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STRATIGRAPHY, SEDIMENTOLOGY, TAPHONOMY AND MAGNETOSTRATIGRAPHY OF THE FOSSIL FOREST AREA, SAN JUAN COUNTY, NEW MEXICO

by

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Submitted in Partial Fulfillment
of the Requirements for the Degree of
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ABSTRACT

In the Fossil Forest area (Sections 13, 14, 23, 24, T.23N., R.12W.) numerous fossil localities occur within a stratigraphic interval of approximately 15 m. This sequence straddles the boundary between the Fruitland Formation and the Kirtland Shale. The boundary, which has been the subject of some controversy, is here drawn at the top of the highest coal over 1 m thick and over 100 m in lateral extent. A basin analysis approach was taken prior to the application of published facies models. On the basis of an overview of fluvial sedimentary controls, the abundance of overbank deposits, the presence of fining upward sequences (both in terms of grain size and cross beds), the presence of common channel-fill deposits and levees, the dispersion of current direction indicators, and the presence of epsilon cross beds, most rocks in the study area appear to have been deposited by muddy, fine grained meandering streams. Two channels (B, D) may represent braided streams of the Platte type, based on coarser grain size, lack of epsilon cross beds, presence of transverse and longitudinal bar deposits, lack of levee deposits, and small dispersion in current directions. Fossils are nonrandomly distributed stratigraphically and sedimentologically, the majority occurring in one downcut complex. One short zone of reversed magnetic polarity occurs in the area and on the

basis of this zone, and a sequence of volcanic ashes and brown laterally continuous sandstones, strata of the Fossil Forest can be correlated with those in Hunter Wash. The age of the strata exposed in the Fossil Forest is late Campanian or early Maastrichtian, when the area was subject to a humid, subtropical climate with some seasonality.

I. INTRODUCTION

Purpose of Study

The purpose of this study is to place the rocks and fossils of the study area in adequate lithostratigraphic, sedimentologic, taphonomic (taphonomy is the study of post mortem processes affecting organic materials), and magnetostratigraphic context. The study area is of palaeontologic and stratigraphic significance and may be subject to coal mining in the near future. It is important that the resources of this area be evaluated and recorded before they are destroyed. There is also a need to collect baseline geologic data to develop mitigation procedures in accordance with the Federal Land Policy Management Act.

Late in 1978, discussions were initiated between New Mexico Bureau of Mines and Mineral Resources (NMBM and MR) and the United States Bureau of Land Management (BLM) in order to develop a programme to evaluate the geology and palaeontology of the study area. A cooperative programme was developed between the two agencies. Research by NMBM and MR was under the direction of D.L. Wolberg and that of the BLM under J.K. Rigby, Jr. In general, responsibilities for the project were as follows:

Vertebrate Palaeontology: D.L. Wolberg, J.K. Rigby, Jr.
Invertebrate Palaeontology: J.H. Hartman
Palaeobotany: C. Robison
Stratigraphy, Sedimentology, Taphonomy: A. Hunt

Scope of Study

This study has involved detailed examination of the stratigraphy, sedimentology, taphonomy and magnetostratigraphy of the study area. During the course of this study it has become apparent that there are several major unsolved problems that impinge on the work in hand. The most basic questions that should be asked about a rock sequence could be answered for the study area, based on previous knowledge. What rock units are present? What is the sedimentological context of these units? Detailed consideration is given to these questions in the following pages. The answering of these questions involves detailed discussion of aspects of the San Juan Basin as a whole, but without this discussion the specific questions cannot be answered with respect to the study area.

The Study Area

The study area, popularly known as the Fossil Forest, is located in Sections 13, 14, 23, 24, T.23N., R.12W., in southeast central San Juan County, New Mexico (Figure 1) in the Navajo Section of the Colorado Plateau (Hawley and Love, 1981). The area is managed by the United States Department of the Interior, Bureau of Land Management. A Preference Right Lease Application (PRLA) is held by Arch Minerals for coal mining of lands including the study area. The PRLA lies within the Bisti Fruitland Field which contains about 1,870 million tons of subbituminous coal beneath less than 76 m of overburden (Shomaker, 1971).

A large portion of the study area is composed of badlands incised into and lying above the mean pediment level (Figure 2). The badland area is incised into a pediment capped with Quaternary deposits. Channels in the study area are tributaries of Coal Creek and subsequently De-Na-Zin Wash, which flows into the Chaco River. Badlands of the Chaco River drainage are predominantly developed on the Cretaceous Kirtland Shale and Fruitland Formation (Wells and Gutierrez, 1983) both of which are exposed in the study area. The most deeply incised subcircular area of badland development, here called the Fossil Forest Badlands, has been formed by headward erosion in a southeasterly direction.

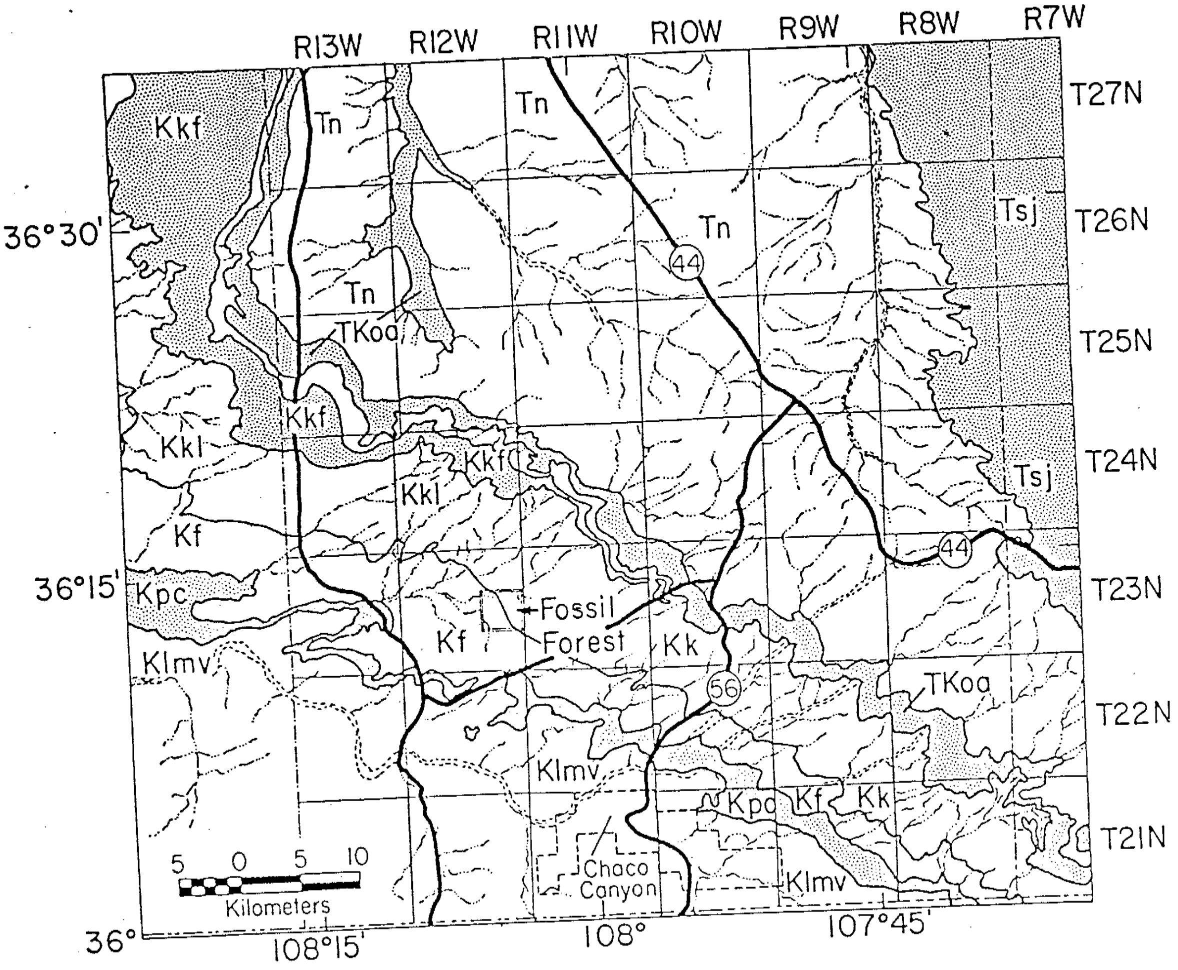


Figure 1. Geologic location map of study area. Klmv, Lewis Shale and Mesaverde Group, Kf, Fruitland Formation, Kkl, lower shale member of Kirtland Shale, Kkf, Farmington Sandstone Member of Kirtland Shale, Kk, Kirtland Shale, Tkoa, Ojo Alamo Sandstone, Tn, Naciemento Formation, San Jose Formation. Boundary between Fruitland and Kirtland follows Reeside (1924).

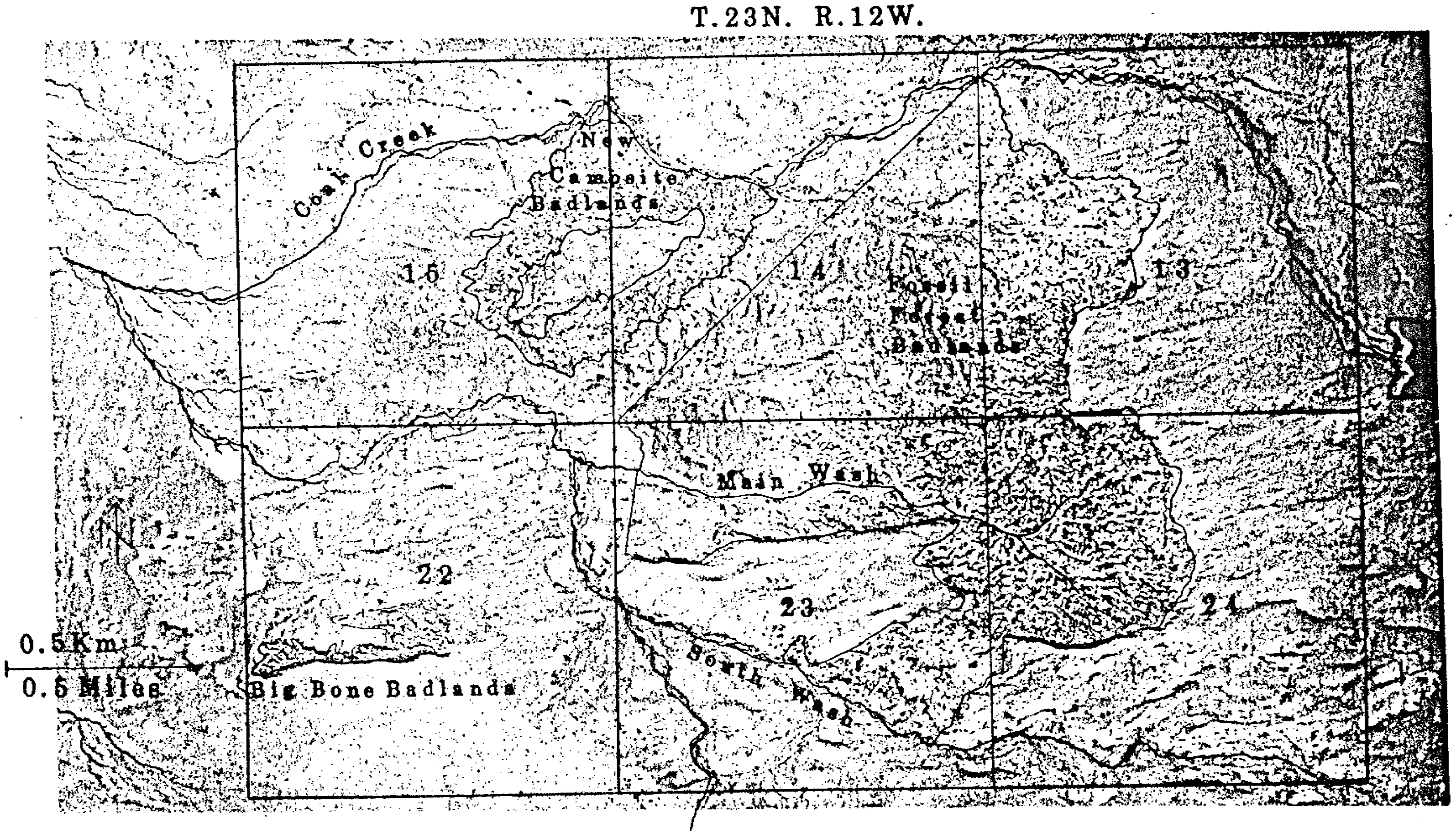


Figure 2. Portion of an aerial photograph of the study area (10-25-73/BLM-ARS/11-18-26) with superimposed section lines and topographic features. Stippled areas represent principal areas of badlands. Photograph courtesy of the United States Bureau of Land Management.

Longitudinal dunes are actively encroaching the area from the westsouthwest. Aerial photographs indicate that the dominant orientation of dunes in this area is WSW-WNW. This appears to be the dominant wind direction in this region of the San Juan Basin, based on alignment of dunes (O'Sullivan et al., 1971; Scott et al., 1979).

Badland geomorphic features, as encountered in the study area, are very similar to those found in other major areas of badland development, for example Badlands National Monument (Figure 3). Vegetation is sparce in badlands, whereas pediment surfaces are grass covered with some tamarisk trees occurring in major channels.

Within badland areas slope angle is controlled by lithology. Well indurated channelform sandstone bodies form slopes greater than 50 degrees with other rock types generally forming gentler slopes. Nonchannelform sandstone lithotypes show much better development of rills and desiccation cracks and exhibit "popcorn" weathering. There is some gradation of weathering characteristics with moderately indurated, organic-rich sandstone bodies showing "sub-popcorn" weathering. Some piping occurs. Well indurated sandstones are most rapidly eroded by undercutting and resulting overhangs may be undercut up to one and a half metres.

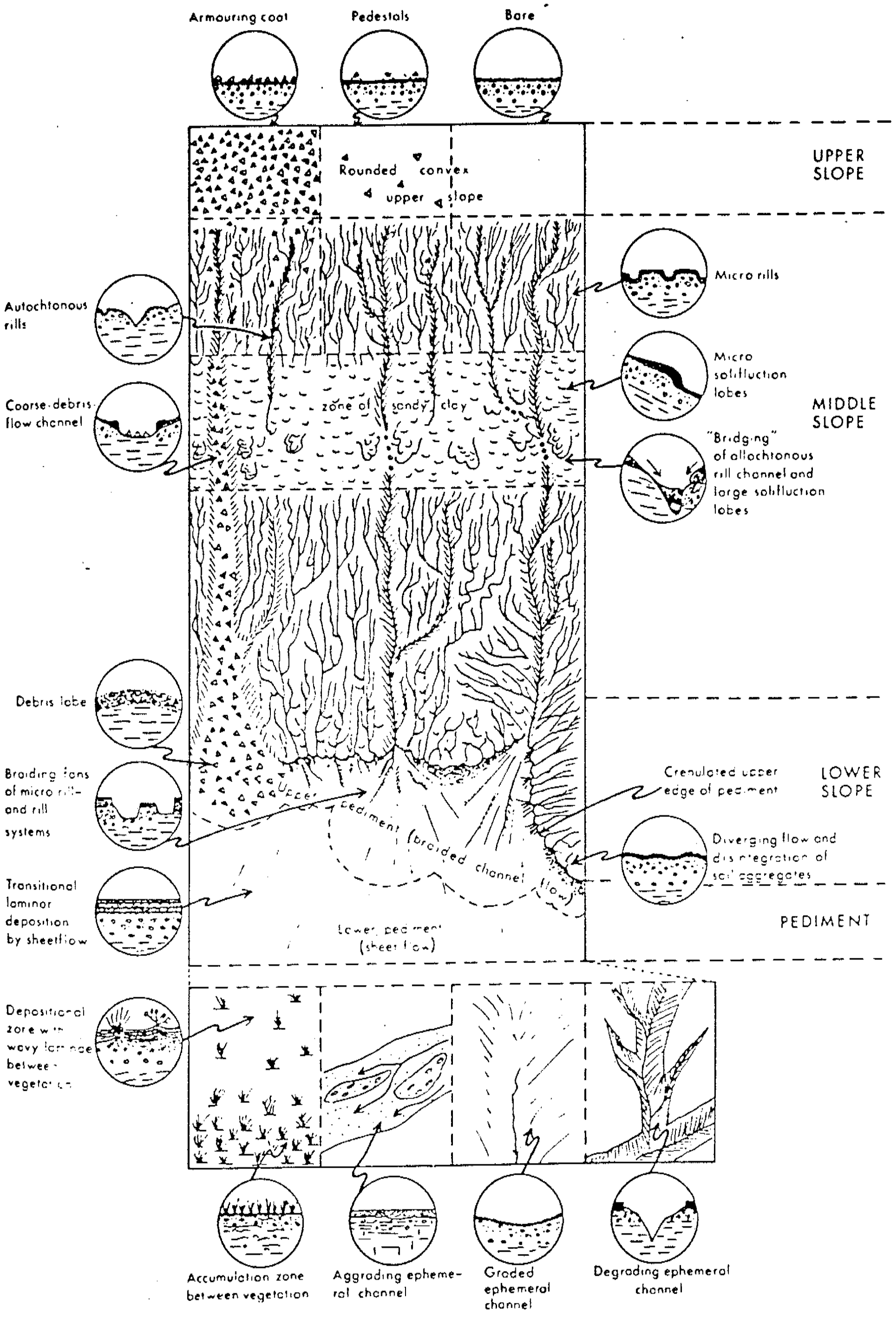


Figure 3. Schematic map and cross sections of surface processes on badland slopes (from Engelen, 1973).

The dip of beds in the study area is 2 to 4 degrees to the northeast. There is very little structural disturbance of strata although uncommon small growth faults have been observed.

Previous Work in Fossil Forest Area

Stratigraphy

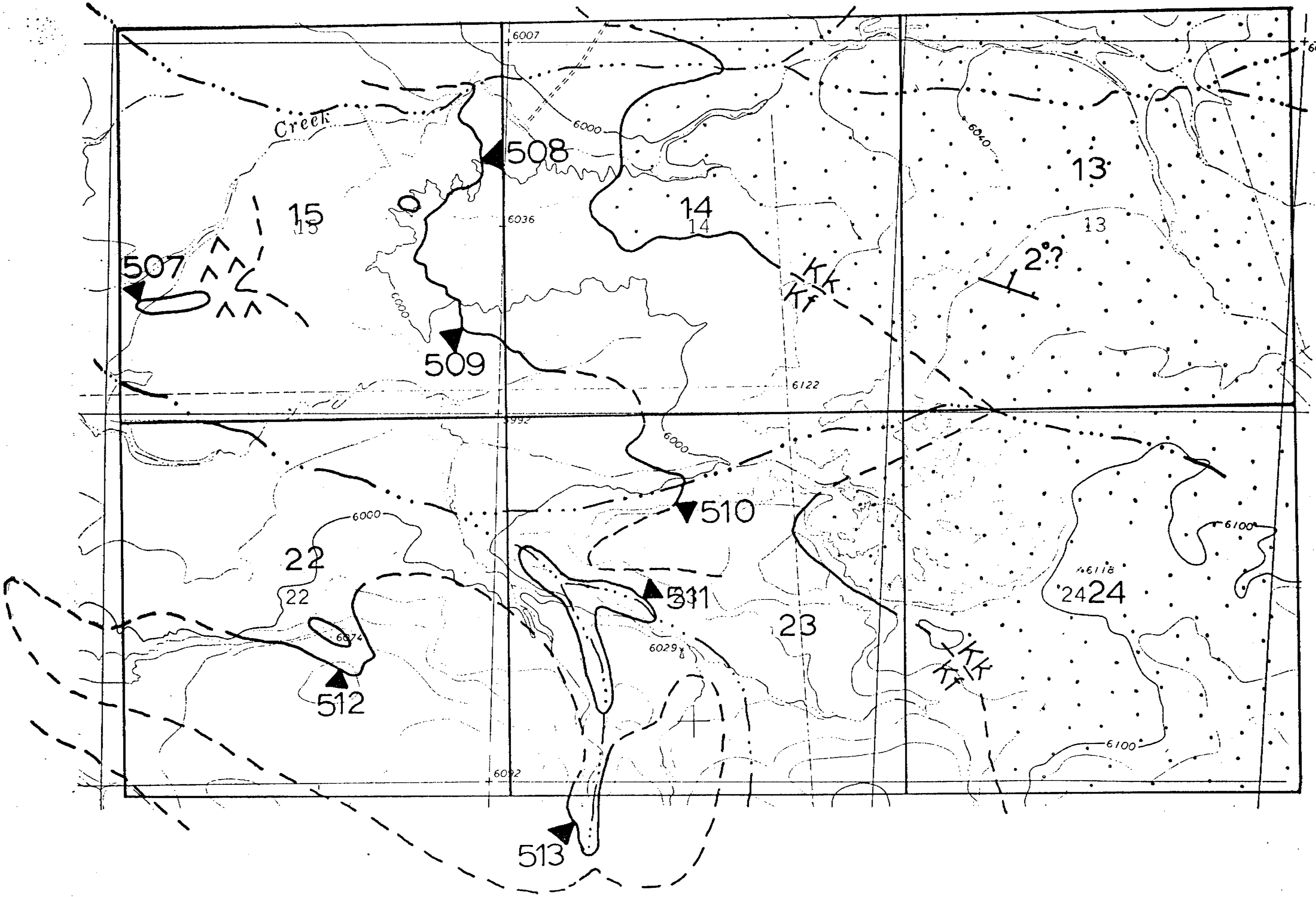
Pre-1917 stratigraphic nomenclature would place the Fossil Forest area in the Laramie Formation (King, 1876). Shaler (1907, plate XXII) shows the study area as being in the basal "Tertiary undifferentiated", his boundary being undefined, but presumed by Reeside (1924) to be within the Kirtland Shale.

The only detailed mapping done of the study area was by Bauer and Reeside (1921, plate XXXIII). Data collected by Bauer and Reeside, and later Reeside alone, was synthesized as plate I of Reeside (1924), which formed the basis for all later maps of the area. More recent USGS mapping has used different criteria for the boundary between the Fruitland Formation and Kirtland Shale which will result in an alteration of Reeside's map.

Bauer and Reeside's map (Figure 4) shows two coals in the study area, one measured at stratigraphic sections (of Bauer and Reeside, 1921) 508, 509, 510, and 512 and one mapped at 507 and 511 and considered to be 25 feet lower. The exposure in the vicinity of 511 and 507 is now covered by aeolian sand leaving only one coal exposed in the study area which is here correlated on the presence of a shared tonstein. Coal outcrop at section 512 in Section 22 also appears to have been affected by an influx of recent sand, being reduced in areal extent.

Although modern section lines are slightly changed, it is obvious that Bauer and Reeside (1921) considered the Fruitland-Kirtland formational boundary to pass through the Fossil Forest area (Figure 4). It is remarkable how accurate their map is, but equally apparent that they did not enter the main badlands in the study area. This is apparent as: (a) it would be hard for even a brief reconnaissance not to encounter abundant fossils and they report none from the study area, and (b) the formational contact is dotted through an area where there is continuous outcrop.

Though Bauer (1917) described the boundary between the two formations as a, "gradational zone containing in many places sandstone of fluviatile origin," it is obvious from unpublished field notes (courtesy of J. Hartman) and descriptions of stratigraphic sections in Bauer and Reeside



e 4. Geologic m f study area en ed from Bauer a side (1921) superimposed on a modern USGS topographic m Triangles are measured sections of coal; solid and dashed lines are exposed and inferred coal seams; dotted and dashed lines are streams; "v"s represent clinker outcrop.

(1921) that the boundary was often drawn at a sandstone, and more particularly a brown sandstone. Given the presence of a brown sandstone in the area of the boundary mapped in Section 14, it is considered that such a boundary was used in this area. It is obvious that the formational boundary was not mapped as carefully as the coal outcrops, whose mapped extents are extremely accurate when transferred to modern topographic maps. This is not surprising since the main object of Bauer and Reeside's party was to assess the coal resources of the region. The only other solid formational boundary line is drawn in Section 23 (Figure 4), where a boundary terminates at the edge of the badlands. A brown sandstone is present in the immediate vicinity of where this boundary is plotted, but it enters the badlands slightly to the east of the mapped boundary. Because this side of the badlands is being actively invaded by aeolian sand, the exact extent of the badlands, as of 1915-17, is not known with certainty, but it appears that the outcrop of the brown sandstone was approximated rather than accurately mapped by Bauer and Reeside (1921).

Of note is the fact that Bauer and Reeside (1921) rightly ignored a brown sandstone, very similar to that used as the boundary, which outcrops stratigraphically higher in Section 13. They also ignored a brown sandstone in Section 22 at their stratigraphic section 512, which does in fact correspond to, if it is not a continuation of, that used by them in Section 23 as the formational boundary.

In this report the boundary between the Fruitland Formation and Kirtland Shale is drawn at the top of the highest subbituminous coal with a thickness of one metre or greater and a lateral extent of greater than one hundred metres. This boundary excludes thin and/or discontinuous coals which occur higher in the stratigraphic section.

Very recently the USGS has compiled geological data on the Pretty Rock Quadrangle. Only a portion of the geologic map of this quadrangle, including the study area, has been published, as part of a larger scale map (Brown, 1983). The USGS now considers the formational boundary in follow the main, tonstein bearing, coal in the study area.

Palaeontology

The earliest reference to the occurrence of fossils in the immediate vicinity of the study area was made by Foster (1913) who described: "A remarkable carbonaceous deposit near Putnam, New Mexico." This deposit was described as lying about 15 miles northwest of Pueblo Bonito (Putnam). Pueblo Bonito is located 14 miles southeast of the study area. Foster indicated that, "there are many petrified trunks of trees lying on the surface, an indication possibly of hot alkaline water action ... . The rocks are principally sandstone, shales and some thin strata of limestone. Fossil remains (heavy bones, etc.) are abundant in the near neighborhood in the shales."

Foster (1913) also noted that: "Eight or ten miles north of the deposit are what are known as the Bad Land shale beds in which are vast numbers of fossils, including the prehistoric horse and large mammals." Holsinger noted several very large tusks (ceratopsian horn cones?) and two very large skulls in this area (Foster, 1913). Eight or ten miles north of the study area are the headwaters of Alamo, Willow, and Hunter Washes, where vertebrate remains are relatively common in the Naashoibito Member including at least partial ceratopsian skulls and isolated horn cores.

Then follows an enigmatic period in the investigation of the study area. In one of the large, lenticular sandstone bodies are five old quarries (Chapter II, III). The particular sandstone body in question contains several dinosaur bones, and it is evident from burlap, plaster, and bone scrap in the vicinity of the excavations that vertebrate fossils were being quarried; almost eleven cubic metres of rock has been displaced. Considering that even excavation with power tools is slow in this sandstone body, due to its induration and the angle of slope face of the outcrop, it is evident that considerable energy was expended here. Obviously, the older the quarries the more labour was expended in their excavation and hence the more important the specimens recovered. The only quarries known to the author of documented age, in a similar rocktype, are two excavated during the early 1960's by the University of Kansas in Section 34, T24N, R13W, at Hunter Wash. A comparison merely suggests that the Fossil Forest quarries are probably tens of years old. The most obvious quarrier is C.H. Sternberg, who collected and prospected north and south of the study area (Sternberg, 1932; specimen locality data in Lull, 1933 and Lull and Wright, 1942) and collected more dinosaurian material from the Fruitland-Ojo Alamo formational sequence than anyone else.

Indeed, two collections made by Sternberg are reported as coming from 9 miles northeast of Tsaya. The quarries in question lie at a distance of 7.65 miles at a bearing of 46.5 degrees from the site of the old, now abandoned, Tsaya Trading Post. Considering the vagueness of most of Sternberg's locality data, this close correlation in location information suggests that the sites of the collections and of the Fossil Forest may coincide. Travelling a distance of 9 miles at a bearing of 45 degrees from Tsaya would place one on the grassy plain of Split Lip Flats where no bedrock is exposed. Even given that his locality data is correct, it would place Sternberg about 1 1/4 miles from the Fossil Forest and given his careful and thorough prospecting technique (Sternberg, 1932), which is to be believed judging from his success in discovering specimens, he must have discovered the Fossil Forest area and its eminently collectable fossils. The specimens in question are:

"Pentaceratops sternbergii, type, No. 6325 AMNH, skull and skeleton (skeleton discarded), collected by C.H. Sternberg in 1922, 9 miles northeast of Tsaya, from the Fruitland Formation (Lull, 1933)."

"Kritosaurus?, No. 4982 AMNH, ischium; No. 4983 AMNH, metapodial, purchased from Sternberg in 1933, from the Fruitland Formation, 9 miles northeast of Tsaya (Lull and Wright, 1942)."

The only complication to the story is that Rowe et al. (1981) state that the type Pentaceratops skull was collected "from a locality 14.4 km east of Tsaya, probably from the NW1/4 T22N R11W." The nine miles of the published locality description is equivalent to 14.48 km (cf. 14.4 km of Rowe et al.) and so it is presumed that the direction was misread by Rowe et al. (1981) and thence extrapolated.

This discovery is of great significance in that skeletal material assignable to the type skull may still be in situ. Although Lull (1933) writes that the skeleton was discarded, Osborn (1923) wrote of the collection of "a fine skull and parts (sic) of a skeleton." Despite Wiman's (1930) referral of a sub-complete skeleton to Pentaceratops, no skeletal material was found associated with any of the described skulls of the genus. Langston (1977) mentions an undescribed skull and partial skeleton collected by J.W.

Stovall now housed in the Museum of Science and History at the University of Oklahoma.

Kues et al. (1977) covered the study area in a contract report on the palaeontological resources of the Bisti-Star Lake area. In the study area they have localities UNM 77-795 to 815.

The study area is referred to three times in detail by Kues et al. (1977, p. 139, 189, 207-208). "This large area contains a unique association of Late Cretaceous fossils ... , an expanse of in situ petrified log and stumps ... unique for the Late Cretaceous of the United States ... . The scientific importance of this area cannot be overestimated, and it should be preserved indefinately from significant land use, as such would destroy or disturb many of the in situ relationships between elements of the biota (p. 207-8)." " ... this area contains a unique association of Late Cretaceous vertebrate, invertebrate and plant fossils ... . This forms one of few places in the world where the interrelationships and ecology of most components of Late Cretaceous biological communities may be studied in a restricted area (p. 189)."

It is considered that the above statements exaggerate the significance of the study area. Unique is an inappropriate term to use for a fossil accumulation. In terms of its palaeontologic, stratigraphic, sedimentologic, and taphonomic features, every accumulation is unique.

Objective criteria must be applied to judge the relative importance of "unique" localities (Wolberg, 1982). Stump fields are relatively common in the Late Cretaceous of North America and several, of varying sizes, occur within the Fruitland-Kirtland formational sequence. The stumps in the study area are smaller and less well preserved than many others. What makes this occurrence interesting is the exumation of a portion of the stump field to about the level of the "forest floor".

In terms of interrelationships of organisms, close geographic proximity of collected specimens is not of prime importance. Two fossils in the same bed are unlikely to have occupied the same ecological niche due to operating taphonomic processes and may not even be exactly the same age (e.g. Shipman, 1981, figure 6.1). Because of the complexity of taphonomic processes, palaeoecology is best conducted on the largest possible sample with due consideration to stratigraphic and facies relationships. Such a sample can only be obtained from a geographic area appreciably larger than the study area. The most important Late Cretaceous palaeoecological studies have been on the Hell Creek and Oldman Formations in areas several orders of magnitude larger than the study area (Sloan, 1970; Sloan, 1976; Van Valen and Sloan, 1977; Beland and Russell, 1978).

In terms of the Fruitland-Kirtland formational sequence, the study area represents an unusual concentration of diverse fossil remains within a small geographic area and therein lies its interest. It does not represent, "one of the few places in the world," where Late Cretaceous palaeoecology can be studied. This statement is taphonomically and palaeoecologically incorrect.

Preliminary work in the study area has been published (Hunt, 1981; Rigby and Wolberg, 1980; Wolberg et al., 1981a; Wolberg et al., 1981b) as has data on the geology and palaeobotany of Hunter Wash where comparative studies were conducted (Hunt et al., 1981; Robison et al., 1981a; Robison et al., 1981b; Robison et al., 1982). The complete results of work of the NMBM and MR and BLM joint study of the Fossil Forest area will be published as a monograph to be edited by Wolberg and Rigby.

Geological Setting

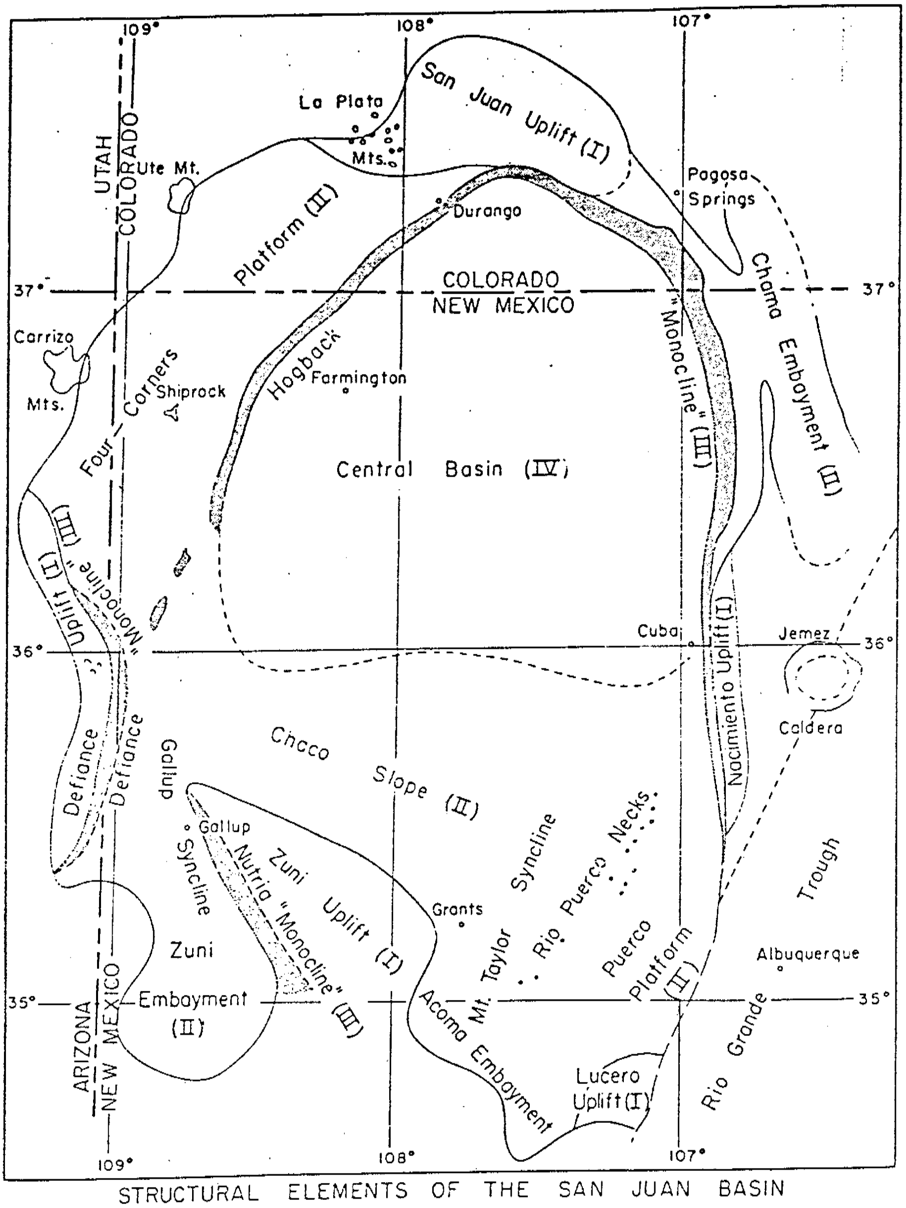
The San Juan Basin

The Late Cretaceous rocks of the study area lie within the San Juan Basin which is an oval shaped structural downwarp of about 50,000 sq. km. The majority of the basin

(Figure 5) is in northwest New Mexico, but it extends northward into Colorado and westward into Arizona (Kelley, 1950). It lies in the southeastern area of the Colorado Plateau (Kelley, 1955). The structural axis of the basin trends southeast-northwest with dips being less than 5 degrees. The basin is not symmetrical as the axis runs northeast of the geographic centre (Baltz, 1967). Although the present basin is of Laramide (Late Cretaceous to Early Tertiary) age the structural evolution of the region dates back at least to the late Palaeozoic when the area was an arm of the larger Paradox Basin (Tweto, 1975).

The San Juan Basin contains Cambrian, Devonian, Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Upper Cretaceous, Tertiary and Quaternary rocks to a maximum thickness of 4276 m on the Precambrian basement. The Upper Cretaceous rocks are about 1800 m thick (Fassett and Hinds, 1971).

All outcrops of the Upper Cretaceous-Palaeocene, Fruitland-Ojo Alamo sequence lie within the Central Basin (Kelley, 1950, San Juan Basin proper of Kelley, 1955) which is bounded on all sides, except the south, by the spectacular Hogback monocline. The study area lies within the western Central Basin.



STRUCTURAL ELEMENTS OF THE SAN JUAN BASIN

Figure 5. Structural elements of the San Juan Basin (from Kelley, 1950).

Upper Cretaceous of the Western Interior

The Upper Cretaceous rocks of the Western Interior were deposited in part of a single sedimentary basin (Figure 6) which extended from the Gulf of Mexico to the Arctic Ocean (Weimer, 1960). These rocks are now found in a series of isolated intermontane synclinal basins formed during the Laramide Orogeny.

The Western Interior Basin in the Late Cretaceous was an elongate, asymmetrical, structurally simple trough approximately 4,800 km long and 1,600 km wide. To the west lay the Cordilleran geanticline which was an area of active tectonism throughout the Cretaceous. Several major periods of uplift produced eastward incursions of coarser clastics into fluvial and shallow marine environments (for a history of the unravelling of this stratigraphic sequence see Waage, 1975). During intervening periods, erosional lowering and/or eustatic rise in Cretaceous sea-levels produced finer grained clastics (Kauffman, 1977). Morner (1981) has persuasively argued that global eustatic sea-level changes in the Cretaceous are an illusion.

The major uplifts and basins appear to be temporally related to drift of the North American plate westward over an eastward dipping subduction zone. Probable mechanisms for the vertical movements are, phase changes with resultant

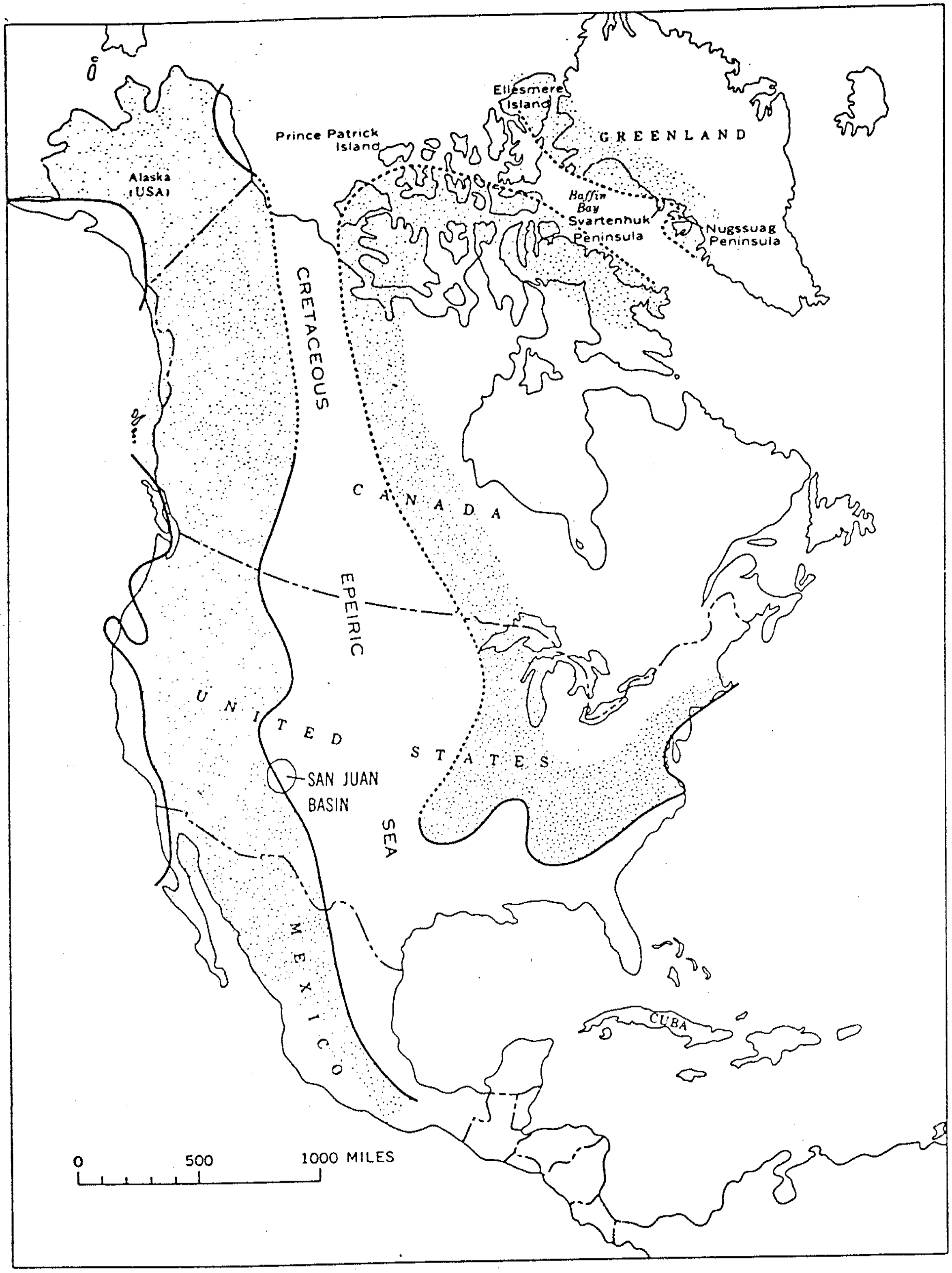


Figure 6. Palaeogeography of the late Campanian with position of San Juan Basin indicated (from Fassett and Hinds, 1971, after Gill and Cobban, 1966).

volume changes in the upper mantle or lower crust (Woodward, 1976), isostatic flexure in front of the rising orogenic belt or subcrustal loading induced by a shallowly subducted plate (Cross and Pilger, 1978).

To the east of the tectonically active margin of the basin, structure is fairly simple, and four major transgressions and regressions of the shoreline may be determined (Weimer, 1960). In the San Juan Basin, only three regressions and transgressions can be recognized, the latest being absent. Important early work on the nature of the intertonguing in this region was done by Sears, Hunt and Hendricks (1941) and Pike (1947). Cycles in the San Juan Basin begin with the Dakota Sandstone (Cenomanian) and end with the last marine unit, the Pictured Cliffs Sandstone (Upper Campanian). This last regression, (regression 8 of Kauffman's worldwide scheme, Kauffman, 1977), produced a series of nonmarine units behind the regressing Pictured Cliffs shoreline which included the Fruitland Formation, and the Kirtland Shale (Figure 7). The Kirtland Shale is divided, in ascending order, into the lower shale member, Farmington Sandstone Member, upper shale member and Naashoibito Member (Bauer, 1917; Reeside, 1924; Baltz et al., 1966).

