of the sandstones is not thought to be significant enough to warrant comparing these bodies to gravel-dominated systems. The fraction larger than $-1\ \phi$ comprises only 12 percent of the total sample which has been taken only from cross-beds containing pebbles.

Many of the characteristics of the upper subfacies sandstone bodies are similar to those in the lower subfacies. Width-to-thickness ratios of both are around 5. Sand/silt ratios are both around .9. Both have abrupt lateral contacts and show the same stacking of fining upward sequences.

A braided origin for these sandstone bodies is ruled out for the following reasons:

- low width-to-thickness ratio of the sandstone bodies
- high percentage of silt and clay in overall section
- lack of indications of lateral migration
- presence of splay deposits
- lack of planar cross-bedding and horizontal laminations
- lenticular shape of the sandstone bodies
- stacks of fining upward sequences
- abrupt lateral contacts

A meandering origin for these sandstone bodies is ruled out for the following reasons:

- low width-to-thickness ratio
- multistory channel deposits
- lack of any indication of lateral migration
- the abrupt lateral contacts

Paleocurrent data for sandstone bodies in this subfacies gives a consistency ratio of .57 which could be expected for either a meandering deposit or an anastomosing stream.

These sandstone bodies are most likely to have an anastomosing origin for the following reasons:

- the low width-to-thickness ratio
- the high percentage of silt and clay
- presence of multistory deposits

- lack of evidence of lateral migration
- lenticular sandstone body shape
- lack of any planar cross-bedding or horizontal laminations
- abrupt lateral contacts
- stacked fining upward sequences

Most of these channels show some evidence of downcutting into underlying sediments. Downcutting is not considered unusual for anastomosing streams considering that the main way for channels to avulse is by enlargement and stabilization of crevasses (Smith and Smith, 1980). In order for the new channel to reach grade with the rest of the system, considerable downcutting would be expected near the crevasse, even in an overall aggrading environment.

At the more distal points on the splay, no downcutting would occur and early, middle and late sedimentary structures associated with the flow would be preserved. One sandstone body interpreted to be a splay deposit shows a gradual increase in sedimentary structures from small-scale trough cross-bedding at the base to horizontal bedding in the middle and a decrease to ripple cross-lamination at the top. This was evidently a single crevasse splay that did not repeat itself. It is the only example of this type of deposit found in the study area. This deposit represents a splay deposit at a more distal location from the crevasse than is normally seen in splay sandstones found elsewhere in the study area.

Reasons for Morphological Changes

The streams' shift in morphological style was possibly caused by an increase in sand in the calcareous mudstone middle subfacies relative to the upper and lower subfacies. This would be in keeping with Schumm's model (Schumm, 1968b). However, it is also possible that there was no shift in overall bed load/suspended load ratios between the subfacies. The nature of an anastomosing system encourages a greater frequency of splays and thus greater overall retention of sand-size material than would be expected for a meandering system, where bed load would be more likely to be flushed through. There does not seem to be a reliable way of gauging bed load/suspended bed load ratios for nonactive systems at this time. The author uses total percentages of fine-grained material versus sand-size material in measured vertical stratigraphic sections, feeling that this is more representative of the total system than sand/silt ratios obtained from channel sandstones.

The reasons for the shifts in morphology among the three subfacies was probably due to a relative increase in local base level as described by Smith and Putnam (1980). There are several possible causes for this change in base level. One cause is that the deposits were in an area of active structural movement at the time of deposition. The compressional forces experienced in the thrust belt to the west may have formed folds that were transverse to local flow direction. These folds would have caused local changes in base level.

A second possible cause for the change in base level was the considerable volcanic activity to the south and west. Lorenz (1981) proposed that easily erodable volcanic sources could have choked some drainages with sediment, causing rapid aggradation. Tributaries that were not carrying the same sediment load would not have been able to keep up with this rapid aggradation and would have been blocked from joining the sediment-choked drainages. This process would have caused short-term ponding and a rise in base level.

A third possible cause for the change in base level would be fluctuations in the level of the Cretaceous seaway. The sediments at the Willow Creek anticline were deposited between the major Claggett and Horsethief transgressions (Lorenz, 1981). However, there were constant minor variations of the shoreline as shown by Gill and Cobban (1973) throughout this time which could have caused local changes in base level.

There is no way to pinpoint a specific reason for the changes in fluvial morphology seen at the Willow Creek anticline. However, the presence of sediments interpreted to be lake deposits in the middle subfacies indicates that closed depressions were forming in this area contemporaneously with the shifts in stream morphology. This would seem to support the first possibility discussed above.

Sedimentary Sources

Due to a lack of time and resources, no extensive provenance studies have been performed on the sandstones found in the study area.

However, some generalized comments can be made about the source of the sand.

Most of the sandstone studied is feldspathic litharenite, or litharenite (volcanic-arenite or chert-arenite), with a minor occurrence of sublitharenite and lithic arkose (Figure 17). Chert and volcanic rock fragments are the most common components followed by feldspar (primarily plagioclase) and quartz with minor occurrences of mica and heavy minerals (primarily biotite and magnetite). Most grains are angular to subrounded with many of the subrounded grains resulting from authigenic alteration of feldspar grains and volcanic rock fragments.

Composition of the sandstones as well as the low level of abrasion indicates that these sands are both mineralogically and texturally immature (Folk, 1974). This is probably due to a minimum of transport and weathering as well as a dry environment that did not cause significant alteration of the feldspars and volcanic rock fragments.

The source of these volcaniclastics were the Elkhorn Mountains Volcanics. Occurring south of the study area, these volcanics gave rise to the Big Skunk Member of the Two Medicine Formation (Schmidt, 1978) which occurs south of the Sun River and west of the Adel Mountain volcanic pile (Viele and Harris, 1965). The Elkhorn Mountains Volcanics are generally andesitic (Klepper et al., 1957, 1971) and would have provided the large amounts of plagioclase found in the sandstones. The large amounts of quartz were also probably derived from these andesites as well as the biotite and magnetite.

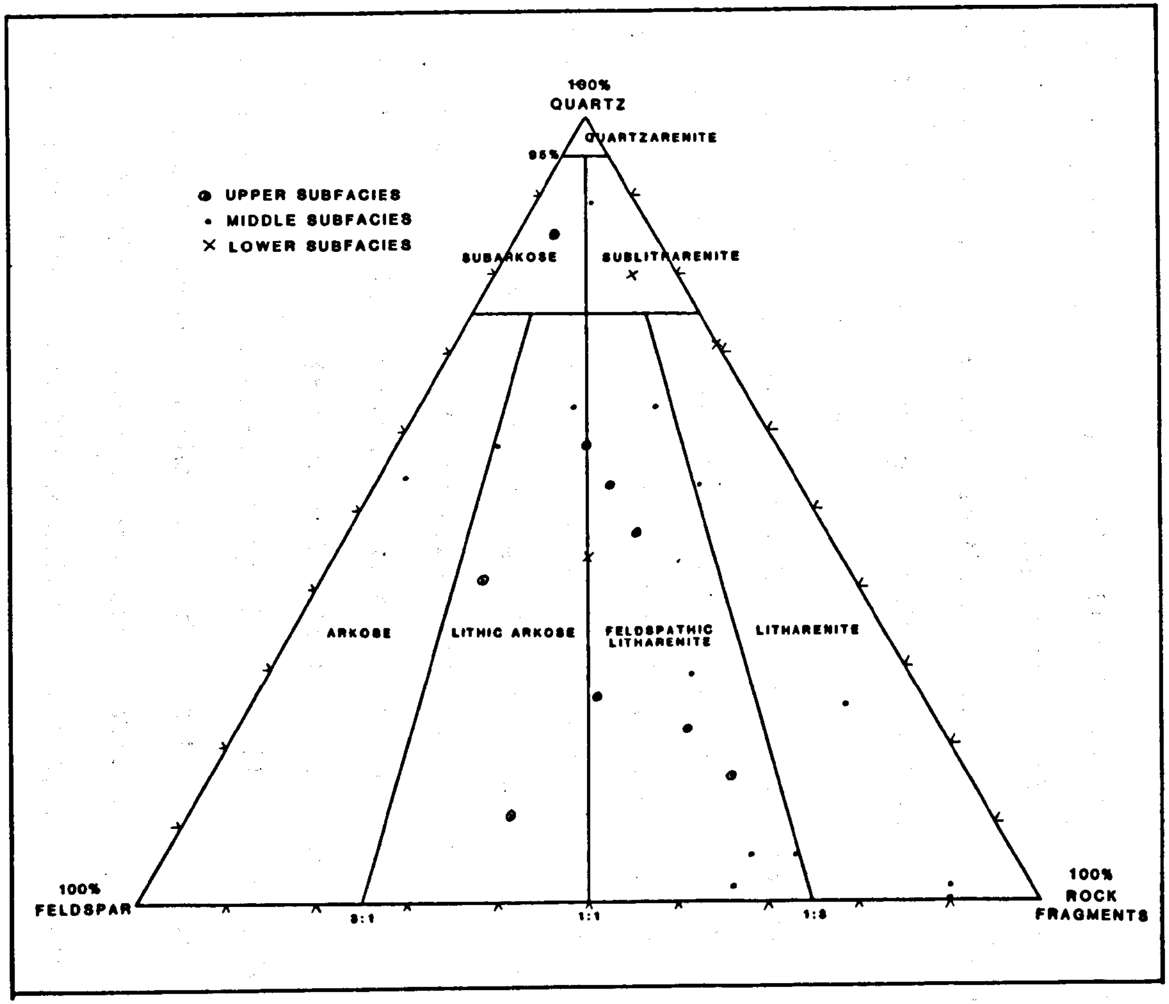

Figure 17. Q-F-R diagram of the sandstone composition of major sand bodies from the various subfacies in the study area.

The lack of transport shown by these sandstones indicates that much of this material must have been deposited by airfalls and reworked close to the site of deposition, or that volcanic sources closer and to the west must have existed. Such sources, now covered by thrust sheets, have been proposed by Mabey et al., (1966), Mudge and Sheppard (1968), and Schmidt (1966), based on gravity, geochemical data, and volcanic clasts found in conglomerates in the Sun River area. Bentonite beds found in and around the study area indicate that volcanism was contemporaneous with deposition.

The other major source for sediments deposited in the study area were the formations exposed by thrusting to the west. Pebbles found in the sandstone bodies of the upper subfacies have been identified by Winston (pers. comm.) to have been derived from the Bonner Quartzite and the McNamara Formations of the Belt Supergroup. These formations currently first occur 30 to 50 kilometers west of the study area, but given the commonly accepted west to east advance of the thrust belt (Bally et al., 1966), it is very likely that the source area for these pebbles was farther west—possibly 15 to 25 kilometers. This estimate is based on the amount of shortening thought to have occurred (Mudge and Earhart, 1980). Cambrian and Jurassic shales also exposed in these thrust sheets probably contributed greatly to the large amounts of siltstone and shale found in the study area. The large amounts of chert found in the sandstones were also probably derived from sources to the west in the thrust belt. The large exposures of Cambrian, Devonian and Mississippian carbonates supplied the material necessary to form the calcareous layers found in the study area as well as the almost ubiquitous carbonate cement found in the sandstones. Some small pebbles of dolomite have also been found in the pebbly lenses of the upper subfacies. These could have been transported from dolomitic formations to the west.

Paleocurrent data derived by Lorenz (1981) for the upper Two Medicine Formation gives overall northeastward transport directions. Data from this study give the same direction (Figure 10). Work by Hooker (in progress) on bone orientation in a catastrophic flood event also gives northeast orientations. These data indicate that the source area for most of study area's sediments was southwest of the study area.