Before a more detailed consideration of the stratigraphy of the area is given, a few more general observations about the Late Cretaceous seaway which are

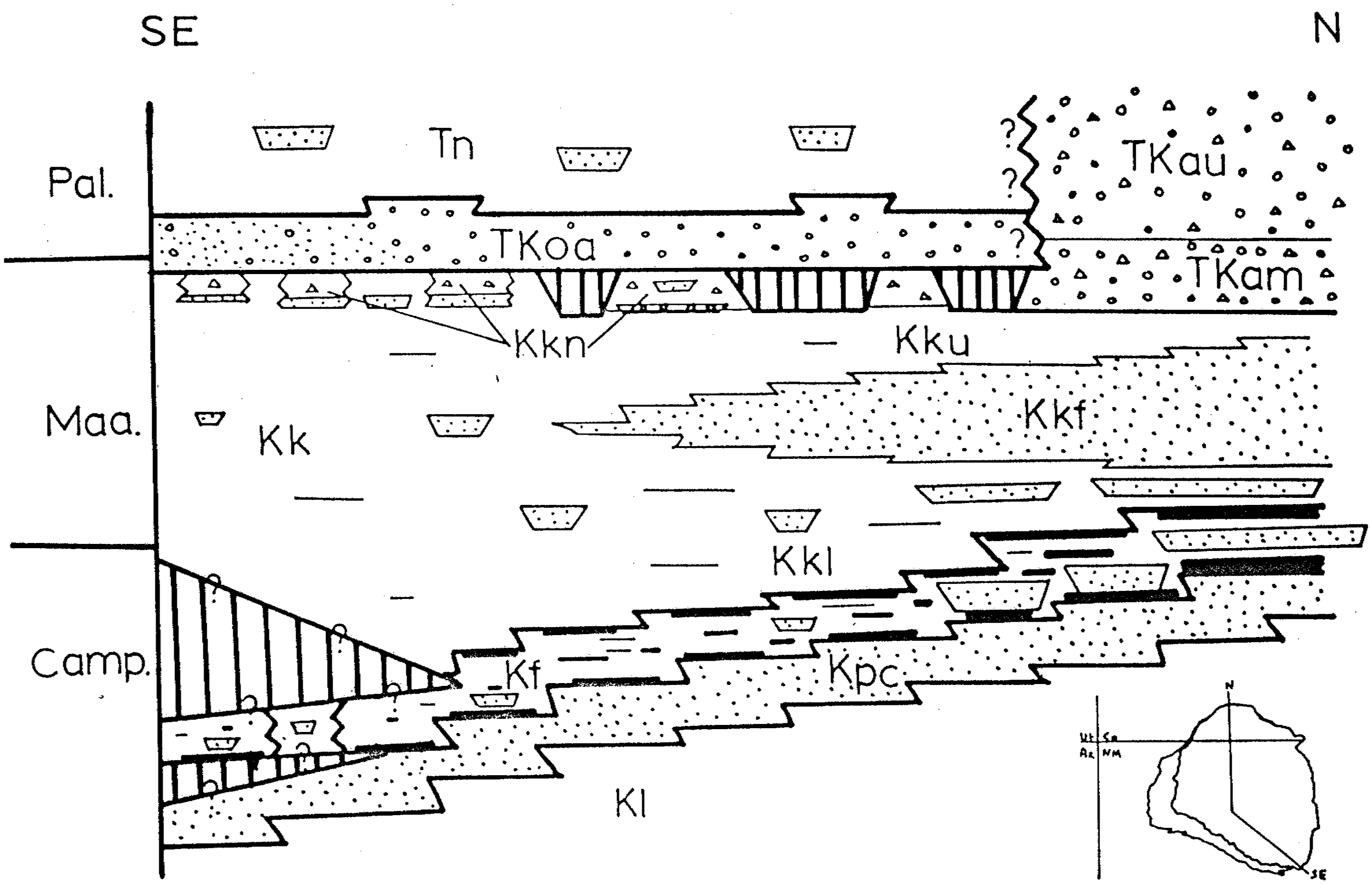


Figure 7. Schematic chronostratigraphic cross section of San Juan Basin. Kl--Lewis Shale, Kpc--Pictured Cliffs Sandstone, Kf--Fruitland Formation, Kkl--lower shale member of Kirtland Shale, Kkf--Farmington Sandstone Member of Kirtland Shale, Kku--upper shale member of Kirtland Shale, Kkn--Naashoibito Member of Kirtland Shale, Kk--undivided Kirtland Shale, TKoa--Ojo Alamo Sandstone, TKau--upper member of Animas Formation, TKam--McDermott Member of Animas Formation, Tn--Nacimiento Formation. Stippled pattern represents sandstone; circles, conglomerate; triangles, volcanic debris; black lines, coal and carbonaceous shale; blank areas dominantly shale; vertical hatching, intervals missing due to erosion. After Reeside (1924), Barnes et al. (1954), Baltz et al. (1966), Baltz (1967), Cobban et al. (1974), and this report.

relevant to the palaeobiology and sedimentology of the area will be noted.

Kauffman (1977) suggests that water temperatures of the seaway in New Mexico were probably subtropical, as measured by fossil biotas related to those characterizing modern marine climatic zones, but in the Campanian and Maastrichtian, a lowering of diversity in marine invertebrates seems to reflect a major global cooling trend (Kauffman, 1977). An alternative explanation for this decrease in diversity, and hence for the apparent cooling trend, is suggested by the shape of the seaway. Within the Western Interior seaway, with its northern and southern constricted apertures, and the influx of freshwater from numerous deltas to the west, low salinities might be expected. Invertebrate faunas support this hypothesis as many normal marine forms are missing or poorly represented within the seaway and diversity is lower than would be expected in a normal marine system (Kauffman, 1977). Actual salinities in the seaway showed a complex pattern of changes related to eustatic sealevel fluctuations (Kauffman and Fursich, 1982). However, only, "at peak eustatic rise (Kauffman and Fursich, 1982)," did normal marine biotas exist in the seaway, at other times brackish surface waters were in existence (Kauffman and Fursich, 1982). Cumella (1981) has also suggested that the presence of siderite concretions in marine shales, such as the Pierre Shale and Lewis Shale, may indicate low salinities, as precipitation of siderite requires water with a low sulphate content. In the latest Cretaceous, the seaway was retreating to the north and, as a result, had a much smaller volume than earlier. In addition the Laramide Orogeny was increasing in intensity, probably resulting in increased rainfall and runoff into the seaway. These two factors together would tend to decrease salinity and cause a resulting decrease in marine diversity in the latest Cretaceous. Thus it is not clear that a decrease in marine invertebrate diversity in the Western Interior seaway can be used as evidence of a major climatic cooling trend. This decrease could result from a decrease in salinity. Even if the diversity decrease is related to a cooling trend, it may be of regional rather than global origin. Withdrawal of the seaway and Laramide uplift undoubtedly resulted in an increasingly variable continental climate for the Western Interior which would tend to decrease diversity in the seaway.

Humid southeasterly winds probably blew against the Cordilleran front and the subsequent orographic uplift and adiabatic cooling of these winds produced abundant rainfall probably giving a humid climate to New Mexico (Cumella, 1981).

Sedimentological Context of Study Area

The sedimentological context of the Pictured Cliff-Ojo Alamo sequence, as here construed, is summarised in Figure 8 and Plate 1. The data employed in the construction of these figures was compiled from many sources, but particularly important were Reeside (1924), Baltz (1967), Fassett and Hinds (1971), and Erpenbeck (1979). Various parts of this sequence of rocks have been observed in the field on the La Plata River, San Juan River, and in Chinde Wash, Cottonwood Arroyo, Brimhall Wash, upper and lower Hunter Wash (sensu Bauer and Reeside, 1921), Alamo Wash, Barrel Springs Arroyo, Willow Wash, Ash-shi-sle-pah Wash, Kimbetoh Wash, Betonnie Tsosie Arroyo, Eagle Mesa, Mesa Portales, and, various parts of the Bisti Trading Post, Alamo Mesa West, Alamo Mesa East and Star Lake quadrangles, and north east of Cuba. The deltaic facies have been extended further northwestward than figured by Flores and Erpenbeck (1982) based on field observations.

(a) Shoreline trend

The trend of the Pictured Cliffs shoreline is important in determining the age of the Fruitland Formation. Only with knowledge of this trend can ammonite data from the east

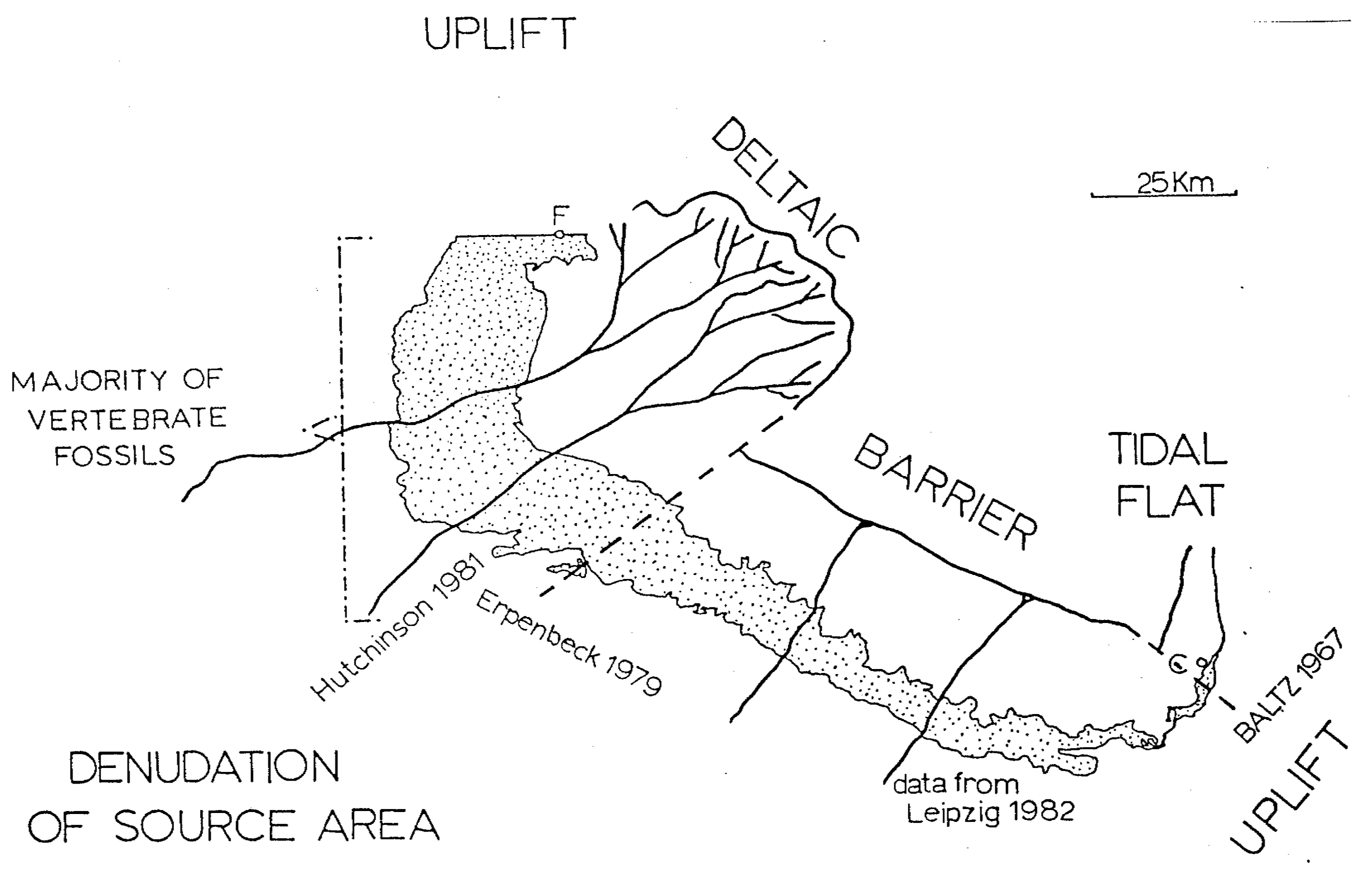


Figure 8. Coastal environments of the Pictured Cliffs sea as determined from outcropping strata of the Pictured Cliffs Sandstone and Fruitland Formation, superimposed on the present outcrop pattern of the Fruitland and Kirtland Formations (stippled), F, Farmington, C, Cuba. References to important works are superimposed.

side of the basin be extrapolated to the west.

Two methods have been used to estimate the shoreline trend of the Pictured Cliffs Sanstone. Berry (1957), Scruton (1961), and Cumella (1981) attribute the pronounced northwest-southeast linearity of the contours of gas production from the Pictured Cliffs, to the shoreline trend at the time of deposition. Fassett and Hinds (1971) argued that the contour intervals between the Huerfanito Bentonite Bed, in the Lewis Shale, and the top of the Pictured Cliffs reflect successive positions of the shoreline.

Cumella (1981) argued convincingly that Fassett and Hinds (1971) were incorrect in their method of estimation of the shoreline trend of the Pictured Cliffs Sandstone. The assumption that the isopach in question reflects the shoreline trend, requires the assumptions of a smooth flat seafloor, no basin uplift during the period between the deposition of the Huerfanito Bentonite Bed and the Pictured Cliffs, and uniform sedimentation and subsidence (Cumella, 1981). It appears that basin uplift occurred in the southeast of the basin, during this time, and that depositional thinning occurred in the southeast, producing an unconformity within the undivided Fruitland and Kirtland Formations and channelling of them down into the Pictured Cliffs (Baltz, 1967). Cumella (1981) also argues, after Devine (1980), that the contours actually reflect the advance of the coastal plain facies not the shoreline. "The assumption that coastal plain advances are parallel with (and by inference, coincident with) shoreline progradation is not accurate for formations undergoing step like stratigraphic rises unless there is uniform, simultaneous progradation and aggradation of the shoreline, a condition that is unlikely (Cumella, 1981)," and is not considered to have occurred.

A plotting of the highest ammonite zones at various localities in the Lewis/Mancos Shale (different names for the same unit in New Mexico and Colorado) is shown in Figure 9 and must reflect the shoreline trend. It agrees with the northwest-southeast trend of the shoreline as suggested by the trend of gas production, at least prior to Didymoceras cheyennense time.

(b) Southwest Source Area

The source for the Pictured Cliffs Sandstone and the majority of the Fruitland Formation, in the portion of the San Juan Basin illustrated in Figure 8 and Plate 1 (except perhaps the higher Fruitland in the northwest and southeast), was to the southwest, in Arizona.

Hayes (1970) has reviewed the Cretaceous palaeogeography of southeastern Arizona and adjacent areas, and considers that the first Cretaceous orogenic event

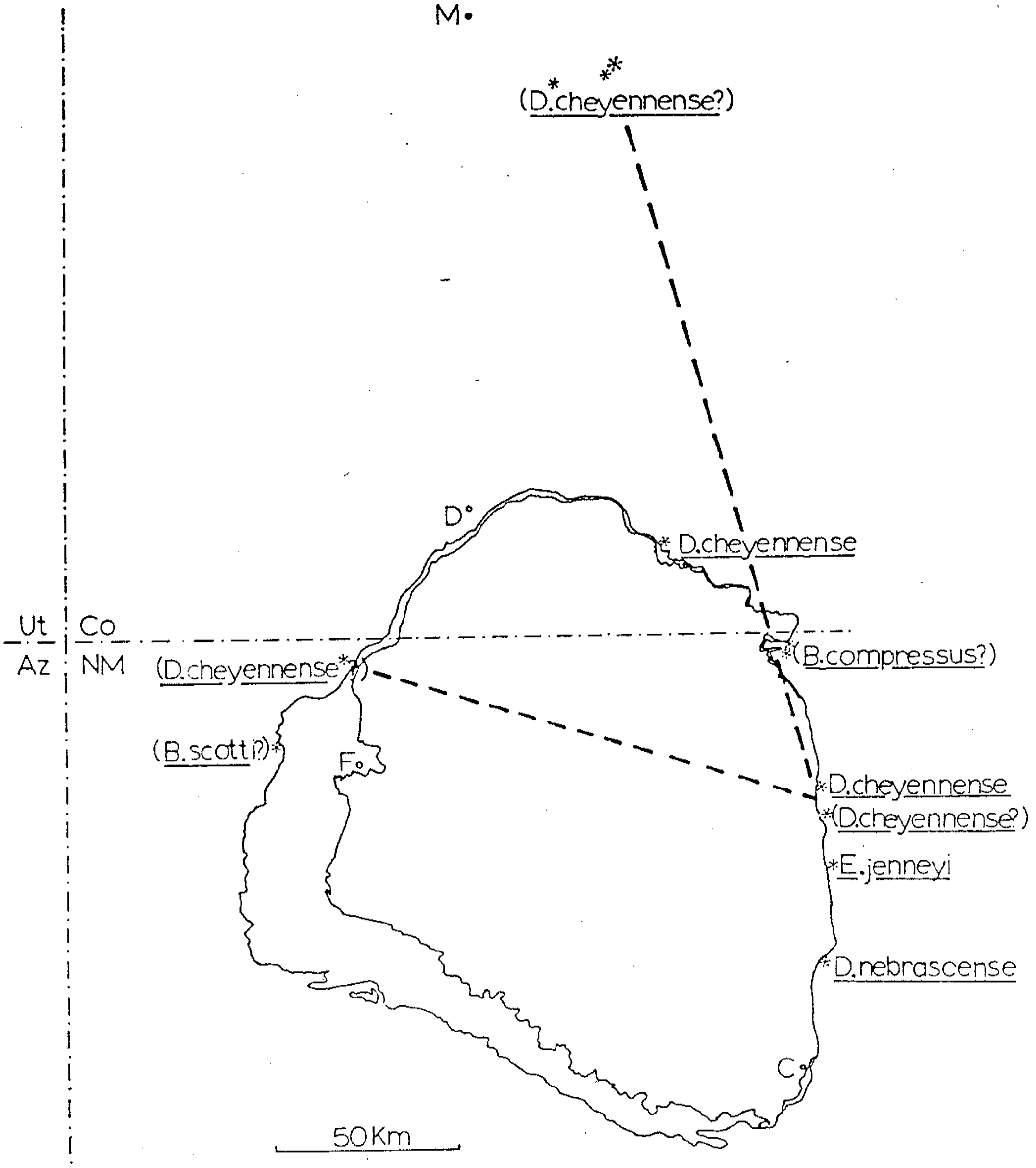


Figure 9. Plot of highest ammonite zone in Pictured Cliffs Sandstone and Lewis Shale with inferred shoreline orientations (from Cobban, 1973; Cobban et al., 1974; Cobban personal communication to Wolberg, 1981). Circles indicate towns, C, Cuba, D, Durango, F, Farmington, M, Montrose. Stars indicate localities of samples of each ammonite zone, B, Baculites, D, Didymoceras. At localities where zone fossil itself is unreported, its name is in parentheses.

occurred during the Late Turonian. After this, southeastern Arizona supplied sediment to the San Juan Basin until the Late Campanian, when there was a period of extensive volcanism representing the initial stages of the Laramide orogeny (Hayes, 1970). This event increased the sediment supply to the Four Corners area, producing bentonite beds in the Lewis Shale and an abundance of volcanic rock fragments in the Pictured Cliffs Sandstone (Cumella, 1981).

(c) North-Northwest Source Area

The majority of the Kirtland Shale has its source in a volcanic highlands in the area of the present San Juan Mountains. Uplift probably began at 73-74 m.y. and is reflected in the deflection of the shoreline between the ammonite zones of *Didymoceras cheyennense* and *Didymoceras nebrascense* (Figure 9), although this deflection was probably also influenced by delta progradation. Volcanic ash deposits are found at least as far south as the study area (and probably further) in the upper Fruitland Formation marking the beginning of the northwest area as a source of sediment. It is possible that even earlier eruptions were responsible for bentonite beds in the Lewis Shale (e.g. Huerfanito Bentonite Bed). Material came from this source during the deposition of the upper Fruitland and the lower shale member of the Kirtland, influencing the northwest of the basin first. This is evidenced petrographically by Burgener (1953) and Grinnell (1951). The braided streams of the Farmington Sandstone represent a clastic wedge produced by a period of active uplift (Reeside, 1924). This was followed by a brief period of quiescence during the deposition of the upper shale member. The petrology of the Upper Fruitland Formation and the Kirtland Shale shows increasing volcanic influence upward (Burgener, 1953; Grinnell, 1950; Dilworth, 1960). The Animas Formation (latest Cretaceous-Palaeocene) represents erosion of the volcanic terrain itself following a period of rapid uplift. The composition of this material is andesitic and rhyolitic (Larsen and Cross, 1956). Alluvial fans came off the highland with the distal facies represented by the Naashoibito Member (see below). The Ojo Alamo Sandstone represents a bed load system whose relation to the Animas is at present unclear (Reeside, 1924; Powell, 1972; Grinnell, 1951; Dilworth, 1960).

The cycle from upper Fruitland Formation to Ojo Alamo Sandstone, south of the San Juan River, represents a major coarsening up sequence from the suspended load streams of the upper Fruitland to the mixed load streams of the Farmington Sandstone to bed load streams of the Ojo Alamo (Plate 1). This is the opposite of the sequence illustrated by Schumm (1977) for the erosional evolution following a tectonic event and represents contemporaneous erosion and uplift of source area.

This volcanic province, which can now only be traced by a series of laccoliths (Burbank, 1936) and the very locally exposed extrusive Cimmaron Ridge Formation (Dickinson et al., 1968), in southwest Colorado, is a continuation into the Colorado Plateau of the Laramide Lineament (Armstrong, 1969). The vast majority of the extruded material was probably eroded by the end of Animas time (Larsen and Cross, 1956).

(d) Ojo Alamo Unconformity

The angularity and age extent of the unconformity at the base of the Ojo Alamo Sandstone is of great significance in determining the age of the Fruitland and Kirtland Formations. If the unconformity is angular and of major extent the Kirtland Shale does not extend into the late Maastrichtian and may be almost entirely Campanian (e.g. Baltz et al., 1966; Fassett, 1979). If the unconformity is not angular, then the Kirtland may extend to the latest Maastrichtian (Lindsay et al., 1981). As the study area lies at the base of the Kirtland, discussion of the extent of this unconformity is relevant to the present study as it has bearing on the age of the exposed strata.

Much evidence has been presented to support the idea of a regional angular unconformity at the base of the Ojo Alamo Sandstone, dipping to the southeast (Baltz, 1967; Fassett and Hinds, 1971). As much as 640 m is suggested to have been removed from the southeast of the San Juan Basin (Fassett, 1981). Undoubtedly there was deep scouring by the Ojo Alamo into the McDermott Member, Naashoibito Member, and Fruitland and Kirtland Formations undivided (Silver, 1950; Baltz, 1967), but it is believed that this unconformable surface is not angular (Hunt, 1983).

It is obvious from Figure 8 and Plate 1 that environments of coastal deposition, from northwest to southeast, would result in a depositional thinning in that direction. Deltas accumulate more sediment than barrier shorelines than tidal flats. Even a cursory examination of the rocks in question shows that rocks of the Fruitland and Kirtland Formations undivided, exposed near Cuba, do not represent an erosional remnant of a sedimentological equivalent of these occurring on the San Juan River. Dane (1936, 1946) noted the lateral variation of the Fruitland and Kirtland across the Basin, and so, implicitly, must have all workers who did not consider these unit names appropriate on the east side of the San Juan Basin (e.g. Baltz, 1967; Fassett and Hinds, 1971).

The purplish beds restricted to the top of the Kirtland Shale, which occur from the type McDermott Member in Colorado south to the area of the type Naashoibito Member (Reeside, 1924; Barnes et al., 1954; Grinnell, 1951; Dilworth, 1960; Baltz et al., 1966; Powell, 1972), are considered to represent a single period of vulcanism and erosion of the northwest source area, prior to the alluvial fan development of the Animas Formation and Ojo Alamo Sandstone. There is no evidence for more than one such episode of vulcanism. The persistence of this purple facies across the Central Basin, from northwest to southeast, argues against an angular unconformity at the base of the Ojo Alamo Sandstone.

Thinning of the Fruitland and Kirtland Formations undivided in the southeast of the San Juan Basin is not only the result of depositional thinning, but also of intraformational unconformities which exist within the sequence (Baltz, 1967). These unconformities are interpreted as being a result of slight uplift in the southeast of the basin. The presence of tidal flat deposits (Baltz, 1967) also argues for positive movement in this area, or at least reduced rates of subsidence.

In the southeast of the San Juan Basin, Krukowski (1982) noted a change of source area at the time of deposition of the undivided Fruitland and Kirtland Formations based on mineralogy and smectite-rich aspect of clays (see also Baltz, 1962, 1967). Krukowski also observed pure smectites in low areas of shales and channel sandstones, possibly representing altered volcanic ashes, which together with their mineralogy suggest a volcanic source rock. Baltz (1962, 1967) also noted volcanoclastic material in the upper undivided Fruitland and Kirtland Formations. The only Late Cretaceous volcanism within 200 miles that could have produced this sediment was that occurring in southwest Colorado. Current directions indicate a northwestern source area for the volcanoclastic facies (Powell, 1972). Therefore the volcanic-rich sediment of the southeast of the Basin must be a lateral equivalent of the Naashoibito Member casting considerable doubt on the existence of a markedly angular unconformity at the base of the Ojo Alamo Sandstone (Hunt, 1983). Baltz's (1967) argument that the above correlation is impossible because of the angularity of the unconformity at the base of the Ojo Alamo Sandstone is circular.

The rocks exposed on Mesa Portales, near Cuba, have caused some controversy as the Ojo Alamo Sandstone intertongues with the Fruitland and Kirtland Formations undivided (Dane, 1936). Proponents of an angular unconformity either consider the lower tongue as being part Fruitland and Kirtland (Baltz, 1967; Lucas, 1981) or propose an obscure unconformity lower in the section (Fassett and Hinds, 1971). Whatever names are applied to this sequence, it is evident that the upper bedload stream deposits interfinger with the lower units. The Ojo Alamo in the southeast and west of the basin consists more of an interbedded sequence of conglomeratic sandstones and shales (Powell, 1972; Fassett, 1968) than the massive conglomerate at the type locality. This is presumed to reflect a falloff of energy with distance from the major source area although pebbles "several inches in diameter" in the southeast of the Basin (Baltz, 1967) must have had a more local source, despite Powell's (1972) current direction data. Interfingering of the Ojo Alamo on Mesa Portales does not rule out an angular unconformity in the northwest of the basin, but does make it more unlikely.

As can be seen from Plate 1, removal of the Farmington Sandstone, obviously a clastic wedge, from consideration of the thinning from northwest to southeast, would remove much of the angularity of the unconformity at the base of the Ojo Alamo Sandstone.

An unconformity at the base of the Ojo Alamo Sandstone cannot be denied, but based on the above evidence it appears that the angularity of this surface, if any, has been greatly exaggerated.

(e) Occurrence of Vertebrate Fossils

Although occurrence of petrified wood appears to be relatively common throughout the Fruitland and Kirtland Formations in the area represented in Figure 8 and Plate 1, (perhaps becoming less common in the Fruitland and Kirtland Formations undivided) vertebrate fossils are not so ubiquitous. The majority of pre-Naashoibito Member vertebrate fossils, within this sequence, are restricted to the mid to upper Fruitland and lower half of the lower shale member of the Kirtland, behind the deltaic facies (Plate 1). The environments of deposition during this interval were upper delta plain-suspended load floodplain facies (this report; Erpenbeck, 1979; Hutchinson, 1981a).

II. STRATIGRAPHY AND SEDIMENTOLOGY

Stratigraphy of the Fossil Forest Area

On the basis of regional stratigraphic relationships (Reeside, 1924), on the basis of the Fruitland-Kirtland formational boundary discussed above, and for reasons previously discussed, the rocks exposed in the Fossil Forest area are considered to lie within the upper portion of the Fruitland Formation and the lower shale member of the Kirtland Shale. Bauer and Reeside (1921) show the formational boundary as going through the Fossil Forest area.

Bauer and Reeside (1921) were principally concerned with documenting the quantity and stratigrapic distribution of coal, and as a consequence, they found it necessary to map formational boundaries. Their coal mapping within the study area is slightly in error. They failed to map an erosional remnant of the main coal in the main wash in the Fossil Forest Badlands just to the east of the north south fence line (stratigraphic sections BAD, BAC), a temporal equivalent (based on a shared tonstein) of that outcropping elsewhere. The tonstein is recognized as such on the basis of characters displayed in hand specimen. These characters include near white colour, sharp contacts, non-fissile, structureless nature, waxy lustre, poorly developed conchoidal fracture and composition almost entirely of clay-sized material, which appears to be kaolinite (Spears, 1970; Williamson, 1970). Locally muscovite, feldspar, and possible zircon crystals can be discerned in the tonstein. The tonstein is considered to represent an altered airfall volcanic ash (Spears, 1970). Tonsteins have been reported from various Rocky Mountain coal fields (Bohor, et al., 1976) and from the Raton Basin (Bohor and Pillmore, 1976), but this is the first reported occurrence in the San Juan Basin. On the basis of criteria cited above, the top of the tonstein bearing coal is taken as the Fruitland-Kirtland formational boundary.

The tonstein present in the coal represents one of three airfall volcanic ashes occurring in the study area. The character of the other two ashes is identical to that of the tonstein discussed above, except in one instance where crystals are more common. The others occur immediately above two marker beds designated Marker Bed one (M1) and Marker Bed two (M2). The marker beds are brown to black, highly carbonaceous mudstones, locally becoming subbituminous coals, which can each be traced for at least 2 km. These marker beds and the coal represent the only beds laterally continuous, over hundreds of metres, in the study area.

The dominant lithologies present in the study area are mudstones, siltstones and fine to medium grained sandstones occurring in laterally discontinuous sheets. Mudstones and siltstones are generally grey or grey green whereas the fine grained sandstones are often khaki. Within this framework are found medium to coarse grained, lenticular crossbedded sandstone bodies with erosional bases.

Twenty five stratigraphic sections were measured in the study area (Appendix 1) and were correlated utilizing the two marker beds and the coal as data (Plate 2).

Gross lithologic trends may be discerned from Plate 2. Upwards through the sections carbonaceous material, within beds and as carbonaceous shales and coals, decreases in quality and quantity. The top of the exposed section is composed dominantly of fine sandstones and siltstones, whereas, lower in the sequence mudstones predominate. The colour of the rocks grades upward from mainly grey beds to dominantly grey green at the top of the exposed section. This colour change can be explained by a trend to increasingly good drainage upward through the section. Support for this interpretation comes also from the decrease in organic content.

Previous Sedimentological Work

Surprisingly, few sedimentological studies have been conducted on the Pictured Cliffs Sandstone to Kirtland Shale sequence, considering the economic importance of the gas in the Pictured Cliffs and the coal in the Fruitland Formation. Recently sedimentological work has begun on this sequence with reference to these energy resources (Erpenbeck, 1979; Erpenbeck and Flores, 1979; Cumella, 1981; Hutchinson, 1981a; Hutchinson, 1981b; Flores and Erpenbeck, 1981, 1982).

Some older sedimentological work exists. Grinnell (1951) and Burgener (1953), both talked vaguely of fluvial deposits in the Fruitland Formation and Kirtland Shale. Dilworth (1960) considered that some of the Farmington Sandstone may have been of shallow marine origin, based solely on the presence of some very poorly preserved marine microfossils, which were probably reworked. His thesis is not accepted as the predominance of sedimentological evidence suggests a fluvial origin for the Farmington Sandstone and the vast majority of the collected fossils from this unit are nonmarine vertebrates.

Erpenbeck (1979) made the very important discovery that the Pictured Cliffs shoreline had at least two major coastal forms. In the Hunter Wash to De-na-zin area was a prograding, fluvial-dominated delta was present in the Black Lake to Ah-Shi-Sle-Pah area, a beach-bar and back-barrier complex was in existence (Figure 8). The study area lies in the area between Erpenbeck's stratigraphic cross sections, a few miles north of his Black Lake study location (Flores and Erpenbeck, 1982). In Hunter Wash, Hutchinson (1981a, 1981b) considered the approximate stratigraphic equivalent of the Fossil Forest area (Chapter VI) as uppermost delta plain and lowermost floodplain.

Recent, more general sedimentological comments can be found, particularly related to coal formation, in Fassett and Hinds (1971), Fassett (1969, 1977) and for the Fruitland-Ojo Alamo formational sequence, as a whole, in Leipzig (1982).

Sedimentology of Fossil Forest

It is apparent that the Fruitland and Kirtland Formations, in the area of the Fossil Forest, represent nonmarine environments, on the basis of position within a nonmarine sequence (Bauer, 1917; Reeside, 1924), the presence of numerous nonmarine organisms including dinosaurs, mammals, crocodiles, and landplants, and the total absence of undoubtedly marine organisms.

All authors agree that the uppermost Fruitland Formation and lower shale member of the Kirtland Shale are fluvial in origin (Bauer, 1917; Reeside, 1924; Grinnell, 1951; Hutchinson, 1981a). This analysis is not contradicted by the gross geometry, internal organisation and relationship of lithologic units observed in the study area. Therefore, the following discussion of the sedimentology of the study area will make the assumption that rocks exposed in the area are of broadly fluvial origin.

Character of Rocks in Study Area

Clastic rocktypes are represented dominantly by lithologies ranging from claystone to medium grained sandstone with larger grain sizes restricted mainly to clay pebble conglomerates. Carbonaceous units range from carbonaceous mudstone to subbituminous coal. All rocktypes except coal show popcorn weathering. Shales are commonly weathered to a depth of 30-50 cm with sandstones weathered to a depth of 1-30 cm, depending on induration.

Sandstones are dominantly of two types. The first (Type 1) are fine to coarse grained and white in colour. They contain greater than 80% quartz, are well indurated and usually occur in lenticular, cross bedded bodies.

Carbonaceous plant remains are represented by clast sized fragments which are well rounded and usually represent less than 5% of the rock. These sandstone beds are moderately sorted with sub-angular to sub-rounded grains. These beds have erosional bases and invariably fine upward. Calcium carbonate is the most abundant cement. Two geometries of units occur: thin parallel sided units (tens of centimetres thick) which fine both laterally and vertically and contain small scale cross bedding and ripple marks, and thicker (metres thick) lenticular bodies which only fine upward, showing large and small scale cross bedding.

The second type of sandstone (Type 2) is grey-green to khaki in colour and medium grained or finer in grain size. They occur in tabular bodies and contained carbonaceous plant debris, which is poorly sorted, often constitutes greater than 10% of the rock. Quartz represents greater than 80% of detrital grains. In contrast to that occurring in the first type of sandstone, carbonaceous material is fragmented, not macerated (rounded), and usually comprises linear stem and root portions, millimetres in length. This type of sandstone often contains an appreciable quantity of clay matrix and tends to be less well indurated than the white Type 1 sandstones. Calcium carbonate is less important as a cement, and clay matrix is more abundant than in the other sandstones. Sand grains tend to be sub-angular to sub-rounded and poor to moderately sorted. Fining upward is common, but not ubiquitous, and the geometry of beds is generally tabular with bases of units being generally nonerosional. Small scale crossbedding occurs but is not ubiquitous. Beds of this type are generally interbedded with tabular shales.

The coarsest clastic material is represented by lenticular bodies of clay pebble conglomerate occurring at the bases of some sandstones of Type 1. Clay pebbles average 1-1.5 cm in diameter and show varying degrees of elongation parallel to bedding. Approximately 50% of this rocktype is composed of clay pebbles the other half being composed of clay-rich, medium to fine grained sandstone and 5-20% organic remains (plant, invertebrate, and vertebrate). Of the organic material, 80% is carbonaceous plant material, three quarters of which is macerated, and the remainder consists chiefly of subrounded vertebrate fragments from .5 to 3 cm in diameter and partial or complete invertebrates (gastropods and bivalves).

Petrologic studies on sandstones of the Fruitland Formation to Kirtland Shale sequence are woefully lacking despite the great economic importance of the Fruitland Formation. The main work on the Fruitland was done by Burgener in 1953. He studied 13 thin sections of siltstones to coarse sandstones from the San Juan River, north into Colorado. Sorting appeared to improve southward towards the San Juan River and all sandstones examined were subarkoses (all classification terms after Folk, 1980) approaching quartzarenites. Euhedral to subhedral biotite was reported as occurring in the upper Fruitland, as was uncommon perthite. Calcite was the most common cement examined, followed by clay and scarce silica and haematite. A gradation upward from non-calcareous to calcareous cement was noted. Recorded grain shapes were sub-angular to sub-rounded with high sphericity.

Grinnell in 1951 studied the petrology of rocks from the same areas as Burgener, but in the Kirtland Shale, and he did sieve analysis of 43 samples indicating that sandstones of the Kirtland are very well sorted and composed of sub-angular to sub-rounded grains. Mineralogically, all sandstones described are good arkoses, averaging about 70% feldspar. The majority of the "heavy minerals" noted were euhedral biotites. Dilworth (1961) found that sandstones of the Farmington Sandstone Member of the Kirtland were arkoses with up to 35% quartz and poor to fair sorting.

More recently Leipzig (1982) made some observations on the petrology of rocks in the Star Lake area. The Fruitland Formation sandstones are moderately sorted quartzarenites, and contained little carbonate cement, the majority being at the base of the formation. Reported Kirtland Shale sandstones were moderately well sorted, sub-rounded to sub-angular subarkoses and arkoses.

Shales (sensu Potter et al., 1980), in the study area, are usually grey green to grey and less commonly dark grey. These colours indicate a mole fraction of Fe^{2+} between 0.5 and organic carbon ranging from 0 to 1.5% (Potter et al., 1980, figure 1.25). Shales occur in tabular beds on the order of tens of centimetres thick, interbedded with tabular sandstones. The colour of shales shows a correlation with amount of plant material, increasing from grey green to grey to dark grey. Plant material is generally in the form of linear stem and root fragments, less than 1 cm long, with isolated leaves being uncommon and accumulations of such material being rare, in pockets. Sedimentary structures are not common in shales, but lamination, ripples and climbing ripples do occur, dominantly in siltstones. Shales are well indurated and tend to have a blocky fracture with mudstones and claystones sometimes having mauve or brown staining along fractures. Claystones show conchoidal fracture.

Carbonaceous beds range from carbonaceous mudstone to subbituminous coal. Carbonaceous mudstones, which laterally grade into thin coals, represent the most laterally continuous beds in the area being traceable over at least 2 km. Only one coal, laterally continuous in lithology, occurs in the study area, and can be correlatable by the presence of a tonstein approximately 10 cm from its top. Carbonaceous mudstones tend to grade down and up from grey mudstone. The vertical sequence is, from bottom to top, grey mudstone to dark grey mudstone to brown carbonaceous mudstone which laterally becomes coally. This vertical sequence shows an upward increase in carbonaceous plant material of all kinds, but plant material is not usually recoverable because of fragility and fissility (of brown and black mudstones) and because of overlapping of plant material. Amber is common in the coal and black mudstones. The black or near black mudstones probably contain 3-5% of organic carbon and 0.9 to 10 mole fraction of Fe2+ (from Potter et al., 1980, figure 1.25).

Three volcanic ashes are recognised in the study area. The first occurs near the top of the main coal, and shows good to altered (tonstein) preservation at stratigraphic sections BAD and BAE respectively. The tonstein appears to be kaolinitic probably indicating a freshwater coal-forming swamp (Bohor, 1977). It is less than 5 cm thick and can be found in all outcrops of the coal in the study area, and in Sections 15 and 22. The second ash, 2 cm thick, occurs 12-15 cm above Marker Bed one and shows less alteration. It has only been found in a small area adjacent to the stumpfield and a few tens of metres towards the main wash, occurring in a sequence of shales. The third ash occurs immediately above Marker Bed two and is also relatively unaltered. It can be found along the eastern margin of Section 14, where it is 5 cm thick and the western margin of Section 13, but is not traceable far into Section 24. Both higher ashes are white to light grey in colour containing scattered carbonised plant debris and large euhedral crystals (1-1.5 mm in diameter), dominantly of feldspars and micas.

Fluvial Sedimentation

There are basically four styles of fluvial-channel, the meandering or high sinuosity (Allen, 1964, 1965a; Jackson, 1978), the braided or low sinuosity (Miall, 1977, 1978a), the anastomosing (Smith and Smith, 1980), and the straight (Schumm, 1981). The first two types of channel predominate. Water discharge determines the dimensions of the channel, but the relative proportions of bed load and suspended load determine the shape, width-depth ratio, and channel style. A suspended load channel has been defined as one that transports less than 3 percent of its load as bed load and a bed load channel as one that transports more than 11 percent as bed load. Other channels are referred to as mixed load channels (Schumm, 1981). The range of channel styles does not form a continuum. Experimental and field studies have indicated that the channel patterns between braided, meandering, and straight streams occur abruptly at thresholds (Schumm, 1979, 1981). These changes occur at critical values of stream power, gradient, and sediment load (Schumm and Kahn, 1972).

The characteristics of braided and meandering fluvial systems have been discussed at length by many authors (e.g. Allen, 1965a, 1970a; Collinson, 1978a; Reineck and Singh, 1980). Essentially a braided stream (Figure 10) results in deposits dominantly of coarse sand size or greater. These deposits represent remnants of islands and bars formed between braiding channels which rapidly migrate laterally. Lateral accretion builds bars downstream at an acute angle to river flow diverting channels laterally, and vertical accretion builds up bars from the surface of lateral accretion. Channels are of low sinuosity and banks have poor stability. The majority of sediment load is as bed load, its coarse nature being a result of large stream power and relatively steep slope. Beds of fine material (silt or finer) are rare partly because the general regime is against their deposition, but more importantly because rapid continuous channel wandering gives them an extremely low preservation potential (Allen, 1970; Schumm, 1981).

In contrast the deposits of meandering rivers are far more varied (Figure 10). Deposits formed within channels are composed of sand, with little gravel or mud, and mainly represent bed load materials of dunes and ripples which have been preserved as scroll bars aggregated onto point bars. Flow is confined to one sinuous channel with the majority of stream load being suspended. The gradient of channels is low with banks being very stable. The only gravel within channels occurs as a channel lag. Above this lag, if

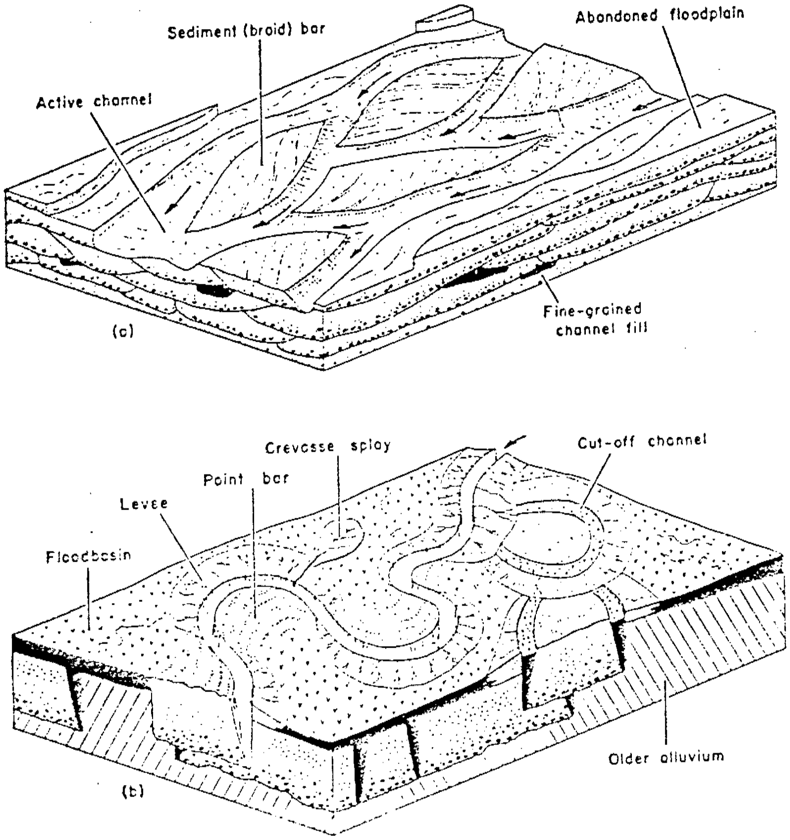


Figure 10. Models of fluvial sedimentation. (a) braided stream, (b) meandering stream. Vertical scales exaggerated (from Allen, 1970).

present, will be a sequence of fining upward sands with a corresponding upward decrease in the scale of sedimentary structures. Much of the suspended load of the stream (silt and clay) is deposited outside the channel as a result of flood events. Channel sandstone deposits are surrounded by these fine grained flood deposits. Some sand is deposited immediately adjacent to the channel perimeter as a result of initial energy loss of floods (Allen, 1970a; Schumm, 1981).