DISCUSSION OF CARBONATES

Due to the terrestrial nature of the enclosing clastic sediments in the study area, it is assumed that all of the carbonates encountered were terrestrially derived. Major terrestrial carbonate accumulations are generally derived from three genetic origins: lacustrine, pedogenic, and thermal. A thermal origin for any of the carbonates in the study area is ruled out due to the lack of associated hydrothermal minerals and the thin, laterally extensive nature of the carbonates found in the study area. This leaves two possible origins for the carbonates in the study area: lacustrine and pedogenic. In this section, the two genetic types will be discussed separately. Due to the interrelated nature of these types, the discussion of lacustrine carbonates will include all lake-deposited sediments.

Lacustrine

Lake deposits are very rare in the geologic record and easily confused with other deposits including flood plain, interfluvial pond, fluvial, and marine. Most of the criteria in the literature used to distinguish lake deposits are contrasted with those of shallow marine environments. Picard and High (1972) list the most commonly used criteria for distinguishing lacustrine deposits from other deposits and comment on their reliability (Table 5). One problem not addressed

Table 5. Commonly used criteria for recognition of lacustrine rocks (from Picard and High, 1972, p. 140).

Characteristic	Remarks
Size	Local to regional (less than about 50,000 square miles)
Shape	Overall "circular"; shape reflects position of bounding positive elements in structural basins
Facies	Narrow shore and nearshore deposits; fining of clastics toward center of basin
Lateral Continuity of Beds	Lacustrine beds generally more continuous than fluvial beds
Sequence	Regressive patterns dominated by offshore deposits
Regional Setting	Enclosed by fluvial units or disconformities
Biota	1. Freshwater organisms; 2. "stress" communities; 3. diversity and quantity gradients
Authigenic Minerals	1. Saline minerals in terrestrial setting; 2. chert-banded, sedimentary, iron ores
Trace Elements	Further studies required; B, Li, F, and Sr may be higher in marine than in freshwater samples; Ga may be higher in freshwater samples
Isotopes	Further studies required; C^{13} may be enriched in marine carbonate samples and depleted in freshwater samples; data on oxygen isotopes not consistent; lacustrine hydrocarbons marked by large variation in sulfur

Table 5.--Continued

	isotope ratios (S^{34}/S^{32}) in contrast to nearly constant ratios in marine hydrocarbons
Freshwater Limestone	Lacustrine limestone probably cannot be distinguished from shallow water marine limestone on present petrographic criteria
Bedding Types	In general, lacustrine rocks not now distinguishable from shallow marine rocks on differences in bedding types; lacustrine deposits can be distinguished from fluvial deposits; varves suggestive of lakes
Sedimentary Structures	1. Ripple marks not more symmetrical in lacustrine than shallow marine rocks; 2. scale of fluvial cross-stratification larger than nearshore lacustrine cross-stratification; 3. type and character of lacustrine shrinkage cracks not diagnostic
Paleocurrents	Bimodal opposed; similar to shallow marine paleocurrent patterns
Sedimentary Cycles	1. Base level; 2. climatic

by this table is the separation of pedogenic carbonate deposits from lake-derived carbonates. This will be discussed later.

Stratigraphy - In his study of the Two Medicine Formation, Lorenz (1981) only noted lacustrine deposits around the Two Medicine River, indicating that lakes were neither common nor extensive in the Two Medicine Formation. It appears that the study area contains extensive lake-deposited sediments which are restricted to the middle subfacies and comprise the charophytiferous limestone middle subfacies. In general these sediments become thicker and more continuous to the south (Plate 2). The main body of the lake seems to have been to the south along the present course of Willow Creek. It is impossible to determine an overall size for the lake due to the lack of outcrops to the south of the study area. However, the restricted vertical extent of the deposits would seem to indicate that the lake was small. The size of this lake probably fluctuated extensively as indicated in Plate 2, due to low relief in the area and seasonal precipitation fluctuations. These fluctuations have led to extensive interfingering of lacustrine and non-lacustrine deposits in the study area. Deposits shown on Plate 2 were probably formed in an east-west oriented arm separated from the main lake by a high which included Egg Mountain.

Clastic Lake Sediments - Facies patterns within the lake subfacies are consistent with those expected in a lacustrine deposit. Clastic sediments are the dominant lithology to the south, toward the center of the lake, while carbonates are common along the edges. This would be expected because shallow water along the edges is the most likely area of both organic and inorganic nonvarved carbonate precipitation (Kelts and Hsu, 1978). There does not seem to be an overall coarsening upward sequence in the deeper part of the lake or a readily apparent fining from the edges toward the center, as is commonly expected in a lake facies model.. However, there are several reasons why this "classic" facies model would not be expected in these deposits. The overall small size of the lake would mean that coarse clastic pulses would probably be dispersed well into the lake. In addition, major water level fluctuations could have brought coarse clastic deposition far in toward the center of the lake during periods of low water level. The fluctuations in water level in a small lake would have caused a stacked regressive sequences similar to those observed in the study area, in contrast to the classic coarsening upward profile of Picard and High (1972).

Sedimentary structures found in the noncarbonate lacustrine sediments are often indistinguishable from those in fluvially-derived sediments. However, some features are specific to the lake sediments. Some beds are composed of layers of thin, even horizontal lamina, usually purple and green. One such laterally extensive bed is the lower marker horizon. Thickness of this bed varies but is greater along Willow Creek than around the anticline. Lorenz (1981) has hypothesized that sediments much like these, around the Two Medicine River, were caused by seasonal fluctuation in pH which affected clay flocculation.

Along the Willow Creek, some of the interbedded fine sandstones display symmetrical ripple marks, indicating a nonfluvial origin.

This also indicates that at some periods these sands were above wave base. These ripples have an orientation of N38°E, indicating that in this area the shore was oriented northeast-southwest. Interbedded with these sandstones are some siltstones which contain desiccation cracks, indicating that this point in the lake occasionally was completely dry. The lack of carbonates indicates that this area was not dry long enough to allow development of carbonate layers. Other clastic deposits associated with known lacustrine sediments were not readily distinguishable from fluvially derived clastic materials. The main criteria is the lateral persistence of the deposit. The upper marker horizon is one such deposit. It is present throughout much of the study area and maintains a relatively uniform thickness of 10 to 15 centimeters.

Throughout the study area no classic Gilbert-type delta facies are noted. This is somewhat troubling because stratigraphic correlations (Plates 2, 3) indicate that fluvial environments existed contemporaneously with the lake and should theoretically have drained into it. It is possible that delta deposits do exist, but are not exposed in any of the outcrops in the study area. Another possibility is that the shallowness of the lake did not allow development of well defined forsets. Instead, the topsets merge into the bottomsets, forming long, very low angle beds that were indistinguishable from normal bedding.

As mentioned earlier in the discussion of reasons for stream morphology change, at the time of deposition of sediments the study area would have been highly conducive to the formation of closed depressions and damming. Factors active in the area included structural depression and igneous activity. In addition, anastomosing and meandering rivers are also common areas for lake formation, with oxbow lakes common for meandering rivers and levee-bounded lows associated with anastomosing systems. These seem rather unlikely as the origin of the lake deposits found in the study area due to their small size and highly temporary nature. A fourth possible source for lakes are landslides in the area. The tectonic activity and abundance of clay and silt in the area might have led to mass movement events. However, there is little indication of much topographic relief in the study area—a necessary component of most mass movement.

Fossils - The charophytiferous limestone middle subfacies contains several fossil types usually found only in lakes. Charophytes are only found in shallow, quiet, alkaline water, according to Peck (1957). *Unio* is restricted to freshwater environments. Stromatolites occur both in marine and freshwater environments but are not thought to grow in fluvial settings.

Fossil remains of a pterosaur found in the study area also support a lacustrine interpretation for the sediments in this area. The remarkable preservation of the animal's bones could only have taken place in a very quiet water environment in which calcium carbonate was readily available to rapidly replace the bones.

Presence of the calcium carbonate-saturated water was also the primary reason for the excellent preservation of many remains found in the lake marginal nesting areas. Many of the hypsilophodont nests found by Horner have been located immediately adjacent to the lake sediments. This proximity to the carbonate-rich waters allowed rapid replacement of dead animals and even allowed preservation of cartilaginous material of embryonic dinosaurs in the shell.

Lake Carbonates - The geochemistry of the lake seems to have been dominated by carbonate precipitation. Descriptions of the occurrence of carbonates and their composition are given in the results section. These limestones were derived from three sources as described by Kelts and Hsu (1978): allochthonous clastic carbonate input, organically derived precipitates, and primary inorganic precipitation. It is felt that allochthonous clastic carbonate input was of little or no significance in the formation of the lacustrine carbonates in the study area because of the virtual lack of calcareous clastic grains in the fluvial sandstones.

Carbonates must have been an important component of dissolved load in these rivers due to the large number of calcareous formations exposed to the west in the thrust sheets. These formations would have been a primary source of carbonate for organic and inorganic precipitation in the lake. A second major source of carbonate would have been the dissolution by groundwater of carbonate originally deposited by aeolian processes. (This will be discussed further under pedogenic carbonates).

Most of the carbonate deposition occurred along the edges of the lake. The sediments along Willow Creek, considered to be towards the middle of the lake, contain no limestones. The limestones around the anticline are usually stacked in repetitive sequences with siltstone, reflecting rapid and frequent water level fluctuations and associated minor regressive sequences.

Many of the limestones contain charophyte-producing green algae which can be a major source of organic carbonate precipitation. The plant secretes calcium carbonate on the vegetative parts, probably as part of the respiratory process (Peck, 1957). In modern environments, chareae are known to be major contributors to freshwater limestones, but their contribution to total carbonate deposits in the study area cannot be determined.

The second major origin of carbonates in the area was inorganic precipitation. While this process is discounted as a source for calcium carbonates in marine environments, it is well documented in lacustrine environments (Kelts and Hsu, 1978) and can be a major source of limestone. The lack of limestone in the deeper portions of the lake indicates that whitings, or spontaneous precipitation of calcium carbonate from lake-wide oversaturation, probably did not occur. This also indicates that nannoplankton was not a major source of calcium carbonate. These free-floating animals would have scattered their tests throughout the lake, forming lake-wide carbonate horizons.

The lakeshores were the most conducive environment for carbonate precipitation. Several factors which directly affect carbonate precipitation would be most active along the lakeshore. Kelts and Hsu (1978) list the following conditions which would lead to carbonate precipitation:

- Increasing water temperature, causing oversaturation of the water with $CaCO_3$

- Increasing the water temperature, causing a reduction in the solubility of CO_2
- Mixing waters with different pH's, leading to supersaturation of $CaCO_3$
- Agitating the water, causing the mechanical release of CO_2
- Evaporation of water, causing local oversaturation

The greatest concentration of plant life would be along the lakeshores which would lower CO_2 levels and help with precipitation. All of the above conditions are accentuated along shores where the water is shallow, causing the greatest precipitation of limestone.

There are no deposits of gypsum in any of the lake sediments, indicating that the lake never became concentrated enough to begin precipitation of gypsum (Eugster and Hardie, 1978). There are some veins of white platy calcium carbonate whose habit strongly suggests that the veins were originally deposited as gypsum and subsequently replaced entirely by calcium carbonate. These veins cut across bedding and are not restricted to the lake subfacies, indicating that they were not primary deposits of the lake.

There is no indication that the lake ever became saline enough to cause precipitation of soluble saline minerals. There are no salts now, nor any dissolution structures nor salt casts to indicate their presence in the past. In addition, the presence of freshwater organisms in most of the lake sediments indicates the lake never became very saline. The lake deposits also lack any carbonaceous material, indicating that an oxidizing environment existed throughout its history.

The limestones were deposited close to shore as biomicrites. Most were deposited at the water-sediment interface and incorporated varying amounts of sand and silt into their matrix. These allochthonous constituents are almost always less than ten percent and usually less than one percent. The large grain size of some of these particles is such that they could not have been transported far from shore, by either wind or water.

In addition to these clearly lake-derived carbonates, there are some carbonate lenses interbedded with lake sediments which appear to be pedogenically derived. These lack any charophyte remains and contain clasts of siltstone and clay in the matrix. They were deposited very close to the lake margin where the water table was close to the surface. Semeniuk and Meagher (1981) have shown that high evapo-transpiration of plants, caused by high air temperatures and wind stress, causes plants to draw upon phreatic and pellicular water at high rates. This causes precipitation of $CaCO_3$. This can cause extensive calcrete development at the top of the capillary rise zone in areas where the water table is near the surface. The distinction between pedogenic and lacustrine carbonates is often difficult and the author feels that only those carbonates containing freshwater fossil remains could be definitely identified as lacustrine.

Pedogenic Carbonates

Terminology - The terminology for pedogenic carbonates is diverse and non-standardized. Terms commonly used in describing current pedogenic carbonates include calcrete, caliche, K-horizon, and caprock. Terms commonly used for older deposits include paleocaliche, cornstone, and concretionary carbonate.

Definitions of the various terms are also diverse and sometimes contradictory. Esteban (1976, pg. 2409) defined caliche as

> "...vertically zoned, subhorizontal carbonate deposit, normally developed with three main rock types: (1)massive-chalky, (2) nodular-crumbly, and (3) laminated and/or pisolitic compact crust or caprock. The position and development of these rock types in the vertical sequences (profile) and laterally is highly variable. The only rather consistent relation is that the massive-chalky rock grades downward into the original rock or sediment through a transition zone, both with strong evidence for in-place alteration and replacement of the original rock or sediment. Colors are commonly white and light browns, but red and black may be important. The predominant caliche fabric is a clotted, peloidal micrite with microspar channels and cracks. Accessory fabrics are poorly laminated micrite, karst products, and rhizocretions. Microspar areas usually show evidence of replacement of relief grains and of other primary and earlier diagenetic microfabrics."

In contrast, Machette (1985, pg. 3) urges the abandonment of the term "caliche" and the use of "calcic soils" for those soils "...that contain a significant amount of secondary carbonate generally in the form of calcic horizons." In addition, he uses the term "calcrete" for

> "...indurated masses of calcium carbonate. Calcrete is herein restricted to near surface or shallow, terrestrial deposits of calcium carbonate that have accumulated in or replaces a preexisting soil, unconsolidated deposit, or weathered rock material, to produce an indurated mass..."

Since Machette's paper was published so recently, it remains to be seen if his terminology will gain widespread acceptance.

Cornstone, the fossil equivalent of caliche, was first defined by Buckland (1821, as cited in Steel, 1974, pg. 351) as:

> "...composed of marl or marlstone, filled with concretions of compact limestone, presenting the fracture and colour of mountain limestone, and varying in size from that of a pea to blocks of many tons, and sometimes spreading itself into thick and compact beds, to the almost total exclusion of the marl. The knotted character which these concretions assume resembles that of a conglomerate animal gland, and the small acini or kernels of which they are composed usually separate under the blow of the hammer. The transfusions of their outer portions and projecting points into the substance of the marlstone, shows them not to be fragments resulting from the destruction of any older rocks of transition limestone, but concretions of contemporaneous origin with the marlstone, in which they are imbedded."

This definition is used today with the understanding that cornstones are pedogenically derived and represent a fossil soil horizon. In addition, cornstones include calcareous layers which are not composed of "knotted" concretions. Instead, they are similar to stage IV caliches of Gile et al. (1966).

Due to the state of flux of current terminology, the author will use the terms "caliche" and "cornstone" to describe the pedogenic carbonates at the time of formation and as they occur today, respectively.

<u>Classification</u> - Classification of caliches was first done by Gile et al., (1965). He proposed a new master soil horizon called the K-Horizon with three sub-categories based on a calcareous soil fabric. In a subsequent paper, he defined four morphologies of carbonate accumulation in soils related to increasing development, with stages

III and IV being representative of the K-Horizon. This classification has been modified by Machette (1985) to include two more, better developed stages (Table 6). Reeves (1970) proposed the use of young, mature, and old for caliche based on age and physical factors. This would eliminate the soil-zone terminology which is "...not always correlative with physical and geological attributes of the caliche, particularly because K-terms are horizons with variable morphology and cannot be related to relative age of development." (Reeves, 1970). Both of these classifications are based on caliches formed during the Quaternary and in many cases they are still part of the soil profile.

Steel (1974) has proposed a categorization of cornstone based on gross form and proportion of host rock still distinguishable for cornstones he found in the New Red Sandstone of Scotland. These were modified by Hubert (1978, pg. 153-154) and are as follows:

> "Type 1. Irregularly shaped calcite nodules of 1-6 cm diameter form up to 10 percent of the mudstone or sandstone. Very rarely the carbonate is dolomite.
>
> Type 2. The calcite nodules are larger, up to 10 cm in diameter and 15 cm vertically elongate. They occupy 10-50 percent of the rock, commonly grading down to type 1.
>
> Type 3. Calcite forms 90-95 percent of the mudstone or sandstone as irregular patches of calcite microspar (4-30μm crystals) or pseudospar (>30μm crystals), veins, or nodules. There is commonly a downward transition to type 2.
>
> Type 4. Relic patches of mudstone or sandstone are less than 5 percent of the rock. The limestone is a "plugged horizon" with more than 95 percent calcite, commonly a complex fabric of nodules, microspar and pseudospar, veins, laminae, clasts and sparry cement—all of calcite. Transitions occur downward or laterally to type 3.

Table 6. Stages of calcium carbonate morphology observed in calcic soils and pedogenic calcretes developed in noncalcareous parent materials under arid and semiarid climates of the American Southwest (Modified from Machette, 1985).

Stage	Gravel content	Diagnostic morphologic characteristics
		CALCIC SOILS
I	High	Thin,discontinuous coatings on pebbles, usually on undersides.
	Low	A few filaments in soil or faint coatings on ped faces.
II	High	Continuous, thin to thick coatings on tops and undersides of pebbles.
	Low	Nodules, soft, 0.5 cm to 4 cm in diameter.
III	High	Massive accumulations between clasts, becomes cemented in advanced form.
	Low	Many coalesced nodules, matrix is firmly to moderately cemented.
		PEDOGENIC CALCRETES
IV	Any	Thin (<0.2 cm) to moderately thick (1 cm) laminae in upper part of Km horizon. Thin laminae may drape over fractured surfaces.
V	Any	Thick laminae (>1 cm) and thin to thick pisolites. Vertical faces and fractures are coated with laminated carbonate.
VI	Any	Mutiple generations of laminae, breccia, and pisolites; recemented.

> Type 4a. A discrete horizon of laminated or brecciated limestone that caps or is interbedded with a "plugged horizon." The calcite laminae are precipitated from water that flows over the impermeable limestone. Even in thick caliche beds of the Quaternary, each bundle of laminae is only 2-5 cm thick. In the New Haven Arkose, type 4a laminated limestone is extremely rare, laterally discontinuous, and only a few millimeters thick."

The classifications of Steel and Hubert correspond roughly to those of Gile and Machette as follows:

Gile and Machette	Steel and Hubert
Stage II	Type 1
Stage III	Type 2, 3
Stage IV, V	Type 4
Stage VI	Type 4a

The author has chosen to use Machette's classifications in describing cornstone found in the study area because of the close correlation to cornstone classifications and its widespread use in the literature.

<u>Origin</u> - Caliche is formed as a soil horizon. Reeves (1976, as cited in Hubert, 1978) notes that areas most favorable for caliche development are semiarid, with seasonal rainfall of 100 to 500 millimeters and a long dry season. Precipitation enriched in CO_2 from organic-rich surface soils dissolves carbonate particles near the surface. The calcite is redeposited deeper in the soil when pH, temperature, and CO_2 decrease, accompanied by an increase in ion concentrations due to evapo-transpiration (Hubert, 1978). The formation of caliche at the top of the capillary rise zone as discussed earlier (Semeniuk and Meagher, 1981) is not thought to be instrumental in caliche formation in areas where the water table is very deep (Gile, et al., 1966). However, in the study area this

mechanism may have been important because the water table might have been close to the surface due to the proximity of the lake and the numerous river channels.

Today, it is generally accepted that the primary source of calcium carbonate to produce caliche is from eolian-derived calcareous dust and Ca^{++} dissolved in rain water derived from weathering sedimentary carbonate horizons. Exceptions to this are those areas composed primarily of calcareous sediments or source rocks. Hay and Reeder (1978) feel that some of the caliche of Olduvai Gorge in east Africa is derived from weathering of natrocarbonatite and nephelinite ashfalls.

Interpretation - The cornstones found in the study area are interpreted to be pedogenic in origin and not diagenetic for the following reasons:

- Clasts of the calcified material are found in stream channels, indicating their formation at the time of stream erosion.
- X-rays and megascopic examination of slabs of the cornstones show root traces penetrating them.
- One of the calcified horizons has been eroded and a stream has deposited sand which has filled cavities in the calcareous horizon. This indicates that the calcareous horizon formed prior to the stream.

Lower Subfacies - The cornstones found in the lower subfacies (as described in the results section) are always nodular. The nodules seem to be equivalent to stage III carbonates developed in fine-grained soils, as classified by Machette. When slabbed, the nodules reveal coalescing smaller nodules and there are many instances in which the nodules seem to follow old root traces. This same characteristic has been noted by Blodgett (1980, 1984) in cornstones of the Dolores Formation of Colorado. Reeves (1970) notes that caliches often use roots, root holes, desiccation cracks, and solutional channels as sites of redeposition of calcium carbonate. Semeniuk and Meagher (1981) note that roots and root casts are often the site of extensive calcium carbonate precipitation.

The pitted nature of the nodules found on the surface is due to dissolution occurring now, with the nodules' exposure on the surface. Buried nodules that have been recovered do not show this pitting, indicating that it was not diagenetic.

Middle Subfacies - In the middle subfacies the cornstones are thicker and form massive layers, which often cap hills and form small ledges. As noted in the results section, the thicknesses vary considerably, both from horizon to horizon and laterally along a horizon. These variations could be due to:

- topography at the time of deposition
- variation in host rock permeability
- vegetation differences at the surface
- post-depositional solution

All of the above factors seem to have had some influence at various outcrops.

The cornstones of this subfacies have been divided into two groups: those showing horizontal laminations and those not.

Cornstones showing laminations are representative of Machette's stage IV morphology. The laminations occur as subhorizontal layers 1 to 10 millimeters thick which branch and coalesce (Figure 18). Composed of sparry to micritic calcite with varying amounts of clay, the laminated areas are up to 10 centimeters thick. Spacing between laminations ranges from 1 to 10 millimeters. The non-laminated areas occur below the laminated layers and vary considerably in thickness.

The laminated cornstones contain abundant rounded clasts of cemented host rock, generally from 1 to 5 millimeters in diameter. There are no signs of root traces or rhizoliths in these carbonates. Gile et al., (1966) have noted that stage IV horizons act as a barrier to roots, thus these carbonates would show no evidence of root penetration after stage IV had been achieved. These cornstones are almost certainly derived in accordance with the classic caliche model developed by Gile et al., (1966) and the laminations represent precipitation of calcite by a layer of free water that formed above an underlying plugged horizon. Modern caliches commonly grade into an underlying nodular zone. However, such underlying nodular zones are rarely observed in the study area.

Non-laminated cornstones are usually massive silty to muddy limestones with rounded clasts of the host rock from 1 to 10 millimeters in diameter that float in the matrix (Figure 19). X-rays or visual inspection frequently show root traces filled with sparry calcite. In addition, X-rays also reveal very light shadows of what appear to be root traces that were subsequently filled with the matrix material. These non-laminated cornstones occur near lake sediments

Figure 18. Photograph of cornstone with subhorizontal laminations at the top. Laminations or veins are composed of sparry to micritic calcite. Dark spots are host rock clasts.