The above descriptions are of ideal models, which contain features that may not be mutually exclusive. Bed load streams may be meandering, and meandering streams may deposit minimal mud (Jackson, 1978). Several authors (Miall, 1980; Rust, 1978; Jackson, 1978) have indicated that the terms, braided and meandering, define morphological characteristics that are not mutually exclusive and that these terms are unsatisfactory as precise technical terms. Meandering and braided will be used herein in the sense of broad categories of channel form. If there are difficulties with defining criteria to distinguish modern braided and meandering streams, there are worse problems with interpretation in the stratigraphic record. This will be discussed later, but for the moment the main features of the various fluvial subenvironments will be discussed, for comparison with facies recognised in the study area.

A general classification of fluvial deposits (Table 1) was proposed by Allen (1965a). Fluvial sediments can be divided into deposits formed by throughflow in an active channel (channel deposits), those formed within an abandoned or decaying channel (transitional deposits), and those deposited outside the channel (overbank deposits).

Channel deposits represent preserved stream bars and channel-lag. In a stream, silt and clay are moved in suspension, essentially at the velocity of the stream, sand is moved less rapidly and intermittently, and gravel size debris is transported slowly, infrequently and only at highest stream discharges (Allen, 1965a). The latter is termed channel-lag. If preserved the channel-lag usually occurs immediately above a scoured surface (Allen, 1962, 1965a).

Stream bars are of two types, point bars and channel bars. Point bars occur predominantly in meandering streams. Flow around meander bends is generally helicoidal with maximum velocity occurring near the outer bank. The thalweg follows the line of maximum velocity. Velocity asymmetry produces erosion on the concave bank and deposition on the convex bank with a consequential lateral migration of the channel and deposition of a lateral accretion product termed a point bar (Allen, 1970a; Collinson, 1978a). Scroll bars are ridges of sand, which develop some distance down the point bar surface. They are elongate and sub-parallel to

CLASSIFICATION OF ALLUVIAL SEDIMENTS (ALLUVIAL FAN DEPOSITS NOT INCLUDED)

Environment of deposition	Deposits	Origin relfected in typical stratigraphical position
Channel floor	Channel-lag deposit	Channel or substratum deposits
Point bar	Point bar deposit	
Channel bar	Channel bar deposit	
Point bar swale or in abandoned braided stream channel	Swale-fill deposit	Overbank or topstratum deposits
Levee	Levee deposit	
Crevasse-splay	Crevasse-splay deposit	
Floodbasin	Floodbasin deposit	
Within abandoned or decaying channel	Channel-fill deposit	Transitional deposit

Table 1. Classification of alluvial sediments (after Allen, 1965a).

the contours of the surface. Scroll bars migrate up the point bar surface until they are at bankfull level whence they are abandoned and a new one moves up behind (Collinson, 1978a). The vertical sequence of a point bar (Figure 11) consists of a fining upward sequence. At the base lies a scoured surface, sometimes associated with a channel-lag. Above this is a sequence of dominantly sandstones which shows an upward decrease in grain size and scale of crossbedding (Collinson, 1978a).

Channel bars are characteristic of braided streams and may be divided into three major types: longitudinal bars, bars in curved channel reaches (including point bars), and transverse bars (Collinson, 1978a). Channel bars are the result of both lateral and vertical accretion. Lateral accretion builds bars downstream at an acute angle to river flow, diverting channels laterally. Vertical accretion builds up bars from the surface of lateral accretion (Allen, 1965a). Any single bar will have had a complex history of erosion and deposition, and vertical sequences vary considerably and may include reactivation surfaces (Collinson, 1978a). Bar sequences have erosional bases and generally fine upward, and are composed, predominantly, of imbricated and crossbedded gravels and crossbedded sands.

Overbank deposits are formed by flood events. Flood water escaping the channel suffers a rapid fall off in turbulence, and suspended sediment is deposited, the

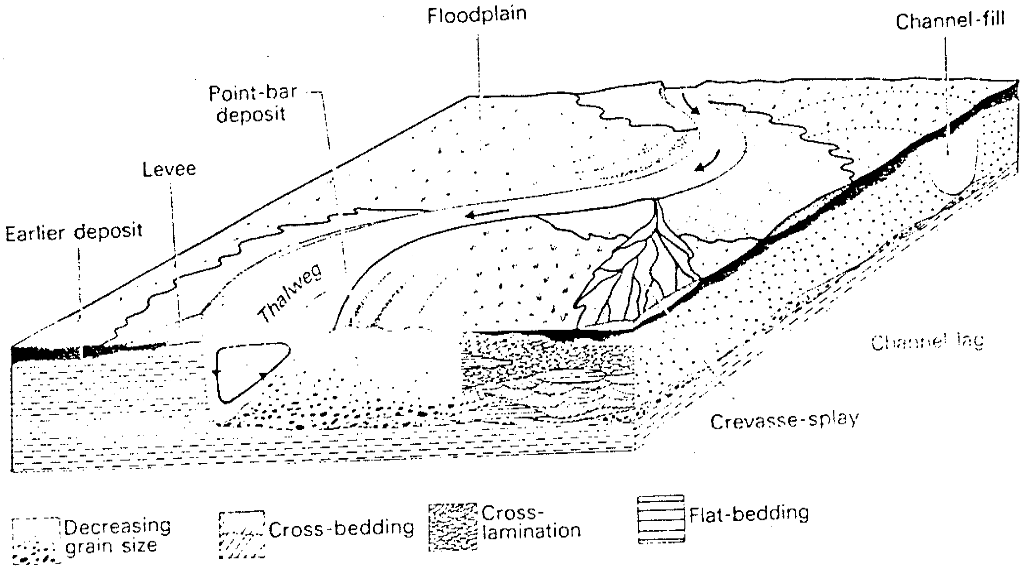


Figure 11. Internal composition of an ideal point bar (from Collinson, 1978a).

coarsest material, forming the levee deposit, being laid down closest to the channel (Allen, 1965a; Collinson, 1978a). Levee deposits immediately border channels and are sinuous with a triangular cross section. They slope and fine away from the channel and are only submerged at the highest flood (Fisk, 1947; Allen, 1965a). Levee deposits have a low potential for preservation as they mainly occur on concave banks, and therefore only escape erosion if the channel is cut off (Collinson, 1978a). If preserved, levee deposits represent the coarser deposits of the topstratum, and their grain size is usually of sand size or finer (Allen, 1965a).

During flood, the levee of the channel may be locally breached through a crevasse resulting in a lobate or sinuous deposit thinning towards the floodbasin. These deposits, termed crevasse splays, are normally of the order of centimetres to scores of centimetres thick (Reineck and Singh, 1980; Allen, 1965a). There is often a marked textural disparity between deposits of crevasse splay and other overbank sediment with which they intertongue.

Floodbasins are the lowest lying parts of fluvial floodplains. They are poorly drained, relatively featureless areas of little or no relief located adjacent to slightly higher alluvial ridges. Floodbasin deposits are composed of fine grained material representing suspension material, and in humid climates, organic matter (Allen, 1965a; Reineck and Singh, 1980).

Rivers that rapidly shift their position do not have a well developed floodbasin, and the name floodplain deposits has been proposed for their overbank deposits (Reineck and Singh, 1980). Such deposits consist of interbedded sands, silts, and mud (Reineck and Singh, 1980). The distinction between floodbasin and floodplain deposits is not clear cut. Floodplain deposits (sensu Reineck and Singh, 1980) can accumulate in the environs of main channel axes whilst floodbasin deposits occur in more distal regions.

Transitional deposits represent material deposited in channels during or after cessation of throughflow. Bed load sand is important in deposits representing decaying flow, whereas in abandoned channels deposition is limited to overbank deposits of still active channels. The three dimensional shape of transitional deposits represents the shape of the existing channel at the time of development of the new channel (Allen, 1965a), and therefore channel-fill in meandering channels tends to be triangular to prismatic in cross section. Channel-fill deposits of meandering streams result from either chute or neck cut off. Deposits resulting from chute cut off are less strongly arcuate in area than those formed by neck cut off (Allen, 1965a).

Lithologic Facies in the Study Area

The term facies has a complicated history (Middleton, 1978), but here the term is used simply to imply a set of characteristics observed in rock units (Walker, 1979). A number of facies can be recognised within the study area. These are defined in terms of lithology, geometry, nature of contacts, and types of crossbedding. The various described facies exhibit both lateral and vertical conformable contacts and are considered to have been deposited as contemporaneous lateral equivalents. The main characteristics of the facies are summarised in Table 2.

The following abbreviations are used in the naming of facies, C (conglomerate), S (sandstone), sh (shale), c (carbonaceous beds), cp (clay pebble), sc (scoured base and crossbedded), m (marginal), s (sheet), and t (transitional).

Table 2. Main characteristics of facies utilized in this study, x-occurs, r-rare.

Facies	Grain Size							Sorting			Sedimentary Structures						Bed Texture			Cross Bedding			Bed Geometry			Biota					Interpretation
	clay	silt	very fine sand	fine sand	medium sand	coarse/very coarse sand	gravel	poor	moderate	well	small scale crossbeds	large scale crossbeds	epsilon crossbeds	flat bedding	current lineation	ball & pillow structure	fining up	coarsening up	lateral fining	uniform fine	interbedded coarse/fine	uniform coarse	sheet	lens	prism	mollusc	vertebrate	plant (transported)	plant (in situ)	trace fossil	
Ccp					x	x	x	x			x	x										x		x		x	x	x			channel lag
Ssc				x	x	x			x		x	x	x	x	r		x					x		x		r	x	x			bar deposits
channel A					x	x			x		x	x	x				x					x		x			x	x			bar deposit
channel B					x	x			x		x	x		x			x					x		x				x			bar deposit
channel C					x	x			x		x	x	x				x					x		x		r		x			bar deposit
channel D					x	x			x		x	x		x		x	x					x		x				x			bar deposit
other				x	x	x			x		x	x	x		r		x					x		x		r	x	x			bar deposit
Sh/Sm	x	x	x	x	x			x	x		x								x		x	x			x	r		x	r	r	levee
Ss	x	x	x	x				x	x		x			x			x	r	x			x	x		r		x	x			crevasse splay
C	x	x								x				x						x			x				r	x			floodbasin
Ss/Ssh	x	x	x	x	x			x	x	x	x			x			x	r	x	x	x		x			x	x	x	x	r	floodplain
St	x	x	x	x	x			x	x	x	x						x			x	x			x	x		x	x	r		channel fill

Facies Ccp: Clay Pebble Conglomerate Accumulations

Observations

Clay pebble conglomerates, in the study area, occur as discontinuous elongate lenticular bodies at or slightly above the erosional base of lenticular cross bedded sandstone bodies.

Lenses of matrix supported clay pebble conglomerate are elongate and up to 50 cm thick with an areal extent of up to 20 m x 6 m. Immediately above the main lens are individual parallel laminae rich in clay pebbles which show more flattening than those in the more massive deposit below. The matrix supporting the clay pebbles is clay-rich, medium grained sandstone. The main lens sometimes shows channelling into underlying sandstone which is identical to that above it, in the main body of the sandstone. Clay pebble conglomerates, less than 30 cm thick, occur directly on the scour surface at the base of the sandstone body and show no vertical sequence as described above. In both cases the deposit consists of approximately 50% clay pebbles, 40% clay-rich, medium grained sandstone, and 10% organic material. The clay pebbles are dominantly from 1 to 1.5 cm in diameter. They show lateral flattening, and the majority are of grey green mudstone or claystone indistinguishable from shales occurring in the study area. None show armouring. Half the organic material present, which all occurs within the sandstone matrix, is macerated carbonaceous plant material with another quarter being fragmented plant material, the remainder is vertebrate or invertebrate material. Vertebrate material consists of bone, turtle shell, teeth, scutes, and scales. Bone usually occurs as abraded, subrounded pebbles from 1 to 3 cm in diameter, whereas other vertebrate remains show less damage and most scales and teeth are unabraded. Rare larger bone fragments with volumes up to tens of cubic centimetres occur. Coprolites containing fish scales and vertebrae are also common. Characters of individual fossiliferous deposits are given in the taphonomy section. Clay pebble conglomerates are not ubiquitous, but scattered clay pebbles occur above most scoured surfaces.

Interpretation

Based on geometry, composition, association with scoured surfaces and similarity to deposits described from modern sediments (Reineck and Singh, 1980), and interpretations of other rock sequences (Allen, 1962; Allen, 1965b), rocks of this facies are interpreted as channel-lag deposits.

Two lines of evidence suggest that each conglomerate had only one source: (a) in each case less than 1% of pebbles show a divergent lithology, (b) clay pebbles show high rates of attrition and are probably only transported tens or hundreds of metres before destruction (Smith, 1972). Clay pebbles were eroded either from stream banks or bar tops (Williams, 1966) or from the underlying sediment (Allen, 1962).

The short period of transport of clay pebbles (Smith, 1972) and the similarity of the material in the pebbles to rocks throughout the sequence exposed in the Fossil Forest area suggest that these deposits represent intraformational conglomerates.

Although roundness and size of clay pebbles can be related to thickness and distance of source deposit (Nossin, 1961) because of the uniform size and roundness of the pebbles, their physical dimensions are presumed to be a result of hydrodynamic sorting.

No pebbles show armouring which could be a result of a clay dominated bed in the stream (Nardin et al., 1962) or, considering the immature nature of the conglomerate as a whole, it might suggest an extremely rapid deposition event.

Clay pebble conglomerates are preserved in elongate lenticular bodies representing filled scours in the channel bottom. Scouring probably predated, but may have been synchronous with, the deposition of the conglomerate.

Facies Ssc: Cross Bedded lenticular Sandstone Bodies with Scoured Bases

Observations

Lenticular bodies of sandstone exhibiting cross bedding and resting on scoured surfaces occur in the study area, within the context of generally sheet-like beds of shale and sandstone. They form the base of fining upward sequences and are greater than 1 m thick. Deposits of Facies Ccp often lie at the base of these beds. Sandstones are white to light grey, moderately sorted and quartz rich (Type 1).

Interpretation

On the basis of the above characteristics of Facies Ssc and their similarity to analogous recent and ancient deposits (Allen, 1965a, 1965b, 1970b) the rocks of this facies are interpreted as representing bar deposits of alluvial channels. They can be differentiated from transitional deposits as they have a scoured lower surface and form the basal not the upper portion of fining upward sequences.

The four largest channels in the study area were examined in detail. These are referred to as Channels A, B, C, and D with A being the Dinosaur Graveyard channel body (Figure 12).

Channel A

Observation

Channel A outcrops in an irregular ellipsoid with maximum and minimum lateral dimensions of approximately 490 and 230 m respectively. The maximum thickness is more than 4 m. Twenty-three bones and five logs outcrop in this sandstone body. More details of its fossil content are given in Chapter III. The best exposures of the channel body occur in the area where most bones are found. The channel body shows lateral asymmetry not only in thickness of margin but also in thickness of the overlying facies (St). On the NNW margin the channel is almost immediately overlain by Marker Bed one, but on the SSW side, 3 m of clay rich sandstone separate the two (Figure 13). Marker Bed one is presumed to be a time line over this short a distance. There is much development of hoodoos, which are pillar or

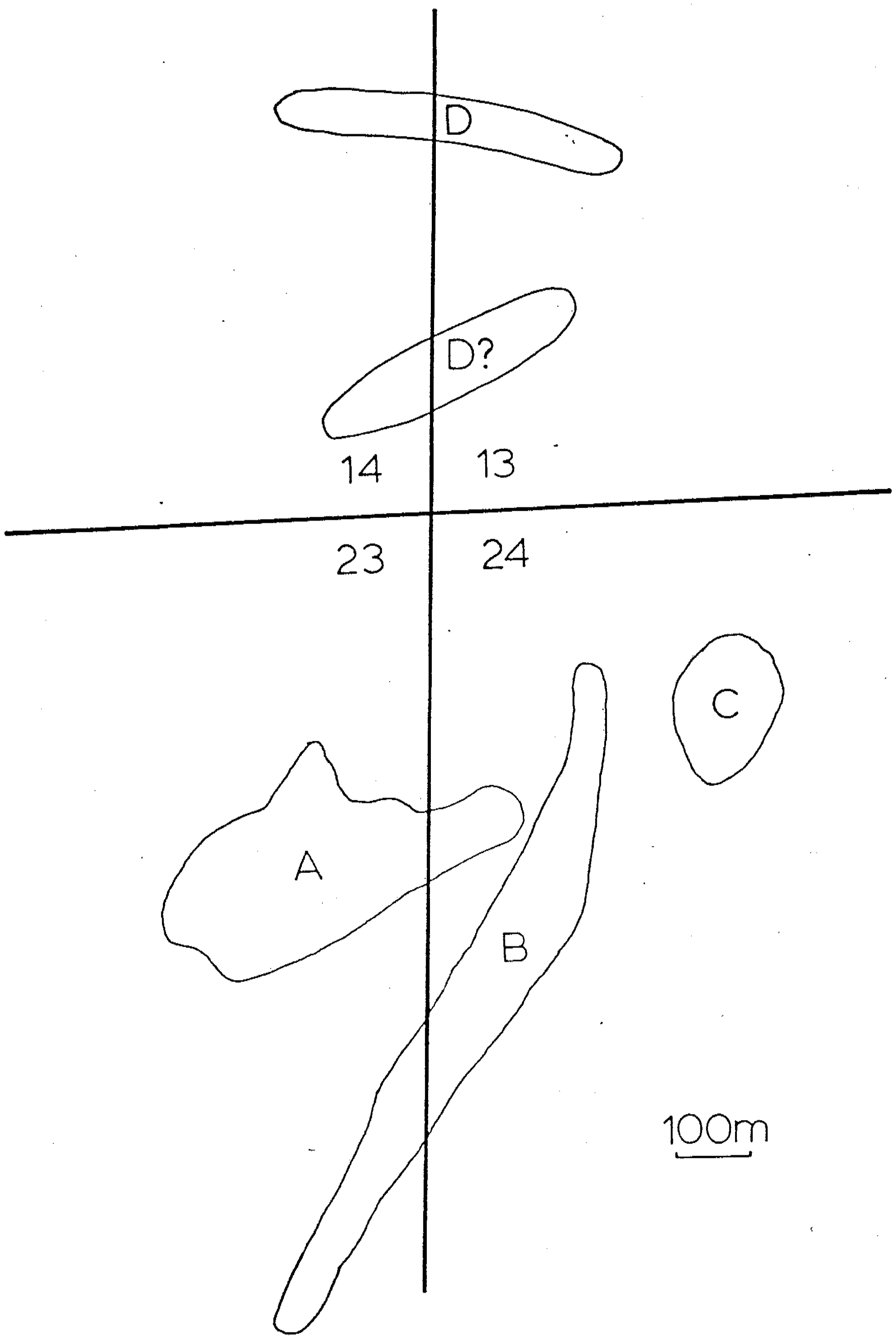


Figure 12. Areal extent of main channels.

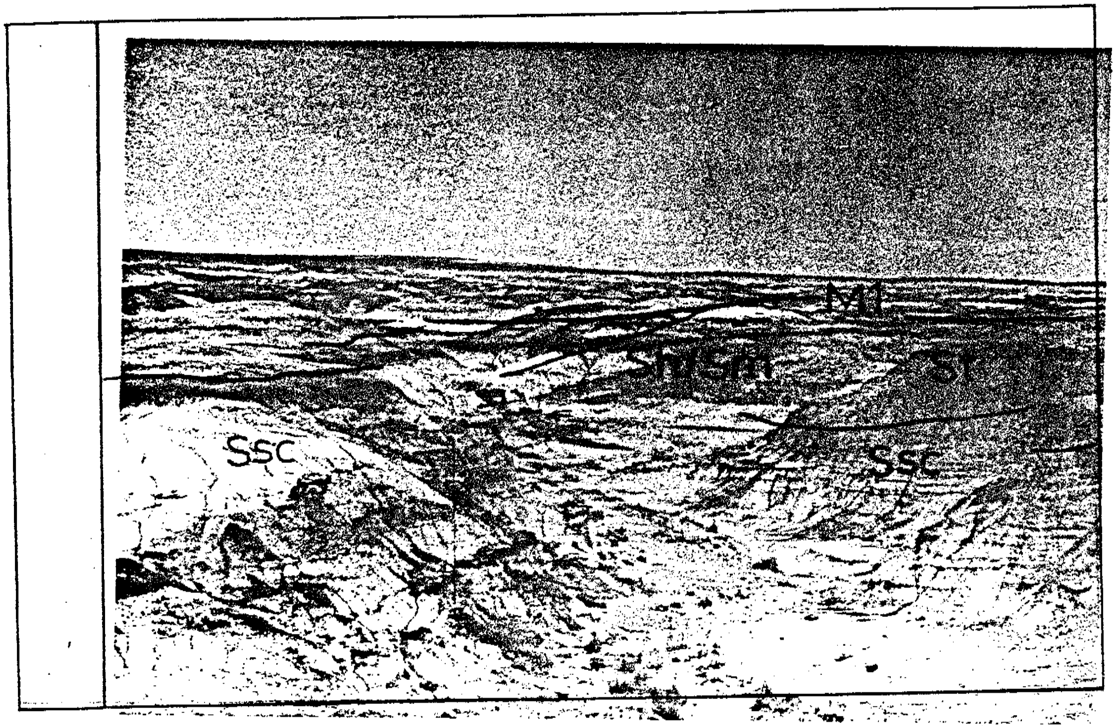


Figure 13. Margin of Channel A showing lateral variation in thickness of facies St between top of Channel A (Facies Ssc) and Marker Bed one (M1) and presence of facies Sh/Sm at the margin of Channel A.

mushroom shaped erosional features produced by erosion of strata of varying hardness in regions where rainfall is seasonal (American Geological Institute, 1976). In the study area the hard units capping hoodoos are calcium carbonate concretions.

Most of the cross bedding is small scale, low angle planar with heights on the order of 10 to 30 centimetres and a width up to 1 metre. Laminae are planar to slightly sinuous. There is some decrease in size of cross beds upward. Intersperced infrequently are much larger isolated cross beds with heights of up to 4 metres and lateral extents up to 15 metres (Figure 14).

On the SSE margin of the channel there is very large scale low angle cross bedding with a height of about 5 metres and a lateral extent of about 25 metres (Figure 15). Similar cross beds are also evident on the NNW side of the channel although there they are much smaller being about 2 metres high and about 12 metres wide (Figure 16). These cross beds extend from the base to the top of the channel. This cross bedding is picked out by clay, whereas, the vast majority of cross beds in the study area are picked out by macerated plant material. Cross beds in the area are almost all highlighted by one of the two means above, the only exceptions being those associated with concretionary material. Small scale cross bedding is often evident in hoodoos, and sideritic concretions may follow cross bed

Figure 14. Channel A exhibiting lateral variation in size of low angle crossbeds. Staff is 1.48 m.

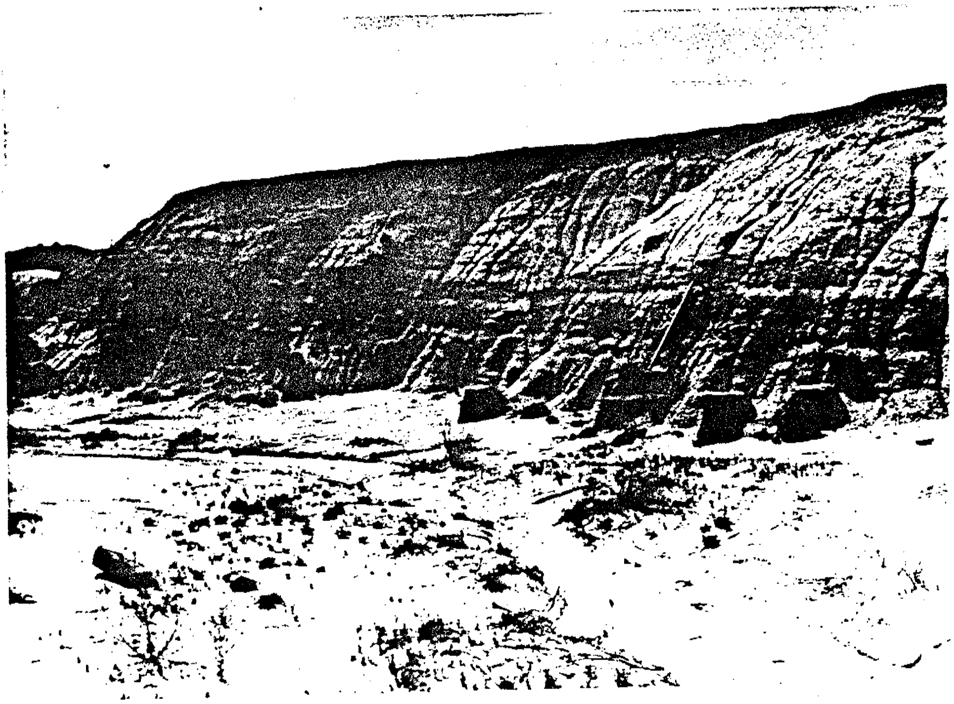


Figure 15. Large scale low angle crossbeds picked out by laminae of finer grain size in Channel A. Staff is 1.48 m.

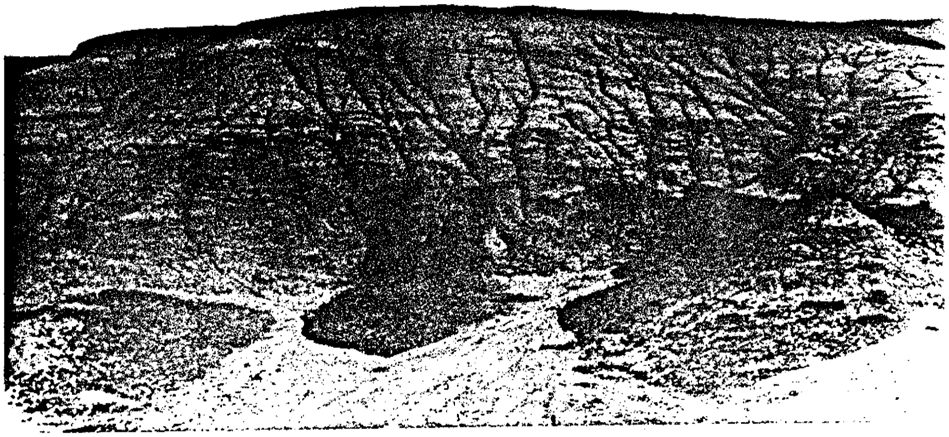


Figure 16. Smaller scale low angle crossbeds picked out by laminae of finer grain size. Staff is 1.48 m.

laminae in which case they are presumed to be nucleated around macerated plant material. The channel is not multistoreyed.

Current directions measured from cross beds indicate a unimodal north flow direction (Figure 17). Orientations of the long axes of bones and logs (Figure 18) give a bimodal distribution (Figure 19), these directions being WNW-ESE and NNW-SSE.

Interpretation

The large scale low angle cross beds picked out by clay-rich laminae conform to the definition of epsilon cross beds (Allen, 1963). Allen (1963) in naming epsilon cross bedding suggested that they represented deposition on the sloping inner face of a point bar. This idea has been accepted by most workers and hence they have inferred a meandering course for a channel deposit exhibiting this type of cross stratification (Jackson, 1978). The fine grained nature of the materal along the cross beds suggests a mud "drape" over the surface of the point bar during a period of slack water. Collinson (1978a) has suggested that the nonubiquity of epsilon cross beds on point bars may be due to the fact that they are only formed during a fluctuating flow regime.

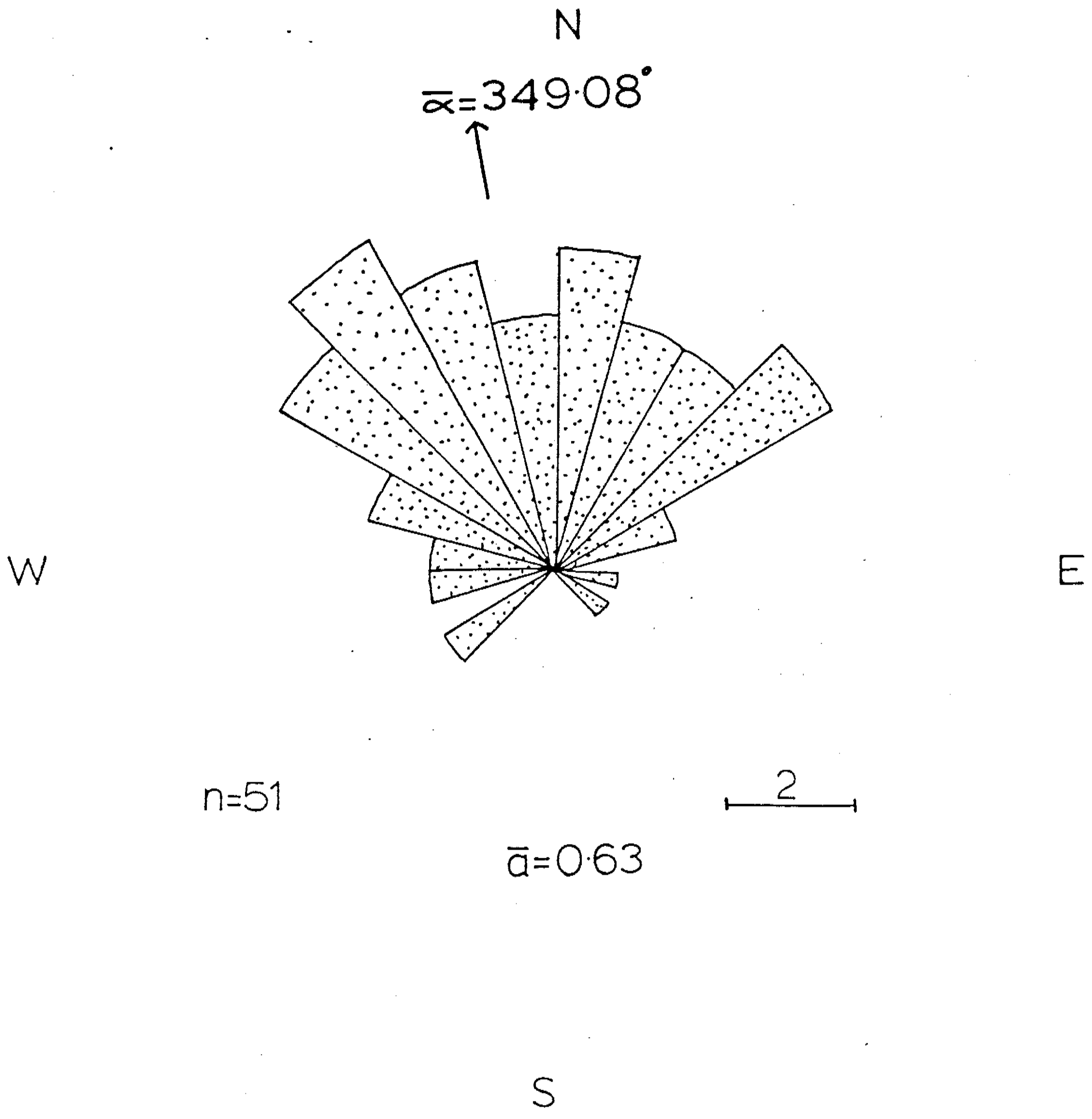


Figure 17. Rose diagram of current directions from Channel A, $\bar{\alpha}$, vector mean, $\bar{a}$, vector strength, N, north, W, west, S, south, E, east, n, total number of readings.

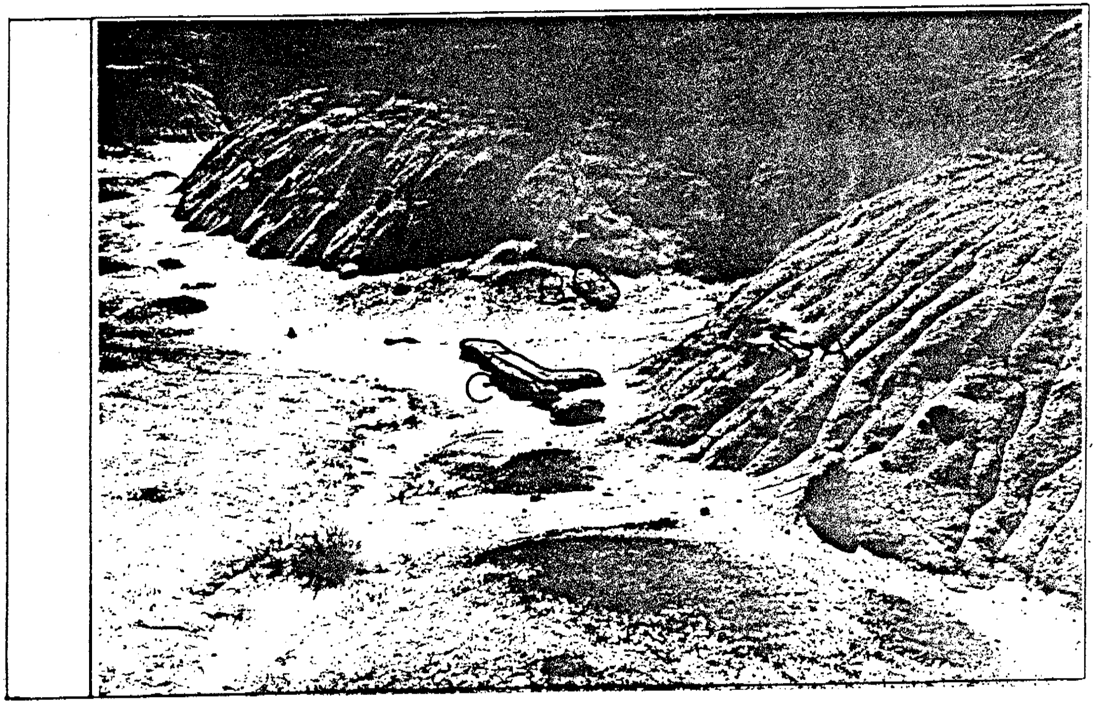


Figure 18. Bone (A), log (B) and calcareous concretion (C) showing subparallel orientation in Channel A. Staff is 1.48 m.

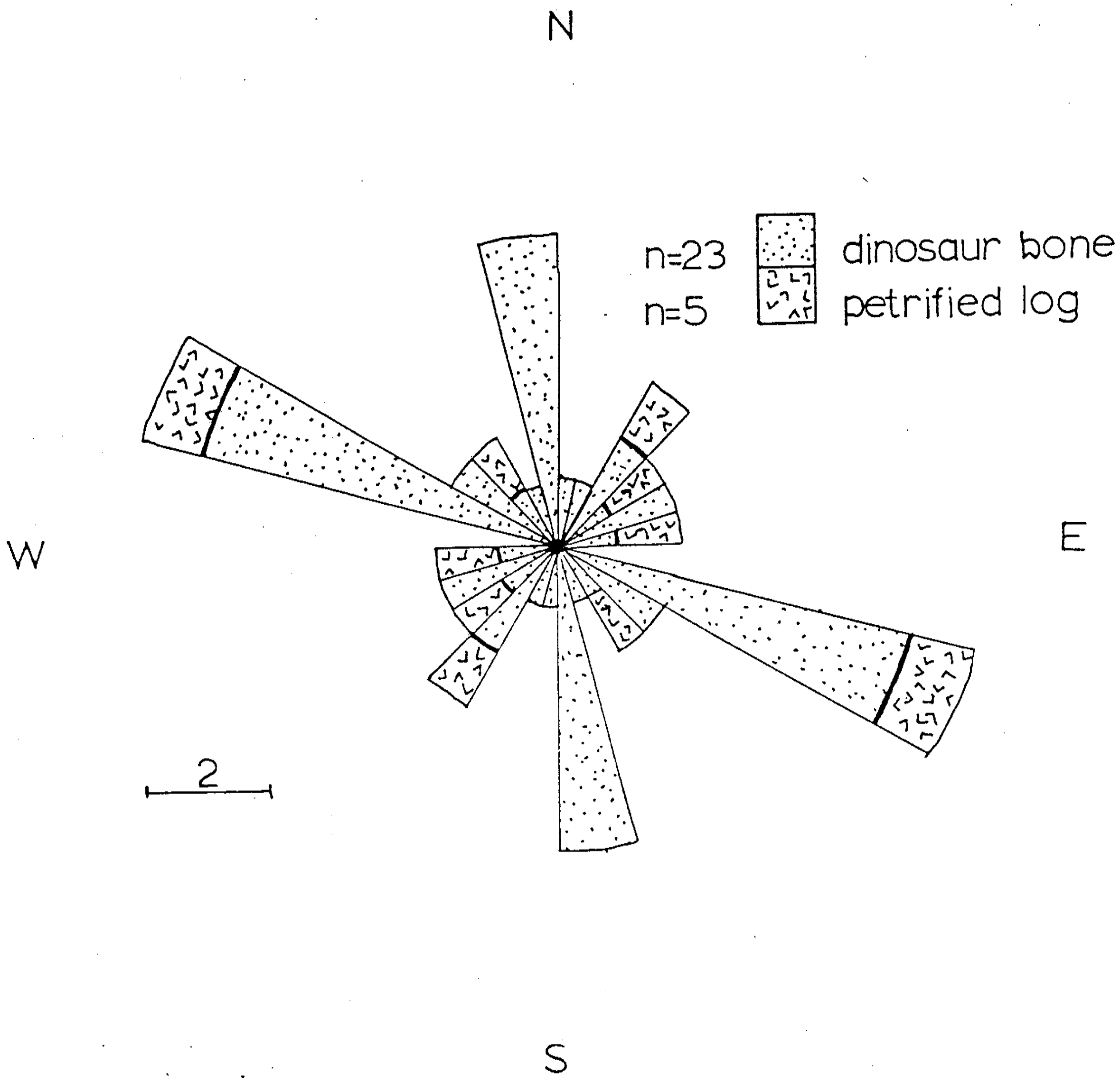


Figure 19. Rose diagram of long axes of logs and bones in Channel A.

Given the presence of well preserved epsilon cross beds, a palaeohydraulic study was conducted following methods outlined by Ethridge and Schumm (1978). Although the results were in agreement with other sedimentologic evidence, conclusions were discarded after consideration of comments by Miall (1978b) and examples shown by Jackson (1978) and Miall (1980). These authors indicate that the extreme complexities evident in some modern fluvial systems present problems in palaeohydraulics beyond present powers of resolution.

The interspercing of large isolated cross beds with smaller scale cross stratification is interpreted as being the result of migration of trains of ripples down the channel with larger cross beds representing intermittent dunes. Dunes indicate a higher flow regime (Allen, 1970) resulting either from changes in flow velocity or depth or more probably a combination of both. As dunes laterally grade into ripples it is likely that the former were formed in the thalweg of the channel with contemporaneous ripples forming on a laterally equivalent bar. Based on the presence of ripples and dunes, it is considered that the flow within the palaeochannel was of moderate to high lower flow regime (Harms and Fahnestock, 1965).

Current directions from cross beds indicate a northerly flow direction with a vector mean of 356.8 degrees and a vector strength of 0.59. These and all following statistical analyses of current directions were carried out on a Hewlett Packard HP11C calculater utilizing a programme written by D.B. Johnson, using the formulas of Pincus (1956). Results from orientations of the long axes of bones and logs are bimodal. However, it is common for the long axes of fossils to be aligned both parallel to and normal to the current direction (Voorhies, 1969) and thus the current direction derived from the long axes of fossils would support a roughly northerly current direction.

Channel A has been considered in some detail as it is so important as a source of fossil vertebrates. The main difference between it and other channels in the study area, apart from its slightly larger size, is the greater development of much larger epsilon cross bedding, which is probably a result of greater periodicity in flow (Collinson, 1978a). Also associated with this channel is development of Facies Sh/Sm and Facies St which is anomalous for the study area. The asymmetry of Channel A is more marked than in other channels.

Channel B

Observation

Channel B outcrops in an elongate ellipsoid. Until it reaches the main drainage through the badlands, it caps hillocks and has therefore been subject to considerable erosion. Its apparent dimensions are 840 m x 110 m x 6 m. Quarry 4 (Taphonomy Section) is a basal conglomerate in this channel. Where it is a capping unit, the top 75 cm is iron red brown in colour, the only other unit in the study area exhibiting this colour is Channel D.

Channel B is different from A both in geometry and internal structure. Externally the channel is very linear in areal extent in contrast to the ellipsoid of Channel A, and the cross section shape of B is a symmetrical lens in contrast to the asymmetry of Channel A. Internally B is characterised by sets of low angle planar cross beds about 75 cm thick with planar bases, horizontal bedding (Figure 20) and large scale scour-and-fill structures. They occur at several levels in the channel. The dip of the cross beds is about 20 degrees, and they are picked out by only a slight change in grain size. The laminae range from planar to slightly concave upward. Sets are laterally persistent for approximately 20 m, although one extends for 100 m. One

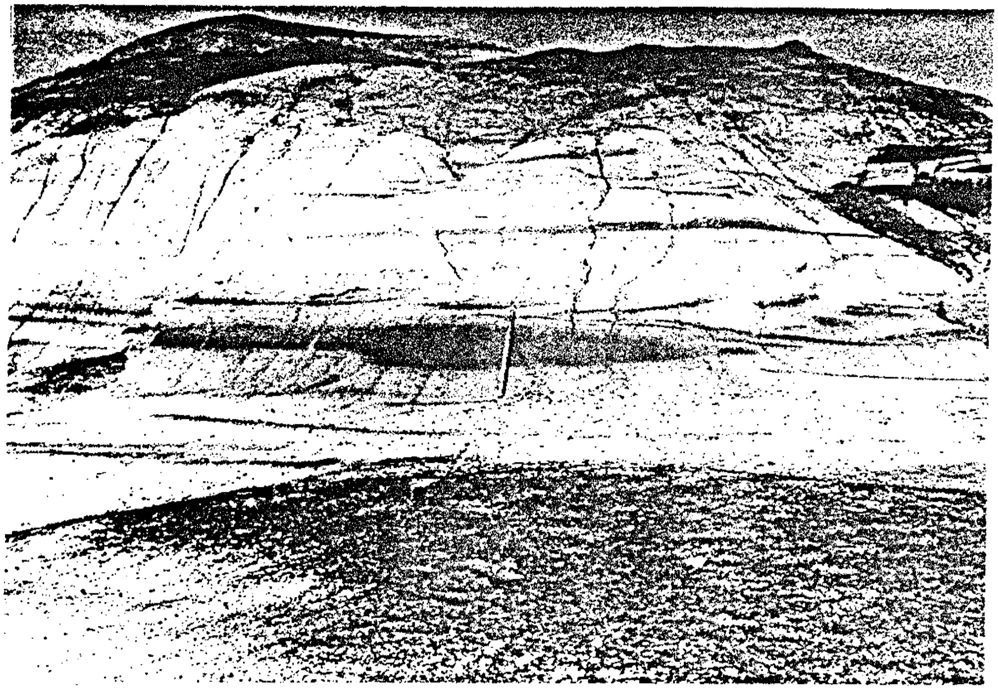


Figure 20. Sets of low angle concave upward crossbeds sandwiched by planar parallel beds in Channel B at staff (1.48 m).

set of these cross beds is of the red-brown colour (Figure 21). Laterally, going into outcrop, this bed shows development of a massive cylindrical carbonate concretion. The brown set is not the highest unit in the channel, but it forms the capping unit due to its resistance to weathering. One exposure shows a large scour approximately 9 m wide and .75 m deep (Figure 22). It is infilled at the base by trough cross stratification showing a decrease in size upward. The coarsest sand sized material (very coarse sand) is found in Section 22 (Stratigraphic Section BAT) in a red-brown sandstone, considered a continuation of Channel B. Measurements from cross beds indicate a north easterly flow direction (Figure 23).