Figure 19. Photograph of non-laminated cornstone with clasts of dark host rock.

and often seem to be proximal to stream channels. Varying considerably in their degree of induration, most non-laminated cornstones are very calcareous and well indurated but some are less developed and crumbly. It is thought that these did not form by the normal caliche process but instead were formed by precipitation in the capillary rise zones as described by Semeniuk and Meagher (1981), discussed earlier. The presence of either type of cornstone was probably based on the proximity of the water table to the surface.

In areas next to the lake where dinosaur nesting took place the non-laminated carbonates are severely disrupted. This is probably due to the repeated bioturbation of the layers by the trampling and digging of the dinosaurs in the course of nesting.

One horizon located above but close to the bentonite layer is characterized by abundant chert in the cornstone layers. The morphology of this layer is described in the results section. The chert is associated with both laminated and non-laminated cornstone. The silica in all cases was deposited after an initial carbonate horizon developed. The chert's affinity for rhizoliths and bone indicates that it might have more easily replaced sparry calcite than the fine-grained calcite matrix. The brecciated nature of the silicious layer indicates that a second period of carbonate development might have followed the deposition of the silica. Reeves (1970) notes that silica deposition is common in older caliches, especially toward the base. Smale (1973) has also noted that silcretes form in old caliches. The alkaline nature of the water depositing the carbonate at the top of the profile allows supersaturation with silica which is then deposited at the base of the profile. However, Reeves notes that soils have very complex mineralogies and simple reciprocal depositional kinetics between silica and calcite may not exist.

Brecciation has been noted as a characteristic of stage V caliches by Machette (1985) and has been observed by Steel (1974) in the New Red Sandstone. Machette noted that the fragments seem to be "...merely rotated out of the plane of the parent carbonate layer..." The brecciated layers in the silicious zone also seem to be locally derived and in some cases appear as if they could be fitted together again. While the mechanism for brecciation is not clear, Reeves (1970) has noted fracturing and deformation of the caliches which he attributes to climatic fluctuations and contractions due to water loss.

The reason for the presence of chert in this horizon and nowhere else in the study area is perplexing and beyond the scope of this study. However, it may be due to this horizon being stable longer, allowing for the slow process of silica deposition to have an impact. A second possibility is that the caliche's proximity to the bentonite bed would have provided a readily available supply of silica from weathering of the ash.

One other carbonate horizon in this subfacies deserves discussion. Capped by the extensive bone deposit, this calcareous layer is well cemented but retains the fabric of the original sediments: ripple-derived laminations in siltstone. This horizon is associated with a channel sandstone that is capped by fine-grained sediments. In many places, the sandstone underlies the siltstone, indicating that this was probably an abandoned channel. The bones and an associated mudstone appear to have been deposited by a catastrophic mud flow (Lorenz, 1981 and Hooker, verbal communication). This flow seems to have followed the old channel where it was confined by the channel boundaries. The underlying siltstone and the included bones were subsequently cemented and replaced with calcium carbonate. The siltstone does not show any of the characteristics of a developing caliche layer, indicating that its carbonate is diagenetic and that this horizon does not represent a soil horizon.

Upper Subfacies - The cornstones of the upper subfacies are much like those of the middle subfacies. The major change is an apparent overall decrease in the number of carbonate layers. Both types of cornstones occur but the non-laminated variety is more common. It appears that the same processes which formed the cornstones in the middle subfacies were active in the upper subfacies. In addition, the extent of cornstone development is the same in both subfacies with one exception: the upper subfacies lacks any carbonate horizons which had developed a silicic stage. The upper subfacies also contains the only example of cornstone development in a sandy layer. Gile et al., (1966) has noted that fine-grained and coarse matrices have different cornstone morphologies. These two morphologies merge in stage IV. The cornstone in the sandstone shows a stage IV morphology with some minor laminations at the top and sand grains and pebble clasts floating in the calcareous matrix.

Caliche Development and Aggradation Rates - Studies of Quaternary caliches in the southwest provide data for a model relating degrees of caliche development with the rate of sediment accumulations. Leeder (1975) used ^{14}C dates of caliches of various stages and river flood plain accretion rates to develop a graph of flood basin accretion rates that would be expected from various caliche thicknesses and morphological stages. Most of these data were derived from stage I and II caliches, with extrapolations for stage III and IV. His model assumes:

- an optimum climate for caliche development
- caliche development in the classic downward movement and precipitation model
- caliche development takes place in a flood basin where accretion is taking place
- the water table is not a factor
- the host rock is composed of sand or silt

A major problem of applying this model to ancient caliches is the fact that the top and bottom of the calcic horizon are very difficult to pick. In modern caliches, Leeder (1975) notes, it is difficult to pick tops and bottoms due to their gradational nature. This problem becomes acute in older sediments in which diagenesis may have altered the more porous, less indurated parts of the profile. In addition, other soil horizons are usually absent and cannot be used as a reference. However, some general conclusions can be drawn from his findings.

In the lower subfacies the stage III cornstones probably took between 6,000 and 10,000 years to form, indicating accretion rates ranging from less than 0.1 millimeters to 2 millimeters per year. Stage IV cornstones associated with the middle and upper subfacies took more than 10,000 years to form and represent accretion rates ranging from less than 0.1 millimeters to 1.5 millimeters per year.

Leeder notes that accretion rates today for most rivers would not allow formation of caliche or would only allow development of stage I morphologies. The presence of stage II, III, and IV carbonates in ancient sediments and in particular their repeated appearance must indicate dramatic fluctuations in accretion rates. Leeder suggests five factors that would cause the accretion rate fluctuations and the subsequent stacking of the caliches.

The first factor is a variation in accretion rates due to location on the flood plain. This assumes that levees would accrete too rapidly to allow caliche development while flood basin margins might develop stage I and II morphologies. The second is a variation in intrabasinal accretion rates due to the migration or avulsion of streams. The third factor is a shift in stream location due to tectonic movements or damming. The fourth is a fluctuation in regional base level which causes rivers to aggrade or degrade with corresponding effects on flood plain accretion rates. The fifth factor is a variation in regional climates with would affect sediment yields and flood frequency.

All of these factors except climatic fluctuations could have led to the sequences of carbonates in the study area. The climatic factor is ruled out because the Cretaceous is generally perceived to have been a period of relative climatic stability (Habicht, 1980).

The less well-developed nature of the carbonates in the lower subfacies as compared to those in the middle and upper subfacies indicates that the lower subfacies had an overall higher accretion rate. This is consistent with an anastomosed stream system—a fluvial system which is aggrading. Avulsion of individual channels and the associated changes in aggradation rate would have allowed development of only thin caliche layers.

The greater development of the middle subfacies cornstones indicates a lower accretion rate, in keeping with what is expected for a meandering system. Most of the cornstone horizons are due to the migrations of the meandering system which would have allowed substantial development of these horizons in areas away from the channel. However, many of these calcareous horizons were a result of water table fluctuations. There are no data available on carbonate accumulation rates due to capillary rise, but it is assumed that the constant presence of carbonate-enriched water would allow much faster development of these horizons than those formed only by the downward flushing of carbonate, which is dependent on periodic rain. The rapid development of these horizons, coupled with the large number of lake and associated water table fluctuations, would have formed a large number of cornstones. The color change in the sediments from primarily red and orange in the lower subfacies to green and gray in the middle and upper subfacies could also be attributed to lower water tables in the lower subfacies and associated higher oxidation rates than in the overlying subfacies.

Cornstones of the upper subfacies are similar to those of the middle subfacies and presumably accretion occurred at the same rate. The shift to an anastomosing morphology without the increase in overall aggradation rate is probably due to either a change in vegetation or the area's relation to the base level obstruction. This is discussed under sandstones of the upper subfacies.

The overall low rate of accretion in the study area, as evidenced by the advanced stages of cornstone development, indicates that this area was not near the head of the alluvial fans of which it is a part. Areas closer to fan apices receive substantially higher amounts of sediment and have a higher frequency of stream migration, causing poor development of caliche horizons.

Cornstone development and inferred sediment accretion rate give some idea of the study area's location relative to the thrust sheet highlands to the west. Dorr (in press) has used the Gandak and Kosi megafans of India as a model for deposits of the Gannett and Wayan Groups of Wyoming which were deposited in much the same geologic setting as those of the Two Medicine Formation. In India, he has found the coarse clastic sediments drop out on the fans after less than 20 kilometers and the majority of the fans are composed of sand and fine-grained sediments. Gradients are generally 20 to 40 centimeters per kilometer on the fans. Dorr refers to this area as a <u>wet</u> alluvial megafan as opposed to most fans which occur in arid environments. The water table along the fan is generally near the surface, even near the apex. Carbonate horizons form in the fan, mainly in higher parts of the interfluves. This model fits the study area fairly well except for the more highly developed and ubiquitous nature of the cornstones found in the study area.

Caliches have also been used as paleoenvironmental indicators. Studies of Tertiary and Quaternary caliches indicate that most caliches develop in semiarid environments with seasonal rain of 100 to 500 millimeters and a long dry season (Reeves, 1976, as cited in Hubert, 1978). Low relief is also necessary to avoid too rapid runoff of surface water. Wind-blown carbonate was probably the main source for the caliches. The only known sources of calcium carbonate are the Paleozoics exposed by thrusting to the west. As a result, it is assumed that the prevailing winds were out of the west.

RECONSTRUCTION

The purpose of this study is to give an environmental and geomorphic reconstruction of the Willow Creek anticline for paleontologists working with the dinosaur remains in the area. This section will develop a climatic model for the area using sedimentologic and computer model information, and will combine it with morphological information developed in the discussion section to reconstruct the depositional environment for each subfacies.

Climate

Sedimentologic evidence - Two sedimentary features of the area give good evidence of paleoclimate: caliche and vadose carbonates. Caliches are somewhat restricted in their climatic occurrence. Their formation indicates a semiarid environment with seasonal rainfall and a long dry season. Rainfall is usually between 100 to 500 millimeters (Reeves, 1976 as cited in Hubert, 1978). Lower precipitation rates do not provide enough water to flush the carbonate down and higher rates would tend to flush it out completely. There is some evidence that caliche can form in wetter climates but there must be expanses of limestone to provide abundant carbonate (Steel, 1974). It is felt that the major carbonate source for caliches is airborne carbonate dust (Reeves, 1970). In the study area this would mean that winds were predominantly out of the west, where the only large carbonate sources are located. The winds must also have been strong enough to have moved the amount of carbonate needed to form the carbonate horizons.

The vadose carbonates also give some important climatic information. In some places the water table was close enough to the surface for plants with small roots to have reached it. In their study of vadose carbonates, Semeniuk and Meagher (1981) note several important climatic factors:

- rainfall is of short duration
- temperatures are high
- humidity is low
- wind is common

The last three of these combine to cause a very high evaporation rate for surface and near-surface waters. In their study area rainfall was high, but the presence of caliche in my area indicates this was not true in the Willow Creek anticline area.

Computer Modeling - Recent advances in developing world atmospheric models combined with paleogeography developed by geologists give rough ideas of world climatic patterns for various geologic periods. These models are very general and very problematical due to the lack of consensus on the degree of effect of various climatic driving forces in the past. Much of the modeling has been done on the mid-Cretaceous because of its extreme difference from today's climate. A detailed study by Lloyd (1982) gives a comprehensive reconstruction of world climatic traits during the mid-Cretaceous. It should be noted that these are highly problematical but the results seem to be corroborated by geologic evidence. Due to the similarities in paleogeography of the mid-Cretaceous and the late Cretaceous (McGookey, 1972), Lloyd's results will be used in developing a climatic scenario for the Willow Creek anticline.