Interpretation

The planar cross bedded units of Channel B appear to correspond in character and scale to the facies of planar crossbedded sandstone named Sp by Miall (1977). These beds could be interpreted as epsilon cross beds (Allen, 1965a) but as Miall (1977) points out epsilon cross beds are picked out by fine grained material along laminae and have angles of laminae less than 15 degrees. The cross beds in question dip about 20 degrees and are picked out by relatively slight changes in grain size. These units are interpreted, following Miall (1977), as representing foreset avalanche

Figure 21. Red brown set of low angle planar crossbeds in Channel B.

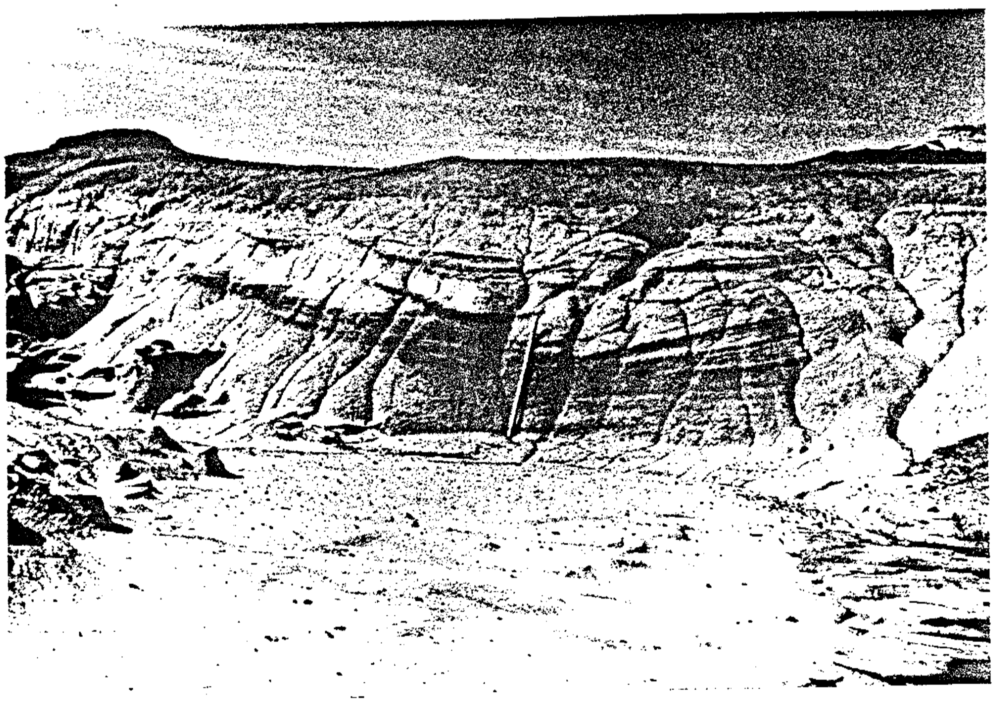


Figure 22. Large scour in Channel B. Staff is 1.48 m.

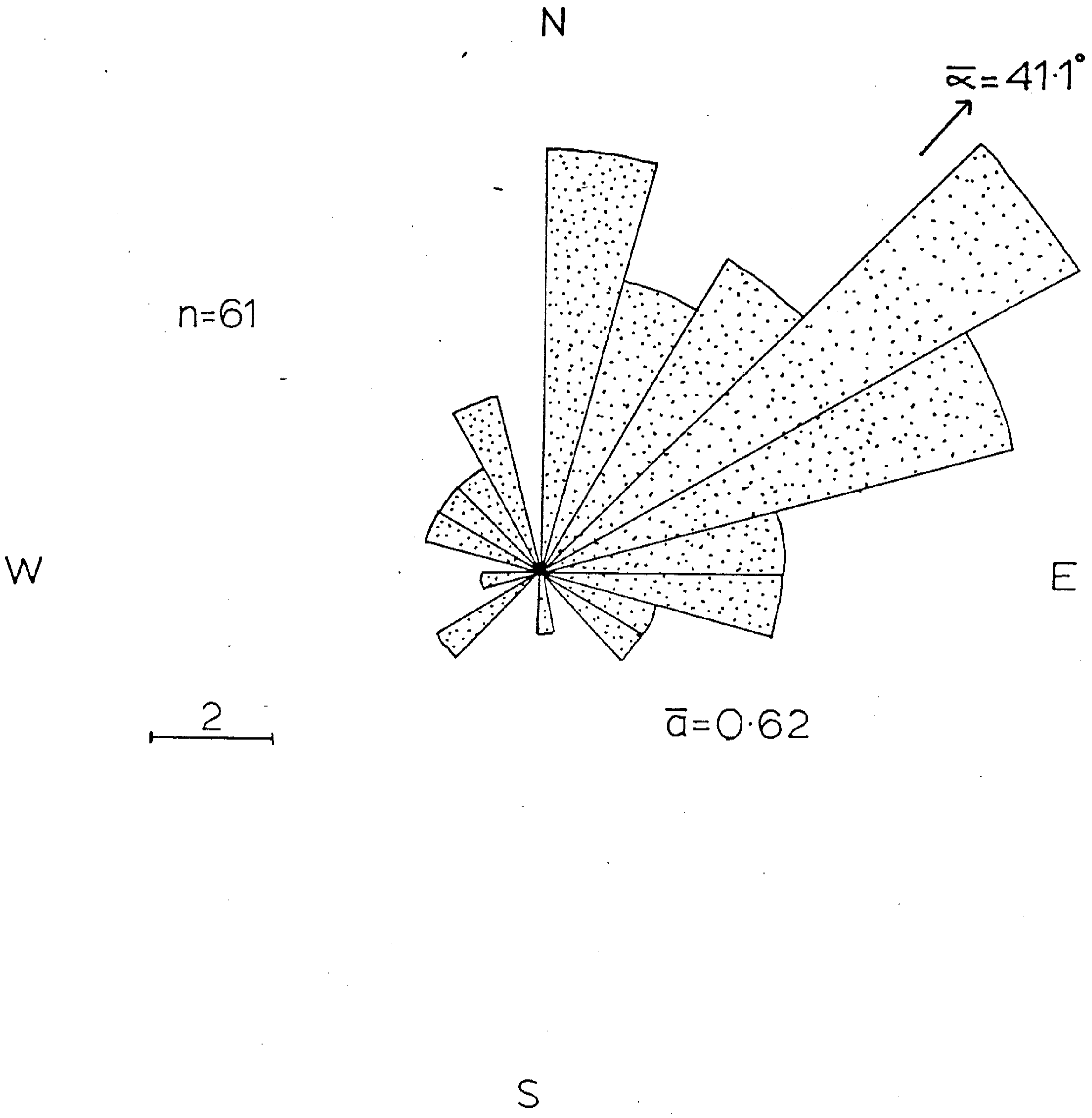


Figure 23. Rose diagram of current directions from Channel B. For explanation see Figure 17.

slopes of transverse bars. Such units could represent linguoid bars, but it is probably impossible to distinguish the two types in the stratigraphic record (Miall, 1977). Alternately, these sets could represent chute bar deposits (Levey, 1978, figure 2). Chute bars only occur at the tops of point bar sequences. The presence of sets of low angle cross beds at several levels in the bar deposit of Channel B precludes their interpretation as chute bar deposits. Laminae range from strictly planar to slightly concave upward, and this difference is interpreted as being a result of differential strength of separation eddies (Miall, 1977). The broad, shallow scour filled by trough cross beds closely resembles facies Ss of Miall (1977), which is interpreted as representing a large scour fill. Perhaps a modern analogy has been observed in the Rio Grande (Harms and Fahnestock, 1965, plate 2, figure 22). This scouring may have been formed by; (a) strong separation eddies in the lee of advancing dunes (Harms and Fahnestock, 1965), (b) local vortex around obstruction(s) (Miall, 1977), (c) minor channel formed by avulsion during high water stage (Miall, 1977), or (d) bar dissection during falling water conditions (Miall, 1977). Horizontal planar bedding in association with planar cross bedded sets may have formed during lower or upper flow regime and may represent in part longitudinal bars (Miall, 1977). Measurements from cross bedding indicate a vector mean of 41.1 degrees and a vector strength of 0.62.

Channel C

Observation

In plan view Channel C outcrops in an oblate circle in plan with approximate dimensions of 190 x 140 x 5 m. In cross section the channel is asymmetric as is the overlying st facies. The channel is single storeyed. There channel contains much large scale low angle cross stratification, which is picked out by marked changes in grain size. These cross beds are about 8 m long and 2 m high. Smaller scale cross bedding is largely low angle and planar with sets less than 75 cm thick and minor planar bedding (Figure 24). There is a decrease in scale of cross bedding and in grain size upward. Channel C contains much hoodoo development. Current direction measurements from cross beds indicate flow to the WNW (Figure 25).

Interpretation

Asymmetric cross section, the presence of large, low angle cross beds picked out by marked change in grain size (epsilon cross beds) and the fining upward sequence, all indicate that Channel C was deposited by a meandering

Figure 24. Channel C showing fining upward sequence and large scale, low angle crossbeds. Staff is 1.48 m.

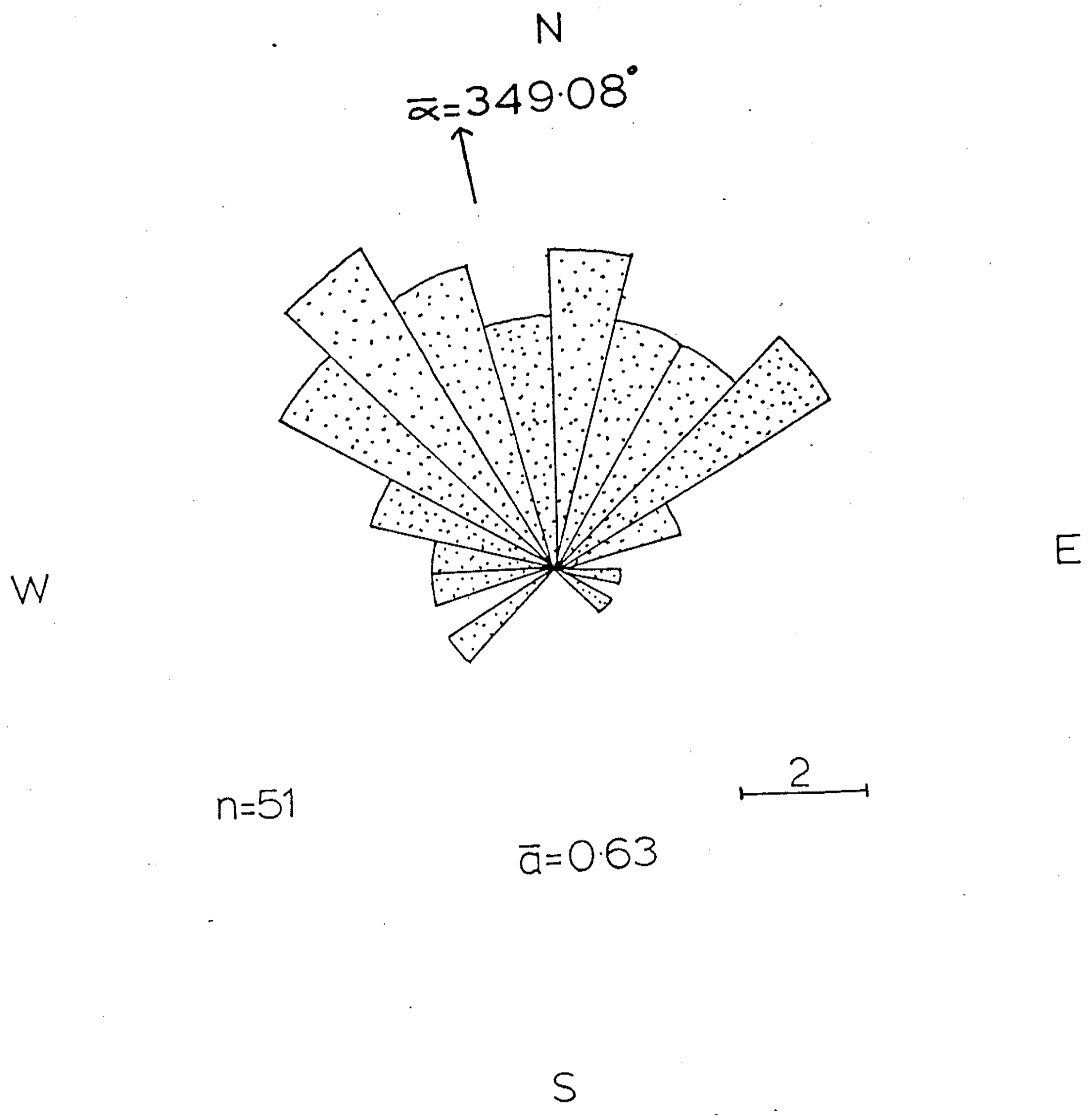


Figure 25. Rose diagram of current directions from Channel C. For explanation see Figure 17.

stream. Based on the presence of intersperced large scale and small scale crossbedding, flow in Channel C would seem to have consisted of dunes intersperced with ripples. The main difference from Channel A is the greater abundance of larger dune cross bedding relative to smaller scale ripple cross bedding. Measurements of current directions from cross beds have a vector mean of 349.1 degrees and a vector strength of 0.63.

Channel D

Observations

Channel D outcrops as a low linear ridge former (single or parallel ridges) 460 metres by 60 metres in area and 4 metres thick. It is capped by a 60 cm red brown resistant layer. As in Channel B, the red brown layer is a set of planar cross beds containing uncommon pillow structures. These cross beds are of lower angle and are more arcuate than those in Channel B and the surface on which they lie is in contrast undulatory. Pillows were noted in a sheet like bicoloured sandstone body of similar appearance in Hunter Wash (Hutchinson, 1981a). Due to the linearity of outcrop and the brown cap this channel appears superficially to be similar to Channel B.

The majority of cross beds are very low angle planar or horizontal with minor trough bedding. Horizontal bedding often erosionally overlies low angle cross beds (Figure 26). Sets of horizontal planar beds 50-75 cm thick are laterally discontinuous. From the base of the channel to the base of the brown cap there is a decrease in size of stratification types. Channel D has a clay pebble conglomerate at its base. Current directions determined from cross bedding indicate an easterly flow direction (Figure 27).

Interpretation

The sequence of horizontal bedding erosionally overlying low angle cross beds is interpreted as representing formation of a transverse bar followed by high flow regime planar bedding, caused by increase in discharge or lateral migration of a channel braid. Discontinuous sets of dominantly horizontal planar bedding may represent longitudinal bar formation (Smith, 1970). The red brown set of planar cross beds is very similar to that present in Channel B, but laminae are more arcuate in Channel B suggesting stronger separation eddies. This and similar sets are interpreted, as for Channel B, as representing foreset avalanche faces of transverse bars. Current direction indicators in Channel D show a vector mean of 83.9 degrees and a vector strength of 0.81.

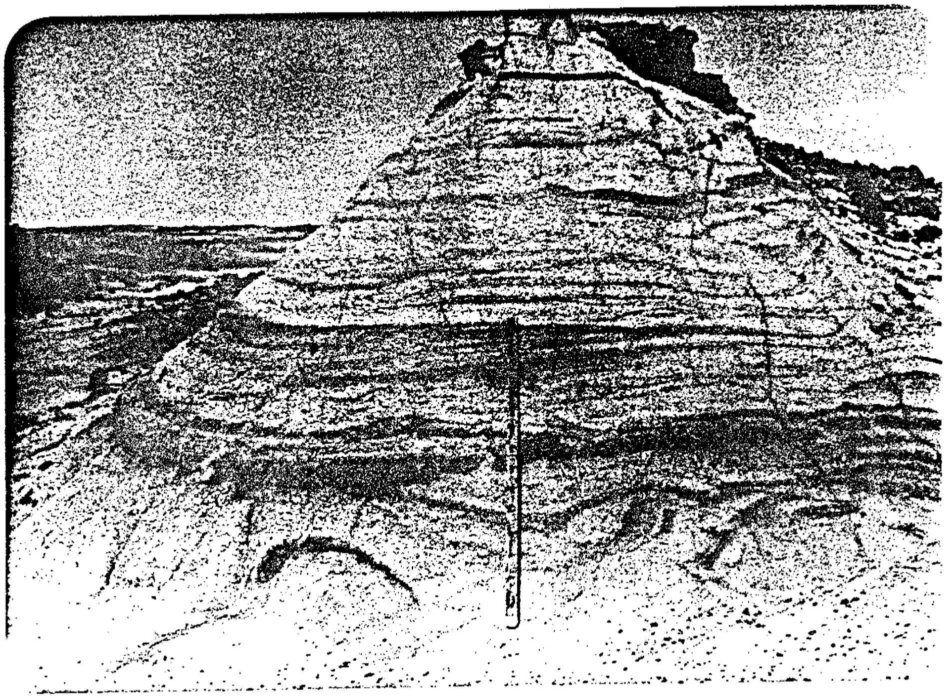


Figure 26. Channel D showing sequence of low angle crossbeds truncated by horizontal planar laminated set. Staff is 1.48 m.

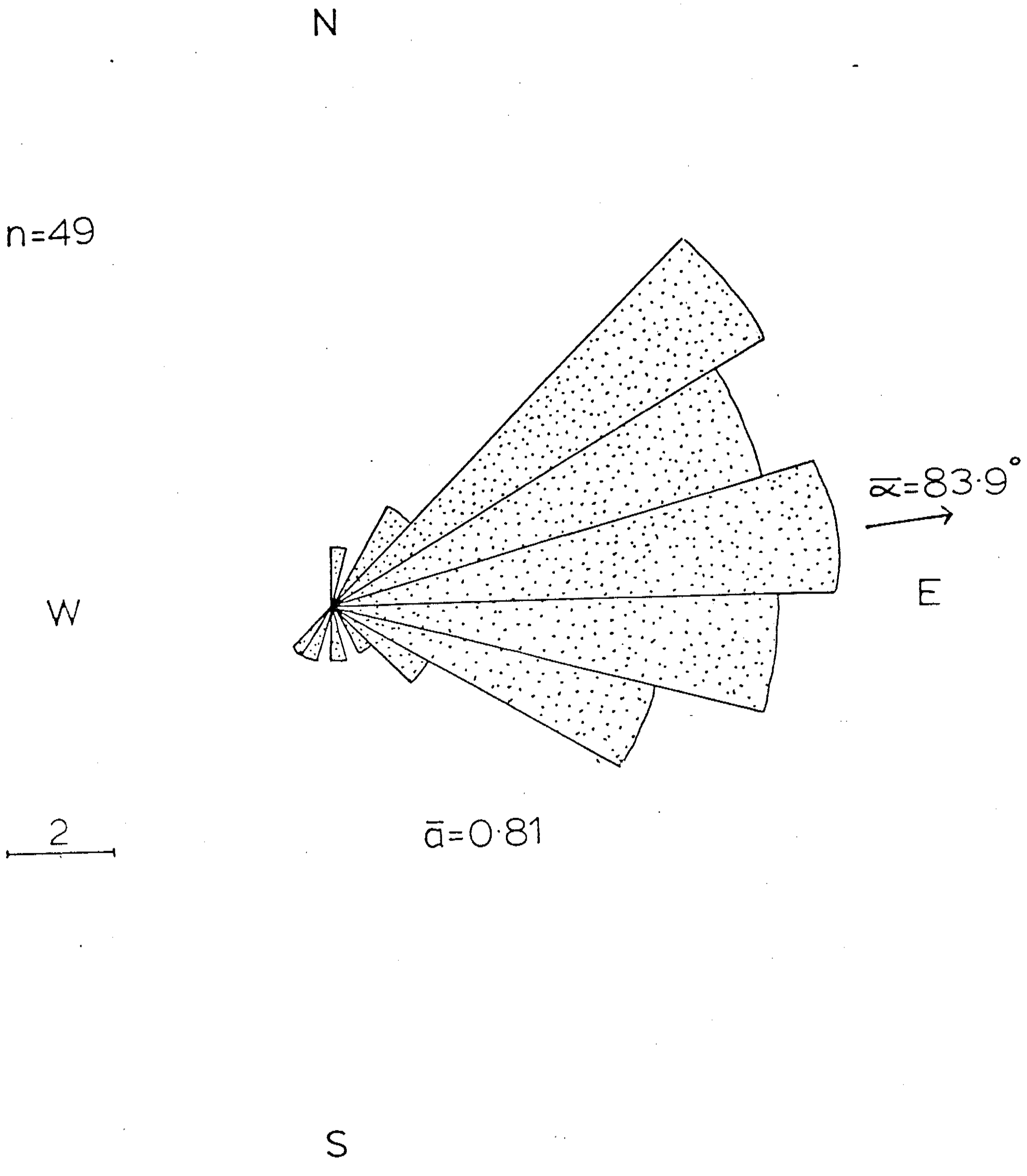


Figure 27. Rose diagram of current directions from Channel D. For explanation see Figure 17.

Other Channels

Observations

The four channels discussed above are the largest in the study area. There are numerous smaller channels. They usually have an ovoid areal extent and are usually less than 3 m thick. They tend to be asymmetrical in cross section and show an upward decrease in scale of cross bedding and grain size. Cross stratification is usually small scale with thickness of sets less than 30 cm and angles of dip of 30 degrees or less. The most common cross stratification is very low angle associated with horizontal bedding. Channels show fining upward both in grain size and scale of cross beds. Parallel lamination occurs and at two locations a parting lineation was developed. Low angle cross stratification (15 degrees or less) picked out by fine grained laminae is common in many of the smaller channels. Very small cross stratification, both planar and trough are sometimes seen in hoodoo concretions. Vertebrate remains occur in small channels but are uncommon. All channels are isolated in fine grained rocks and are never multistoreyed.

Interpretation

The smaller channels show no evidence of the cross beds interpreted in Channels B and D as having been channel bars but do contain fining upward sequences and epsilon cross beds (low angle picked out by fine grained laminae), which are characteristic of point bars. The above features indicate that the rocks under consideration were deposited by meandering streams. The majority of the small scale cross stratification is probably due to the migration of ripple trains (Allen, 1963). Rare parting lineation indicates occasional flow in upper flow regime (Harms and Fahnestock, 1965).

Facies Sh/Sm: Sandstone/Shale Bodies Marginal to Facies Ssc Exhibiting Lateral Fining

Observations

Along part of the southeast margin of channel A is a massive tabular body as thick as the channel and approximately 10 m wide. It is composed of fine grained homogeneous muddy sandstone with about 3% macerated carbonaceous plant clasts. It weathers khaki, but when fresh, is light grey green in colour. There is no evidence of subaerial exposure. There is lateral fining away from the channel and interfingering with the channel deposits (Facies Ssc), and these deposits lap over the top of the channel. Elsewhere on the east side of the same channel are similar deposits interfingering with the channel margin.

On the margin of channel C and smaller channels are thin (<1 m) deposits immediately bordering the channel. They fine laterally away from the channel over the order of 10 m, from medium or fine grained sandstone to siltstone or mudstone. They contain occasional clay pebbles and about 10% unmacerated plant fragments. Sandstones are poor to moderately sorted, rich in clay matrix and white to grey green in colour (Type 2).

Interpretation

On the basis of geometry, proximity and interfingering with channel deposits (Allen, 1965a), and fining away from them (Fisk, 1947), rocks of this facies are considered to represent levees.

On the basis of the thinness of this facies, except associated with Channel A, it appears that levees were generally low (cf. Erpenbeck, 1979).

Facies Ss: Sheet Cross Bedded Sandstone Bodies Exhibiting Lateral and Vertical Fining

Observations

Rock of this facies are represented by tabular sandstone bodies with a thickness of less than 1.5 m. The lower contact of units of this facies is always sharp and often scoured. The lateral extent of individual beds is 10 to 50 m with lateral fining being grossly apparent. Vertical fining is well developed, and locally vertical coarsening occurs. These beds are conspicuous due to their white or light grey colour against the generally drab tabular sandstone and shale deposits, with which they are interbedded. Rocks of this facies are composed of medium to fine grained moderately sorted sandstone with plant material, locally forming 15% of the rock. _Araucauria_ remains have been found on the base of these sandstones with other well preserved coalified plant remains. Planar cross beds and ripple cross laminations are common. Sandstones are poor to moderately sorted, yellow to grey green in colour and of fine to medium grain size (Type 1).

The Turtle Heaven fossil deposit (Chapter III) has a similar geometry to other beds of this facies, but the sandstone is more clay rich and poorly sorted. At this locality there is little vertical fining although there is a notable lateral variation in grain size.

The deposit which covers the main stumpfield (Chapter III) represents a bed an order of magnitude larger than those discussed above, but it is considered a representative of Facies Ss. Although the vertical thickness of the facies at the main stumpfield averages only 75 cm, the lateral extent is approximately 800 x 700 metres. Lateral, and some vertical, fining is apparent as is small scale cross bedding.

Interpretation

On the basis of geometry, location within sequences of tabular sandstones and shales, vertical and lateral fining, and nature of the lower contact, rocks of this facies are considered to represent crevasse splay deposits. Crevasse splays form a minor portion of the overbank deposits, less than 5% of the total, but are more common lower in the sequence, below Marker Bed one.

Facies C: Carbonaceous Beds

Observations

Beds attributed to this facies are highly carbonaceous and are represented in the study area by coals and carbonaceous mudstones. Geometry of the beds is sheet-like and they represent the most laterally continuous beds in the study area.

Only one laterally continuous coal outcrops in the study area, although carbonaceous shales are locally coally. The coal represents the highest laterally continuous thick coal (>75 cm) in the Fruitland-Kirtland formational sequence in the area. It is black, subbituminous and contains <3% of rounded amber blebs 1-4 mm in diameter. The coal extends at least 5 km from west to east and 3.5 km from south to north. The overall thickness varies from half to one and a half metres, the variation in thickness results mainly from intraformational erosion and at several localities it is totally cut out.

A tonstein (volcanic ash) occurs within the top 70 cm of the coal as a linear band(s) and lenses. Lenses of tonstein separated from the main layer are not uncommon (Williamson, 1970). At the Big Bone quarry the tonstein is relatively unaltered, and crystals of mica are easily discernable, but elsewhere it occurs as a linear band within the coal, composed of white kaolinitic clay with only rare crystals evident.

Two laterally continuous carbonaceous mudstones, which locally become coals, occur higher in the sequence. These are generally underlain by a very dark grey or brown carbonaceous mudstone and overlain by grey mudstone, and are about 10 cm in thickness. They represent the most laterally continuous beds in the study area (M1 and M2). Less laterally continuous carbonaceous mudstones occur especially between the coal and M1. They tend to be thinner than Marker Beds one and two and have a lateral extent of tens of metres.

Interpretation

The high percentage of plant material in these beds suggests poor drainage as this is necessary for preservation of coalified plant material (Weimer, 1977), and the small quantity of clastic material together with lateral continuity of the beds suggests formation away from main channel axes. Therefore these beds are interpreted as floodbasin deposits.

Facies Sh/Ssh Interbedded Sheet Sandstones and Shales

Observation

Beds of this facies consist of interbedded sheet sandstone and shale bodies. These beds usually have a thickness of less than half a metre, but their areal extent varies from hundreds to thousands of square metres. Lithologies range from medium grained sandstone to claystone. Most beds have a limited lateral extent measured in tens or scores of metres. Lateral margins are either gradational or abrupt and erosional at channels and crevasse splays (facies Ssc and Ss). Gradational vertical contacts occur but do not predominate.

Sandstones (Type 2) are generally finer grained than those in channel bodies (Facies Ssc). They contain a moderate amount of clay giving drab colours of khaki and grey green as opposed to the whites and light greys of the cleaner bar and crevasse splay sandstones (Facies Ssc and Ss). Small scale cross bedding and ripple cross laminations occur but are not common.

Shales are interbedded with sandstone. Internal lamination is relatively common, usually from 1-5 mm thick, and often undulatory. If present such lamination is picked out by differences in colour or grain size or percentage of plant remains. In a small number of beds dominantly mudstones, subvertical linear coalified plant fragments are found. Sedimentary structures are not common, but climbing ripples were observed at the Dinosaur Quarry which occurs in this facies. Rarely sandstone and shale interbedding occurs on a small scale with beds being about 2 cm thick. Concretions identified as dominantly sideritic (R. Jensen, personal communication, 1982) occur in shale beds, sometimes associated with organic remains (Forest Litter, Main Stumpfield).

Trace fossils are rare in the study area. The only recognised trace fossils are assigned to the genus Trypanites (Frey and Howard, 1982, figure 3; Howard, 1966, figure 9). Trypanites is interpreted as the preserved excavations of a wood boring Teredine (Frey and Howard, 1982). Trypanites occur in two contexts, firstly as separate but associated borings as illustrated by Frey and Howard (1982, figure 3B) and secondly as tightly interwound castings (Howard, 1966, figure 9; Frey and Howard, 1982, figure 3C). In each case the boring consists of clay-rich sandstone tubes of ovoid cross section, 1 to 30 cm in length with a diameter of .8 to 1.2 cm surrounded by a thin carbonaceous layer (less than 2 mm thick). Isolated Trypanites are subvertical and occur in grey mudstones. Interwound examples occur at the base of crevasse splay/small channel sandstones (Facies Ssc and Ss) and individual tubes are rarely more than 3 cm long. Only two examples of each type of occurrence have been discovered. Both examples of the interwound type were found in close association with two upper and one lower jaw of a hadrosaur and a carbonised log. The overall dimensions of the interwoven bodies is 25 cm x 20 cm x 10 cm with the shape being a well defined flattened spheroid.

Interpretation

These sheet sandstone and shale bodies, which form the majority of the rock volume in the study area, are interpreted on the basis of geometry, lithologies, interbedded relationships, and rarity of sedimentary structures as representing floodplain deposits.

The extent to which individual beds represent individual flood events is not known as a single flood can deposit a complex sequence of beds (McKee et al., 1967). The preservation of a ceratopsian skull in overbank deposits (Hutchinson, 1981a) and evidence from the Dinosaur Quarry suggests individual flood events may have deposited a sequence of several beds. Locally shales may represent ponds as in the case of the Leaf Locality (Taphonomy Section).

Internally structureless shale beds are probably caused by rapid sedimentation from suspension, or by intense bioturbation, and thin lamination is probably normally characteristic of floodplain shales (Potter et al., 1980). Bioturbation by terrestrial vertebrates could produce structureless beds if there was a high rate of trampling and a low sedimentation rate (La Porte and Behrensmeyer, 1980, figure 4). In the absence of microscopic examination both bioturbation and rapid sedimentation are assumed to have occurred (Potter et al., 1980). The rarity of trace fossils and the virtual absence of remains of plant roots suggests post depositional bioturbation was an important factor.

There is little good evidence for soil formation on the floodplain, for example mottled coloured beds (as seen at many Naciemento fossil localities), or a sequence of an organic layer underlain by a leached zone. Siderite concretion development may, in some instances, represent a period of soil development (Collinson, 1978a) as in the main stumpfield (Taphonomy Section). In situ subvertical carbonaceous remains are interpreted as roots.

Based on the presence of coals, carbonaceous shales and abundant plant remains in other lithotypes and the absence of evidence for dry subaerial conditions, for example mudcracks or palaeocaliches, it is assumed that interchannel areas were poorly drained.

Facies St: Sandstone Bodies Transitional Between Facies Ssc and Sh/Ss

Observations

Rocks of this facies occur immediately above facies Ssc (channel deposits) as the medial portion of a fining up sequence. They are composed of clay and plant rich sandstone (Type 2) to mudstone and are asymmetrical in cross section. Such an asymmetrical body can be seen in the southwest of Channel A where clay rich fine to medium grained sandstone grading up to mudstone occurs in a triangular shaped wedge with the thicker side to the SSE (3 m thick). In areal view this deposit is linear. Above other channels asymmetrical to symmetrical bodies occur, composed of a fining up sequence from medium grained sandstone to mudstone; the mudstone is usually light to dark grey and contains 10-20% plant material. Beds of this facies, which are usually less than 2 m thick, occur above most outcrops of Facies Ss.

The Big Bone Quarry consists of 1.7 m of sandstone containing poorly sorted plant debris and bones at the top of a channelform sandstone body.

Interpretation

Based on geometry, location above a cross bedded sandstone with a scoured base interpreted as a channel (Facies Ssc), and, within a fining upward sequence, these deposits are interpreted as representing channel-fill deposits.

The direction of thickening of the channel-fill deposit indicates the direction in which the formerly active channel lay (Allen, 1965a), as in the case of Channel A to the SSE. As the deposit is not strongly curved it is presumed to be a result of chute cut-off.

The dark grey colour and plant content of mudstones occurring in channel-fill deposits suggests poor drainage which would be expected in the topographic low that would result from meander loop abandonment.

Concretions

Although no detailed consideration was made of concretions during this study, field observations were made and are noted below.

The most abundant concretions appear to be sideritic. They are light brown, dark brown, or shades of maroon in colour showing compositional layering. A few concretions at the level of, and in, the main stumpfield are more magnetitic (R.M. North, personal communication, 1980), being dark blue to black, with a metallic lustre, being heavier, more spheroidal and more competent than the sideritic ones.

The commonest occurrence, of sideritic concretions, is as flattened oblate spheroids with the long axis subparallel with the horizontal. The dimensions of these bodies average .3-2 m in length, .5-1 m in width, and 10-60 cm in thickness. They occur isolated or in layers with the interval between individual concretions being from one to ten concretion diameters. One layer may extend over scores of square metres. Less commonly, concretions occur as sheets, mainly in channelform sandstones, usually less than 10 cm thick, being laterally continuous over metres or rarely tens of metres. Layers of spheroid concretions may or may not pass through lateral lithology boundaries. A minority of concretions are septarian with calcite or rarely barite veins.

Approximately half of all concretions occur in sandstone with two thirds being in channelform bodies. Of the others, two thirds occur in grey mudstones and a third in other lithotypes. They do not occur in carbonaceous mudstones, coals or volcanic ashes.

Cumella (1981) noted seven types of sideritic concretions in the Lewis Shale to Fruitland Formation sequence. Only his types four and five occur in the study area, these being within thickly bedded sandstones and as laminations in thickly bedded sandstones.

Siderite concretions show affinities particularly for organic rich beds (but not carbonaceous mudstones or coals). Plant, invertebrate and vertebrate, particularly turtle, remains can be found in many concretions although hardness and adhesion of concretionary material prohibits prospecting in these bodies. Cumella (1981) recognised a similar affinity of concretions for organic matter. Primary precipitation of siderite requires a sedimentary environment which has negligible sulphide activity and low Eh values. The first of these requirements is met by meteoric water and the second by decomposing organic matter (Cumella, 1981). The distribution of iron in a rock may be directly related to the presence and concentration of organic matter (Huber, 1958). In channelform sandstones siderite often follows cross laminae and is presumed to be following carbonaceous plant material. In lithologies other than channelform sandstones concretions often occur at lithological boundaries.

Sideritic material is very resistant to weathering once the concretion has shattered into angular shards which have a volume of only a few cubic centimetres or less. Sideritic shards cap hillocks, line the floor of washes, and mark high water lines of washes which may be a metre or so from the present bed indicating major flood levels. Concretionary material often armours shale pebbles.

Rarely, sideritic concretions grade into calcium carbonate concretions (Figure 28). Calcium carbonate concretions are restricted to channelform sandstones. They form spheroid, planar and cylindrical shapes and due to their resistance to weathering, protect less resistant rocks from weathering (hoodoos). These concretions often form with some linearity related to sandstone body lineation. They are generally white in colour and occasionally light brown on weathering. They may form at several different layers in a channelform sandstone. Such concretions occasionally form directly above vertebrate fossils but show no general relationship with organic material. Hoodoo type concretions are ubiquitous in thicker sandstone bodies (greater than 1 m thick).

Far less common than the above types of concretions are thin layers of cone-in-cone calcareous concretions less than three centimetres thick. Layers are laterally extensive only over a few metres and are light brown in colour. Fibrous calcite, often in rosette form, also occurs in

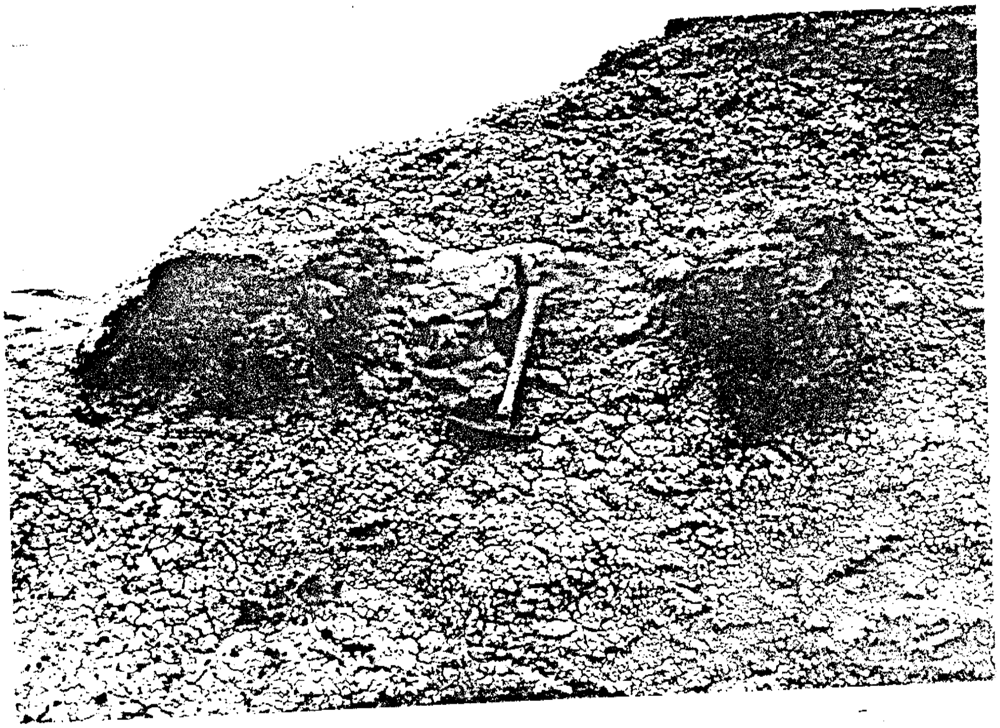


Figure 28. Rare example of calcium carbonate concretion (white) grading laterally into sideritic (brown) concretion.

shales.

Depositional Synthesis

Fluvial Facies Models

"Since the fining-upward cycle model for meandering-river deposits was published in 1963, about a dozen facies models have been defined for rivers of varying sediment grain size, channel multiplicity and sinuosity. However, this suite of models is inadequate for the interpretation of many deposits because it does not incorporate the effects of a variety of outside-the-basin (allocyclic) sedimentary controls (Miall, 1980)."

The classic work of Allen (e.g., 1963, 1964, 1965a, 1965b) on fining upward cycles encompassed a single restricted range of environments being that of a sandy, single-channel river with broad meanders, flowing in a basin undergoing moderate subsidence, in an indeterminate climate (Miall, 1980). In response to this understanding, there are now at least twelve fluvial facies models (Miall, 1980), five for high sinuosity meandering streams (Jackson, 1978), six for low sinuosity braided rivers (Miall, 1978) and one for anatomosed rivers (Smith and Smith, 1980). Despite the plethora of models, they have not kept up with increased understanding of the complexity of geomorphology (Miall, 1982). Sequences in fluvial sediments can be produced by a variety of mechanisms and as Miall (1980) states: "Only in the later stages of ... work is it appropriate to make comparisons with published facies models and to attempt an interpretation of fluvial style." To begin with all fluvial sedmentary controls affecting the basin of deposition and strata under consideration must be considered (Miall, 1980). "A basin analysis approach to the problems concerning the controls on the geometries and morphology (of channels) is attaining widespread acceptance (Eberth and Berman, 1983)."

Fluvial Sedimentary Controls

Explicitly following Miall (1980) a basin analysis approach is taken herein before consideration is given to the fluvial style of channels in the study area. This consideration of fluvial controls follows Miall (1980, table 1) and all interpretations of geomorphic and sedimentary responses to controls follow this work.

The fluvial system in consideration is late Mesozoic in age, which implies that vegetation probably occupied most ecological niches, moderating runoff in humid climates (Environmental Indicators). Sedimentary responses would include stabilisation of channels by vegetation and common mixed or suspended load channels.

Two source areas contribute to the Fruitland and Kirtland Formations and therefore, possibly to the study area. The source area in Arizona probably had relatively low relief by this time (Cumella, 1981), and its rate of uplift was less than that of its erosion. These factors imply gentle stream slopes with a tendency for higher sinuosity streams and a decrease in stream power. Resulting deposits would tend to be finer and part of an overall fining upward sequence.

The second source area, in southwest Colorado, had, in contrast, probable high relief and uplift at a higher rate than erosion, as evidenced by the alluvial fan development of the Animas and Ojo Alamo Formations. Expected responses would be a coarsening upward sequence, seen in the Fruitland-Ojo Alamo formational sequence, and a tendency for coarser deposits to occur, evidenced in the Farmington Sandstone.

The climate of the southwestern United States, and hence of source areas, in the Campanian and Maastrichtian was humid (Lawson, 1972; Cumella, 1981; this report). Such a climate implies abundant vegetation, perennial runoff, low to high discharge variability with mixed or suspension load streams being common. Fine deposits would be expected to be dominant, with channel braiding rare.

Subsidence of the basin of deposition during Upper Cretaceous time was rapid, is shown by the 1,800 m of accumulated sediment. As evidenced by fluvial deposits, this would suggest rapid aggradation, with channel scouring minor and preservatiion of intact channel sequences.

The climate of the basin of deposition during Fruitland-Kirtland time was warm and humid (Cumella, 1981; this report). Such a climate suggests dense vegetation with mixed and suspension load streams being common. Braiding would be rare, and there would be a tendency for streams to have high sinuosity.

The basin of deposition was large (about 400 km to southwest source) suggesting that the deposit type would be internally consistent with a marked facies contrast across the basin. Large trunk rivers might be expected. The northwest source area was nearer, on the order of a maximum of 150 km, and would probably give rivers which were short and steep with limited water and sediment storage capacity. Coarser and more variable deposits would be dominant.

In the study area meander enlargment or translation by the lateral accretion of point bars is suggested by the presence of epsilon cross beds (Allen, 1963). Given the operation of such a mechanism, classic fining upward cycles are to be expected.

There is evidence of chute cutoff (Facies St) in the study area, a process that would result in scouring of point bars, development of chute bars, and abandonment of meanders (possibly resulting in oxbow lake development). Resultant observable features should include chute structures imposed on point bars and fine-grained channel fill.

Interpretation of Facies Ss indicates that crevassing occurred in the channel systems under study. Crevassing results in progressive meander abandonment and the development of crevasse splays. As a result of crevassing, small coarsening upward sequences are to be expected in the floodplain.

Channels B and D are interpreted as exhibiting channel bar migration, which would give rise to the development of sand flats and islands. The expected internal composition of beds would be planar cross bedded sequences and the formation of fining upward cycles where sand flats overlie channel lag and dune deposits.