Winds were out of the west across the Cordilleran high, blowing off the proto-Pacific, over the mountains and across the Cretaceous seaway. Lloyd's model gives ocean surface temperatures for the Cretaceous epeiric sea adjacent to the study area as 16° C during January and 24° C during July. These are important points for the discussion of climate around the study area.

Paleogeography

The next important concept in a reconstruction is the regional paleogeography. To the west of the study area were the mountains formed by Sevier thrusting. There are no estimates of the height of the mountains adjacent to the study area but Lloyd has used the Andes as a model for areas adjacent to active subduction zones. This gives a mean height for the volcanic arc and thrust belt area of 3 to 4 kilometers above sea level along the axis. In order for the Bonner Quartzite to be subject to erosion, 1.8 kilometers of overlying sediments would have been exposed, not including any Cretaceous sediments. This is based on Mudge's stratigraphic column for the Sun River Area (1972a). 1.8 kilometers would be a minimum elevation assuming no piggy-backing of thrust sheets had taken place. Jordan (1981) has estimated that the mountains of the Wyoming thrust belt in the Cretaceous to be 2-4 kilometers high, based on computer modeling.

Even using the low estimates for the height of these mountains, they would have been high enough to significantly affect the regional climate.

The width of the Cordilleran land mass is very difficult to estimate due to the accretion of exotic terrains that has occurred since the Cretaceous. Most likely, the west shore was probably located in what is now eastern Washington. Location of the east shore is easier to determine and research by Gill and Cobban (1973) places the Cretaceous seaway's shore 100 to 150 kilometers east of the study area during upper Campanian time. This would make the Cordilleran land mass approximately 500 to 600 kilometers wide near the study area, or about twice the width of Florida.

The location of the study area relative to the front of the mountains is once again very problematical. Timing of thrusting and even the sequence of thrusting are still uncertain. The source area for the Bonner Quartzite pebbles, as discussed earlier, was probably 50 to 75 kilometers to the west. However, there is solid evidence that some volcanic highs existed to the west of the study area. These highs might have placed the front of the mountain range closer to the study area.

The paleolatitude is given by Habicht (1980) as 48-50^{o} north. This is not very different from today's latitude of 47^{o} 37'.

The study area was located on gently sloping alluvial megafans. The Elkhorn Mountains volcanic pile to the south, combined with the thrust fault area to the west, gave these fans a northeast slope (Lorenz, 1981).

Regional Climate

The above criteria can be used to develop a tentative model for the climate around the Willow Creek anticline. The west-to-east winds coming off the proto-Pacific would have dropped most of their moisture as they climbed over the Cordilleran mountains and cooled (Figure 20). This process would have caused a rain shadow over the upland areas to the east of the mountains, including the study area, during most of the year. During the summer, the land would have been warmer than the epeiric seaway. The land would have heated the surrounding air causing it to rise and to be replaced by moist air from the seaway which turned into rain in convective storms (Figure 21). Gartner and McGuirk (1979) proposed a similar model of land-sea breezes in which slowly rising warm air and associated thunderstorms over the land combine with dry sinking air over the oceans to form convective cells. This process would cause most of the precipitation to occur during the summer while the rest of the year would have been dry, much like the tropical monsoons of today. Florida would probably serve as a model for the convective summer showers. The temperature would have been buffered by the proximity of the Cretaceous seaway and probably would have been temperate. This climate would have been ideal for the formation of caliches.

Vegetation

The type and amount of vegetation in the area is very difficult to determine. As noted earlier, very little carbonaceous material is

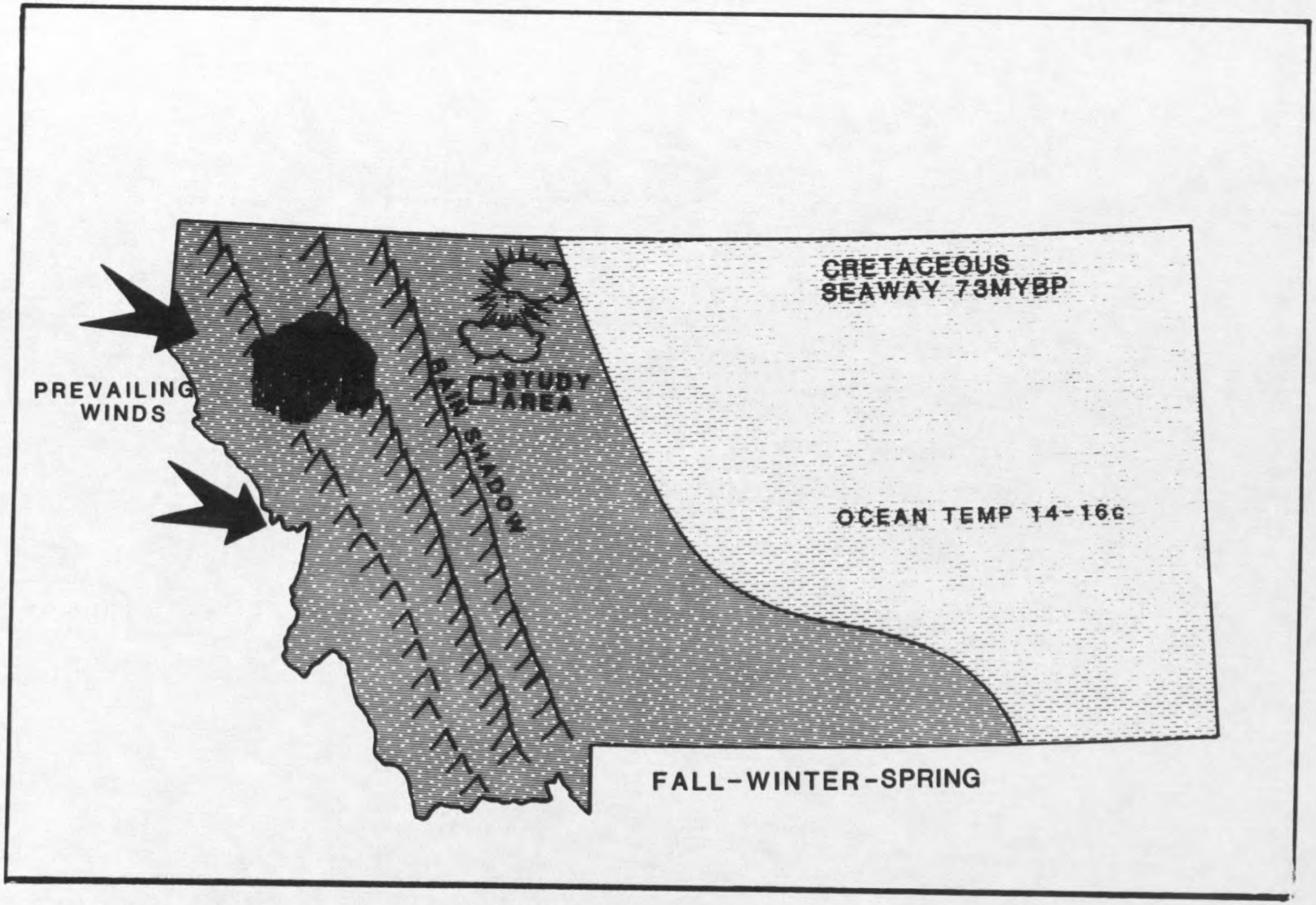

Figure 20. Diagram of meteorological conditions affecting the study area during the fall, winter and spring. Shoreline location from Gill and Cobban (1973). Wind and temperature data from Lloyd (1982).

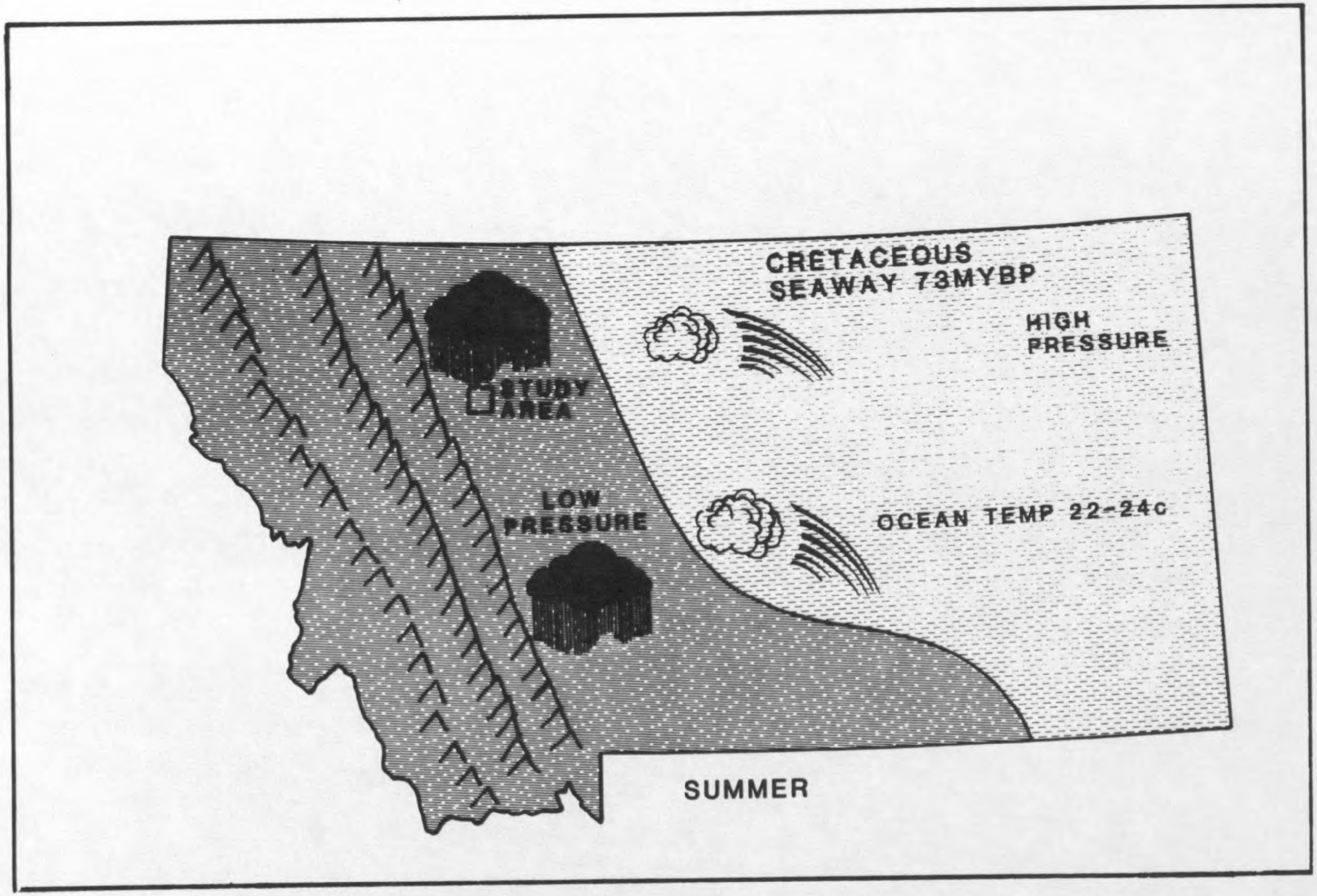

Figure 21. Diagram of meteorological conditions during the summer. Moist air drawn off Cretaceous seaway by rising warm air over land causes rain over the study area.

found in the area, indicating an overall oxidizing environment. The presence of rhizoliths throughout the study area indicates that plants were common. All of the rhizoliths found are derived from small root systems with no evidence of large tap roots, indicating that large trees may have been absent. Pollen analysis of samples from Willow Creek anticline indicate that the vegetation was similar to those found in the Judith River Formation (Lorenz, pers. comm.).

Habicht (1980) places the line for the equatorward limit of deciduous forests during the Cretaceous just south of the study area. Most research on vegetation near the study area has focused on the lowland environments rather than uplands due to the preservation of material in the lowland environments. As a result, it is not known what correlation can be drawn between lowland faunas and upland faunas which would include the study area. In view of the extreme differences seen in faunas found between coastal and upland areas, it would seem that very little could be said about upland faunas of the Cretaceous based on lowland varieties.

It can be said that substantial amounts of vegetation must have been present during some parts of the year to support large herds of nesting dinosaurs, possibly as many as 10,000 animals (Hooker, pers. comm.). Horner (pers. comm.) has stated that the rapid growth of dinosaur hatchlings during the nesting season would have required substantial amounts of vegetation in the area.

Reconstruction of Subfacies

The following reconstruction of the environments at the times of deposition of the various subfacies are based on interpretations developed in the previous discussions. In many ways they exceed the normal scope of sedimentologic investigations which normally deal with specific physical characteristics of facies and link them with a possible mode of origin. It is hoped that this reconstruction will help paleontologists better understand dinosaur behavior and in turn will provide a clearer picture of this portion of the earth at specific instances in time.

Lower subfacies - The climate for this subfacies was warm and dry, possibly more so than for the subsequent subfacies. The abundance of red, orange and yellow in this subfacies indicates that oxidizing conditions were more prominent than for the other subfacies, possibly due to a deeper water table which in turn was due to a drier climate than in subsequent times.

Precipitation (less than 500 millimeters per year) occurred during the summer in monsoon-type rains. It is during this time of year that the major floods occurred and the flood plain received its major deposition. During this monsoon season vegetation was most abundant and therefore it is assumed that the dinosaurs nesting in the area would have migrated up from the lowlands at this time of year. Many of the nest sites in this subfacies are along the levees of the river system, where food and water would have been most plentiful. In addition, the levees would have been less likely to be flooded than adjacent low-lying flood plains.

During the dry season, vegetation was concentrated along the levees of the river where water was more abundant, as described by Rust (1981) near Coopers Creek, Australia. Vegetation away from the channels probably died or took on the water-conserving modes of plants in semiarid environments today. Any interchannel ponds that formed during the monsoon season dried up, not allowing any preservation of carbonaceous remains such as those noted by Smith and Putnam (1980) in temperate anastomosing systems.

The river system in this subfacies was anastomosing (Figure 22) with several interconnected channels bounded by levees which were reinforced by the roots of the vegetation which grew along them. In some cases, the levees surrounded low-lying areas between channels. It is possible that this stream system was ephemeral, flowing primarily during the monsoon season.

Other than the levees, the topography was relatively flat, allowing development of caliche throughout most of the area (Figure 22). The slope of the land was low, 20 to 40 centimeters per kilometer, much like the mid- and outer fan segments of large alluvial fans today. To the west were the highlands of the Cordilleran mountains and some small volcanoes.

Middle subfacies - The climate during the time of deposition of the middle subfacies was in many ways the same as the lower subfacies. The major difference was an increased amount of moisture in the area. The presence of the lake and the higher water table caused reduction

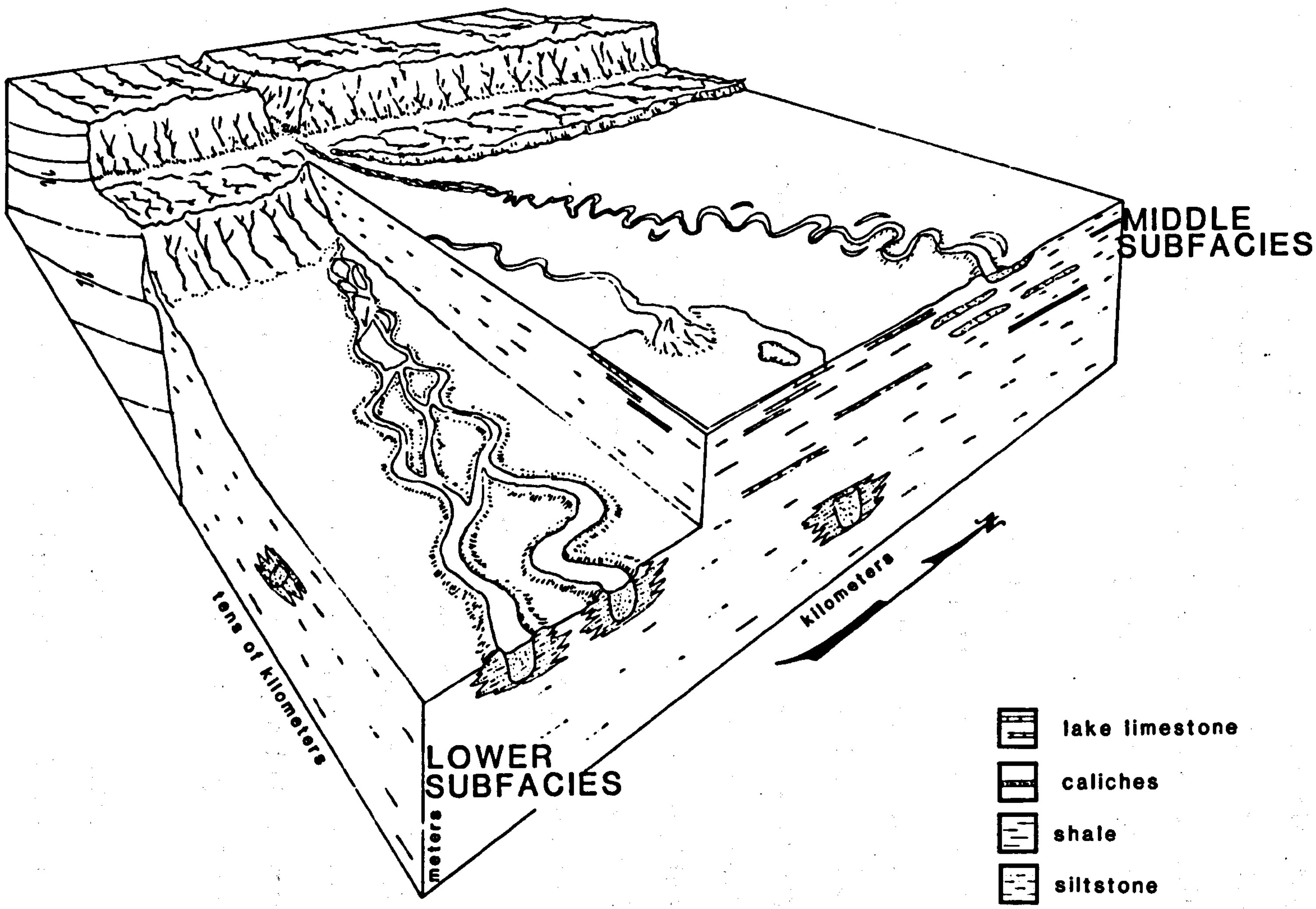

Figure 22. Block diagram of the study area during deposition of the lower and middle subfacies showing anastomosing river of lower subfacies and meandering river and lake of middle subfacies.

of the sediments, giving them their characteristic green and gray. Other than this, the climate was the same. Rain came during the summer monsoons and the rest of the year was dry. Precipitation was possibly greater than at the time of the lower subfacies deposition but still less than 500 millimeters per year. Temperatures were warm with little seasonal variation.

There was a small lake in the area (Figure 22) containing islands and a shoreline with peninsulas. The low relief of the area caused major shoreline fluctuations with any lake level fluctuation. The presence of the lake caused abundant precipitation of carbonates in the vadose zone near the water table. This freshwater lake supported aquatic plants and algae. The peninsulas and islands were used by herds of nesting dinosaurs whose constant digging and trampling disrupted the carbonate horizons in the immediate area. Water level fluctuations occasionally asphyxiated egg clutches before they could hatch and the abundant carbonate in the water allowed rapid petrification of the remains. The higher water table supported more abundant vegetation than at the time of deposition of the lower subfacies. This vegetation was utilized by the large herbivore population. Indications are that the lake rarely dried up completely, even on an annual cycle, but it may have been filled by sediments and reformed over several periods.

The river system had taken on a meandering morphology. Vegetation was less restricted to the river banks than for the lower subfacies. Levees still formed along the banks and there was the occasional crevasse splay event. The rivers were probably perennial.

Volcanic activity to the south and west was more pronounced than earlier with several ash falls. One eruption killed a large number of dinosaurs which were subsequently swept down to the study area by a mud flow and deposited in an abandoned channel.

In areas where the water table was deep below the surface, caliche development was very advanced. Sediment accumulation rates on the flood plain were very low and had long hiatuses due to the migration of the stream.

The geography was similar to the lower subfacies: The Cordilleran mountains were to the west and volcanoes existed in the west and south. The alluvial megafan surface was relatively flat with an even lower gradient than for the lower subfacies.

Upper subfacies - The climate during the time of deposition of the upper subfacies was the same as for the middle subfacies. The water table remained near the surface, allowing deposition of vadose carbonate. Rain occurred during the summer in an overall semiarid environment. Temperatures were temperate.

The lake no longer existed in the study area but some sort of downstream blockage caused the river system to shift to an anastomosing morphology. This blockage must have been fairly near the study area because the rate of accretion remained the same as for the middle subfacies. Aggradation associated with an anastomosing stream must have occurred higher upstream. The stream system appears to have increased competency from that of the lower two subfacies, and now included pebble-size clasts from the Belt Supergroup exposed to the west. Once again, vegetation was abundant along the levees, helping to stabilize the banks and causing the stream to aggrade vertically. Small interfluve lows occasionally contained standing water, but these probably dried during the dry season.

In areas where the water table was deep below the surface caliches developed into the advanced morphologies associated with low aggradation rates. Vadose carbonates also developed thick layers.

The topography of the area was subdued with the highs primarily associated with the levees. Gradient was low but was in the process of changing. Volcanic activity seems to have been less than during the deposition of the middle subfacies, but volcanoes probably still existed to the west and most assuredly to the south. The Cordilleran mountains still loomed to the west, 50 or 60 kilometers away.

SUGGESTIONS FOR FURTHER STUDY

Paleoenvironmental reconstruction of the study area has been severely hampered by the lack of data on the flora that might have occurred there. This is due in part to the lack of carbonaceous remains found in alluvial fan environments. However, some layers in the study area and presumably elsewhere contain some organic debris that might be useful in determining the type of vegetation that occurred in the area. In addition, a close examination of rhizoliths occurring in sandstones and carbonates in the area may shed some light on the type and frequency of occurrence.

Many of the sandstones in the area contain abundant heavy minerals. These appear to be primarily magnetite but the author has not attempted a close examination of these. Their study would give a much better understanding of the provenance of the sandstones as well as some insight into the type of volcanics now covered west of the study area.

A final intriguing problem is the occurrence of conglomerates in the Two Medicine Formation in the syncline along the North Fork of the Sun River. The Two Medicine deposits have been mapped by Mudge (1972a) and have been examined by the author. These conglomerates contain cobble-size clasts whose provenance could presumably be identified. Such a study could lead to a better understanding of the progression and timing of thrusting along the disturbed belt.

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APPENDIX

APPENDIX

Descriptions of Measured Sections

SECTION 1

?.......Green friable sandstone.

9'......Red shale.

6'......Gray shale.

7'......Gray shale with some calcite.

6"......Reddish green fine sandstone.

?.......Red shale with lenses of limestone containing gray chert.

SECTION 2

?.......Green friable sandstone.

4'......Red shale.

3.5'....Gray shale.

5'......Red shale.

6'......Reddish calcareous, resistant mudstone.