The age and climate of the basin, the distance of the southwestern source area, and its climate would all be expected to produce, in the study area, mixed to suspension load streams with high sinuosity and dominantly fine grained deposits. The proximity of the northwest source area might suggest coarser grained, steeper gradient, less sinuous streams with bed load being predominant. Based on the rapid subsidence of the basin of deposition, intact channel sequences are expected to occur. Meander translation, crevassing and chute cutoffs are suggestive of a meandering fluvial style whereas the presence of channel bars suggests braiding.

Cyclicity

It is apparent from examination of the stratigraphic sections that there are several scales of cyclicity in the study area:

(a) Fining up sequence consisting of a scoured base overlain by a cross bedded medium to coarse grained sandstone overlain by shales. Scale 1.5 to 6 m.

(b) Coal or coally carbonaceous mudstone overlain by one or more of (a). Scale 6-12 m.

(c) Interbedding of tabular sandstones, siltstones, mudstones, and claystones. Scale 1-3 m.

(d) Interlamination of siltstones and mudstones or claystones. Scale centimeters.

In view of the apparent cyclicity, a numerical treatment, proposed by Selley (1969), was applied to 24 measured stratigraphic sections in the study area. The facies described above were not used in the consideration of cyclicity, as facies by definition are not indicative of environments of deposition. Instead ten lithosomes were delineated in the measured sections and utilized in the numerical treatment. The term lithosome has been defined in a number of contradictory ways (Moore, 1957; Weller, 1958). Herein lithosome is used to describe "a body of sediment deposited under uniform physico-chemical conditions (Sloss in Weller, 1958)." Lithosomes utilized below were recognized on the basis of lithology, organic content, cross bedding and nature of the lower contact.

Sc. Channelform sandbodies composed dominantly of white to light gray, medium grained sandstones. Cross bedding, generally planar, is common and clay pebbles are common near the scoured base. These sandbodies tend to be ellipsoid in areal extent with a lenticular cross section. Interpreted as channel bar, point bar and associated channel lag deposits. This lithosome is equivalnt to Facies Ssc.

S. Sandstone bodies generally tabular to elongate and lenticular in cross section.

They are much more laterally continuous than those in Sc. They are composed of medium to fine grained sandstones generally of yellow and green colours. Some small scale cross bedding. Interpreted as flood deposits and channel-fill. This lithosome is equivalent to Facies St, Ss and parts of Facies Sh/Sm and Ss/Ssh.

slg	Grey siltstones occurring in tabular sheets and rich in plant remains. Interpreted as deposits in a poorly drained (on account of abundant plant remains) floodplain by overbank flow. This and the following five lithosomes are equivalent to parts of Facies Sh/Sm and Ss/Ssh.
slgg	Grey green siltstones. Depleted in plant remains. Geometry and mode of origin as slg, but deposited in a well drained (on account of lack of abundant plant remains) floodplain.
mg	Grey mudstones rich in plant remains. Geometry and deposition as slg.
mgg	Grey green mudstones deplete in plant

	remains. Geometry and deposition as slgg.
clg	Grey claystones rich in plant remains. Geometry and deposition as slg, mg.
clgg	Grey green claystones deplete in plant remains. Geometry and deposition as slgg, mgg.
cm	Carbonaceous mudstone occurring in thin tabular sheets laterally extensive over kms (cf. slg, slgg, mg, mgg, clg, clgg extensive over tens or hundreds of metres). Facies cm interpreted as deposits of poorly drained floodbasins. This lithosome is equivalent to parts of Facies c.
c	Coal occurring in laterally continuous sheets extensive over kms. Interpreted as deposits of poorly drained floodbasins. This lithosome is equivalent to part of Facies c.

Thickness data for lithosome and lithologies derived from 24 sections measured in the study area are recorded in Table 3. Apart from channel sandstone (Sc) and carbonaceous mudstones (cm) most lithosomes show a fairly uniform thickness. Almost half of the rock thickness in the study

Table 3. Thickness data for facies, lithologies and depositional environments

Lithosome	Total Thickness*	No. of Beds	% of Beds	Average Thickness	% of Total Thickness
Sc	4494	38	12.14	118.26	28.77
S	2964	61	19.49	48.59	18.98
slgg	663	17	5.43	39.0	4.24
slg	1006	24	7.67	41.92	6.44
mg	2412	76	24.28	31.74	15.44
mgg	2226	47	15.01	47.36	14.25
clgg	650	9	2.87	72.22	4.16
clg	378	12	3.83	31.5	2.42
cs	333	18	5.75	18.5	2.13
c	493	11	3.51	49.3	3.16
TOTAL	15619	313	99.98	49.84**	99.99

Lithology	% Total Thickness	Average Thickness of Beds	Total Thickness of Beds
Sandstone	47.75	99	7458
Siltstone	10.68	41	1669
Mudstone	29.69	123	4638
Claystone	6.58	21	1028
Carbonaceous Shale	2.13	18	333
Coal	3.16	11	493
TOTAL	99.99	313	15619

Thickness of strata representative of subenvironments	Thickness	% Thickness
Non channel sandstone (S)	2964	18.98
Poorly drained overbank (mg, slg, clg, cs, c)	4551	29.14
Well drained overbank (mgg, slgg, clgg)	3610	23.11
Total overbank & transitional deposits (all above)	11125	71.23
Channel sandstone (Sc)	4494	28.77
TOTAL	15619	100.00

*All thicknesses in centimetres

**Average of average thicknesses

area is composed of sandstone with another third being mudstones. Siltstones, claystones, and carbonaceous beds are of minor volumetric importance. It appears that poorly drained overbank conditions were not much more common than well drained. However, this conclusion is largely an artifact produced by the definitions of facies given above. The facies, interpreted as representing well drained floodplains (slgg, mgg, clgg), contain common plant debris and have greenish grey colours indicative of reducing conditions (Potter et al., 1980). It is apparent that these rocks were laid down in areas of relatively poor drainage. No overbank deposits in the study area exhibit the purple or red colours indicative of oxidising conditions.

The methodology proposed by Selley (1969) is as follows. Three data arrays are contructed. The first records all vertical transitions between lithosomes with the lithosome in any given row overlying that in a corresponding column; this is the Observed Data Array (Table 4). The second array gives predicted values for the transitions, assuming a random arrangement of lithosomes (Table 5). It is calculated by cross-multiplying the row and column totals of the observed data and dividing by the total number of transitions; this is the Predicted Data Array. The third array is obtained by subtracting the second from the first array; this is the Difference Array (Table 6).

OBSERVED DATA

	Sc	S	slg	slgg	mg	mgg	clg	clgg	cs	c	TOTAL
Sc	0	14	0	2	11	7	1	0	2	0	32
S	5	11	6	7	13	8	2	3	5	1	61
slg	2	3	1	3	1	1	0	0	1	0	12
slgg	4	5	1	2	4	5	1	1	1	0	24
mg	6	11	3	7	17	13	3	6	5	3	74
mgg	6	8	1	1	14	4	1	1	2	0	38
clg	1	1	0	0	2	2	1	1	0	0	8
clgg	2	5	0	1	1	1	0	0	0	0	10
cs	1	2	0	0	9	2	0	0	1	3	18
c	3	0	1	0	7	0	0	0	0	0	11
TOTAL	30	60	13	23	79	43	9	12	17	7	293

Table 4. Observed data for lithosome analysis.

PREDICTED DATA

	Sc	S	slg	slgg	mg	mgg	clg	clgg	cs	c	TOTAL
Sc	3.79	7.58	1.64	2.90	9.98	5.43	1.14	1.51	2.15	0.88	37
S	6.24	12.49	2.71	4.79	16.44	8.95	1.87	2.50	3.54	1.46	60.99
slg	1.23	2.46	0.53	0.94	3.23	1.76	0.37	0.49	0.69	0.28	11.98
slgg	2.46	4.91	1.06	1.88	6.47	3.52	0.74	0.98	1.39	0.57	23.98
mg	7.58	15.15	3.28	5.80	19.9	10.86	2.27	3.03	4.29	1.77	73.93
mgg	3.89	7.78	1.69	2.98	10.24	5.58	1.17	1.56	2.20	.91	38
clg	0.82	1.64	0.35	0.63	2.16	1.17	0.24	0.33	0.46	0.19	7.99
clgg	1.02	2.05	0.44	0.78	2.70	1.47	0.31	0.41	0.58	0.24	10
cs	1.84	3.69	0.80	1.41	4.85	2.64	0.55	0.74	1.04	0.43	17.99
c	1.13	2.25	0.49	0.86	2.96	1.61	0.34	0.45	0.64	0.23	10.96
TOTAL	30	60	12.99	22.97	78.93	42.99	9	12	16.98	6.96	292.82

Table 5. Predicted data for lithosome analysis.

DIFFERENCE DATA

	Sc	S	slg	slgg	mg	mgg	clg	clgg	cs	c
Sc	-3.79	6.42	-1.64	-0.90	-5.44	-1.95	-0.87	-1.51	-1.54	-0.88
S	-1.24	-1.49	3.29	2.21	-3.44	-0.95	0.13	0.50	1.46	-0.46
slg	0.77	0.54	0.47	2.06	-2.23	-0.76	-0.37	-0.49	0.31	-0.28
slgg	1.54	0.09	-0.06	0.12	-2.47	1.48	0.26	0.02	-0.39	-0.57
mg	-1.48	-4.15	-0.28	1.20	-2.9	2.14	0.73	2.97	0.71	1.23
mgg	2.11	0.22	-0.69	-1.98	3.76	-1.58	-0.17	-0.56	-0.20	-0.91
clg	0.18	-0.64	-0.35	-0.63	-0.16	0.83	0.76	0.67	-0.46	-0.19
clgg	0.98	2.95	-0.44	0.22	-1.70	-0.47	-0.31	-0.41	-0.58	-0.24
cs	-0.84	-1.69	-0.80	-1.41	4.15	-0.64	-0.55	-0.74	-0.04	2.57
c	1.87	-2.25	0.51	-0.86	4.04	-1.61	-0.34	0.45	0.67	0.23

Table 6. Difference data for lithosome analysis.

From the Observed Data Array is constructed an Observed Lithosome Transitions Diagram showing the most common upward and downward transitions for each facies (Figure 29). From the Difference Array is constructed the Preferred Relationships Diagram which shows the largest numbers of upward and downwards transitions that occur for each facies, after subtracting those predicted if the beds were randomly arranged (Figure 30).

The Observed Lithosomes Transitions Diagram shows a complex pattern, but certain relationships can be seen. There is a broad fining upward sequence from channel (Sc) to channel-fill/overbank sandstone (s) to shale. Mudstones and claystones are often interbedded with grey mudstone (mg); this is merely a reflection of the abundance of beds of lithosome mg. Coals and carbonaceous mudstones appear to be closely related to lithosome mg indicating, unsurprisingly, that carbonaceous material was best preserved in poorly drained areas with little clastic input.

The Preferred Relationships Diagram shows two basic successions

(a) Sc-> S-> slg-> slgg-> Sc
(b) Sc-> S-> cm-> c-> clg-> mgg-> mg

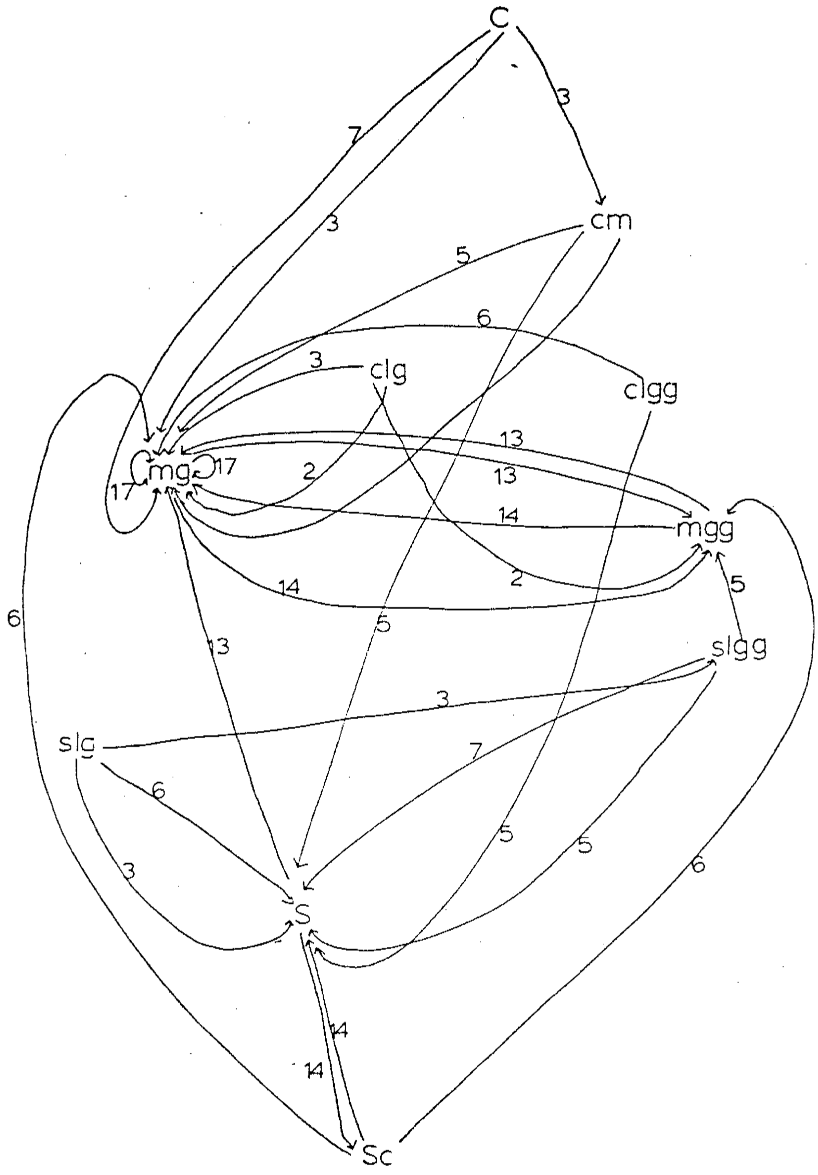


Figure 29. Observed transitions diagram.

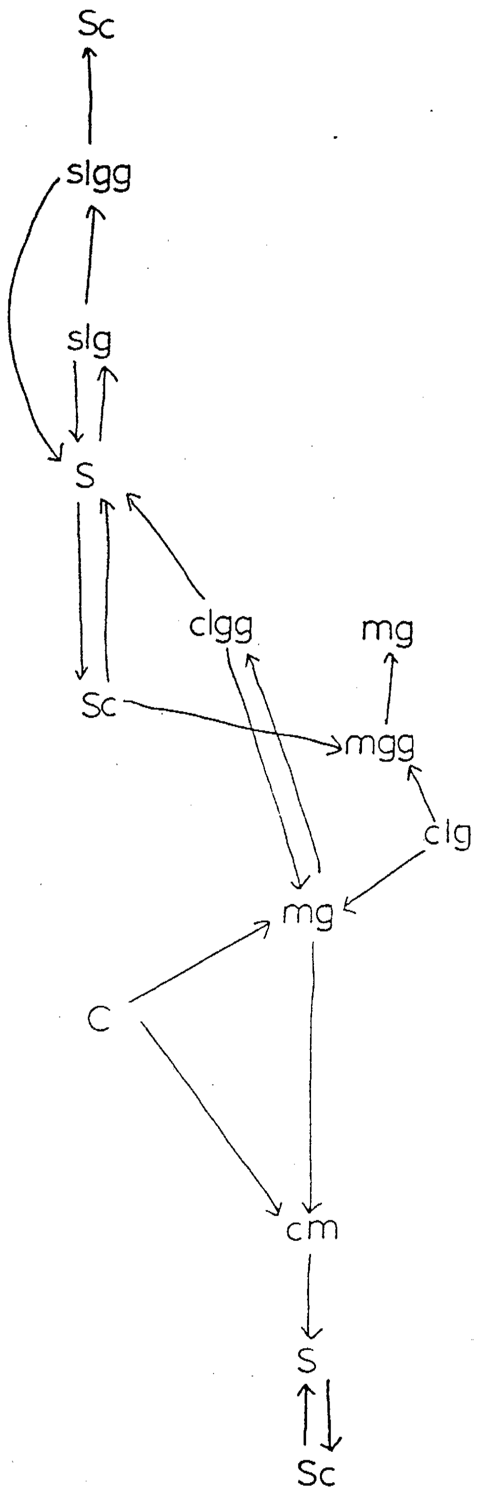


Figure 30. Preferred relationships diagram assuming lithosomes are not randomly distributed.

The first sequence represents a fining upward sequence of essentially inorganic clastic deposition, whereas, the second involves the accumulation of a large quantity of organic material, and less inorganic clastic, material. In terms of drainage: (a) becomes progressively better drained, whereas, (b) is initially poorly drained becoming more so before it tends to become better drained. Siltstones and sandstones, as opposed to mudstones, claystones, and carbonaceous beds, constitute the well drained sequence based on the interpretation of lithosomes given above. The coarser grain size and hence probable increased permeability of the well drained sequence are probably related. The coarser grain size of the better drained sequence may also be explained by a higher energy of deposition, rapidly infilling topographic lows, whereas, away from centres of deposition, where deposits are finer, low lying areas would be poorly drained. Coal is dominantly overlain by grey mudstone suggesting that clastic input, possibly interacting with a change in water table, terminated peat development.

Fining up sequences are well documented in fluvial environments (e.g. Allen, 1962, 1964, 1970; Miall, 1980) and probably have one of four possible causes:

(i) Autocyclic cycles, e.g. related to channel migration or bankfull floods

(ii) Allocyclic cycles: tectonic control

(iii) Allocyclic cycles: climatic control

(iv) Allocyclic cycles: change of base level
to which rivers empty

As the rivers of the study area were draining into a regressing sea, there is a possibility that cyclicity was due to changes in base level, but this is considered unlikely because of the small timescale that must be represented by each cycle. There is no evidence of dramatic climatic change during the Upper Cretaceous of the southwestern United States, which would affect either source areas or the environment of deposition over the short timescale represented by the cyclicity. Climate is not considered to have caused the evident cyclicity. It is difficult to distinguish the effects of tectonic controls from other sedimentary mechanisms (Miall, 1980). Tectonic effects are likely to be on a larger scale, both vertically and areally, than those autocyclic sedimentary mechanisms (Miall, 1980). Although vertical sequences controlled by tectonic mechanisms may be only 10 m thick (Miall, 1980, figure 3A), the vertical scale of fining upward sequences in the study area argues against tectonic control as being important in causing cyclic sedimentation. Only Channel B and possibly Channel D seem to have lateral sedimentological equivalents which show fining upward. Except perhaps for Channels B and D, cyclicity of sedimentation in the study area is attributed to channel migration and bankfull floods.

The cyclicity of coal or coally carbonaceous mudstones may be related either to meadering of stream axes far from the study area or periodic rise in water table, possibly related to change in base level. Weimer (1977) noted that "the position of groundwater table relative to the depositional interface is critical in the preservation of organic material. In the poorly drained swamps where organic material accumulates rapidly and the depositional interface is continuously covered with water, little oxidation occurs and peat forms. However, in well-drained swamps the accumulating organic material is exposed to the atmosphere for several months a year, which is adequate time to allow for oxidation and removal." Weimer (1977) lists five critical factors necessary for the formation of commercial thicknesses of coal (a) fresh clear water, (b) accumulation of only land-derived organics, (c) balance between ground water table and depositional interface, (d) favourable climate, (e) persistence of conditions in time and space and a favourable basin-wide and/or local tectonic influence on sedimentation. Significant deposits of peat needed to form the lowest thick coal may have formed by subsidence of interchannel areas or possibly as a result of the doming mechanism suggested, for fluvial coals in the Palaeocene Upper Fort Union Formation, by Flores (1981), in which a continuous rise in groundwater table is postulated to have given rise to thick coals.

Palaeocurrent Dispersal

The dispersion of current indicators has been taken to be indicative of fluvial style. Meandering streams were thought to be characterised by a large dispersion, often greater than 180 degrees, and braided streams by a low dispersion, often less than 90 degrees (Jackson, 1978).

It is logical to assume that braided streams, which are generally of low sinuosity, would be characterized by lower directional variance than other more or less unimodal flow systems, such as meandering streams, but there are several complicating factors (Miall, 1977). Sedimentary structures form a hierarchy with each scale characterized by a different range of directional variance. Also directional variability depends, to a considerable degree, on discharge level with uniform direction often only occurring at high water stage. At low water, flow is more controlled by the topography of larger bedforms. Finally, braided streams often have extremely variable flow which may not give bedforms enough time to reach equilibrium (Miall, 1977). As a result of these factors, braided streams may show dispersion of current directions indistinguishable from meandering streams (Jackson, 1978).

Bedforms, in the study area, from which palaeocurrent measurements were taken, were all of Rank 5 (Miall, 1974). That is they were internal structures within bars. Approximately three quarters of these readings were from small scale (Allen, 1963) planar cross beds.

Palaeocurrent directions from Channels A, B, C, and D have been replotted as percentages (Figure 31). It is apparent that Channels A, B and C differ markedly from Channel D, in having a lower vector strength of the vector mean of current directions. Channels B and D differ from Channels A and C in having a more northerly as opposed to easterly directional trend. Variance of current direction indicators has been used to differentiate between braided and meandering streams (Table 7). The low vector strength of the vector mean of Channel D may indicate that flow in that channel represents braided flow whereas Channels A, B and D represent more meandering flow. Both meandering and braided flow can occur in different reaches of the same stream. The vector means of Channels B and D (41.1 degrees and 83.9 degrees respectively) are in marked contrast to those of Channels A and C (356.8 degrees and 349.1 degrees respectively).

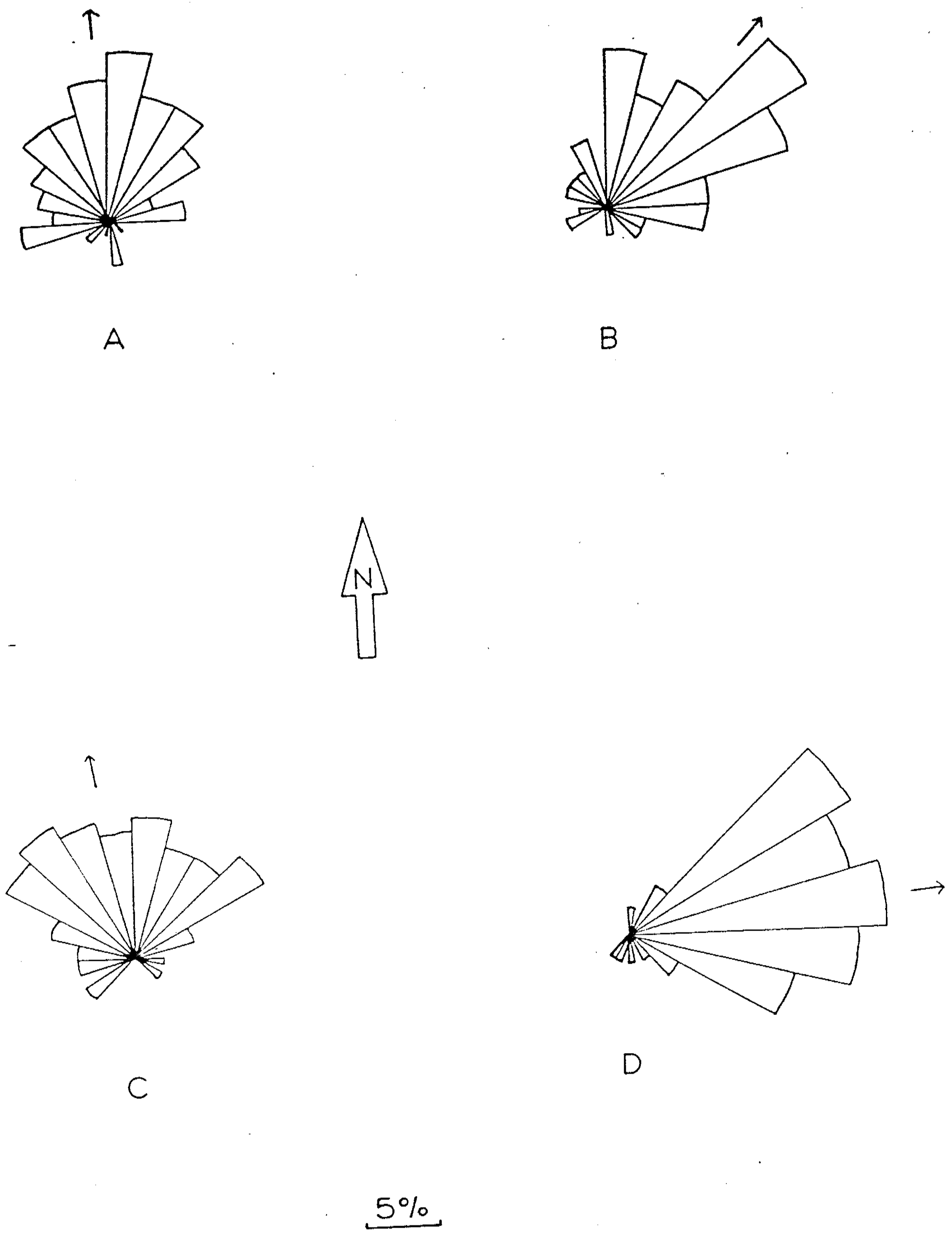


Figure 31. Rose diagrams of current directions from Channels A, B, C
and D. Solid arrows indicate vector mean directions.

Depositional Synthesis

Before consideration is given to the overall style of fluvial sedimentation in the study area, one further fact needs to be elaborated upon.

At the stratigraphic level of the Fossil Forest a tabular brown capped sandstone occurs in Hunter Wash (this report), in Ash-shi-sle-pah Wash (Reeside, 1924), and in cottonwood Arroyo (Reeside, 1924) over a distance of 60 km. These sandstones are correlated lithostratigraphically and were used, at least in some areas, to delimit the Fruitland-Kirtland formational boundary (Reeside, 1924; plate II). These sheet sandstones are generally less than 5 m thick and contain planar and trough cross beds and ball and pillow structures. The upper half of the sandstone is locally or continuously red-brown in colour and the lower, light grey to white. The lower contact is undulatory and erosional. The sandstone is coarse to very coarse in grain size and moderately sorted. These sandstones are conspicuous and distinct from other sandstones in the sequence from the Pictured Cliffs Sandstone to the Farmington Sandstone Member of the Kirtland Shale in the area under discussion, because of their tabular geometry, lateral extent, and red-brown colour. Further north on the Navajo Mine Lease of Utah International, sandstones with characteristics similar to those under discussion occur throughout the Fruitland and Kirtland Formations. The lateral extent of this facies has been commented upon, without documentation, by Hutchinson (1981a). Hutchinson (1981a) speculated that this sandstone represented a "delta top" sandstone representing the branching of the deltaic trunk stream at its dispersal centre. However, as Erpenbeck (1979) has indicated, deltaic facies do not extend from Hunter Wash to Ash-shi-sle-pah Wash. It seems logical to assume that Channel B and possibly Channel D are genetically related to this regional pattern of sandstone deposition.

An anastomosing channel model is rejected for the interpretation of channels in the study area, because of absence of coarse channel deposits (gravel) in association with organic rich overbank deposits (Smith and Smith, 1980). The style of sedimentation of channels in the study area is either meandering or braided.

A number of criteria have been commonly cited as being diagnostic of meandering or braided streams (Table 7). Jackson (1978) has reviewed these criteria and considers several to be extremely unreliable and several to be essentially valid, but whose application is to be treated with caution. One commonly cited criteron used for the recognition of deposits of meandering streams is the presence of epsilon cross beds (Allen, 1963). Although Jackson (1978) is highly critical of this criterion, Miall (1980) considers that it is useful and cites several studies

TABLE 7. Commonly Cited Sedimentological Criteria for Fluvial Deposits

Criterion	Meandering	Non-meandering
(A) Considered extremely unreliable (Jackson, 1978)		
Vertical sequence of lithofacies	Fining-upward cycles (of grain size and sed. structures)	No consistent sequence
Fine member	Normally common and appreciably thick	Uncommon and thin
Rock gravel in coarse member	Small amounts; few large clasts	Can be abundant, with large clasts
Scroll bars	Common	Absent
Scouring surfaces in coarse member	Uncommon	Abundant
Continuity of sand and gravel beds (in coarse member)	Often great, with little lateral change in texture	Beds often lenticular and discontinuous
(B) To be considered with caution (Jackson, 1978)		
Channel-fill and deposits	Common, esp. in muddy streams; long and arcuate	Minor; short
Chute-fill and chute bars	Expected in "coarse-grained" streams	Uncommon
Natural levees	Often prominent	Minor
Dispersion of current indicators	Large, often less than 180 degrees	Small, often greater than 90 degrees
Exhumed meander belt	Can be expected in proper sections	Absent
(C) Considered reliable by Miall (1980), but not by Jackson (1978)		
Epsilon-cross stratification	Common	Absent

where it has proved of use. In this study, well developed epsilon cross beds are considered characteristic of the point bars of sinuous meandering channels.

A body of evidence argues for the presence, in the study area, of deposits produced by meandering streams. An overview of fluvial sedimentary controls effecting the area suggests that stream deposits might be dominantly fine grained and the result of deposition by mixed to suspension load streams with a high sinuosity. The abundance of overbank deposits (Table 3), the presence of fining upward sequences (both in terms of lithology and cross beds), the presence of common channel-fill deposits and natural levees, the dispersion of current direction indicators (Channels A and C), the presence of epsilon cross beds (indicating lateral accretion), all argue for the rocks in the study area having been deposited by meandering channels. None of the above criteria would, in themselves, be adequate to define the style of fluvial sedimentation in the study area, but in association they are considered to do so. Based on lack of rock gravel as bed load, thickness of the fine member, the presence of epsilon cross bedding and levees, and the absence of chute deposits, deposition falls within the lithofacies model of Jackson (1978) for muddy fine grained streams.

Certain lines of evidence suggest that Channels B and D represent braided streams. The coarser grain size (up to very coarse sand size), the lack of epsilon cross beds, the presence of sedimentary sequences interpreted to have been caused by transverse and longitudinal bars, the lack of associated levee deposits, and the small dispersion (Channel D) in current directions all point to Channels B and D being the results of braided stream deposition. In terms of facies models for braided streams Channels B and D are most similar to the Platte Type (Miall, 1977, 1978a). The Platte type of stream is characterized by an abundance of linguoid bar and dune deposits (planar and trough crossbedding) and may only be braided at low water (Miall, 1977).

Schumm (1981) notes that the "sedimentologist should not be surprised when he finds extreme variations in fluvial deposits such as those between braided channels and meandering channels within the same stratigraphic unit. There are abundant reasons for abrupt vertical and longitudinal variations," which include vegetation stabilization, change in type of sediment load, changes in valley floor gradient, and tectonic activity (Schumm, 1981). Thus it is not unreasonable to postulate the presence of braided and meandering streams within the short stratigraphic interval outcropping in the study area.

The correlation of red-brown sandstones in Hunter Wash, and possibly in Ash-shi-sle-pah, with those in the study area implies a short term change in sedimentological conditions. The red brown sandstone in Hunter Wash has an average thickness to lateral extent ratio (about 5 m: outcropping 4 km) which would preclude it from being formed by a meandering stream according to the criteria of Collinson (1978b, figure 2), and it may have resulted from a sheet flood event (cf. Collinson, 1978b). Friend (1978) has suggested that sheet style sedimentation may be related to rates of aggradation. Slow aggradation may cause much reworking of sediment and hence more discrete channel scours. One explanation for Channels B and D is that they represent a brief period of braided stream deposition at the end of Fruitland time. Reason for this change in fluvial style could include ("proto-Farmington Sandstone") uplift of the northwest source area causing a pulse of higher energy sedimentation (possibly indicated by the more easterly flow directions of Channels B and D) or clogging of streams by volcanic ash. The fact that channels similar in character to those in the study area are much more common in the northwest of the Central Basin, nearer the northwest source area, argues for Channels B and D being higher energy braided streams. Both Channels B and D almost immediately overlie on airfall ash. It is important to remember that only a slight change in the controlling variable may cause a change in fluvial style, if channels are near pattern thresholds (Schumm, 1981). Alternatively Channels B and D may represent braided reaches of otherwise meandering streams. Several factors may cause streams to show different styles of fluvial deposition along their length (e.g. Jordan River, Schumm, 1977). If this solution is correct, it does not answer the question as to why this mode of sedimentation only occurs at this stratigraphic interval.

Based on present evidence it is not clear if Channels B and D represent braided channels or braided reaches of meandering channels. In either case some short lived sedimentological, tectonic, or hydrologic change caused a metamorphosis of channel style near the boundary between the Fruitland Formation and Kirtland Shale.

Depositional Sequence

The vertical sequence as exposed in the study area is interpreted as having been a result of the following sequence of events (Plate 3).

A) Poorly drained floodbasin (swamp) which persisted for time sufficient to deposit peat which formed the main coal. Near the end of peat formation, airfall volcanic ash covered the area.

B) Incision of a meandering channel system into the swamp. This system was more erosive than those which followed. It eroded through the peat and gave rise to numerous flood events. The majority of animal and vegetable fossils are preserved from this period of time. Approximately 25% of the invertebrate, 80% of the petrified wood, and 70% of the vertebrate localities are from this interval. These localities include the Big Bone Quarry, Dinosaur Graveyard, main Stumpfield, Forest Litter, Quarry 1, Quarry 2. Quarries 3 and 4, Turtle Heaven and the Dinosaur Quarry occur above this interval. Downcutting through the coal can be seen near stratigraphic sections BAO, BAD, BAE and erosional thinning at BAT. Channel A is the largest channel-form sandstone body in this interval. It appears that channels in the study area did not often erode a coal or coally carbonaceous mudstone. Channel A and its associated sediments are an exception, but Channels B and D directly overlie Marker Beds one and two, respectively, without eroding down into them and similar behavior can be seen in smaller channels. Triplehorn (1982) has recently noted peat restriction of downcutting of stream channels in Tertiary coals in Alaska. Flow seems to have been to the northnortheast. The downcut sequence is recognisable mainly in Section 23, where the coal occurs as laterally discontinuous beds with erosional lateral boundaries. In Section 22 the coal has been channelled down into but not removed. In Section 15 and westernmost Section 14, the coal is uneroded. The coal is not exposed elsewhere within the study area. Crevasse splays are more common in this interval than in others.

C) Poorly drained floodbasin swamp of lesser temporal extent than in (A), producing Marker Bed one, followed soon after by second airfall ash.

D) Stream system (Channel B), exhibiting characteristics of a braided stream where viewed, flowed through area in a more easterly direction than the preceding channel system.

E) Stream system (Channel C), exhibiting characteristics of a meandering stream where viewed, flowed through area in a north north west direction.

F) Poorly drained floodbasin swamp of similar duration to (C) produces Marker Bed two followed by third volcanic ash fall.

G) Stream system (Channel D), exhibiting characteristics of braided flow where viewed, flowed through area in an east north east direction. Overbank deposits at this time and afterward contain more siltstone and fine grained sandstone and less mudstone and claystone (section BAZ) than at lower stratigraphic intervals.

There is a trend upward through this sequence of beds becoming less organic rich and coarser grained. At the base of the exposed section is a relatively thick coal overlain by overbank deposits, containing a lot of grey organic rich mudstones. The top of the section, in contrast, consists of a thin coal overlain by a sequence of dominantly nonorganic rich grey green siltstones and fine grained sandstones. Fossil remains of all kinds decrease upward. This upward trend reflects a change seen regionally in the transition from the Fruitland Formation to the Kirtland Shale, which is probably related to an increase in drainage and a change in fluvial style (and possibly climate) associated with the withdrawal of the Pictured Cliffs sea and the uplift of the northwest source area.

The stratigraphic interval represented by stage B is of great interest owing to the large number of fossil localities that it contains. Channel A is the largest channel in the study area. Channel A and other contemporaneous channels (stratigraphic sections BAD, BAP, BAT) were more actively erosive than later channels evidenced by their erosion of the coal, whereas other large channels (Channels B and D) immediately overlie coally carbonaceous shale and do not cut down into them. This suggests high discharge and high sediment transport. The nature of flow was periodic, evidenced by large scale epsilon crossbeds in Channel A and an anomalous number of flood events recorded in the large number of crevasse splays and floodsheets (e.g. burying main stumpfield). The combination of high discharge and periodicity of flow may account for the large number of fossil localities. High discharge would move large amounts of skeletal debris. Periodicity in flow would result in "dumping" events and frequent floods burying skeletal material lying on the floodplain.

III. TAPHONOMY

Introduction

Taphonomy, as first defined by Efremov (1940) is the study of everything that happens to an organism between the time that it dies and the time that you find it, if you ever do, as a fossil (Table 8). Efremov called this, "the science of the laws of embedding."

At present, taphonomy is one of the most rapidly growing subdisciplines of palaeontology (recent books include: Behrensmeyer and Hill, 1980; Brain, 1981; Shipman, 1981), but emphasis has been dominantly on the Plio-Pleistocene of Africa as a background to the study of hominid evolution (notably the work of Behrensmeyer, Brain, Hill, Shipman, and Van Couvering). Studies of the taphonomy of Mesozoic deposits are by comparison very few in number. Among the most important Mesozoic studies are those by Olson (1958, 1962), Dodson (1971), Hotton (1967), Lawton (1977), Gradzinski (1970), and Dodson et al. (1980). All these studies were conducted on rock sequences containing particularly abundant or well preserved specimens. The importance of the present study lies in the fact that Fruitland-Kirtland fossils are neither abundant nor particularly well preserved. One of the most accomplished

Events forming boundaries between intervals	Disciplines	
Discovery		
	Diagenetic studies	Taphonomy
Final burial		
	Biostratinomy	
Death		
	Paleoecology	
Birth		

Table 8. Classification of palaeontological disciplines concerned with environments of fossil organisms between their time of birth or hatching and discovery as fossils (from Raup and Stanley, 1978, after Lawrence, 1968).

dinosaur workers, Charles Gilmore (1930, p. 20) wrote of a Smithsonian vertebrate collecting expedition: "As a collecting field for fossil vertebrates, the San Juan Basin area, taken as a whole, is disappointing. Extensive areas of well dissected bad lands with surfaces practically free from vegetation and debris, an abundance of "float" or surface indications of fossils, are ideal conditions that give every promise of yielding rich returns. It was found, however, that in the greater number of instances, the clues followed led only to a single or at most two or three bones of a skeleton. It was readily apparent that individual skeletons had been widely scattered before internment, and that isolated or partially articulated specimens are rarities." Gilmore's comments are based on fieldwork in the most fossiliferous part of the Fruitland-Kirtland outcrop belt from Kimbetoh north to the San Juan River. The Fossil Forest area is anomalously rich in fossil biota for the relatively poorly fossiliferous Fruitland-Kirtland sequence which makes it doubly interesting.

A consideration of the general taphonomic features of the area is followed by more detailed discussion of the most important localities and comparison of them, where possible, with other Mesozoic fossil accumulations.

Previous Taphonomic Work on the Fruitland and Kirtland Formations

Taphonomic data is virtually impossible to glean from the work of older authors. A rare exception is found in Sternberg's memoirs (Sternberg, 1932) where the type skull of Pentaceratops fenestratus Wiman is said to come from a very hard, clay rich sandstone and to have been underlain by "a great deposit of leaves of forest trees." He illustrates this locality with a photograph (Sternberg, 1932, figure 55) which, together with the above description, seems to indicate that the skull was recovered from a channelform sandstone. A ceratopsian skull would rarely be moved by stream velocities on the order of those present in channels of the Fruitland or Kirtland Formations and thus any vegetable material under it would be protected. Sternberg also noted a concentration of fossil logs in the region.

More recently Hutchinson (1981a) noted that biotas, "that existed in fluvial, forest, floodplain, and paludal paleoenvironments on the delta plain are generally better represented than the others." The "forest" and floodplain environments are said to be particularly fossiliferous where much wood is found, some in situ. Bones are said to be uncommon on the floodplain as skeletons resting there would rarely receive sediment cover sufficient to protect them from predators (and weathering). The present study indicates that bone material is slightly more common on the floodplain than in channel sandstones, although less well articulated. Hutchinson considered only the time intervals between floods, which are indeed poor for preservation, rather than the floods themselves which are perfect for preservation representing geologically instantaneous deposition events. The lack of relatively complete material in floodplain deposits, in contrast, is probably due to the incremental nature of sedimentation in this environment. The thinness of most of these flood deposits would not provide sufficient cover from scavengers or weathering processes to protect complete skeletons nor would they possess the energy to move whole carcasses, except in the shortlived "bloated" state. Channel deposits could, in contrast, provide rapid burial for entire carcasses.

Hutchinson (1981a) reports that the probable locality of the partial skull of Pentaceratops collected by the University of Arizona, occurs in a sequence of overbank shales. Ceratopsian skulls are too massive to be moved by normal current velocities and might be expected to occur isolated in overbank deposits representing the ultimate in winnowed samples. Deposition rates in the floodbasin, at this locality, must have been very high to cover the skull and protect it from scavengers and weathering, before it was destroyed.

Further southeast, in the Star Lake area, Leipzig (1982) noted wood and rare dinosaur remains at the base of "channel sandstones" and a ubiquity of wood in the Kirtland Shale. In the Fruitland Formation, he found "no vertebrate or invertebrate fossils," only fossil wood. The overall depositional setting in the Star Lake area was probably not of a deltaic system, as in the vicinity of the study area, but rather that of a linear barrier beach and back barrier system (Chapter I).

Clemens (1973) reported on the first microvertebrate sites in the Fruitland-Kirtland sequence, from Hunter Wash. The "largest collections of small vertebrates were obtained from the sand and siltstones of a channel filling" and the stratigraphically highest in a lenticular silty sandstone. These localities were from 40 feet below, to 55 above the base of the Kirtland Shale taken to be a "thin but wide-spread coal (Clemens, 1973a)." Lucas and Mateer (1982) also note that, "accumulations of small vertebrate remains occur frequently in coarse to gravelly beds at the bases of the sandstones," in the Fruitland Formation. These accumulations are actually not frequent, being restricted geographically and stratigraphically. Hutchinson (1981a) also noted that small vertebrates were common as channel lags.

The only other adequately described microvertebrate fauna from the Fruitland-Kirtland sequence is that of Armstrong (1976; Armstrong-Zieglar, 1978). To judge from her sketches and poor descriptions (Armstrong, 1976), it seems that her three main localities occurred in clay pebble conglomerate lenses within, rather than at the base of, channelform sandstones in the Fruitland Formation. The Fossil Forest microvertebrate fauna, currently being studied by Wolberg and Rigby (Rigby and Wolberg, 1980), has been recovered from four quarries (Quarries 1-4) discussed below. Preliminary taphonomic data on the Fruitland Formation may be found in Hunt (1982).

General Taphonomy

Carbonised and Compressed Plant Fossils

Plants represent the majority of the fossilised biota in the Fossil Forest area. Macerated plant material, usually carbonised, is almost ubiquitous. Mudstones and siltstones contain from 0 to 60% of usually sub-linear carbonised plant fragments up to 2-3 cm in length, but usually .5 cm or less. Fragments of well preserved leaves, flowers, and fruiting bodies are uncommon and tend to be concentrated at discrete localities. In general the greater the amount of carbonaceous plant material present, the more poorly it is sorted.

Sandstones and some siltstones contain plant material which is usually subrounded and carbonised and of medium to very coarse sand grain size. Such material is more common in overbank sandstones than in channelform bodies, and in the former, usually only accounts for a poorly sorted 10-20% of the volume of the rock. In channelform bodies, plant material is well sorted and constitutes 1-10 % of the rock by volume.