1.5'....Red siltstone.

4'......Gray siltstone.

0.5'....Resistant calcareous gray mudstone.

4.5'....Gray shale.

3"......Limestone.

1'......Gray shale.

2"......Limestone.

1'......Gray shale.

3"......Limestone.

1'......Gray shale.

4"......Limestone.

SECTION 3

Tentative section of Egg Mountain

?.......Friable green sand.

6'......Covered.

2'......Red shales with lenses of greenish calcareous shales.

3"......Reddish, very calcareous, resistant mudstone

15'......Red shale.

1.5'....Reddish resistant calcareous mudstone.

9.5'....Gray shales.

2'......Resistant gray limestone.

13'......Gray shales with interbedded lenses of calcareous mudstones.

SECTION 4

?.......Variegated yellow and gray shales and siltstones, 1-2" thick. Some red near top. Thin sand at top, flaggy, moderately indurated, gray, very fine grained.

2'......Variegated red, yellow and gray shales.

6'......Gray sands, fine grained, weathering to brownish red with splotches of yellow, flaggy, finely laminated.

11'......Alternating red siltstones and more resistant layers of very fine grained sandstones. Sandstones are blocky, mottled, reddish and greenish, very small trace fossils with hematite replacement.

6'......Variegated green and red siltstones grading to purple at top.

4.5'....Red siltstones with some calcareous zones.

5'......Purple and red siltstones.

2'......Gray and green fine to medium grained, friable sandstone, bioturbated at top.

13.5'....Variegated red and gray siltstones tending more toward gray. Some thin layers of nodular calcareous zones.

1'......Greenish gray sandstone, cross laminations, fine grained, some bioturbation.

8'......Mottled red and green-gray siltstone.

2.5'....Friable greenish gray sandstone, fine to medium grained.

4.5'....Red siltstone.

0.5'....Grayish red, well indurated, very fine grained sandstone, bioturbated, flaggy.

1'......Red siltstone.

0.5'....Very calcareous reddish siltstone.

0.5'....Red shale.

4'......Greenish gray, friable sandstone, medium to fine grained.

2'......Grayish red calcareous siltstone, heavily bioturbated with a mini-Karst-like surface.

8'......Greenish gray friable sandstone.

4'......Gray-green shales mottled with red.

0.5'....Calcareous reddish siltstone.

4'......Red siltstone.

5'......Gray shale with lenses of very calcareous shale.

5'......Four layers of argillaceous limestone, 2-6" thick, alternating with gray shale.

7'......Grayish red siltstone.

5'......Alternating layers of reddish siltstone and very calcareous mottled red and green siltstone.

14'......Reddish siltstone.

2'......Gray to red-gray siltstone, very calcareous and resistant, weathers to a reddish tan with a pitted surface.

11'......Gray siltstones.

1'......Very argillaceous gray limestone with floating sand grains, weathers to tan.

SECTION 5

?.......Gray-green friable sandstone, fine to medium grained, trough cross-bedding.

1.5'....Red siltstone.

0.5'....Gray-green sandstone, cross laminations.

0.5'....Red shale.

0.5'....Sandstone as above.

1'......Red siltstone.

2"......Greenish gray sandstone, flaggy, fine grained, ripple cross lamination.

1'......Red shale.

2"......Sandstone as above.

13'......Variegated orange, purple and gray siltstones with thin sands.

4"......Resistant, very calcareous, sandy siltstone.

5.5'....Gray siltstone with some reddish banding near top.

4'......Reddish purple siltstone.

0.5'....Very calcareous purple siltstone.

6'......Reddish siltstone.

4"......Very resistant reddish gray sandstone, very fine grained, bioturbated.

4'......Red siltstone.

0.5'....Very fine gray sandstone, flaggy, very bioturbated.

1.5'....Purple siltstone.

0.5'....Gray sandstone, medium to fine grained, moderately well indurated to friable, bioturbated, no visible cross-bedding.

14'......Green siltstone.

3"......Reddish pink bentonite.

11'......Alternating red and green siltstone with thin lenses of calcareous siltstone.

1'......Very calcareous siltstone, greenish gray, sand grains floating in matrix.

1.5'....Greenish red siltstone with occasional lenses of calcareous siltstone.

1'......Calcareous siltstone, reddish with green splotches, thinly laminated in places.

3'......Reddish siltstone.

2'......Dark purple siltstone.

3'......Gray sandstone, fine to medium grained, coarsens upward, cross laminated, calcareous, friable, flaggy.

9'......Siltstone, dark reddish purple.

5'......Reddish siltstone with irregular zones of calcareous siltstone.

18'......Gray green shale and siltstone.

3'......Mottled green and purple siltstone, laminated in places, resistant, non-calcareous, bioturbated.

9'......Greenish gray sandstone, fine to medium grained, trough cross-bedded, clay-pebble lag at base, friable, bioturbated at top.

3'......Purple and green mottled siltstone.

8'......Orange and green siltstone.

3'......Green and purple resistant calcareous siltstone.

3'......Purple mottled with green siltstone.

0.5'....Purple, very calcareous, resistant siltstone.

10'......Red and green siltstone, mostly covered.

3'......Resistant, very calcareous siltstone, mottled purple and green.

5.5'....Greenish siltstone.

6'......Greenish, very friable sandstone, trough cross-bedded, medium grained, slightly calcareous, resistant top.

1'......Green and purple siltstone.

4'......Gray siltstone.

2'......Greenish friable sandstone, medium to fine grained, trough cross-bedded, fines upward.

12'......Purple, gray and green siltstone.

?.......Gray fine grained sandstone, grades up into a very calcareous siltstone.

SECTION 6

?.......Reddish purple siltstone, mottled green.

6'......Greenish gray sandstone, trough cross bedded, well indurated, fine to coarse grained, basal lag of clay clasts, heavy minerals in base of troughs, non-calcareous.

15'......Reddish siltstone.

10'......Red and green mottled siltstone.

1'......Purplish red and green mottled, resistant, calcareous, siltstone.

4'......Reddish and green mottled siltstone, non-resistant.

7'......Greenish gray sandstone, very fine grained to fine grained, small trough cross-beds, flaggy, slightly calcareous.

2.5'....Reddish purple resistant siltstone, very sandy, capped by very sandy gray green siltstone.

6.5'.....Gray green siltstone.

3'.......Gray sandstone, fine grained, cross laminated, bioturbated, calcareous.

5'.......Covered but seems to be purple siltstone with lenses of sandstone.

?.......Green and olive sandstone, trough cross-bedded, fine to medium grained, friable, non-resistant.

SECTION 7

?.......Covered, possibly red and orange siltstones with limestone nodules.

13'......Gray sandstone, very fine to fine grained, heavily bioturbated, more resistant near top.

6.5'....Red to orange siltstone, surface covered with limestone nodules.

12.5'....Gray siltstones, lots of limestone nodules covering slope, some red siltstones near top.

6.5'....Gray to white sandstone, weathers to a brown, trough cross-bedded, moderately resistant to friable, fine to medium grained, abundant biotite, bioturbated, calcareous.

4.5'....Gray siltstone.

2'......Sand, as above.

2'......Very sandy, red to gray siltstone, bioturbated, non-resistant.

1.5'....Sandstone, as above.

0.5'....Resistant, calcareous, purple siltstone.

1.5'....Gray sandstone, very fine grained, well cemented, bioturbated, ripple cross-lamination.

3'......Gray siltstone.

5'......Gray sandstone, very fine grained, bioturbated, calcareous, abundant biotite, slightly flaggy.

3'......Yellow green siltstone, abundant bones, carbonaceous in places.

3'......Red and green siltstone.

3''.....Bentonite.

8'......Green gray siltstone.

15'......Reddish siltstone.

3'......Greenish red sandstone, very silty, friable.

9'......Red siltstone.

10'......Red mottled green siltstone, very resistant, contains purple and green clay clasts.

?...... Green gray siltstone with layers of argillaceous limestone, 1-5" thick, containing microfossils.

SECTION 8

?.......Gray siltstone.

6'......Greenish gray sandstone, very resistant, non-calcareous, trough cross-bedded, fine to coarse grained.

21'......Red and green gray siltstones, color is laterally variable.

2'......Green gray siltstone layers, resistant, 6" thick, alternating with gray green and red non-resistant siltstone layers.

4'......Gray sandstone, very fine grained, with 6" lenses of gray green siltstone.

0.5'....Gray siltstone, resistant, calcareous.

2'......Gray siltstone, with some sandstone lenses.

1.5'....Purple siltstone, very resistant, calcareous.

2'......Gray sandstone, very silty, friable, very fine to fine grained, grades into siltstone laterally.

0.5'....Purple siltstone, sometimes resistant.

10'......Red and green siltstone.

SECTION 9

24'......Purple, gray and green siltstones with some lenses of resistant calcareous siltstones, and thin sandstones.

6'......Gray sandstone, fine grained, and very sandy, red and gray siltstone.

0.5'....Gray limestone, very argillaceous and silty.

12'......Gray and red siltstone, occasionally sandy.

19.5'....Gray green sandstone, trough cross-bedded, moderately friable, fine to medium grained, basal lag of clay pebbles and bones.

11'......Purple and gray green siltstone, some discontinuous, resistant, calcareous zones.

15'......Green sandstone, friable, bioturbated, trough cross-bedded.

?.......Green sandstone, lenses of pebbly sandstone with pebbles up to 1", trough cross-bedded, friable, like sandstone above.

SECTION 10

?.......Lower marker horizon.

5'......Gray sandstone, weathers brown, trough cross-bedding, moderately friable, fine to medium grained, more resistant and bioturbated at top.

25'......Beds of gray, green, and red siltstone, 1-5' thick, and some thin layers of flaggy sandstone.

1'......Purple and red siltstone, fissile.

3'......Greenish gray sandstone, trough cross-bedded, moderately friable, fine to medium grained, calcareous.

3.5'....Green gray siltstone.

13'.....Alternating layers of purple and green gray siltstone with thin layers of flaggy, very fine grained sandstone, bioturbated.

11'......Gray sandstone, fine to medium grained, trough cross-bedding, pebble lag at base containing volcanic and metamorphic clasts, as well as bone fragments. Grades up into a gray siltstone.

7'......Gray sandy siltstone, top green gray.

2'......Purple and gray siltstone.

1'......Gray green sandstone, very fine to fine grained, heavily bioturbated, calcareous, moderately indurated.

0.5'....Red purple siltstone, very resistant and calcareous.

6.5'....Green gray siltstone.

1'.....Green gray siltstone, very calcareous, resistant, with sand grains floating in matrix.

10'.....Greenish gray siltstone, with scattered lenses of resistant, calcareous siltstone. Scattered lenses of pebbly sandstone, fine to coarse grained, friable.

1'.....Very calcareous resistant siltstone, with abundant pebble inclusions.

SECTION 11

?.......Top lower marker horizon.

8'......Green gray siltstone.

3'......Gray mottled red limestone, very argillaceous, sandy.

5'.....Red and green siltstones, with thin flaggy sand in middle. Resistant at top and bottom.

5.5'....Purple and green siltstone, with fissile mottled layer near base.

2.5'......Gray siltstone.

4.5'....Gray sandstone, medium grained, slightly calcareous, trough cross-bedded, moderately resistant.

2'......Gray to purple siltstone, very resistant at top.

2'......Green, gray and purple siltstone.

3'.....Green to green gray sandstone, medium grained, friable, slightly calcareous, trough cross-bedding.

1'......Purple siltstone, resistant, calcareous.

6.5'....Gray green sandstone, sedimentary structures go from ripple cross laminations at the base to trough cross-bedding to planar cross-bedding to trough cross-bedding at top. Top grades up into alternating silts and fine sands.