Rocks containing over 60% of plant material are virtually all fine grained and are here referred to as carbonaceous mudstones, and subbituminous coals with ascending plant content. Carbonaceous mudstones range from very dark grey to chocolate-brown with increasing plant content, with the brown shales being very fissile. Subbituminous coals form a continuous sequence showing increasing lustre, amber (up to 5% in large blebs several millimetres in length) and a more blocky fracture.

Carbonaceous mudstones contain, relatively, much less highly macerated plant material than other fine grained rocks. Most of the macerated material is several square centimetres in area and coalified. Leaves are present, but are often difficult to collect due to poor preservation and overlapping of plant material. In brown shales, fissility and poor induration pose additional problems for collection of leaves. Well preserved leaves were only found in quantity at one locality, as compressions in a fine grained claystone.

Carbonised plant material in sandstones is often concentrated in distinct laminae which are usually planar, but which may follow cross lamination. Such laminae may contain greater than 80% of macerated plant material usually of a size greater than the sand grain size, but less than one square centimetre in area. Beland and Russell (1978) suggested that analogous units in the Oldman Formation represent, "reworked faeces of large ornithischian herbivores." This speculation is based on little evidence except that reworked dung occurs in an observed African river and the obvious truism that dinosaurs produced a lot of dung. The large amount of vegetable matter in all sediments, at least in the Fruitland Formation, requires no ad hoc explanation. Periods of slack water, forest fires, or storm damage could easily account for these laminae. Allen (1965a) reports that in top stratum deposits, drifted plant debris may form thick layers. An element of input from faeces, especially at stream crossings and watering locations, must have occurred, but would have tended to occur in the subaerial environment where weathering and coprophagous insects, already present in the Cretaceous (Beland and Russell, 1978), would have rapidly destroyed them.

Clay pebble conglomerates usually contain approximately 20-40% of poorly sorted carbonised plant material including isolated leaves, and rarely portions of laterally compressed logs up to 60 cm x 20 cm x 10 cm in size. In channelform sandstones, some carbonised plant material is almost always found associated with bones, the plant material is usually poorly sorted, and sometimes containing pieces up to 30 cm x 10 cm in area.

Sideritic concretions often contain nonmacerated plant material but it is virtually impossible to extract due to the hardness of the concretions. Sideritic material sometimes follows laminae, often cross laminae rich in plant material, in channelform sandstones.

Clinker (rock baked by burning coal--Wood et al., 1983) is not abundant in the Fossil Forest area but where it does occur, it is brick red and fine grained or white and coarser grained; in each case it contains abundant red plant material. This material is often several square centimetres in area but is virtually always unidentifiable. Leaves have not been found in clinker despite careful searching in the Fossil Forest and at Hunter Wash. Given the scarcity of such material in the unclinkered rocks this is not surprising.

Petrified Wood

Of petrified material, wood is undoubtedly the most common, occurring as stumps, logs, or unidentifiable fragments, always replaced by silica. Petrifaction has resulted in moderate to poor preservation of internal structure. Silicified wood is very resistant to weathering and breaks up to form angular, blocky fragments which are widespread in occurrence. Pieces of wood that were small (<50 cc) prior to petrification are far less common than logs or stumps and are often waterworn and rounded, and appear to be as common in overbank deposits as in channels; they average dimensions of about 30 cm x 10 cm x 10 cm, which represents a strong size bias. As preserved stumps so commonly show rotting, it is likely that the large surface area to volume ratio of small pieces of wood would lead to their rapid disintegration as would their greater susceptability to biodegradation and transport (cf. small bones, Dodson, 1973). Two occurrences show a silicified piece of wood becoming coalified as it enters a carbonaceous mudstone, and in one instance a piece of silicified wood was found in a carbonaceous mudstone with a carbonised outer layer.

Stumps occur predominantly in fine grained overbank deposits and not commonly in channelform sandstones (Table 9). If they do occur in channels, it is either at the edge

Fossil Type	Shale	Sandstone	Associated with Concretions	Unknown Sediment Type	Clay Pebble conglomerate (microvertebrate accumulation)	Notes
Stumps (not including stump field)	177	17	35	79	0	35 rootmasses only not included in other categories
Logs (including stumpfield)	45	12	15	28	0	Average length (n = 21) 6.47m
Dinosaur Bone	96	88*	37	6	12	
Turtle and other vertebrate remains	77	14	15	3	12	
Invertebrate	12	8	24	5	12	

*two hadrosaur tails counted as one unit each

Table 9. Fossil occurrences related to lithotype. Data obtained from inventory sheets from a United States Bureau of Land Management palaeontological inventory of the study area. Data was collected in 1980 by a field crew consisting of C. Robison, G. Engelman, M. Leaf Lucas and J. McKinney under the direction of J. K. Rigby Jr. Data was not collected for the purpose for which it is used herein, and therefore, it is incomplete and has been added to and amended. Inventory sheets area on file with the United States Bureau of Land Management offices in Albuquerque and Farmington.

or rarely the top. A large number of stumps show central rotting prior to fossilisation. The vast majority of stumps are conifers (at least 90%) with a small number of palms, dicots and cycads (C. Robison, personal communication, 1981). Root masses are presumed to represent stumps that suffered severe rotting before fossilisation. It is not common to find vertebrate material intimately associated with silicified wood, although a small amount of bone (both dinosaur and turtle) does occur in the main stump field and the Forest Litter areas. Stumps are usually less than a metre high and .5 to 1 m in diameter.

Logs occur mainly in overbank deposits but are far more common in channelform sandstones than stumps (Table 9). This would be expected as stumps are in situ whereas logs, are in the main, presumed not to be. The fact that logs are often associated with sideritic concretions (Table 9) appears not to be reflection of the fact that many logs occur in channels; more logs associated with concretions occur in overbank deposits than channels. Two or three smaller logs show some rounding attributed to transport abrasion. All but one of the logs are conifers, the one exception being a dicot (C. Robison, personal communication, 1981).

Vertebrate Remains

Vertebrate material is dark brown in colour, possibly suggesting impregnation by manganese (cf. Voorhies, 1969, p. 15) or iron (Gradzinski, 1970), or light grey-white as a result of weathering. Several turtle shells have been discovered where lighter coloured portions have been collected on the surface with darker fragments of the same individual being still buried. High iron content might be expected in bones of this age as this could indicate a subtropical or tropical climate (Houston, et al., 1966).

Exposed bones in sandstones are much better preserved in the sense of being unfractured than in shales. This is a result of fracture within fine grained beds producing abundant slickensides, swelling of clay minerals upon weathering and differential compaction. Scattered clay pebbles and plant debris are usually found associated with the lower surface of bones occurring in channel sandstones. Excavated bones from shales are usually as well preserved as those from sandstones, but more fragmented. The vast majority of bones, in all rocktypes, are isolated, but associations of several bones are far more common in channelform sandstones.

No evidence has been found of carnivore damage on bones, in the form of tooth marks or punctures, suggesting that carnivores and scavengers were not important in the disarticulation and scattering of skeletal elements. However, all vertebrate remains are disarticulated. The absence of evidence of predation has been reported from other Upper Cretaceous deposits and may not indicate that it did not occur (Dodson, 1971). The only examples of carnivore damage to bones, known to the author, from the Fruitland or Kirtland Formations, are a hadrosaur thoracic vertebrae, in the collection of New Mexico Bureau of Mines and Mineral Resources, from the Naashoibito Member showing tooth punture marks and an uncollected limb element in Ah-Shi-Sle-Pah Wash showing characteristic carnosaur tooth striations.

Small pieces of bone, showing rounding, probably due to water transport, are not common. Complete bones of small dinosaurs, such as coelurosaurids, ornithomimids and smaller animals, are extremely rare, except in microvertebrate accumulations. This scarcity can be attributed to predator and scavenger destruction, rapid surface weathering (due to high surface to volume ratio), high dispersal potential (Dodson, 1973), or possibly bioturbation by terrestrial vertebrates (La Porte and Behrensmeyer, 1980).

Bone is often found within ironstone concretions, but it is usually fragmented and is extremely difficult to extract. No bone or invertebrate material has been found in coals or carbonaceous shales. Hutchinson (1980a) reports rare invertebrate and bone scrap in Fruitland carbonaceous beds as does Wolberg (1980). A poorly drained swamp can preserve non-plant fossils (Lund, 1970; Rigby and Lucas, 1977; Muller, 1979; Krebs, 1980) and one of the most complete fossil primates came from such beds (Shipman, 1981). Such environments may have slow weathering rates (Behrensmeyer, 1978) which would favour preservation. However, slow deposition rates, low pH, high degrees of compaction and lack of petrifying minerals do not bode well for the discovery of abundant or well preserved animal fossils in highly carbonaceous beds.

Dinosaur Bone

Dinosaur bone is slightly more common in overbank than channel deposits. Table 9 is biased by the fact that bones in sandstones occur more often in association (at least fifteen associations of six bones or more). The table does not include dinosaur material from microvertebrate assemblages.

Two articulated hadrosaur tails are known from the Fossil Forest area. In addition Gilmore (1930) illustrates another from the Kirtland Shale, and Boss collected another, with three associated elements, from north of Hunter's Store (Gilmore, 1935; Lull and Wright, 1942). An isolated articulated carnosaur tail is reported by Gradzinski (1970) from the Upper Cretaceous Nemegt Beds of Mongolia, and isolated articulated necks and tails of sauropods appear to be fairly common in the Jurassic Morrison Formation (McIntosh and Berman, 1975; Holland, 1915; Lawton, 1977; Keller, 1973). It has been suggested, for sauropods, that tails and necks were detached from the complete carcasses by pressure at nodal points during recurrent flow (Keller, 1973; figure 8). A similar explanation may apply to the occurrence of isolated tails in the Fruitland-Kirtland sequence although the very long slender caudal and cervical series of sauropods would appear the most susceptable to this mechanism.

Dodson (1971) proposed decompositional classes for excellently preserved dinosaur skeletons from the Oldman Formation of Alberta (Table 10). Fossil Forest specimens fall into two of his classes, G-incomplete articulated skeleton, J-isolated bones, and a class proposed herein, L-incomplete inarticulated skeleton.

DECOMPOSITION CLASSES OF DINOSAURS

Class	Condition
A	specimen complete or nearly so
B	specimen complete or nearly so, some drifting of major elements
C	skull and scattered skeleton
D	skull and scattered bones
E	skeletons without heads
F	skull with incomplete articulated skeleton
G	incomplete articulated skeleton
H	skull with jaws
I	skull wihout jaws
J	isolated bones
K	incomplete articulated specimens-extent of original specimen unknown

Table 10. Decompositional classes of dinosaur remains (from Dodson, 1971).

The majority of dinosaur bones represent limbs, ribs, and vertebrae; skull material is uncommon. Two left dentaries of Kritosaurus have been recovered from the Dinosaur Graveyard. Another lower dentary of an unidentified hadrosaur has been recovered from Section 15, 1-5 m below the main coal, together with upper jaw and skull material. The bones occurred in a white, crossbedded lenticular sandstone at the lower erosional contact with a mudstone in direct association with Trypanites. Three very fragmentary ceratopsian frills have been found in the Fossil Forest. Most dinosaur remains, from the study area, are of Voorhies Dispersal Groups I and II (Voorhies, 1969) suggesting that hydrodynamic factors were important in sorting bone material. The total assemblage is therefore considered a taphocoenose brought together by taphonomic processes, after the death of the animals.

Voorhies Groups appear generally applicable to mammals of all sizes (Dodson, 1973; Behrensmeyer, 1975; Korth, 1979). Shape appears more important than size in the fluvial transport of skeletal elements (Hanson, 1980), and therefore Voorhies Groups may be broadly applicable to dinosaur remains given that the other main variable, density, may have been similar in dinosaurs and mammals (Enlow and Brown, 1957). Absolute size is still an operating variable and the greater size of dinosaur bones would mean that all but the smallest elements would rarely be moved by normal current velocities. Behrensmeyer (1975) noted that bones greater than 1000 cc, of animals such as hippopotamous and elephant, will only move at flow velocities greater than 150 cm/sec.

Turtle and Other Vertebrate Remains

Turtle material is second only to petrified wood in frequency of occurrence. This appears to represent a true relative abundance although the tendency of turtles to "explode" into many pieces immediately upon weathering tends to bias the picture. As with dinosaur bones, about a quarter of all occurrences are associated with siderite concretion development (Table 8). Turtles appear to be more complete in channel sandstones, but this could be because they are very succeptable to fracture which results when clays expand in dominantly shaly overbank deposits.

Crocodile and goniopholid? remains are uncommon outside-microvertebrate assemblages, occurring at five localities in overbank deposits. They are usually represented by scutes and teeth or less commonly by vertebrae and limb bones.

Most crocodile remains are found in association with clay pebble conglomerates where are also found all mammals (mainly teeth), lizards (mainly jaws), fish (teeth and scales), skates and rays (teeth), amphibians (jaws), and many turtle fragments, dinosaur bone fragments and isolated dinosaur teeth. Almost all smaller dinosaurs (e.g. coelurosaurs) are represented only by isolated teeth in such rock types. Shark coprolites are fairly common in these assemblages, being elongate twisted spheroids .5-8 cm in length, fine grained in texture, sandy yellow in colour, and containing fish scales and vertebrae. Coprolites also occur isolated, or rarely in groups, in fine grained sediments. The largest association, six, was found in a dark grey mudstone. These tend to be ellipsoidal and about 2 cm long or cylindrical and about 4 cm in diameter, 6-8 cm long, and contain plant fragments. The latter are presumed to have been produced by herbivorous dinosaurs.

Invertebrates

The only invertebrates obtained from the study area are bivalves and gastropods. Molluscs this high in the Fruitland and Kirtland Formations are dominantly freshwater forms (Hartman, 1981) and occur mainly in poorly sorted clay pebble conglomerates with plant and vertebrate debris. They also occur in shale beds but are usually less concentrated. In sandstones, shell material is uncommon and less well preserved than in shales. Concretionary material is almost always found associated with shell material. Molluscs from the study area exhibit poor to good preservation but are not among the best collected from the Fruitland-Kirtland sequence. They are present in all stages of completeness from attached valves, open and closed, to isolated entire values and shell fragments, but none are in situ.

Taphonomy of Major Localities

Introduction

Detailed observations were made on the taphonomic, sedimentologic, and stratigraphic context of the major localities illustrated in Figure 32. Such information is important for providing baseline data for comparison with other Mesozoic vertebrate accumulations. From such comparisons generalisations concerning the context of such accumulations can be induced. This data will also be of value to future workers in the Fruitland and Kirtland Formations who will be able to get a "feel" for the type and quality of fossil localities that may be found. Excavation of material from most of the discussed localities is at a preliminary stage and more detailed investigations will further clarify some problems.

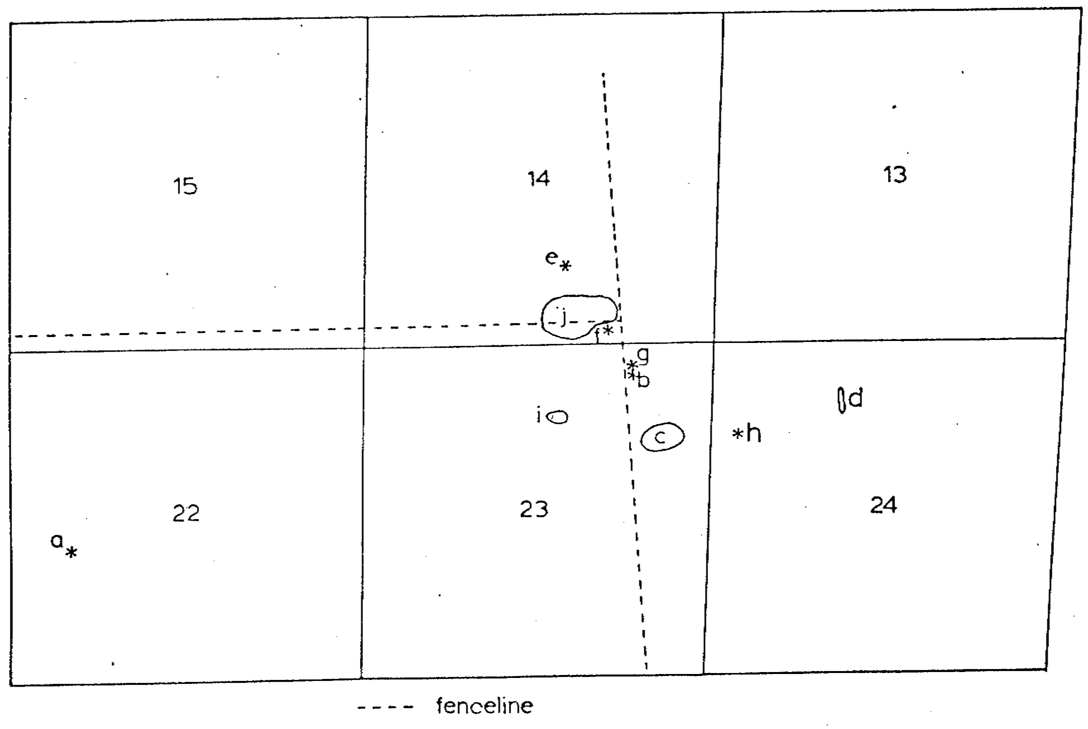


Figure 32. Map of location of main fossil localities discussed in the text. Localities are coded by letters, a--Big Bone Quarry, b--Dinosaur Quarry, c--Dinosaur Graveyard, d--Turtle Heaven, e--Quarry 1, f--Quarry 2, g--Quarry 3, h--Quarry 4, i--Forest Litter, j--main stumpfield.

Big Bone Quarry

The locality lies just outside the study area in Section 22. Initially this quarry was considered to contain the only postcranial material of a carnosaur known from the Fruitland or Kirtland Formations. Lucas (1981) has suggested that the absence of carnosaurs is a true reflection of the original animal community but this is doubted because of the abundance of large prey animals, particularly hadrosaurs and ceratopsians. The field identification of one element from the quarry as carnosaurian is incorrect.

The locality lies above the coal but below M1 (stratigraphic section BAT). The bones, numbering at least twelve, consist of a large femur, two cervical vertebrae, and several ribs and other fragments. The enclosing matrix is a yellow khaki clay-rich medium grained sandstone containing approximately 30% plant remains. The large size of the plant fragments is conspicuous, being often over five square centimetres; seeds are common and scattered, partial leaves occur. Also present in close proximity to (below) the femur are four Araucaria fragments. Elsewhere five Araucaria fragments have been found associated with bones. They were presumably resistant to abrasion and acted as large sedimentary particles somewhat in the manner of bones. Parker (1976) reported on Araucaria material, occurring in point bar deposits of the Upper Cretaceous Blackhawk Formation of Utah and considered that the specimens were transported a long distance from a highland area.

The deposit is approximately 30 m long, all bones occurring within 15 m. Two vertebrae and several rib fragments were found in immediate association with the femur. Laterally other rib fragments are progressively less common. The femur is approximately 1.68 metres long and shows plastic deformation being arched at about its midpoint with an offset of 30 degrees.

This sandstone body appears to represent channel fill of a channel which slightly erodes the main coal. The channel exhibits parallel lamination, alternating clay and non-clay rich bands, and has a high width to depth ratio.

Dinosaur Quarry

This quarry has produced by far the greatest number of bones so far collected from one locality within the study area. The productivity of this locality is in part due to the fact that it is the only mass occurrence so far discovered in shale, from which it is far easier to excavate fossils than from most sandstones. Ease of excavation has been an important factor in initial studies as only a small crew has been employed. Perhaps 45 man hours were required to excavate one hadrosaur jaw from the well indurated sandstone of the Dinosaur Graveyard, whereas a ceratopsian jaw from the Dinosaur Quarry required only two man-hours.

The deposit occurs stratigraphically above M1 (stratigraphic section BAV) and consists of two well defined units. The lower unit is approximately 18 cm thick and consists of finely laminated silty mudstone. Laminations are picked out by the presence of laminae approximately 1 to 3 mm thick consisting of 80 to 90% macerated plant material. Climbing ripples and soft sediment deformation structures occur in this unit. Grading up from this unit is a 45 cm thick layer of grey green shale containing abundant bones (Figure 33) in close proximity. In this layer subvertical linear coalified plant fragments are common. This sequence is interpreted as a flood deposit characterised by an earlier high energy climbing ripple phase followed by a "dumping" phase, when bones and subvertical plant fragments were deposited.

Large slickensides, several tens of square centimetres in area, are common in the bone layer and have broken bones laterally. Slickensides of such size are uncommon elsewhere. They presumably represent a compaction phase of the initially poorly consolidated bone layer.

Bones vary in preservation from a well preserved sacrum, to a femur showing strong longitudinal step fractures, to fragments of ceratopsian frill. Most, if not

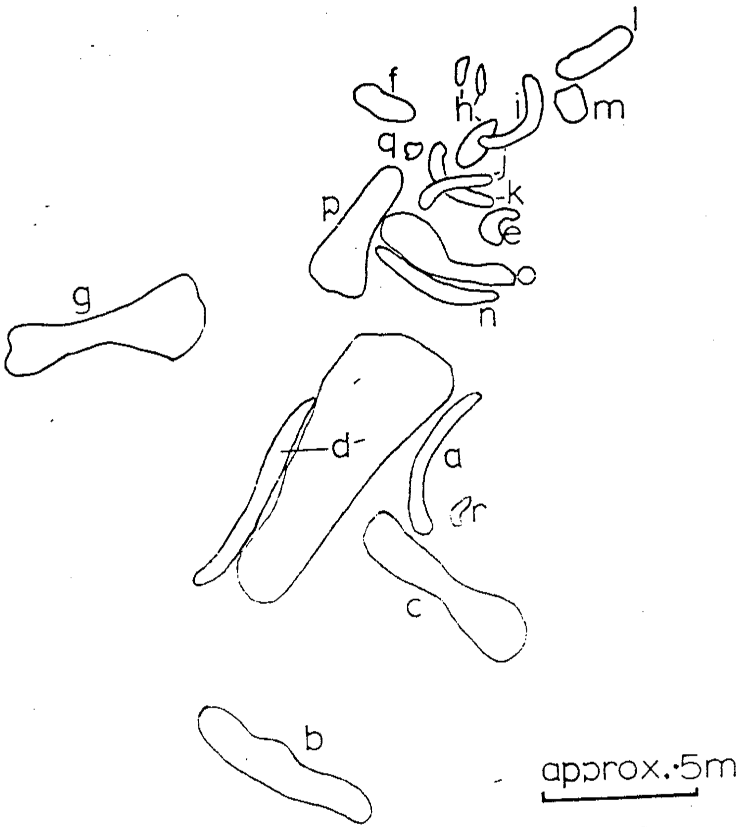


Figure 33. Sketch-map of Dinosaur Quarry from unpublished field notes of Mateer, 1980. Dinosaur remains are a, dorsal rib, b, illium, c, ceratopsian left femur, d, near complete ceratopsian sacrum, e, fragment of pelvic bone, f, mandible of ceratopsian, g, ceratopsian humerus, h, ceratopsian frill fragments, i, dorsal rib, j, dorsal rib, k, dorsal rib, l, ceratopsian metatarsal, m, second phalange of ceratopsian, n, ceratopsian ischium, o, ceratopsian illium, p, ceratopsian pubis, q, pubis (hadrosaur?) fragment, r, cranial fragment (hadrosaur?).

all, the bones appear to represent one subadult specimen of Pentaceratops showing strong similarities to bones referred to P. fenestratus by Wiman (1930). The association of so many elements from one animal probably indicates short transport with the lack of orientation of bones or plants probably indicating short high energy transport followed by rapid loss of energy. Given the grain size of the entombing rock, it is likely that there was insufficient energy to have carried the bones far, and it is possible that cadaver(s) decayed in place. In either event, the deposit appears to have been winnowed, presumably by water, as most of the most transportable elements (e.g. vertebrae) are absent.

The range of preservation of specimens seems to indicate a period of subaerial exposure followed by transport and deposition by a overbank flood. Step fractures probably indicate damage to relatively dry bone (Shipman, 1981), but there is no surface texture alteration which might be expected from long subaerial exposure (Behrensmeyer, 1978). There is no evidence of carnivore damage; therefore fracturing may be due to trampling (La Porte and Behrensmeyer, 1980). It is strange that the massive skull is represented by only a few fragments whereas the delicate sacrum is complete. Trampling might give such random damage. The association of broken pieces of several ribs argues for breakage prior to burial.

The one collected dentary, of a ceratopsian, lacked teeth, and only one isolated hadrosaur tooth was found in the quarry. Teeth are subject to rapid fragmentation (Behrensmeyer, 1978), and edentulous dentaries are not uncommon.

Bones appear to be concentrated only in the area depicted in Figure 33, although the actual deposit may be 20 m by 10 m. Concentration within a limited area could indicate a small palaeotopographic low at this point.

Turtle Heaven

Turtle Heaven is an unexcavated but potentially important deposit occurring between M1 and M2. Approximately thirty partial turtles, six dinosaur bones and thirty or more coprolites occur in a clay-rich, yellow sandstone (weathers light grey). The sandstone is fine grained and contains 20% scattered coalified plant material. Such plant material locally constitutes 60% of the rock in discrete laminae, which define small scale ripple marks and planar crossbeds. The underlying bed is a medium grained laterally continuous sanstone.

As exposed, the deposit extends at least 50 metres laterally and is 70 cm thick. Lateral fining, tabular geometry and ripple marks suggest a crevasse splay or at least flood event. There appears to be little vertical fining and therefore the deposit probably represents a near instantaneous deposition event.

Quarry 1

Quarry 1 is a microvertebrate locality occurring at the base of a 190 cm thick channelform sandstone which exhibits large scale, low angle, and some high angle crossbeds. The trend of the sandstone body is 40 degrees with current directions measured from crossbeds ranging from 350 degrees to 80 degrees. There is sheet-like concretion development along some cross laminae and some hoodoo formation within the sandstone. A Kritosaurus femur has been recovered from the same sandstone body. The sandstone body, interpreted as a channel, is approximately 30 m x 10 m in extent. The outcropping extent of the producing horizon is 13 m x 10 m. The producing horizon is usually 40-50 cm thick, and the majority of this is a clay pebble conglomerate with rounded grey green mudstone and claystone pebbles averaging 1 cm in diameter forming 40-70% of the rock. The clay pebbles lie in a poorly sorted clay rich medium grained sandstone. Animal fossils represent less than 3% of the rock, 5-20% of the rock being composed of carbonised plant fragments. Rare carbonised, compressed log fragments up to 40 cm x 15 cm x 6 cm have been found. Rare, whole leaves occur, but most plant remains are broken, unidentifiable, fragments of several square centimeters in area.

Clay pebbles show flattening, but compaction appears to have been greater in the surrounding sandstone, resulting in distortion of lamination around pebbles. The main clay pebble conglomerate horizon shows small scale channelling into the underlying sandstone. The underlying sandstone is similar to interbeds within the clay pebble conglomerate; it is cleaner than the matrix of the conglomerate and is medium grained and poorly sorted containing 5-10% of macerated carbonaceous fragments. Scattered laminae contain 60-90% of carbonaceous material.

Most lamination within the deposit is planar parallel with minor undulatory development. Above the main deposit clay pebbles grade up from a concentration to occurrences on selected laminae. Twenty centimetres above the main deposit, clay pebbles are scattered and uncommon. The main clay pebble zone exhibits sideritic concretion development which seems to be concentrated around particularly plant rich pockets.

Animal fossil occurrences include, gar scales, fish vertebrae and teeth, lizard jaws and long bones, crocodile teeth, dinosaur teeth and bone fragments, mammal teeth and long bones, abundant snail operculae and a small amount of mollusc shell material. The presence of large numbers of calcitic snail operculae and few aragonitic snail shells is presumably a diagenetic effect. Bone fragments are dominantly pebble sized (cf. Dodson, 1971) with the largest piece being an abraded dinosaur thoracic vertebrae about 10 cm x 10 cm x 5 cm. Fragments show varying degrees of abrasion with teeth, both mammalian and non-mammalian, and gar scales showing significantly less damage than other elements. Quarry 1 is approximately 10 cm above M1.

Quarry 2

Quarry 2, which is a microvertebrate locality, occurs approximately 48 cm above M1 at the base of a 300 cm thick sandstone body interpreted as a channel. The channel is characterised by low angle planar cross beds and planar bedding, with local hoodoo development. The base of the channel, at the quarry, is undulatory and subhorizontal.

The rocktype of the locality is clay pebble conglomerate, essentially the same as Quarry 1. However, in contrast to Quarry 1, the biota is characterised by abundant bivalves, often with both valves preserved, few snail operculae, no leaves and no sideritic concretion development. The deposit, as exposed, appears to be at least 20 m by 6 m in areal extent, but other lenses occur about 15-20 m laterally near the base of the same channel. Two of these other lenses appear particularly rich in small coprolites (<2 cm in diameter). These lenses are associated with concretionary development in contrast with the quarry area.

At the quarry, the clay pebble conglomerate is 30-40 cm thick and internally is bisected by a 20 cm thick lens of much cleaner sandstone. Current directions, for the superposed channel, as determined from crossbedding measurements, range from 350 degrees to 50 degrees. One metre from the quarry, a very badly weathered ?ceratopsian tibia and vertebra were excavated.

Quarry 3

Microvertebrate locality Quarry 3 occurs in a grey green siltstone at the base of a channelform sandstone 140 cm above M1. It is characterised by large bivalves up to 8 cm long. The quarry layer is up to 30 cm thick and extends over an area of 10 m x 20 m. There is a small amount of sideritic concretionary development associated with the fossils. The siltstone contains 30% clay minerals and 20-30% macerated plant fragments. Vertebrate remains are rarer than at Quarries 1 and 2. The overlying sandstone body is 2 m thick, contains small scale cross stratification, and trends 290 degrees. It contains hoodoo and sideritic concretion development.

Quarry 4

Quarry 4 lies directly upon M1 at the base of a brown capped channelform sandstone (Channel B of Chapter II). The quarry lies in a clay pebble conglomerate characterised by abundant, well preserved bivalves and less than 3% of vertebrate fragments. Fifty percent of the rock is a clay rich, poorly sorted, medium grained sandstone and 50% is composed of grey green clay pebbles averaging 1-1.5 cm in diameter. The deposit is 10-15 cm in thickness and extends over an area of approximately 40 m x 15 m. Sideritic concretions occur locally within the clay pebble conglomerate and elsewhere there is purple colouration, suggestive of sideritic enrichment. The overlying sandstone body is 4.5 m thick with the top 70 cm showing brown iron staining and resistance to weathering. The brown portion of the sandstone exhibits low angle planar cross stratification indicating a probable current direction of approximately ten degrees. The channel is laterally continuous and linear, trending about 20 degrees. Planar crossbeds near the quarry are picked out by laminae rich in macerated plant material. Rare scattered shells occur within the basal 1 m of the channel.

Forest Litter

An exumed surface of limited extent (60 m x 20 m), 300 cm below Ml, contains over 50 compressed root or branch fragments. They occur throughout a 20 cm thick siltstone with a large amount of siderite concretion development, mainly limited to the immediate vicinity of the "roots". The "roots" themselves are silicified and laterally compressed and occur like "pigs in the blanket" wrapped in siderite. Four or five poorly preserved small stumps (50 cm or less in diameter) occur upright. Most wood is coniferous although palm also occurs. Most "roots" are weathered, and the longest are over 20 cm long, 5 cm wide and 2.5 cm thick, and show some sinuosity. Paleobotanical study should determine if the wood represents *in situ* roots, or transported roots and branches, or a combination of transported and *in situ* elements. This accumulation could thus represent an advanced stage of rotting of a stumpfield or a water transported accumulation. Current directions indicated by a plot of the long axes of "roots" (Figure 34) show a fairly random distribution. A bimodal distribution would be expected for water transported linear elements (parallel and normal to the current). There is some indication of a radial pattern to some of the "roots". Present evidence would seem to indicate a lack of water transportation.

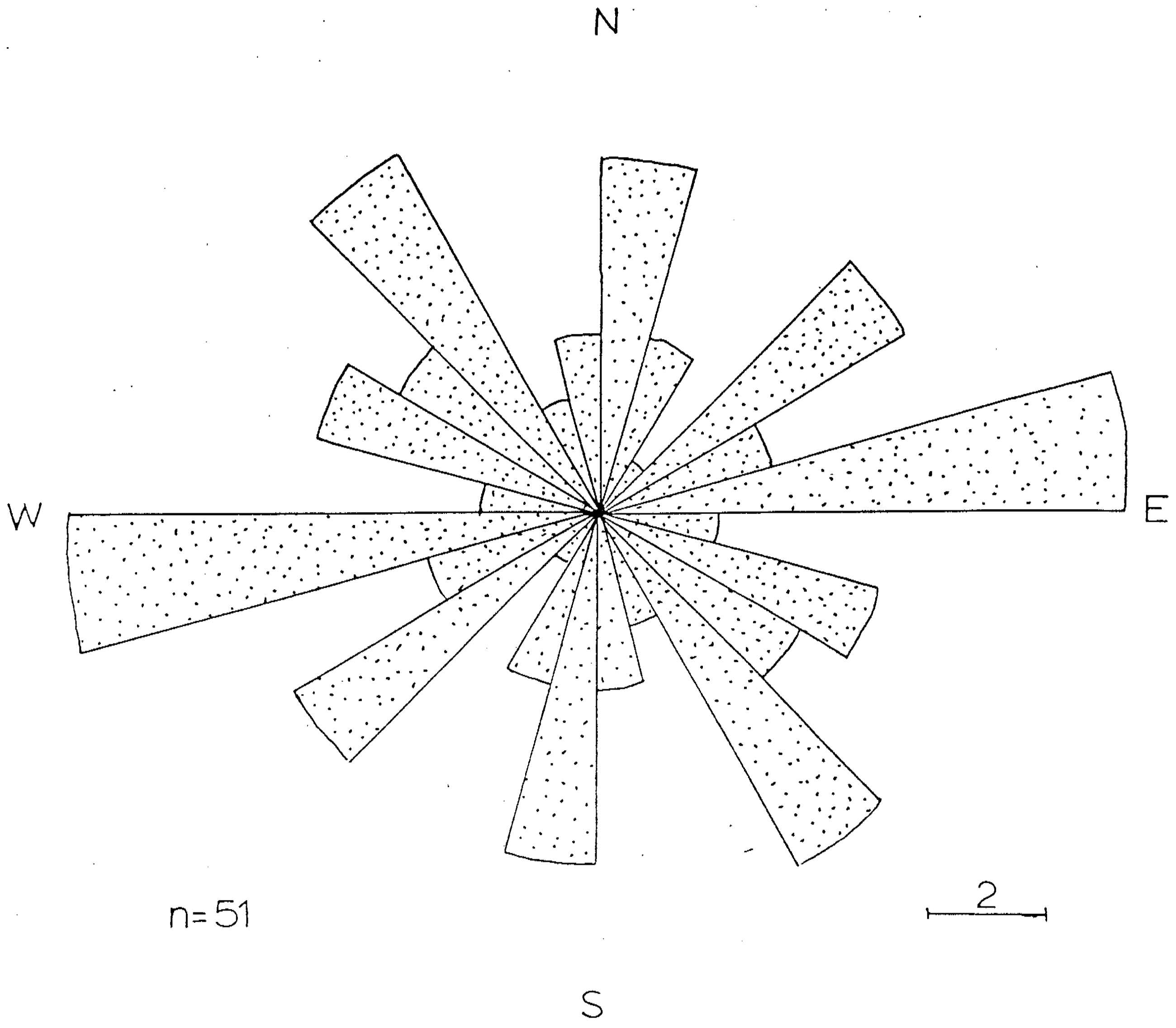


Figure 34. Rose diagram of long axes of "roots" from Forest Litter locality.

Main Stumpfield (Fossil Forest)

The term fossil forest is appropriate for this locality as it consists of a group of stumps which are clearly in position of growth at a distinct stratigraphic level (Jefferson, 1982). The literature on fossil forests has been reviewed by Jefferson (1982).

A few pieces of turtle and dinosaur bone occur at the level of the stumpfield, but only two turtle fragments appear to be in situ in the large areal extent of this deposit.

The stumpfield consists of 40 stumps and 11 logs (Plate 4 and Table 11). An additional 23 stumps and one log occur at the same stratigraphic height, southward to the main wash through the badlands. The stumpfield has been exumed to approximately the forest floor level.

The base of the entombing bed is 60 cm below M1 although emergence of the roots might suggest local erosion of 5-10 cm of the original soil. Some correlative stumps outcropping in the main wash through the Fossil Forest Badlands are separated from M1 by at least two crevasse splays as well as overbank deposits giving a stratigraphic difference of 1.7 m between these stumps and those in the main stumpfield, relative to M1.

Stump	Width (m)	Stump	Width (m)
1	.88	21	1.5
2	.47	22	2.5
3	.3	23	2.5
4	1.5	24	.62
5	.5	25	1
6	.61	26	1.5
7	1.25	27	3
8	2	28	1
9	.46	29	1.5
10	1.75	30	.45
11	2	31	1.25
12	.7	32	.45
13	.79	33	.48
14	.9	34	1.4
15	1	35	1
16	1	36	1
17	1.25	37	1.5
18	1.2	38	1.25
19	2	39	.7
20	2	40	3.7

MEAN WIDTH = 1.27 m

Log	Length	Bearing of long axis (degrees)	Max Width (m)
1	2	110	.3
2	23.4	78	1
3	9.8	299	.95
4	1.7	111	.32
5	8	324	.45
6	7	274	.4
7	7	274	.42
8	9	210	.61
9	5	70	1
10	1.5	92	.4
11	1	160	.3

MEAN LENGTH = 7.48 m

MEAN WIDTH = .56 m

Table 11. Dimensions of logs and stumps in Main Stumpfield.

The entombing stratum varies from a light grey medium grained sandstone to khaki siltstone about 75 cm thick which fines to the south and extends over an area of approximately 800 m by 700 m. The stumpfield occurs where this bed is most sandy. It may be predicted that petrified stumps will be uncommon in the finer grained portions of this bed as grain size and porosity are two major variables controlling the silicification of wood (Jefferson, 1982). Up to 20% of the rock is composed of carbonised plant fragments, many of which are linear (up to 3 cm x .5 cm) and seem to have some preferred orientation, approximately north-south. The enclosing stratum, where sandy, is dirtier (in terms of macerated and non macerated plant material and occasional clay pebbles) near logs, particularly on their northern sides. Occasional euhedral mica crystals occur in the otherwise quartzitic sandstone. Small scale cross lamination occurs in the sandstone which suggest a southerly direction of flow. Hoodoos occur where the matrix is sandy. As the grain size of the enclosing matrix becomes finer, there is more iron concretion development mainly sideritic but also some which appears to be haematitic. This concretion development seems to be restricted to a horizon approximating the "forest floor", possibly related to a soil horizon. Siderite concretion development is common in the immediate vicinity of the stump bases.

Below the bed enclosing the stumps is a light grey mudstone underlain by a dark grey mudstone containing abundant carbonaceous material underlain in turn by a grey green mudstone. Araucaria remains and broken carbonised plant fragments are common in these three beds. Roots extend into all three of these beds. The dark grey mudstone is traceable between stumps in the badlands at the edge of the stumpfield, but in the wash bisecting the Fossil Forest Badlands it can only be found directly under stumps suggesting local erosion by the burying sand sheet.

There is little apparent evidence of a preserved palaeosol. Lack of a well developed soil profile may have been due to waterlogging or to insufficient time between depositional events (Jefferson, 1982). Recent mature soils may take a minimum of 5,000 years to develop (Jefferson, 1982). The dark grey mudstone bed contains 20% or more of carbonised plant debris and is locally coally. The highly carbonaceous nature of this bed, usually less than 10 cm thick, suggests a high water table. The lack of preserved roots in the "soil" zone may be due to compaction. Compaction that was greater than 90 percent was calculated by Jefferson (1982) for a Cretaceous soil in Antarctica. An alternative explanation for the dark grey mudstone is that it represents the organic-rich layer which is sometimes found at the base of flood sequences (Hack and Goodlett, 1960). Siderite concretions are commonly associated with grey, fine members of alluvial sequences and, particularly below coal seams. They are interpreted as being due to precipitation from slightly reducing groundwater in a permanently saturated soil (Collinson, 1978a).

Fritz (1980a, 1980b, 1981a, 1981b) has shown that stumps can be transported and deposited upright although this is disputed by some (Retallack, 1981; Yuretich, 1981). However given the traceability of the three beds in which most of the stumps seem to be rooted, this is considered improbable for the majority of the stumps at this locality.

Virtually all wood is silicified, and this indicates that substantial quantities of silica-rich fluid were available before substantial decay could occur. Where the dark grey mudstone horizon intersects them, the normally silicified roots are coalified. Most stumps are less than 2 m in diameter and virtually all are less than 1 m high. Most logs are less than 10 m long and 1 m wide and show lateral compression. Excavation indicates that the exterior of all wood was coalified (Figure 35) to a depth of less than 2 cm. Jefferson (1982) noted "a carbonaceous coating" on silicified root casts but not stumps. This mode of preservation suggests several explanations; that petrification began from the inside and proceeded outward and that the exterior became carbonised before petrification began, or at least was completed; or that the possibly weathered exterior of the wood had an internal structure unsuitable, in some way, for petrifaction. Another, though below coal seams. They are interpreted as being due to precipitation from slightly reducing groundwater in a permanently saturated soil (Collinson, 1978a).

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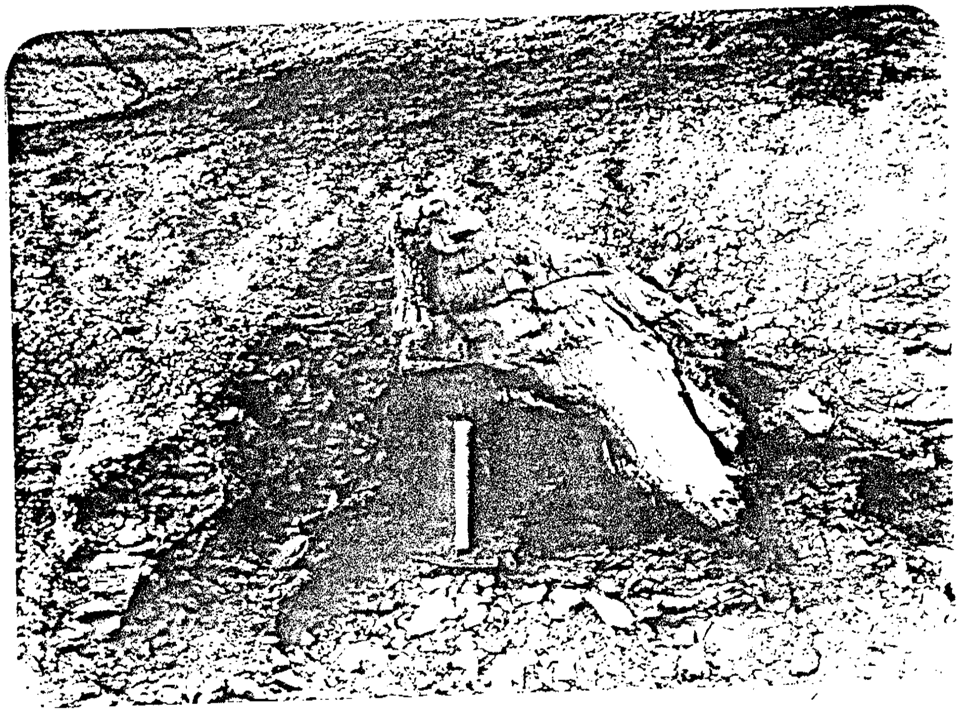


Figure 35. Excavated stump from Main Stumpfield showing carbonised outer layer and extent of preserved roots. Marker Bed 1 is the dark streak at the top of the photograph.

less likely, explanation is that petrifaction starting from the centre and proceeded outward but that the silica supply was terminated before all the wood had been affected. Coalification of the outer wood is not inconsistent with the relative lack of compression of the silicified portion of the stumps (relative to normal coal formation) as coalification may occur under conditions of little or no compressive distortion (Baird and Woodland, 1982). Bark appears to be rare in both stumps and logs (M. Arct, personal communication, 1983) and most stumps show central rotting.