1'.....Gray siltstone, resistant, calcareous

5'.....Gray, green and purple siltstone, fissile in upper half, slightly calcareous.

?.......Gray green sandstone, friable, trough cross-bedded.

SECTION 12

?.......Lower marker horizon.

8'......Greenish gray siltstone.

2'......Purple mottled with green siltstone, resistant, calcareous, weathers brown.

6'......Purple and green gray siltstones.

1'......Purple mottled with green siltstone, resistant, calcareous.

3'......Green gray siltstone.

2.5'....Purple and green siltstone, fissile, resistant, top is resistant, argillaceous limestone.

8'......Green gray siltstone.

2.5'....Purple and green gray siltstone with resistant calcareous zone at top.

6'......Green gray siltstone with 0.5' thick layer of medium grained sand 2 feet below top.

2'......Green and purple siltstone and shale, fissile, more calcareous and resistant at top.

6'......Olive green sandstone, very friable.

1'......Olive green siltstone, sandy, resistant.

22'......Gray green sandstone, trough cross-bedding, clay balls and clasts in lower part.

SECTION 13

?.......Olive green siltstone, somewhat sandy, resistant.

9'......Purple and gray green siltstone, top 0.5' is purple, fissile siltstone.

1'......Gray sandstone, fine to medium grained, moderately resistant, bioturbated.

1'......Gray green siltstone.

0.5'....Purple siltstone, calcareous, resistant, mottled green.

6'......Gray green and purple siltstone.

4'......Purple mottled with green, shale, fissile, slightly calcareous.

9'......Olive green sandstone, friable, medium grained, calcareous, trough cross-bedding.

5.5'....Purple and gray green siltstone, some fissile areas.

1'......Gray sandstone, bioturbated, ripple cross laminations.

2'......Gray green siltstone and purple shale.

1.5'....Sandstone as above.

8'......Greenish gray siltstone with several calcareous, resistant horizons.

4'......Mottled purple and green shale, fissile, slightly calcareous.

2'......Sandstone as above.

11'......Greenish gray siltstone with some thin sandy horizons.

3'......Purple shales and siltstones bounded at bottom and top by 6" of very fine grained sandstone.

SECTION 14

Teton Butte, NW 1/4, Sec. 22, T.24 N., R.7 W.

16'......Greenish gray siltstone, sandy, very calcareous, occasional calcite nodules.

5.5'....Greenish gray siltstone, sandy, slightly calcareous, alternating with lenses of grayish green sandstone, slightly calcareous, trough cross-bedded, occasionally carbonaceous, very fine to fine grained.

7.5'....Greenish gray sandy siltstone.

2'......Greenish gray sandstone, slightly calcareous, very fine grained, abundant biotite, carbonaceous, bioturbated, capped by a resistant calcareous greenish gray siltstone.

7'......Grayish green sandy siltstone.

0.5'....Gray brown limestone, resistant, very argillaceous.

5'......Greenish gray sandy siltstone with thin lenses of very fine sandstone.

6'......Greenish gray sandy siltstone.

6'......Gray green sandstone, fine to medium grained, trough cross-bedded, moderately to very friable, alternating with green gray sandy siltstones.

0.5'....Resistant calcareous siltstone with abundant dinosaur remains.

7'......Greenish gray siltstone capped in places by gray limestone lenses.

4'......Greenish gray sandstone, trough cross-bedded, friable, fine to medium grained, calcareous, siltstone pebble lag at base with eggshell fragments and bone.

3'......Greenish gray siltstone, sandy.

0.5'....Gray limestone, sandy, argillaceous.

2'......Greenish gray sandstone, carbonaceous, bioturbated, resistant.

2'......Gray siltstone, sandy, with resistant silty limestone at top.

28'......Gray siltstone, sandy, occasional thin lenses of sandstone, 1-3" and some calcareous nodules.

5'......Yellowish gray siltstone with 6-inch lenses of sandstone.

7.5'....Yellowish gray sandstone, friable to moderately indurated, trough cross-bedding, very fine to medium grained.

21'......Mostly covered but appears to be sandy yellow gray siltstone.

0.5'....Resistant gray limestone.

30'......Mostly covered but appears to be sands and siltstones as above.

SECTION 15

Teton Butte, SW 1/4, Sec. 22, T.24 N., R.6 W.

60'......Greenish gray sandstone, friable, calcareous, fine to medium grained, basal lag of bivalves, gastropods, wood, bones and claystone pebbles, occasional lenses of coarser sand and pebbles throughout the sand body.

(Top of this sand appears to be the base of Section 14).

SECTION 16

?.......Upper marker horizon.

2'......Sandstone, lenticular, medium grained, subrounded, calcareous.

2'......Purple green shale, resistant, slightly silty.

10'......Green and purple siltstone.

13'......Greenish gray sandstone, fine to coarse grained, trough cross-bedded, upper part is ripple cross laminated, clay pebble clasts scattered throughout.

2'......Siltstone and very fine sandstone, gray and purple.

10.5'....Reddish and gray green siltstones, top is 3" of purple mottled with green shale.

19'......Gray green sandstone, friable to moderately indurated, trough cross-bedding, irregular basal contact, very fine to coarse grained, upper part is very fine to silt size, bioturbated.

17'......Green gray and reddish siltstones, with occasional layers of argillaceous, sandy limestone. Limestone near top has pebbles of chert and quartz floating in matrix.

97'......Mostly covered but appears to be green gray and reddish siltstones with abundant thin lenses of very fine grained sand.

3'......Green gray siltstone, very resistant.

35'......Green gray and yellow gray siltstones with thin sands and some lenses of resistant calcareous siltstone.

24'......Gray green sandstone; lower part is fine to medium grained, poorly to moderately indurated with some thin silt lenses, arkosic, trough cross-bedding and some cross laminations. Middle part is more resistant, mostly trough cross-bedded with some cross laminations, lenses of silty limestone 2' thick with rip-up clasts and overlying sandstone. Upper part is fine to coarse grained, arkosic, trough cross-bedded.

(Moved 100' laterally)

1"......Bentonite.

9'......Gray green and yellow siltstone.

6.5'....Yellow siltstone, very resistant, calcareous, sandy, with burrows and root casts.

5'......Gray and yellow sandstones interbedded with lenses of green and yellow siltstone.

7.5'....Green and yellow siltstone with occasional layers of resistant calcareous siltstone.

1'......Gray sandstone.

18'......Gray green siltstone.

21'.....Gray green to yellow green sandstone, very fine grain at base and layered with siltstone, upper two-thirds is trough cross-bedded, very fine to medium grained.

16'......Alternating sands and silts, gray to yellow.

90'......Mostly covered but appears to be yellow and yellow green siltstones.

SECTION 17

?.......Reddish gray silty claystone.

1.5'....Olive green sandstone, poorly sorted, rounded, trough cross-bedded, base is fine to very coarse grained. Upper part is fine to medium grained.

9'......Reddish gray siltstone interbedded with thin lenses, very fine sand and silt.

4'......Gray green sandstone, trough cross-bedded, very resistant. Base is very fine to coarse with clay clasts. Middle is fine to medium grained. Upper part is very fine to medium grained.

7'......Reddish gray and greenish gray siltstone.

3'......Purple and green gray siltstone. (Lower marker horizon).

SECTION 18

Two Sections 50 Feet Apart

13.5'....Greenish gray sandstone, fine to medium grained, friable with occasional layers of more resistant brownish sand with clay clasts, coarse grained.

3'......Reddish gray siltstone, lens shaped--probably a finger.

4'......Greenish gray sandstone, fining upward sequence, lowest part is fine to medium grained grading up into reddish siltstone at top.

14.5'....Gray to greenish gray sandstone, very fine to fine grained, lenses of coarser sandstone, top contact grades into reddish siltstones interlayered with very fine grained sandstones.

(Section 50 Feet West, Same Level)

33'......Reddish, purple, gray, gray green siltstones with small limestone nodules which occur in layers 3-4" thick.

SECTION 19

?.......Reddish siltstone, sandy, with thin lenses of very fine grained sand, covered by calcite nodules.

9.5'....Greenish gray siltstone, sandy, with calcite nodules.

23'......Green gray sandstone, very fine to medium grained, trough cross-bedded with lenses of coarser sand containing clay pebble clasts.

16.5'....Reddish siltstone, sandy, with some flaggy sands near the top.

15.5'....Light reddish and gray green siltstone, with resistant calcareous layers at 9' and 11' which are 6" thick.

3.5'....Greenish gray sandstone, moderately resistant, very fine to medium grained.

4.5'....Reddish siltstone with 6" of resistant calcareous siltstone at base.

4.5'....Gray sandstone, very fine to medium grained, bioturbated.

?......Greenish gray siltstone with some yellowish carbonaceous layers.

SECTION 20

Pine Butte, Center Sec. 17, T.24 N., R.7 W.
Two Medicine - Horsethief Transition

?.......Silty claystone and shale, gray to gray brown, slightly lignitic.

13'......Cream to tan sandstone, very fine to fine grained, well sorted, flaggy, with zones containing abundant bivalves and gastropods.

3.5'....Gray to dark gray sandstone, carbonaceous, poorly cemented, no apparent cross-bedding, silty, fine to very fine grained.

25'......Gray to gray brown shale, carbonaceous, containing bivalves, alternating with lenses of sand, flaggy, very fine grained.

11'......Gray to gray brown siltstone, top foot is resistant gray black siltstone with abundant large bivalves.

1'......Bentonite.

26'......Dark brownish gray silty shale, slightly carbonaceous.

5'......Cream to buff sandstone, flaggy, slightly calcareous, silty to very fine grained, bioturbated, trough cross-bedding.

209'......Covered with talus and soil but seems to be mostly shale with some lenses of sand.

40'......Cream, light gray green sandstone, silty to very fine grained, slightly to moderately calcareous, platy to thin-bedded, resistant.

22.5'....Cream to light gray yellow sandstone, moderately calcareous, silty to very fine grained, very thin lamina with siltstone lenses.

23'......Yellow gray to cream sandstone, silty to fine grained, cross laminated, non-calcareous, very resistant, bioturbated in places, cliff former, rare bivalves.

10'......Sandstone as at 22.5' above.

9'......Sandstone as at 23' above.

14'......Sandstone, thin bedded to lamina, slightly calcareous, fine grained.

35'......Sandstone, non-calcareous, very fine to fine grained, cross laminated with occasional lenses containing shells, bone fragments, plant debris and clay pebbles.

SECTION 21

?.......Gray green siltstone.

4'......Yellowish sandstone with 6" of carbonate pebble conglomerate at base with egg fragments and bones.

90'......Covered.

6'......Green siltstone with nodular calcite.

35'......Covered.

5'......Green gray siltstone with calcareous blocks containing abundant black woody material.

10'......Covered.

5'......Red siltstone.

145'......Covered.

4'......Green gray siltstone.

2'......Sandstone.

7'......Green gray siltstone.

1'......Yellow sandstone with abundant bone and plant fragments, hematitic.

6'......Green siltstone with limestone nodules (equivalent to camposaur).

3'......Red siltstone.

3'......Dark gray green siltstone.

4'......Green sandstone.

3"......Bentonite.

11'......Dark gray siltstone alternating with clean carbonates 6" thick.

9'......Green gray siltstone.

3'......Calcareous red siltstone.

SECTION 22

?.......Top of sand measured in Section 18.

7'......Red claystone and siltstone with nodular limestone forming irregular beds 3-4" thick.

22'......Variegated red and gray siltstone with nodular calcite and occasional sandy lenses.

4'......Gray sandstone, poorly to moderately indurated, very fine to fine grained, calcareous, trough cross-bedded at base and ripple cross laminations at top, bioturbated.

4.5'....Gray and red siltstone.

2"......Bentonite.

72.5'....Covered.

3'......Red siltstone, calcareous, resistant.