All trees in the stumpfield appear to be taxodiaceous (C. Robison, personal communication, 1981). The presence of taxodiaceous trees implies the presence of swamps with standing water or wet bottomlands (Taggart and Cross, 1980). It seems that the forest cover was of low diversity, possibly even monotypic, representing a specialised or successional situation. It may be that these trees had, because of certain physiological characteristics, been able to occupy and dominate alluvial flats along with flooding, as have the modern redwoods (Stone and Vasey, 1968). In general, floodplain vegetation tends to be open and colonised by only a few plant species and even fewer woody species (Ferguson, 1971).

The preservation of the wood by permineralisation varies from poor to good. Well defined growth rings are apparent in most of the wood. Such growth rings are probably annual, as non-annual growth rings are usually drought-controlled (Cook and Jacoby, 1979), and there is no evidence, sedimentologic or palaeontologic, for aridity in the Late Cretaceous of North America. Well defined growth rings indicate marked seasonality with fluctuation of the climatic limiting factor (Jefferson, 1982).

A plot of the long axes of logs (Figure 36) from the stumpfield has a nonrandom distribution. Logs may align either parallel or perpendicular to a current. Bearing in mind the lateral fining of the entombing beds, from north to south, it is likely that this represents the direction of flow and the orientation of logs could support this. If the logs are mainly normal to the current, it would seem from Figure 36 that the flow was from northnortheast to southsouthwest. Prone logs appear to have collected debris on their up current sides. Thus, a sheet flood from the northnortheast is presumed to have preserved the trees.

Work on the inundation of forests has been carried out both for forestry management and as part of interdisciplinary studies on flooding. The establishment of trees in a floodplain is dependent on: (a) a supply of suitable seeds, (b) timing of seed dissemination and germination, (c) favourable soil conditions, and (d) periods

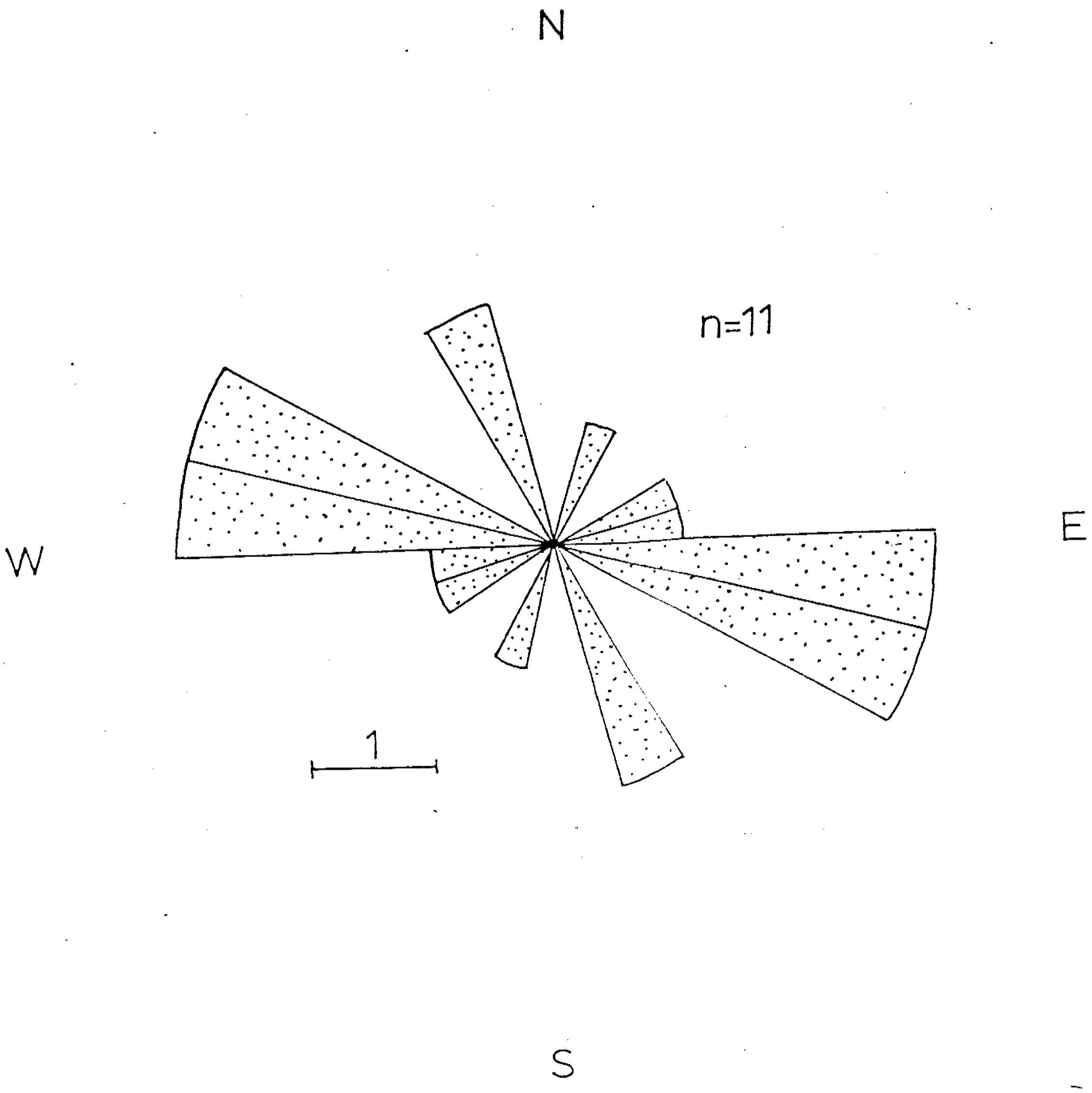


Figure 36. Rose diagram of long axes of logs from Main Stumpfield.

of favourable environment related to the flow regime of the tree (Sigafoos, 1964). During the early stage of growth trees are very susceptable to flood damage (Hadley, 1961; Shull, 1922; Sigafoos, 1964) and the establishment of silvan growth indicates a period of several years during which large scale flooding did not occur (Shull, 1944; Sigafoos, 1964). Thus, it can be inferred that there had been no major flooding in the area of the stumpfield for several years prior to the event which buried the trees.

Logs are far less common than stumps in the study area. This is in marked contrast to the Yellowstone Park fossil forests where more than 60 percent of trees are horizontal (Fritz, 1980a) but similar to the fossil forests from Alexander Island (Jefferson, 1982). There are three possible explanations for the scarcity of prone logs. Firstly, the logs may have rotted in place. This is considered unlikely as the "rotted logs" would have occurred in the same horizon as logs and stumpss which did not rot and which do not show high degrees of rotting. Secondly, the logs may have been swept away by the flood which buried the stumps. Some evidence for this hypothesis comes from the local erosion of the "soil" (dark grey mudstone). However, most trees felled by high flood water are partly uprooted, in contrast to wind damaged trees which are not (Sigafoos, 1964). Uprooting is particularly apparent in the large logs of the Ojo Alamo Sandstone which often show greater preservation of the root base than exhibited by logs in the study area. Uprooting of stumps has not been observed in the study area. Also transported trees often become wedged against standing trees during flood events (Sigafoos, 1964). This phenomenon has not been observed in the study area. The evidence suggests that logs were not transported away during a violent flood event. Thirdly, following the flood event that buried the forest, the area was subject to a period of standing water during which time logs drifted away (cf. Jefferson, 1982). Remaining logs may have been more covered by sediment than those removed, or they may represent the largest individuals which were never removed due to the shallow depth of the standing water. There is no positive evidence in favour of this scenario, but strong evidence against the conflicting hypotheses suggests that it is correct.

The two characteristics of the actual flood event most damaging to floodplain trees are the high velocity of the water and the large quantity of transported sediment (Sigafoos, 1964). High water alone does not kill trees but extended periods of flooding and heavy sedimentation will (Sigafoos, 1964). The depth to which a tree can be buried before it dies is not clear, and several depths are recorded in the literature, 9 m (30 ft) (Helley and La Marche, 1975), 6 m (20 ft) (Helley and La Marche, 1968), and 3 m (10 ft) (Featherly, 1941). Sigafoos (1964) notes that .9 m (3 ft) of sediment does not kill trees. The actual depth of burial may not be as important as the decrease in drainage caused by thick alluvium cover (Harper, 1938). Health and age (size) of trees must also be important in determining if trees survive. Even allowing for compaction the trees in the fossil forest were not buried by thickness of sediment quoted above. Therefore, it is probable that sediment burial did not kill the trees.

Survival of partially buried trees should be detectable in stumps by successive levels of root formation (Helley and La Marche, 1968; Sigafoos, 1964; Stone and Vasey, 1968) or flask-shaped basal portions (Jefferson, 1982). This has not been observed in stumps preserved in the study area. Damage caused by earlier floods is not apparent in the study area (shearing and scarring), although such features are commonly observed in floodplain forests (Sigafoos, 1964). This is probably due to coalification of the outer wood and pre-fossilisation rotting of the bark. It is apparent that trees in the study area did not survive inundation.

The timing of flooding is very important in determining the amount of damage that trees suffer. Submergence during the dormant season will not kill floodplain trees, but submergence, even for short periods, during the growing season will kill some trees, and for extended periods of several years, will kill all trees (Sigafoos, 1964; Turner, 1930). All woody species may be killed if the forest is flooded for 60% of the growing season (Hall and Smith, 1955). Turner (1930) found that a high water from April to mid June did the most damage. Growth rings in trees in the study area indicate seasonal growth, and therefore, it seems likely that if flood waters killed the trees in the study area, the flood occurred during their main growing season.

Rare, large floods are probably important for forest ecology, clearing area for the growth of plants that require much sunlight (Hack and Goodlett, 1960), but extremely rare severe floods will destroy all trees on parts of the floodplain (Sigafoos, 1964).

Reasons for flooding are complex (Benson, 1962, 1964) and cannot be deduced with certainty for the study area. One possibility is that flooding was associated with volcanism and the precipitation of volcanic ash clogging streams. Some volcanic activity was occurring at about this time, as evidenced by the three volcanic ashes in the study area. In addition euhedral mica is found in the entombing bed.

It is apparent that the trees in the fossil forest were inundated by a flood which deposited a layer of sediment that has now compacted to a thickness of 75 cm. Standing water, probably associated with the flood event, resulted in the loss of most prone logs. The high stand of water could have killed the trees. Alternatively, the trees could have died before the flood, but this is considered highly improbable. Age and disease would not kill all trees, and fire would be evident by the presence of much carbonised wood. It is probable that not all trees were alive at the time of inundation. Some stumps exhibit rotting, possibly indicating pre-burial decay. It is considered probable that a high water stand killed the trees. The preservation of stumps and logs is a result of their burial within a sediment with a high primary porosity through which substantial quantities of mineral enriched fluid passed before decay occurred (cf. Jefferson, 1982). Exposed wood would have decayed over a time period of several decades (Jefferson, 1982).

Dinosaur Graveyard

The Dinosaur Graveyard is a large channelform sandstone body containing numerous dinosaur remains. A detailed consideration of its sedimentology is given elsewhere (Channel A of Chapter II).

Approximately 66 dinosaur bones (Figure 37) and 3 turtle shells are still exposed in situ or have been removed in the last three years. These include a partial articulated hadrosaur tail and foot. At four localities three or more bones are associated (excluding the tail and foot). As exposed, these associations are ribs and a jaw, pelvic elements and ribs, vertebrae, and ribs. There is a strong possibility that two of these associations represent

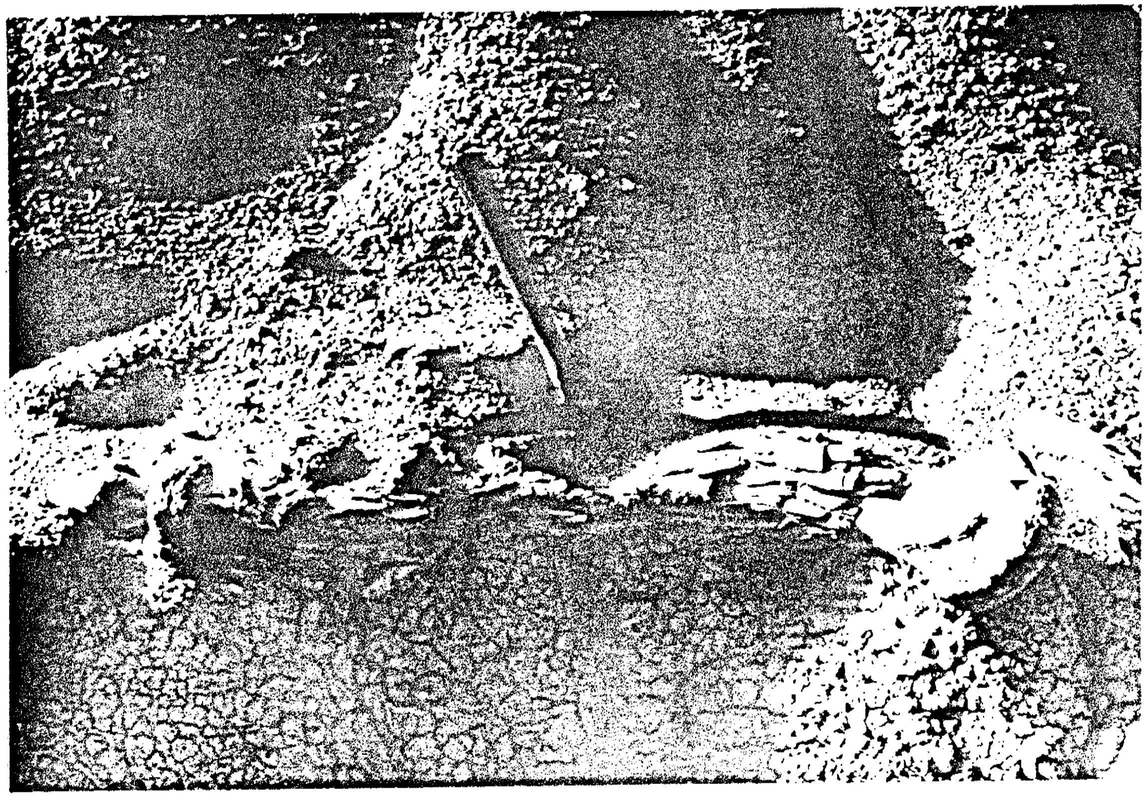


Figure 37. Dinosaur remains weathering out of Dinosaur Graveyard sandstone.

portions of partial skeletons. Bones appear to be reasonably evenly distributed throughout the sandstone in the area of the Graveyard, elsewhere they occur randomly. There is no clear association between types of sedimentary structure and bone occurrence, but one of the localities containing several elements lies on a large scale epsilon crossbed indicating deposition on the face of the point bar. In general, it would appear that larger bones and associations of bones are found in a context of larger scale crossbeds than smaller isolated bones. This association probably reflects the higher energy required to move bone material in quantity although epsilon crossbeds represent a lower energy environment where specimens would become "stranded".

The most important specimens recovered from this locality have been two left mandibles of Kritosaurus navajovius, an articulated partial tail of a hadrosaur, a partial foot of a hadrosaur and ankylosaur dermal plates in association with vertebrae. In the immediate vicinity of all bones are found clay pebbles and carbonaceous plant debris.

At least five old quarries occur in this sandstone body (Chapter I; Figure 38). All contain bone in situ or bone scrap in the immediate vicinity. Three contain or are associated with remains of old plaster and burlap. Age of the quarries is hard to determine but from degree of

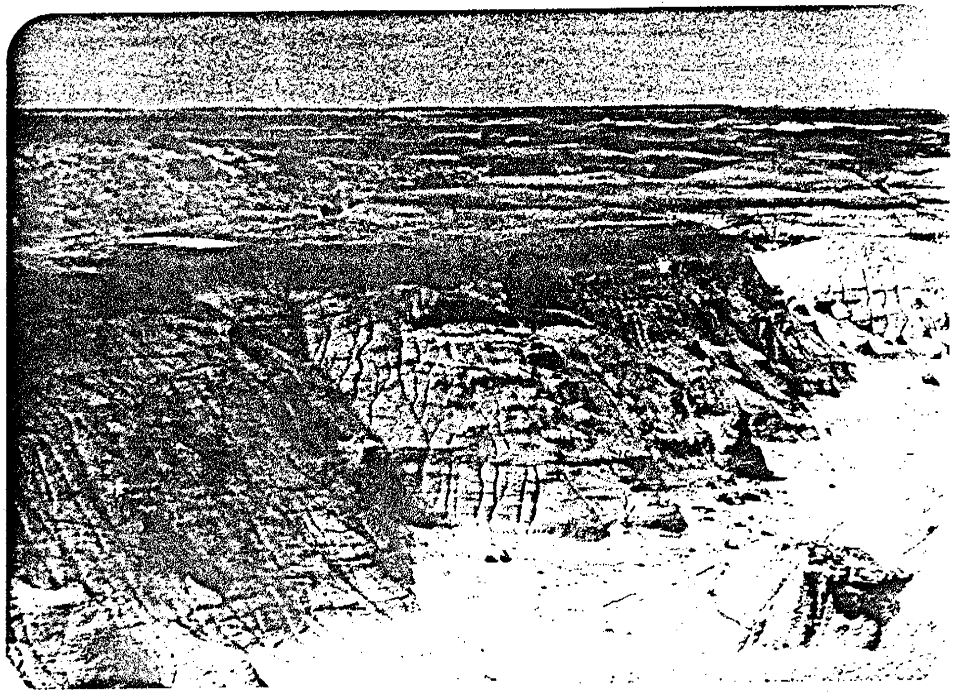


Figure 38. Old quarry in Dinosaur Graveyard (Channel A) indicated by arrow.

weathering of excavated debris it should be measured in tens of years. The approximate combined volume of the excavation is 10.9 cubic metres, the largest accounting for over half (7.2 cubic metres). Excavated material appears to have been moved to one particular quarry to provide a working platform. All the quarries are in the upper 1.5 m of the sandstone body and presumably represent the most complete or most spectacular (in terms of display, and hence retail potential) specimens. As the sandstone is very hard, making even excavation with power tools fairly slow, the importance of specimens recovered presumably is increased with the size and age of the quarry. The largest quarry presumably yielded a fairly complete partial skeleton or a skull, possibly the type specimen of Pentaceratops (Chapter I).

Leaf Locality

Although this locality is outside the study area it is mentioned due to its importance and the fact that it was found during comparative stratigraphic studies in Hunter Wash. The locality occurs in the SW1/4 NE1/4 of section 32, T24N, R13, in the vicinity of Hunter Wash. It occurs within a 19.37 m stratigraphic section of channel sandstones and floodplain deposits (Figure 39). The locality is on the shoulder of a hill and has been fortuitously preserved from weathering by an overlying siderite concretion.

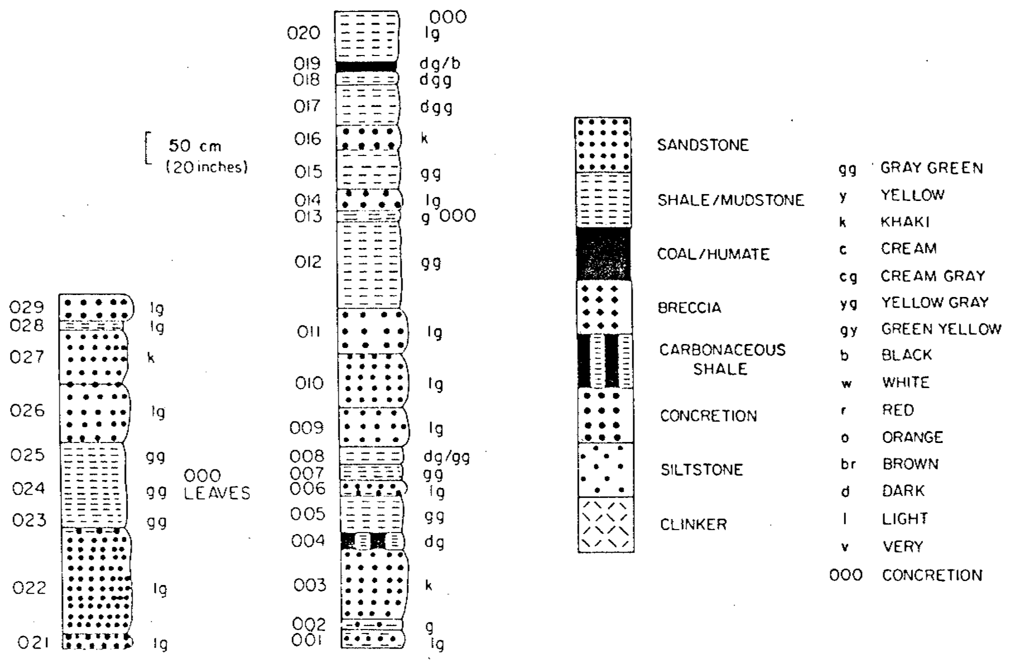


Figure 39. Stratigraphic section of Leaf Locality.

The deposit is dominantly a claystone (Figure 40) in which are found abundant light brown compressions of leaves, partial and whole, other plant material including seeds and rare, small, poorly preserved invertebrates. The deposit extends laterally only about 3.5 m.

On the basis of the presence of Salvinia, an aquatic fern, aquatic invertebrates, the very fine grained nature of the deposits and its limited lateral extent, this deposit is considered to represent a small body of standing water. The sedimentation rate must have been high enough to bury the leaves but of low enough enery not to macerate them. Higher energy, coarser portions of the deposit lack well preserved leaves (Figure 40). It is not clear how much of the Fruitland Formation and particularly the shale members of the Kirtland Shale are the result of lacustrine deposition. A rose diagram of the long axes of 93 leaves (Figure 41) and stem fragments indicates a flow direction trending northeast to southwest.

The recovered florule is the most diverse ever recovered from the Fruitland or Kirtland Formations, despite the abundance of plant material that they contain. For a preliminary study of the palaeobotany, stratigraphy, and taphonomy see Robison et al. (1982).

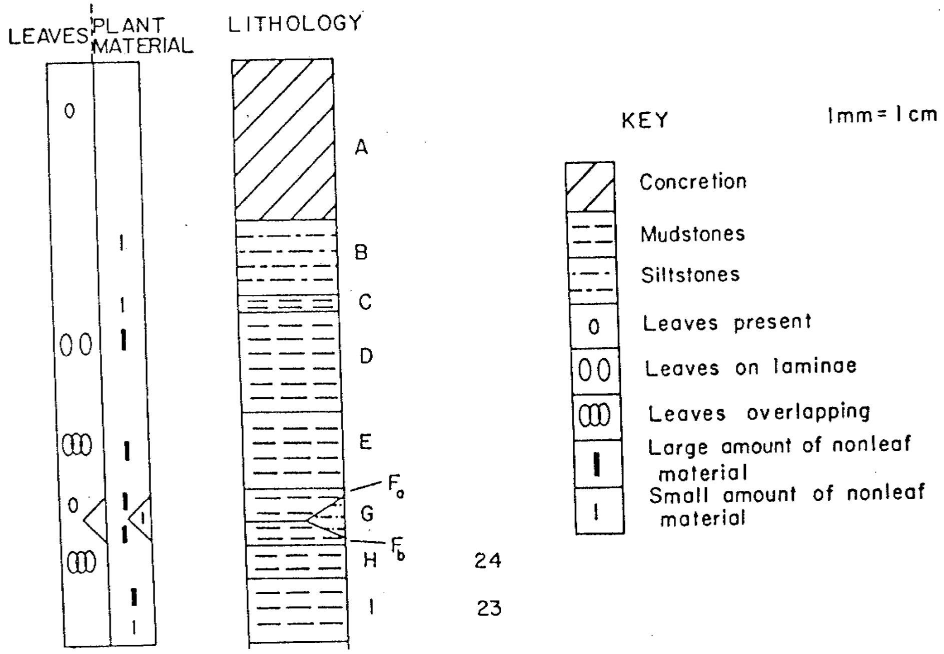


Figure 40. Microstratigraphy of Leaf Locality.

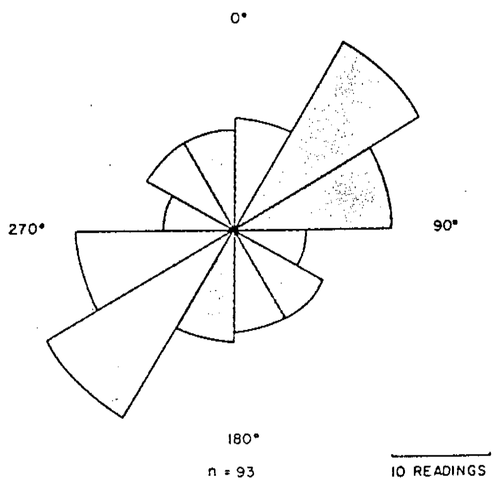


Figure 41. Rose diagram of long axes of plant remains from Leaf Locality.

Discussion

Microvertebrate Accumulations

Microvertebrate accumulations are a distinctive mode of fossil occurrence consisting of small, disarticulated or broken bones and isolated teeth (Mellett, 1974). They are important in the Cretaceous, as they are virtually the only source of information on animals with a body size less than 5 kg (Fisher, 1981).

Three origins have been proposed for microvertebrate accumulations; (a) Hydrodynamic sorting (Wolff, 1978; Wilson, 1960); (b) Scatalogical, either avian, carnivore, or crocodilian (Mellet, 1974; Mayhew, 1976; Dodson and Wexlar, 1979; Simpson, 1937; McGrew, 1963), and (c) Ants (Shipman and Walker, 1980).

Although ants evolved before the Late Cretaceous (Carpenter, 1977), the fact that some fragments at microvertebrate localities must have weighed an order of magnitude more than the 0.5 g dry weight maximum for ant transport (Shipman and Walker, 1980) and that all accumulations in the Fossil Forest occur in channelform sandstones suggest that ants had no part in their formation.

Criteria for recognition of faecal accumulations were proposed by Korth (1979). These criteria are, a high percentage representative of bones of the animals present (>60%), most limb bones being whole, skulls being common and whole, and lack of evidence of abrasion. In addition, teeth ingested by crocodilians would lose their enamel (Fisher, 1981). None of these criteria are met by microvertebrate accumulations in the study area.

Several factors point to hydrodynamic sorting as having been important in forming the microvertebrate deposits in the Fossil Forest (Quarries 1-4): these are, very high tooth:vertebrae ratio (Behrensmeyer, 1975), the varying mechanical abrasion and rounding of many of the fossils (Korth, 1979); low percentage representation of bones for all animals (Korth, 1979); evident size sorting, and presence of all deposits in association with clay pebbles in channelform sandstones. It seems unlikely that faecal material would remain cohesive enough in a stream to be deposited as a scat accumulation (Korth, 1979) although hydrodynamically sorted materal could have initially entered the fluvial environment in faeces.

Bones of small animals have been shown to have a great suceptability to dispersal by flowing water (Dodson, 1973). It seems apparent that most Mesozoic and in particular Late Cretaceous microvertebrate accumulations occur in channel deposits (e.g. Dodson, 1971; Estes and Berberian, 1970;

Lupton et al. 1980) and that non channel deposits are the exception (Carpenter, 1979). In contrast, it appears that some Tertiary deposits can be attributed to a scatalogical origin (Mellett, 1974; Mayhew, 1976; Behrensmeyer and Boaz, 1980; Brain, 1981). Significantly, the supposed originators of most of these scats are nocturnal and diurnal birds of prey and carnivores, which did not evolve until the Tertiary (Feduccia, 1980; Clemens et al., 1979). Another possible explanation of the scarcity or absence of Mesozoic scatalogical accumulations could be that large reptiles and dinosaurs demineralised bones and teeth during digestion as do modern crocodiles (Behrensmeyer, 1975; Fisher, 1981). Freeman (1979) on little evidence, suggested that a Jurassic microvertebrate assemblage was scatalogical in origin.

Macrovertebrate Occurrences

The majority of taphonomic research has been on the Tertiary and particularly the Palaeogene of Africa as a background to studies on hominid evolution. Taphonomic studies on the Mesozoic, when taphonomic processes were undoubtedly different (e.g. lack of bone crushing carnivores, immense size of many animals and mildness of worldwide climate throughout most of the Jurassic and Cretaceous), are not abundant.

In order to facilitate comparison, the main features of the most important Mesozoic taphonomic studies of macrovertebrate assemblages, will be given and an attempt will be made to deduce some generalisations as to biostratinomy. The units considered below are dominantly nonmarine and nonlacustrine.

Lithological Unit: Beaufort Series (Karroo System)

Age: Permian-Triassic

Location: Karroo Basin, South Africa

Climate: cool to warm, seasonal

Environments of deposition: shallow marine-deltaic-fluvial, braided and meandering, lacustrine red beds

Taphonomy: Fossil reptiles in all degrees of preservation, of preservation, small fragments to complete skeletons (animals up to 8 feet long. Most specimens occur in nodules (calcareous, haematitic or siliceous). Fossils in sandstones and clay pebble conglomerates are almost exclusively fragments occurring at base of sandstones or thin bands. Bones in shales, thin siltstones tend to be unbroken and often only partially disarticulated. Several associations of only skulls. A few *in situ* "mired" specimens but most transported. Mixed load streams contain water worn skulls, tusks, and limb bones of synapsids. Complete skeletons of Lystrosaurus in lake facies with fish, plants and insects. Bedload streams contain only fragmented bone. Some petrified wood.

References: Hotton (1967), Hobday (1978)

Lithological Unit: Vale and Choza Formations (Clear Fork Group)

Age: Permian

Location: Northern Texas

Climate: Moderately high temperature, monsoonal

Environments of deposition: Alluvial and lacustrine, redbeds

Taphonomy: (Table 12) Floodplain sites, animals low in frequency at a given site - usually are two or three. Pond facies - skeletons disarticulated except at margins. Stream channels - fragmentary skeletons, a few subcomplete. Skeletons usually at best subcomplete. Some petrified wood.

Reference: Olson, 1958

Lithological Unit: Brushy Basin Member, Morrison Formation

Age: Jurassic

Location: Dinosaur National Monument, Utah

Climate: Variable

Environments of deposition: Bar, stream of generally braided character with fluctuating current and variable flow

Taphonomy: Articulated strings of caudal and cervical vertebrae. Most elements articulated or closely associated. Some evidence of subaerial exposure of carcasses. 1052 bones still in situ or laboratory. Three bone layers. Petrified "logs" in channel lag.

Reference: Lawton, 1977

Lithological Unit: Morrison Formation

Age: Jurassic

Location: Utah, Colorado, Wyoming

Formation	Pond Shale	Pond Grit	Pond Total	Stream Gravel/ Sandstone	Stream Conglomerate	Silt Channel Fill	Clay Pebble	Channel Total	Floodplain Shale	Floodplain Sandstone	Floodplain Total	Total Others	Notes
Lower Vale	156	0	156	1?	162	0	0	163	11	13	45	19	Perennial meandering streams *Individuals not specimens
Middle Vale	118	11	129	2	143	205	143	493	3	5	8	150	Meandering
Upper Vale	300	0	300	0	87	1	0	91	6	8	14	8	Braided predominantly
Lower Choza	384	0	384	0	14	28	0	42	2	0	2	12	
Total	958	11	969	3	406	234	143	789	22	26	69	189	Total all localities 2016
Percentage	47.5	.5	48.1	.1	20.1	11.6	7.1	39.1	1.1	1.2	3.4	9.3	

Table 12. Taphonomic data from the Permian Vale and Choza Formations (derived from Olson, 1958).

Climate: high average rainfall and seasonal extremes of dryness and humidity, hot

Environments of deposition: Broad, low relief plain formed by coalescing fine grained alluvium, fluvial, paludal, lacustrine development on plain, rivers perennial with episodic flow

Taphonomy: Isolated bones are widely distributed, single skeletons, characteristic of formation are large accumulations with thousands of bones (20-60 individuals) which show low to moderate sorting, contrasted with Cretaceous Cloverly, Oldman, Nemegt where solitary highly articulated forms are found. From Table three environments of localities are

Channel	Overbank	Pond	Swamp
8	7	4	3

Of mass accumulations 4 of 5 are from channel top. From table 5, of five major bone accumulations, all are of channel associated origin (channel, channel top or levee). Channel sands represent 15% of total section but account for 1/2 of documented occurrences, 66%+ of total section is fine grained overbank but constitutes 1/2 of occurrences. Petrified wood not common.

Reference: Dodson et al. (1980)

Lithological Unit: St. Mary River Formation

Age: Upper Cretaceous (Edmontonian)

Location: Western Canada

Climate: Humid subtropical

Environments of deposition: Deltaic

Taphonomy: All vertebrate remains from shales, mudstones and siltstones, incomplete skeletal material, weathering before burial, no evidence for scavenging, bonebeds

Reference: Langston (1976)

Lithological Unit: Upper Nemegt Beds

Ages: Upper Cretaceous (?Campanian - Maastrichtian)

Location: Gobi Desert

Climate: warm humid, seasonal drought, high precipitation and large variations in water table

Environments of deposition: Fluvial variable flow, braided-meandering, broad alluvial plain

Taphonomy: Complete skeletons predominate, single bones rare, most remains in sandy and gravel sediment, associated with channel or point bars. Most dinosaurs buried in varying states of disarticulation _in situ_ or close to place of death. Bones/skeletons mostly in sands/gravels, rare in siltstone, never in claystone. Fragments mainly in intraformational conglomerates, skeletons chiefly in sandstone with intraformational clasts, no bone beds. Bone dispersed within sediment except seven skeletons within 700 sq m.

Polish Mongolian Expedition

Intraformational conglomerates and pebbly-sandy sediment = 11 specimens; sands with intraformational gravel intercolation = 20; sands or sandstones = 1; sandy siltstone with intercolations of intraformational clasts = 1; sandy siltstone = 1

Almost all larger dinosaur remains associated with large scale cross strata. Turtle, fish usually in sandy or gravely beds, rare crocodiles in sandy sediments. Few calcified logs.

Reference: Gradzinski (1970)

Lithological unit: Javelina Formation, Tornillo Group

Age: Upper Cretaceous (Lancian)

Location: Big Bend National Park, Texas

Climate: Humid sub-tropical seasonal

Environments of deposition: Braided to meandering fluvial

Taphonomy: Most material isolated, water worn. Only a few partly articulated and incomplete skeletons. Bone in braided streams highly abraded. Bone in meandering streams better preserved. Isolated bones in channel lag have abraded ends. Best and most complete material found in sandstone/pebble sandstone/siltstone of small streams and splays. One scattered partial skeleton on a palaeosoil. Few and very fragmentary remains in claystones of poorly drained floodplain. Abundant petrified wood.

Reference: Lawson (1972)

Lithological Unit: Oldman Formation

Age: Upper Cretaceous (Judithian)

Location: Alberta

Climate: warm temperate equable

Environments of deposition: Braided/meandering fluvial system

Taphonomy: 72 of 84 quarries in channel environment-70% of sediments are sandstones, many specimens complete or subcomplete, but all stage of completeness, little evidence of carnosaur activity, high number of mudstone-sandstone interfaces yield bones, bone beds (Table 13). Few petrified logs.

References: Dodson (1971)
Beland and Russell (1978)

The preceding studies represent a very small sample yet they represent several of the most important Pre-Tertiary terrestrial vertebrate accumulations. Two major vertebrate bearing units, noticeably lacking, are the Late Cretaceous Hell Creek-Lance complex and the Jurassic Tendaguru

Decompositional Classes		Environment of Deposition							
		channel	channel base	channel top	slow channel	shallow channel	channel fill	flood-plain	TOTAL
Class A:	complete	9	2	1	1	0	4	0	17
Class B:	complete, drifted	3	2	1	2	0	2	0	10
Class C:	complete, scattered	3	1	0	1	0	0	0	5
Class D:	skull, a few bones	4	0	0	0	0	0	0	4
Class E:	skeleton, no head	1	1	1	1	0	2	0	6
Class F:	skull, part of skeleton	2	1	0	1	0	1	0	5
Class G:	part of skeleton, no head	1	2	0	0	0	0	0	3
Class H:	skull, jaws	4	0	1	1	0	0	0	6
Class I:	skull, no jaws	6	2	1	0	2	2	1	14
Class J:	isolated bones	1	1	0	0	0	0	0	2
Class K:	condition unkown	7	2	2	1	0	0	0	12
TOTAL		41	14	7	8	2	11	1	84

Table 13. Occurrence of dinosaur remains with relation to depositional environment in the Judithian Oldman Formation (from Dodson, 1971). Numbers indicate number of quarries.

Formation although some sample data can be gleaned for the latter from Russell et al. (1980). Several generalizations can be induced from the above data:

1) In formations where accumulations are mainly not in bone beds, well preserved bones tend to be restricted either to the channel or to the non-channel environment (Beaufort Series, Vale and Choza Formations, Nemegt Beds, Oldman Formation; El Gallo Formation, Morris, 1967).

2) Permo-Triassic and Cretaceous deposits contain isolated skeletons (Beaufort Series, Vale and Chaza Formations, Nemegt Beds, Oldman Formation, Cloverly Formation; Ostrom, 1970; El Gallo Formation, Morris, 1967) whereas Jurassic deposits are characterised by bone beds (Morrison Formation, Tendaguru Formation). This difference between the Jurassic and the Cretaceous was noted by Dodson et al. (1980). The Cretaceous St. Mary River Formation seems to be an exception, but the study on it (Langston, 1976) is only of two quarries. Interestingly, many Cretaceous bone beds are dominated by a single species of ceratopsian (Sternberg, 1970; Langston, 1976; Currie, 1980) which may have palaeocological significance.

3) Most complete skeletons are isolated, not in bone beds (Oldman Formation, Nemegt Beds, Beaufort Series). This can be explained by the fact that most bone beds are the result either of a catastrophic flood event (Voorhies, 1969)

or a hydrodynamic accumulation (Lawton, 1976; Russell et al., 1980), both of which might be expected to jumble up skeletons. The only bone beds which might be expected to contain complete or subcomplete skeletons are those produced by miring events (Stokes, 1961) or in situ death (e.g. Belgian Iguanodonts of Bernissart).

4) Although detailed sedimentology has not been done at most of these locations, where it has (Nemegt Beds, Oldman Formation) channels containing bones often show features intermediate between bedload and suspended load channels (mixed load).

5) Several formations show sedimentological evidence of seasonality in climate (Beaufort Series, Vale and Choza Formations, Morrison Formation, Nemegt Beds, Tendaguru Formation). Some degree of intermittent or fluctuating fluvial flow, which would result from seasonality, may provide preferential conditions for preservation. It may produce "dumping" and covering of remains as against continual abrasion within the channel, and more flooding outside it.

6) Petrified wood, in quantity, is not commonly found with fossil bone (Morrison Formation, Nemegt Beds, Oldman Formation; but see Morris, 1967).

7) Gradzinsky (1970) noted that most dinosaur remains were associated with large scale cross strata.

8) Most vertebrate remains are found (preserved) in a coastal (delta) or alluvial plain setting (Karroo System, Vale and Choza Formations, Morrison Formation, St. Mary River Formation, Nemegt Beds, Javelina Formation, Oldman Formation).

9) Bone is better preserved and more common in meandering than braided streams (Javelina Formation, Beaufort Series).

The Fruitland and Kirtland Formations contain neither the quantity nor the quality of the preservation of the other discussed formations yet several of the above generalisations apply to them. Generalizations one and six do not apply to the Fossil Forest area, but the more general two and eight and the more specific four, seven and nine do. Generalisation three refers to complete skeletons which do not occur in the Fruitland-Kirtland sequence, but it is applicable in terms of the most complete specimens that are preserved.

Most bone in the study area is associated with meandering channels (generalization nine), bone in the two bed load channels (B and D of Chapter II) is restricted to channel lag microvertebrate accumulations.

Generalisation five is very interesting, as the single most productive unit in the study area, in terms of vertebrates, is a channel (Dinosaur Graveyard/Channel A) which shows anomalous periodicity (for the study area) of flow in the form of epsilon cross beds. In other channels bones are scarce or absent although some contain epsilon crossbeds. Climate is further discussed in Chapter V.

Generalisation six does not apply for the study area area as a whole, although at the individual locality level bone is rarely found in association with petrified wood. As regards generalisation seven, it appears that in the study area at least on of the larger accumulations of bones within Channel A occur associated with large scale cross beds.

Generalisation eight is very broad and reflects the fact that coastal plain deposits are far more widely preserved than highland areas, but note that fossils are more common in alluvial than lacustrine lagoonal systems, although there are significant exceptions, e.g. Eocene Green River Formation, Jurassic Bavarian Lithographic Limestone.

It appears that in the Fossil Forest area the majority of fossils occur in a single downcut complex. Data from the above studies does not allow such precise sedimentological delineation. It is probable that vertebrate fossils are rarely evenly distributed throughout a formation (Beland and Russell, 1978). The majority of vertebrates in the

Fruitland-Kirtland sequence appear to occur in the upper part of the Fruitland Formation and lowest Kirtland Shale in the west central San Juan Basin. This area seems to represent fluvial facies landward of prograding delta complexes (Figure 8, Plate 1). In contrast vertebrate remains are uncommon in fluvial facies behind the barrier shoreline. This difference is presumed to be due to a greater rate of sediment deposition. High rates of deposition are necessary to protect potential fossils from predators and the elements, although associated energies too high may result in mechanical destruction.

Most studies treat taphonomy as a background to palaeoecology whereas it can be a valuable tool in sedimentology. Detailed sedimentological comparison of fossil accumulations and experimental work such as that by Hanson (1979) will eventually allow induction of the conditions favouring preservation. The preservation of a single bone or an entire skeleton is a sedimentological event which if properly interpreted can provide importance evidence as to the conditions of deposition and diagenesis.

Plants

Land plants are different from animals in a number of ways that effect their response to taphonomic processes. Plants represent a larger biomass than animals and are presumed always to have done so. In the majority of cases land plants have their lower portion buried and burial is an important element in becoming a fossil. Plants have very few hard parts. Chemical weathering is more important than mechanical abrasion in destroying plant remains (Krasilov, 1975). The majority of land plant debris is essentially two dimensional (Spicer, 1980). Most land plants inhabit areas of net sediment erosion rather than accumulation (Knoll et al., 1979).

Megafossils of plants are almost invariably preserved as fragments of varying sizes (Beck, 1970) in contrast to invertebrates. In the study area, no entire plants have been found, and isolated elements, for example leaves, are rarely preserved whole. This fragmentation is the result of two forms of disintegration, physiological (or functional) and traumatic (Krasilov, 1975). Traumatic disintegration is caused by elements (wind, rain) or other organisms (insects, fungi). Physiological disintegration is caused by shedding of assimilating organs, detachment of organs related to reproduction and detachment of organs that have or have not fulfilled their purpose (Krasilov, 1975). Given the fragmentation of most plant debris in the study area, the specific disintegration mechanism cannot be speculated upon with certainty. However, the widespread occurrence of plant debris in the study area does not require an ad hoc explanation, such as dinosaur faeces (Beland and Russell, 1978), forest fires, or storm damage. Annual litter fall in a modern wetland habitat (Apalachicola River floodplain, Florida) in which one of the dominant species is taxodiaceous (Taxodium-Bald Cypress), which may be considered grossly analagous to the environment represented in the study area, amounts to 800 gm/sq m/year (Elder and Cairns, 1982). The completeness of plant material preserved as detritus depends on the relative timing of flooding and litter fall. If litter fall occurs before flooding, material will decay before being transported away or buried, whereas, if the events are synchronous, undecayed plant matter will be immediately transported away (Elder and Cairns, 1982). Plant material may lie on the forest floor for six months, with only half the material being decomposed, although the time period for decay is highly species dependent (Elder and Cairns, 1982). Decay is much slower in dry than wet conditions (Elder and Cairns, 1982). Significant mechanical fragmentation of transported leaves only occurs after microbial colonisation (Spicer, 1980). There is both fluid and biological sorting of potential plant megafossil during transport and deposition which produces a complex pattern of preservation (Spicer, 1980).

Floods are important in the transport (Elder and Cairn, 1982) and deposition (Krasilov, 1975) of plant litter, and flood deposits yield a statistically good sample of the local flora (Spicer, 1980). Flood deposits contain seeds, fruits, and assorted fragments (Big Bone Quarry) as well as leaves, whereas, low energy deposits (Leaf Locality) yield mainly leaves (Spicer, 1980). The Leaf Locality is interpreted as being a small pond and so it also would be expected to give a good sample of the local flora. Larger bodies of standing water tend to be biased in favour of small "sun" leaves at the expense of large "shade" leaves (Spicer, 1980).

Not all plant material in the study area is transported. All stumps are interpreted as being in situ. Unlike animals, most land plants possess both aerial and subterranean organs. It would be expected that subterranean organs such as roots, being already buried, would commonly be preserved in situ. Roots are often found in situ but are more often found in secondary burial (Krasilov, 1975). Only hadrophyles and plants of accumulative lowland areas have some chance of being buried autochthonously. The vast majority of plant material is transported (Krasilov, 1975). This is the case in the study area as only the petrified stumps are in situ. They must have lived in areas of aggradation and been preserved in porous lithologies through which mineralising fluids could pass (Jefferson, 1982). Krasilov (1975) considers that a high concentration and uneven distribution of organic matter in a bed is necessary to produce intensive migration of elements and ensure a sufficient supply of fossilising substances. All stumps in the study area are petrified and replaced by silica. Eicke (1959) studied silification of coniferous wood, which comprises most of that found in the study area, and documented more than one phase of crystallisation.

Krasilov (1975) recognised two main forms of fossilisation of plants. Phytoleumas are coalified remains which form a gradation sequence into petrified remains. Both forms of preservation are encountered in the study area. Essentially all wood is petrified; the remaining plant remains, which are in the vast majority, are phytoleumas. There are rare exceptions to each case. Only stumps are recognised as biocoenoses, all other plant remains are taphocoenoses. Of the taphocoenoses the majority fall in the upper range of mesotaphocoenoses (fragments 200 microns to 2mm) and the lower range of macrotaphocoenoses (>2 mm) as defined by Krasilov (1975). The majority of taphocoenoses are dispersed as opposed to concentrated with fragments being separated from adjacent pieces by more than their average lengths (Krasilov, 1975).

There is an obvious need for more study of the taphonomy of plants. As is the case with vertebrates, studies have been concentrated on the spectacular, rather than the more common, but less spectacular, localities. As a consequence, essential background data is lacking. The taphonomic circumstances which produce spectacular accumulations of fossils will never be understood until mediocre and poor localities are more studied and understood.

Invertebrates

Studies of the palaeoecology of nonmarine invertebrate faunas of the Late Cretaceous and Early Tertiary of the Western Interior are very small in number (e.g. La Rocque, 1960; Hanley, 1976; Lawrence et al., 1982). Detailed taphonomy of the invertebrate fauna of the Fossil Forest must await taxonomic work (Hartman, in preparation), but general observations can be made.

Invertebrate localities rank above microvertebrate localities and below macrovertebrate and plant localities in abundance. All localities are disturbed neighbourhood or transported assemblages (Scott, 1970), on the basis of disarticulation, fragmentation and parallel alignment. Invertebrates occur in concentration in channel lag (most common) and floodplain deposits and also in bar, levee and crevasse splay deposits (Table 2). The only recognised facies from which invertebrates are totally absent, is that interpreted to represent the floodbasin. Hanley (1976) noted a similar absence: "Mollusks have not been collected from strata representing the paludal facies. Either mollusks lived in this habitat and were not preserved or they found conditions unfavorable. I favor the former hypothesis for several reasons. Standing-water areas rich in aquatic vegetation are ideal habitats for aquatic pulmonate gastropods and pisidiid bivalves. In such environments, acidic conditions develop in association with decomposition and incomplete oxidation of organic debris. This can be particularly true in the substrate, where shells of mollusks can undergo post mortem dissolution."

Vertically through the Fruitland and Kirtland Formations differences can be seen in the sedimentologic context of invertebrate concentrations. At the base of the Fruitland Formation most invertebrates in the West Central Basin are brackish organisms (Hartman, 1981). Often molluscs, particularly oysters, are found in great concentrations with thicknesses of several centimetres, and areal extents of hundreds of square metres. These coquinas may contain minor amounts (<5%) of clastic material. Higher in the Fruitland, molluscs are found in channel deposits and floodplain environments. By the uppermost Fruitland and lowest Kirtland Shale (study area) the majority of mollusc concentrations occur in channel lag deposits. Higher in the Kirtland molluscs are rare, as are vertebrate remains, and plant remains become uncommon. No invertebrates are known from the highest, Naashoibito, Member of the Kirtland. This upward progression is probably a result of progressive increase in the drainage of energy of streams and a progressive increase of interchannel areas.

IV. MAGNETOSTRATIGRAPHY

Introduction

Although Brunhes discovered reversals of the Earth's magnetic field in 1906 and Mercanton, in 1926, attempted to delineate the times when the field was reversed, the first quantitative time scale for geomagnetic reversals using the K-Ar technique was by Cox et al. (1963a, b). Early studies were conducted on nonmarine lavas from the Late Tertiary to Recent, but, with the hypothesis of Vine and Mathews (1963) work was extended to marine rocks, and back to the Cretaceous.

Recently interest has arisen in relating mammalian biostratigraphy to magnetostratigraphy (e.g. MacFadden, 1977; Lindsay et al., 1981; Butler et al., 1981). To aid biostratigraphic and lithostratigraphic correlations of the study area a small scale magnetostratigraphic study was conducted.

Collection of Samples

Thirty-seven specimens were collected from nine sample localities at spacings of approximately 2.5 m (Figure 42). The first sample locality (001) was 2.5 m above the basal coal in the study area. Subsequent sampling localities were numbered sequentially, and they followed the line of stratigraphic sections up the main wash through the Fossil Forest Badlands.

For each specimen, a flat surface was planed on unweathered rock. For this surface dip and strike measurements were taken *in situ*. Sampling localities were picked only in fine grained sediments and specimens collected had a minimum volume of 16 cc.

From each site the best three specimens, in terms of volume and fineness of grain size, were sliced, with a rock saw, to fit inside 1.7 x 2 x 2 mm plastic boxes. This size of container was chosen to fit sample holders at the University of Arizona Paleomagnetism Laboratory. The three specimens from each sampling site were labelled A, B, and C. Care was taken in the cutting of the samples to preserve the horizontality of the surface planed off in the field.

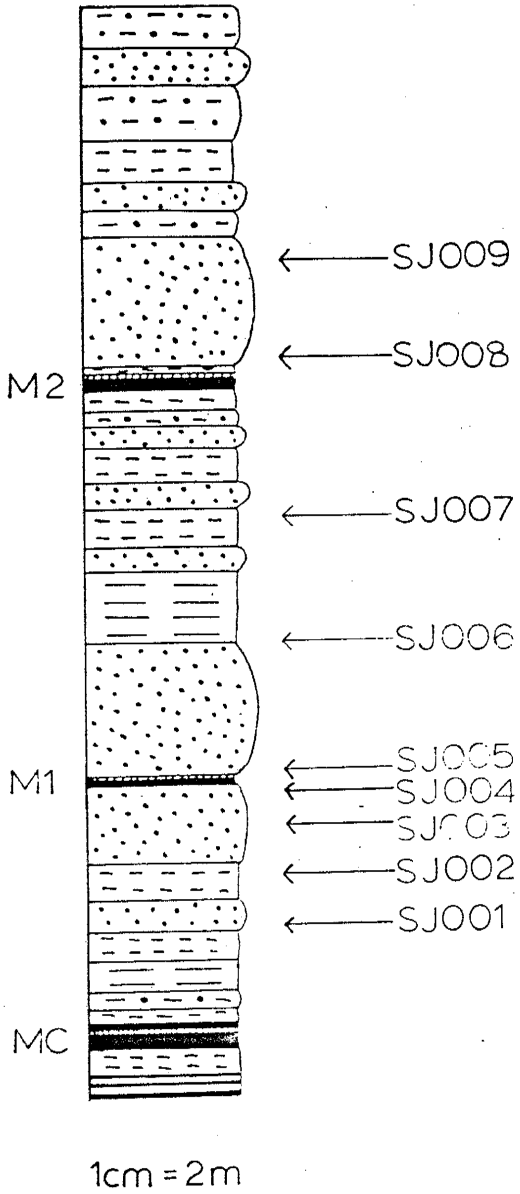


Figure 42. Palaeomagnetic sample localities. For explanantion of lithologic symbols see Plate 2. M1, Marker Bed one, M2, Marker Bed two, MC, Main Coal.

Measurement

All measurements were conducted at the Paleomagnetism Laboratory of the University of Arizona at Tucson. Demagnetisations were performed using a Schonstedt GSD-1 Single Axis Tumbling Specimen AF Demagnetiser. Alternating field demagnetisation involves placing the specimen in an alternating magnetic field (peak value H). All magnetic domains with coercive force less than H cos theta (where theta is the angle between the domain coercive force and H) follow the field as it alternates and as the alternating field is slowly decreased to zero, domains with progressively lower coercive force become fixed in different orientations. Eventually all domains with coercive forces less than H will have random orientation (McElhinny, 1979).

Magnetization measurements were conducted using a Superconducting Technology Two-Axis Cryogenic Magnetometer C-102 with computer interface for real-time data aquisition and analysis. Cryogenic magnetometers operate using superconducting sense coils in which a DC persistent current is induced by the insertion of the sample (Goree and Fuller, 1976). The current gives, via a flux transformer, a field at the SQUID (Superconducting Quantum Interference Device) sensor, which is detected as the measure of the magnetisation of the sample (Goree and Fuller, 1976). The sense coils, transformer, and detector are housed within a superconducting shield. Cooling is provided by liquid helium. Cryogenic magnetometers are relatively faster and more sensitive than other types of magnetometers and thus are widely used for palaeomagnetic studies of sedimentary rocks in which many weak samples must be processed. The main disadvantage is the high initial, and subsequent maintainance, costs. A programme designed to measure cored samples was utilized which compensated for orientation of the planed surface.

The Natural Remanent Magnetization (NRM) was measured for each specimen. In addition, specimen A from each locality was stepwise demagnetised in steps of 10 mT to 40 mT. Specimen FF003A was demagnetised to 50 mT as the specimen inclination was showing a steady decline from negative to positive. Specimens B and C from each locality were measured at demagnetisations of 20 mT and, depending on the stability of the readings, also at 40 mT. As the readings of FF003A had not been equivocal, FF003B and FF003C were demagnetised at steps of 10 mT. FF008C and FF009B were demagnetised at 60 mT to confirm decreasing and increasing trends respectively. NRMs were typicaly about 3 x 10-3 amp/metre with FF009 being appreciably higher at about 2 x 10-1 amp/metre. This compares with values rarely exceeding 5 x 10-6 gauss (5 x 10-3 amp/metre) obtained by Lindsay et al. (1981) for San Juan Basin samples. The Median Destructive Field (MDF) which is the value of the alternating field required to reduce the NRM by a factor of two was typically 10-20 mT.

Vector demagnetisation Zijderveld plots were made for fifteen specimens using the NMIMT DEC 20 and the NMIMT Geophysics Group Tektronics CrT printer; two examples are illustrated in Figures 43 and 44. Specimen FF001A (Figure 43) shows single component behavior which would be expeted for a sample of normal polarity. In contrast specimen FF003B (Figure 44) shows distinct two component behavior as would be expected from a reversed sample with a normal overprint.

Upon demagnetization to 10 mT, and to a lesser extent to 20 mT, there is a large directional change in the behavior of all specimens. The large change is attributed to a large component of low coercivity viscous magnetisation. Following further demagnetisation there is evidence of a more stable component taken to be a primary NRM.

Progressive demagnetisation indicates that the carrier of the primary NRM has a significant proportion of its remanent coercivity spectrum in the 15 to 40 mT range. This is a common property of sedimentary rocks in which the primary NRM is a Depositional Remanent Magnetisation (DRM) and is carried by a fine grained magnetite or titanomagnetite (Archibald et al., 1982). Butler (1982) in considering samples from Hunter Wash, 16 km distant, concluded that the DRM in Fruitland and Kirtland Formation samples was carried by detrital titanomagnetite. DRM records the magnetic field penecontemporaneous with deposition (Verosub, 1977). Butler's (1982) conclusions were based on polished section examination and on experimentally determined thermomagnetic curves. Haematite shows much higher remanent coercivities (Dunlop, 1972).

Sample mean directions were calculated using the standard statistical method of Fisher (1953) from a programme on the NMIMT Geophysics Group Northstar computer interfaced with a Centronics 730 printer. Values chosen to be included in the calculations were determined by examination of measurements and of Zijderveld plots. Two means were calculated for FF008 as two specimens (B,C) had negative NRMs and became progressively more positive, although B actually remains reversed, and one specimen (A) started normal and then showed reversed and then normal inclinations with increased demagnetisation. Hence two means were calculated for FF008, one using three reversed values and one using two normal and one reversed values.

Virtual Geomagnetic Plates (VGP) latitudes were calculated from the means derived from the Fisher statistics for each sample and then the VGPs were themselves analysed by Fisher statistics. These calculations were carried out on the NMIMT Geophysics Group Northstar computer.

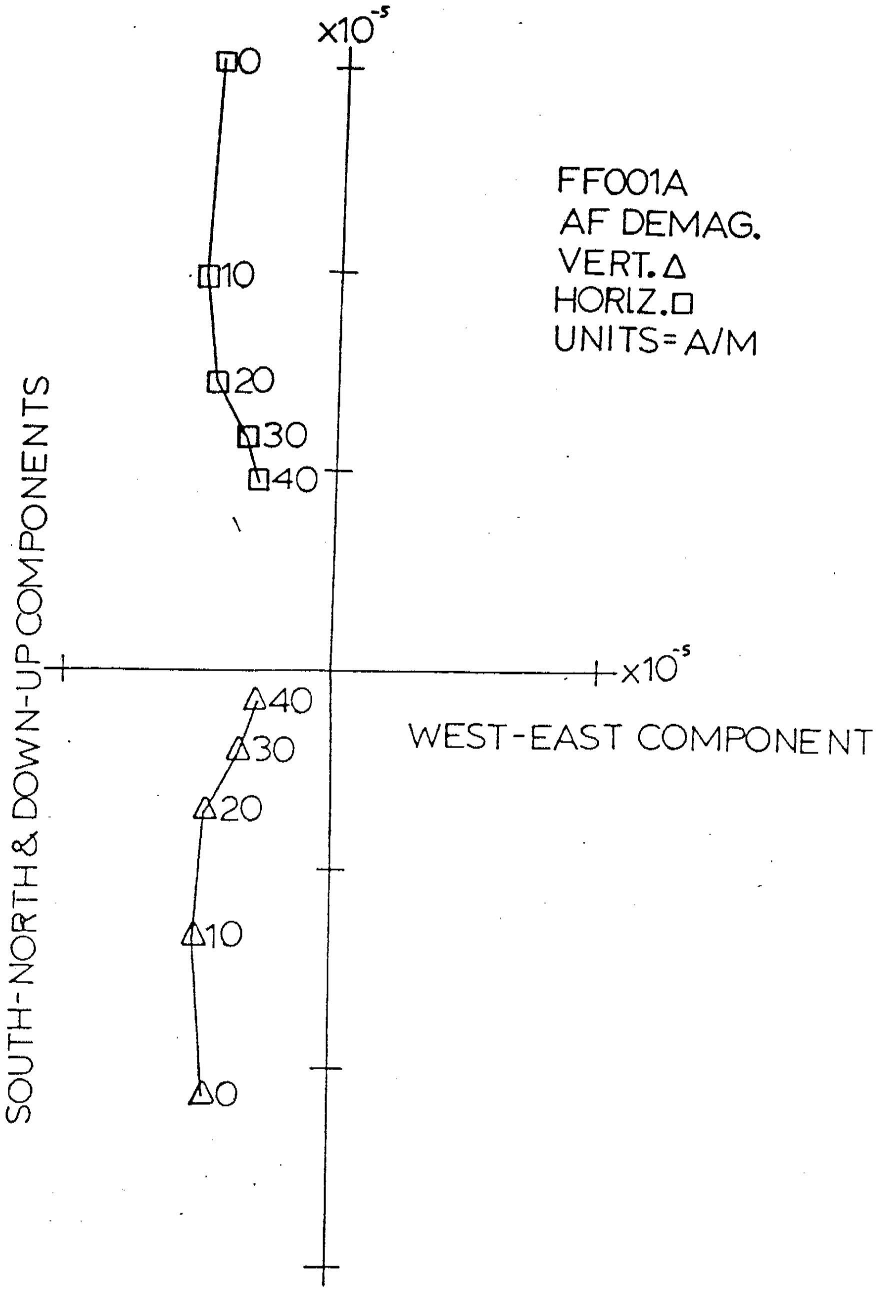


Figure 43. Zijderveld vector demagnetization plot for FF001A.

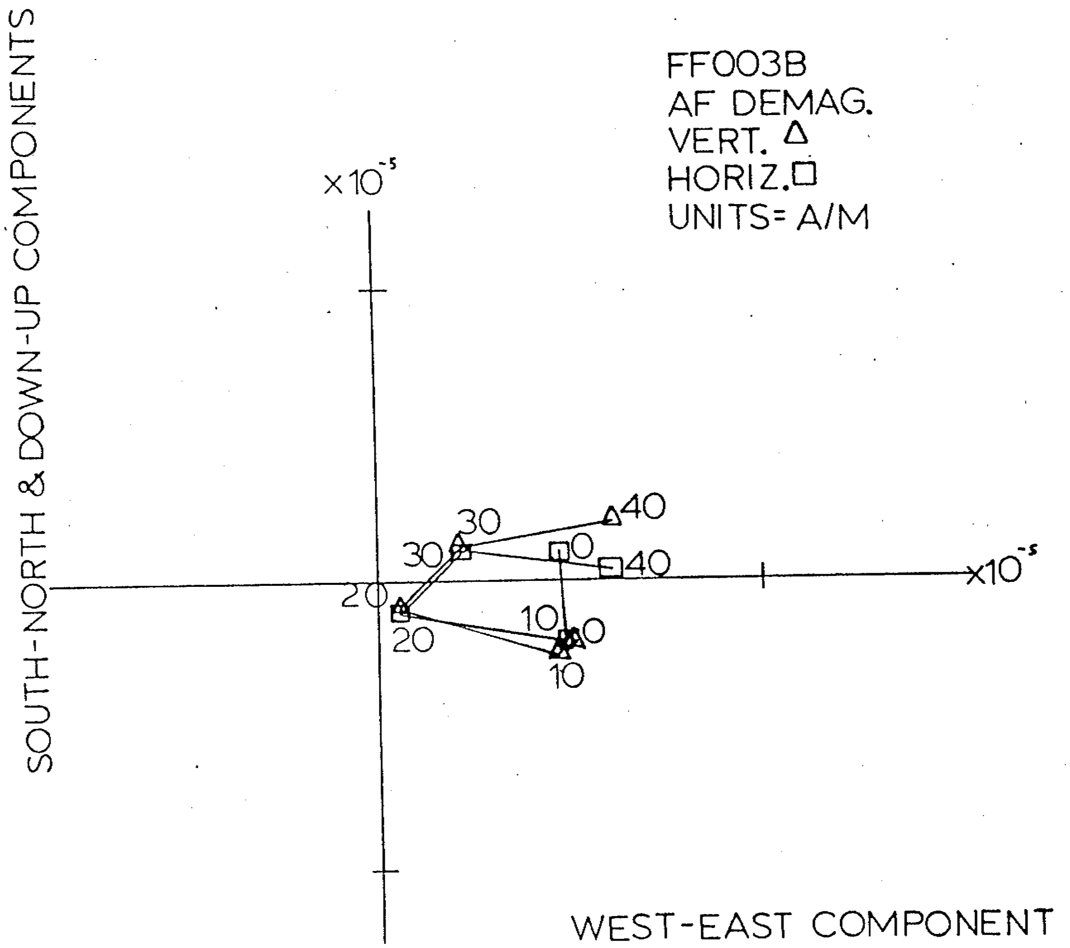


Figure 44. Zijderveld vector demagnetization plot for FF003B.

Data obtained from the above procedures are tabulated in Appendix 2.

Results

A set of criteria was developed to establish the polarity of samples where the specimens showed unclear or contradictory results. Lerbekmo et al. (1979) considered samples reversed if at least one specimen was reversed and sites normal if three specimens were normal. This method is biased in favour of finding reversed polarities. Payne et al. (1983) considered samples reversed if one or more specimens were reversed and less than two were normal, and considered sites normal if two or more specimens were normal. This method is biased in favour of finding normal polarities. A set of criteria was established using the most stringent component of each method whereby a site was considered normal if it contained three normal specimens and considered reversed if one or more specimens were reversed and less than two were of normal polarity. Otherwise sites were considered indeterminate.

The nature of the polarity of the specimens was determined by calculating the plot of the latitude of the VGP (Virtual Geomagnetic Pole) relative to the position of the Late Cretaceous pole (Table 14). This calculation was

Sample Designation	Demagnetisation Step (mT) Used in Calculation	Plot of VGP Latitude Relative to 73.0° (degrees)	Sample Polarity Designation	Site Polarity Designation Criteria of Lerbekmo et al. (1979)	Site Polarity Designation Criteria of Payne et al. (1983)	Site Polarity Designation This Report
FF001A	20	81.4	N	N	N	N
FF001B	20	76.8	N			
FF001C	20	64.8	N			
FF002A	20	-3.4	I	I	N	I
FF002B	20	71.0	N			
FF002C	20	80.0	N			
FF003A	30	-55.4	R	R	R	R
FF003B	20	-36.4	R			
FF003C	40	-20.2	I			
FF004A	30	76.4	N	N	N	N
FF004B	20	68.6	N			
FF004C	20	39.1	N			
FF005A	30	-13.0	I	I	N	I
FF005B	20	81.3	N			
FF005C	40	78.1	N			
FF006A	30	-42.7	R	R	I	I
FF006B	20	-11.9	I			
FF006C	40	30.7	N			
FF007A	20	-30.9	R	R	I	I
FF007B	20	67.4	N			
FF007C	20	58.4	N			
FF008A	30	42.2	N	I	N	I
FF008B	20	17.5	I			
FF008C	20	41.1	N			
FF008A	40	48.7	N	I	N	I
FF008B	20	17.5	I			
FF008C	40	65.9	N			
FF009A	40	57.6	N	N	N	N
FF009B	40	36.9	N			
FF009C	40	44.7	N			

Table 14. VGP latitudes and polarity designations for palaeomagnetic samples and sites.

conducted on the NMIMT Dec 20 system using a programme written by W. McIntosh. The VGP is the palaeopole position which would result from the magnetization direction obtained from a sample. The Upper Cretaceous-Lower Tertiary palaeomagnetic pole for North America (80-40 m.y.) was 186 degrees E, and 73 degrees N (Irving, 1977). A sample of normal polarity, given this pole position, would have an inclination of 61 degrees and a declination of 339 degrees, whereas samples of reversed polarity would have an inclination of -61 degrees and a declination of 159 degrees. Plots of latitudes of VGPs for samples of normal and reversed polarity, with the above pole position, would be 73 degrees and -73 degrees, respectively. Bearing in mind the above, the following criteria were used to establish the criteria of specimens. If the plot of the latitude of the VGP was between -30 and 30 degrees the specimen was considered indeterminate. If the plot of the latitude was greater than 30 degrees or less than -30 degrees the sample was considered normal or reversed, respectively. Sample and specimen polarity designations are summarised in Table 4.

FF001. All three specimens have normal inclinations and the mean inclination is 56.7. This sample is considered normal.

FF002. All specimens have stong normal inclination, the mean being 75.0, but one of the VGP positions (A) is reversed whereas the other two are normal, therefore this sample is considered indeterminate.

FF003. Specimen A began demagnetisation with a reversed inclination, became normal and then became reversed again but tended to become less so with demagnetisation. Specimen B started normal and then became reversed, but became less so with demagnetisation. Specimen C showed a decreasing positive inclination with demagnetisation and then an upswing at 40 mT. When one reversed and two normal values were used in calculating Fischer Statistics (30mT-A, 20mT-B, 40mT-C) a worse kappa of 1.4 as against 2 and a worse alpha 95 of 180.0 as opposed to 37.92 were obtained than if two reversed and one normal values were used (30mT-A, B, C). The mean inclinations in these two cases were 4.2 and -45.2, respectively. In the calculation of the VGp latitude higher kappa (3.5 against 3.0) and lower alpha 95 (32.90 as against 35.81) were obtained assuming a normal polarity for FF003. Specimen C appears normal based on all evidence. Specimen A moved to a normal inclination from a reversed on demagnetisation to 50mT with a low intensity but the trend of the Zijderfeld plot would indicate a reversed polarity. Specimen B becomes reversed from normal but the trend of the Zijderfeld plot from 30mT to 40mT would indicate a normal polarity. The polarity of the sample is considered reversed based on the above proposed criteria.

FF004. The mean inclination is 57.9 and VGPs of all specimens are wholely normal. This sample is considered normal.

FF005. All three specimens have a strong normal inclination and the mean from Fisher statistics is 67.2, however of the VGPs one is negative and two are positive, and therefore this sample is considered indeterminate.

FF006 has two reversed specimens and one normal based on inclinations. The Fisher statistics give very poor results with an alpha 95 of 180. Based on VGP latitudes this sample is considered indeterminate.

FF007. Specimen A is consistently reversed with regard to inclinatio whereas Specimen B is solidly normal. The inclination of Specimen C starts reversed, becomes normal and then declines in positivity with increasing demagnetisation. Fisher statistics show a normal inclination but with an alpha 95 of 180. Based on VGP latitudes this sample is considered indeterminate.

FF008. Specimen C starts demagnetisation with a reversed inclination and becomes normal, whereas, Specimen B has a reversed inclination and Specimen A goes from normal to reversed to normal inclination with increasing demagnetisation. Due to the confusion in the data, two sets of data were subjected to Fisher statistics, one gave a reversed inclination and the other a normal. Three reversed values (30mT-A, 20mT-B, 20mT-C) give a mean inclination of -21.1 with a kappa of 6.7 and an alpha 95 of 51.75 whereas two normal and one reversed values (40mT-A, 20mT-B, 40mT-C) give a mean inclination of 9.7, a kappa of 2.0 and an alpha 95 of 41.03. Use of the reversed value in calculation of the VGP latitudes gave better results using Fisher statistics (Kappa of 4.1 against 3.5, alpha 95 of 29.0 against -32.09). This sample is considered normal on the basis of VGP latitudes.

FF009. All specimens have a strong normal inclination, and the sample is considered normal based on VGP latitudes.

Conclusions

The proposed magnetostraphic sequence for the rock sequence exposed in the study area is shown in Figure 45. Only sample 003 is considered reversed upon utilizing the above discussed criteria (Table 14). Sample 004 is considered normal and 002 is indeterminate although it is normal according to the criteria of Payne et al. (1983). A reversed polarity zone is thus assigned to sample 003 with all other samples considered normal. This reversed interval is correlated with the reversed subzone recognised by Lindsay et al. (1981) in Hunter Wash at approximately the same stratigraphic height at approximately the

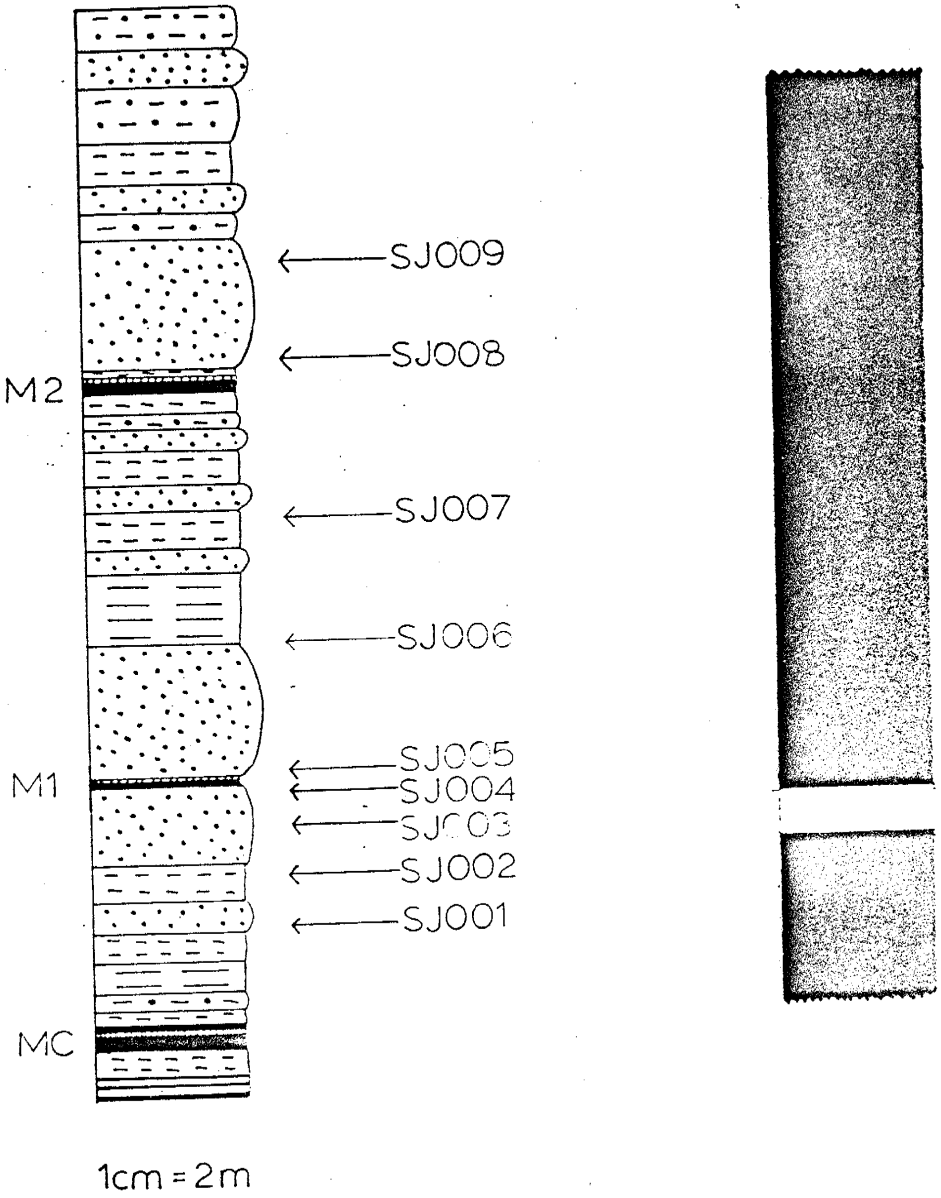


Figure 45. Proposed magnetostratigraphic zonation correlated with lithologic column. For explanation of lithologic symbols see Plate 2. In magnetostratigraphic column on right black indicates normal polarity and white reversed polarity. M1, Marker Bed one, M2, Marker Bed two, MC, Main Coal.

Fruitland-Kirtland formational contact (Figure 46). At Hunter Wash the reversed subzone is represented by two sites separated by a stratigraphic thickness of 0.5 m (Lindsay et al., 1981). As palaeomagnetic unit boundaries are conventionally placed midway between sampling sites, the stratigraphic extent of the reversed subzone in Hunter Wash is 1 m. In the Fossil Forest area the reversal is represented by a stratigraphic interval of 1.05 m.

The reversed zone in Hunter Wash is correlated by Lindsay et al. (1981) with the reversed interval between normal polarity zones 30 and 31, but this is considered improbable. This reversed interval had a duration of 0.11 m.y. (Ness et al., 1980), and if deposited over 1.05 m would give a minimum deposition rate for that interval in the study area of .95 cm per 1,000 year and at Hunter Wash of 0.9 cm per 1,000.

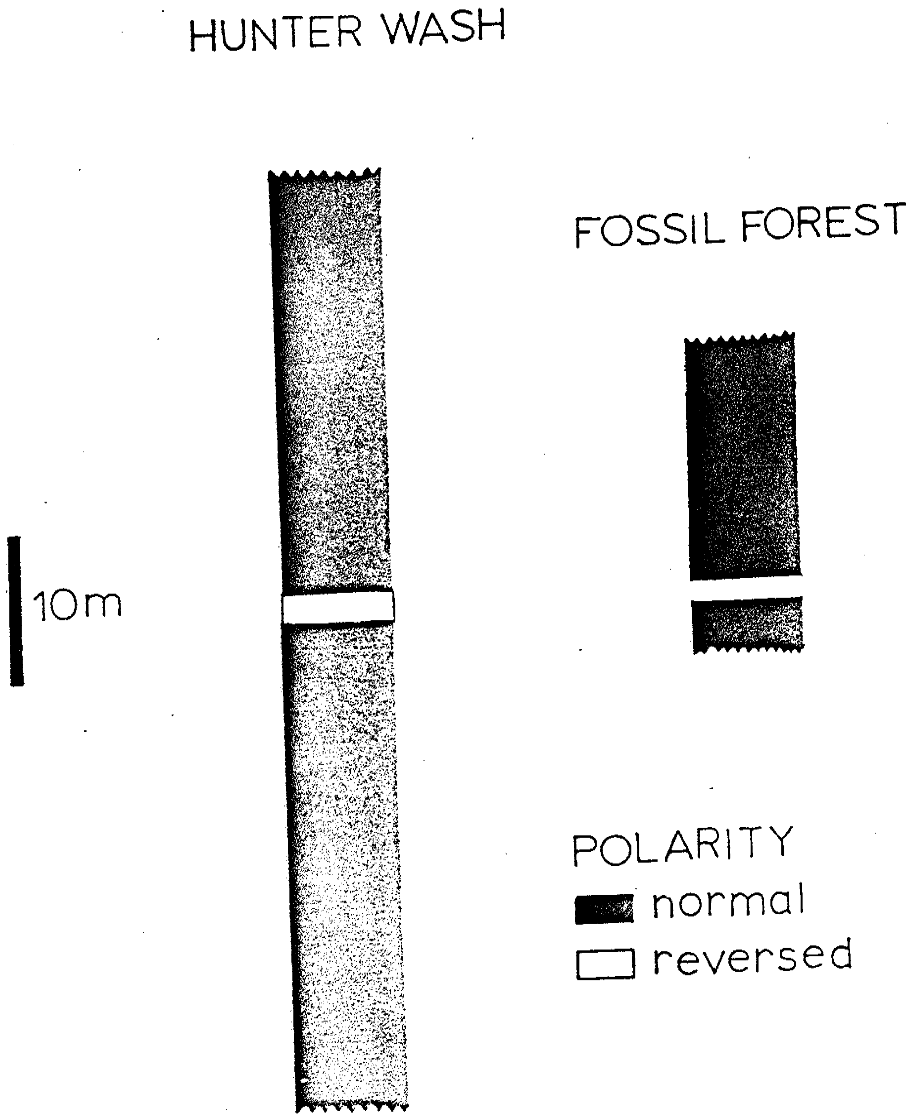


Figure 46. Proposed magnetostratigraphic correlation between Hunter Wash and the Fossil Forest area.

V. ENVIRONMENTAL INDICATORS

There is a progression from the Pictured Cliffs Sandstone to the upper Fruitland Formation from marine to freshwater. The sequence from brackish to freshwater is currently being documented in the nonmarine invertebrates of the West Central San Juan Basin by J.H. Hartman (1981). There appears to be a cut off between brackish influence and wholey freshwater conditions at about 35 m above the base of the Fruitland, in the deltaic facies west of the Central Basin (Hartman, 1981). The Fossil Forest area is probably about 80 m above the base of the Fruitland on the basis of correlation with Hunter Wash (Chapter VI). On the basis of Hartman's careful study, the total absence of marine or brackish fossils and the abundant occurrences of terrestrial vertebrates and plants in the study area, the rock sequence in the study area, is presumed to have been deposited in a freshwater context.

Vertebrate remains from the study area, in their present state of taxonomic study, cannot give detailed information as to the environment in which the rocks of the study area were laid down. Dinosaurs are poor indicators of climate (Ostrom, 1970) as are small mammals, but the presence of other vertebrates elsewhere in the Fruitland and Kirtland Formations (for faunal lists see Lehman, 1981;

Lucas, 1981) give clues as to the environment. Crocodiles, trionychids, teiids, elopids, and lepisosteids are all today primarily tropical or subtropical, and aniliid snakes are totally tropical (Estes, 1964). The diverse turtle fauna, apparent in the study area, would also indicate a subtropical environment. Modern relatives of Fruitland-Kirtland Urodeles are mostly warm-temperate in habit, but the large size and larval habit of the Fruitland-Kirtland forms make them most similar to eastern Gulf and Atlantic coast subtropical forms (Estes, 1964). Recent discoglossid frogs, as represented in the Fruitland-Kirtland sequence are, except for one genus, warm-temperate animals (Estes, 1964). The majority of the vertebrate fauna from the study area, and elsewhere in the Fruitland and Kirtland Formations, therefore, indicates a subtropical climate.

The term "palaeoclimate" has been used rather loosely by palaeobotanists to refer to conditions of temperature and moisture rather than to the total environment under which a fossil flora existed (Dolph and Dilcher, 1979). To evaluate palaeoclimate, two different approaches have been used. The first is that of the nearest relative, which involves comparing fossil genera with the nearest living relative and extrapolating from the environmental tolerances of the latter back to the fossil form. This approach has two major problems, firstly it requires accurate naming of genera, and secondly it can only be used with great care with floras older than the Neogene. The second method involves foliar physiognomy in which attributes of leaf morphology are related to climate. This suffers from the problem that climatic variables and leaf characteristics are not closely correlated, although general and relative statements can be made (Dolph and Dilcher, 1979).

Both the nearest relative approach (Tidwell et al., 1981) and the foliar physiognomy method (Robison et al., 1982) have been applied to the flora of the Fruitland-Kirtland sequence and they both indicate a warm temperate to subtropical climate. The leaf flora from the study area is currently under review by Robison, but it is substantially similar to the local flora from Hunter Wash, discussed by Robison et al. (1982).

Water temperatures in the Western Interior Seaway in New Mexico, as measured by fossil biotas related to those characterizing modern climatic zones, were subtropical (Kauffman, 1977). Such a climate is also suggested by the latitude of this area in the Campanian-Maastrichtian (Lillegraven et al., 1979, figure 14-1).

Seasonality of climate, at least in terms of moisture, is suggested, in the study area, by well developed growth rings in petrified wood, by epsilon crossbeds in channel form sandstones, and by the similarity of Channels B and D to the Platte River form of braided stream. Seasonality was not marked enough to discourage subtropical animals.

Almost all evidence from fossils and sedimentology points to a subtropical climate for the Fruitland and Kirtland Formations in general, and for the study area in particular, probably with seasonal rainfall.

VI. CORRELATION

Outcrop in the vicinity of the study area is discontinuous and exact correlation, with the regional stratigraphic sequence, is difficult. To facilitate such correlation, stratigraphic investigations, including the measurement of 13 stratigraphic sections, (Figure 47) were carried out at Hunter Wash in the area of the site of the Bisti Trading Post (Hunt et al., 1980). In Hunter Wash and associated drainages there is continuous outcrop from the lower Fruitland Formation to the Nacimiento Formation. The Bisti area lies 16 km to the eastnortheast of the Fossil Forest area (Figure 48). Magnetostratigraphic investigation was carried out in the Hunter Wash area by Lindsay and Butler (Butler et al., 1977; Lindsay et al., 1981), whose work has been correlated to a lithostratigraphic column in this report (Figure 49) by use of a shared volcanic ash (E. Lindsay, personal communication, 1983). The magnetostratigrphic column of Lindsay et al. (1981) does not encompass the whole Fruitland Formation, but extends to within about 25 m of its base.

In both Hunter Wash and the Fossil Forest (Figure 49) the highest thick coal (> or = 1 m) in the rock sequence contains a tonstein or altered volcanic ash (ashes (a) and (l) respectively). Above this ash, at both locations, is a

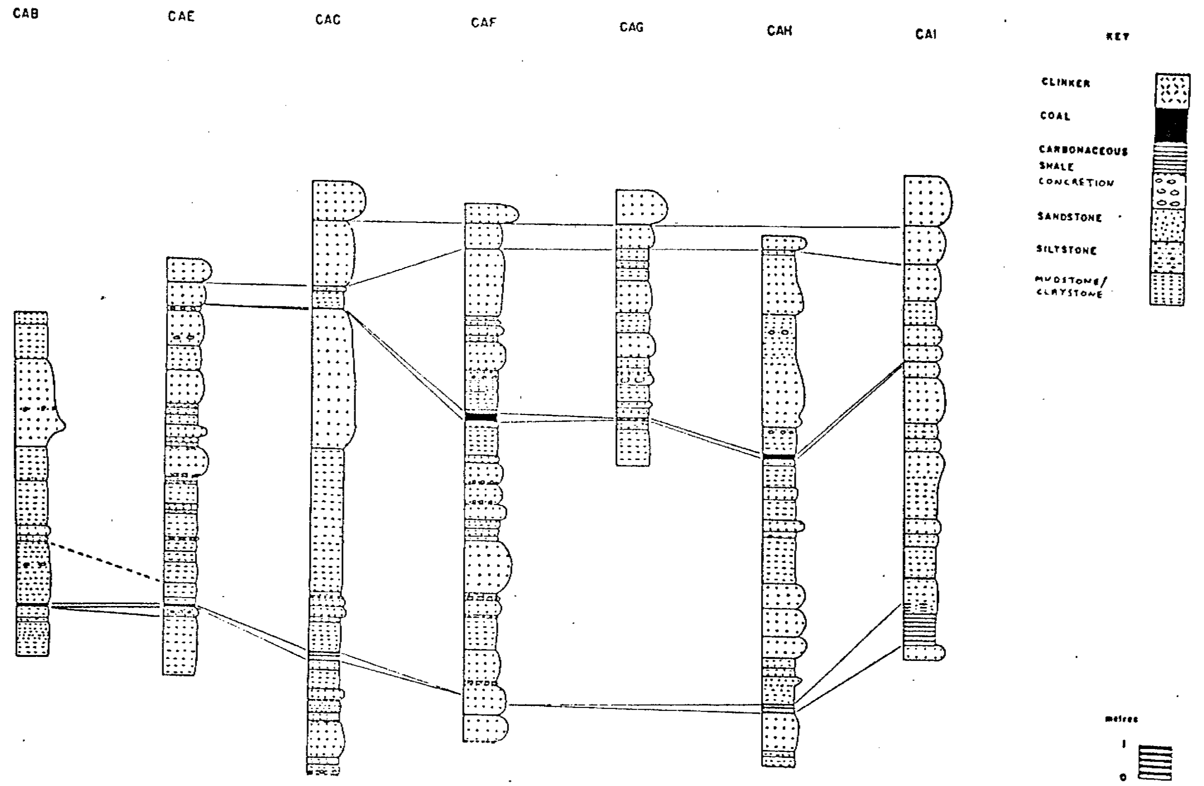


Figure 47. Stratigraphic correlations in Bisti area at Hunter Wash. Datum is base of red brown capping sandstone.

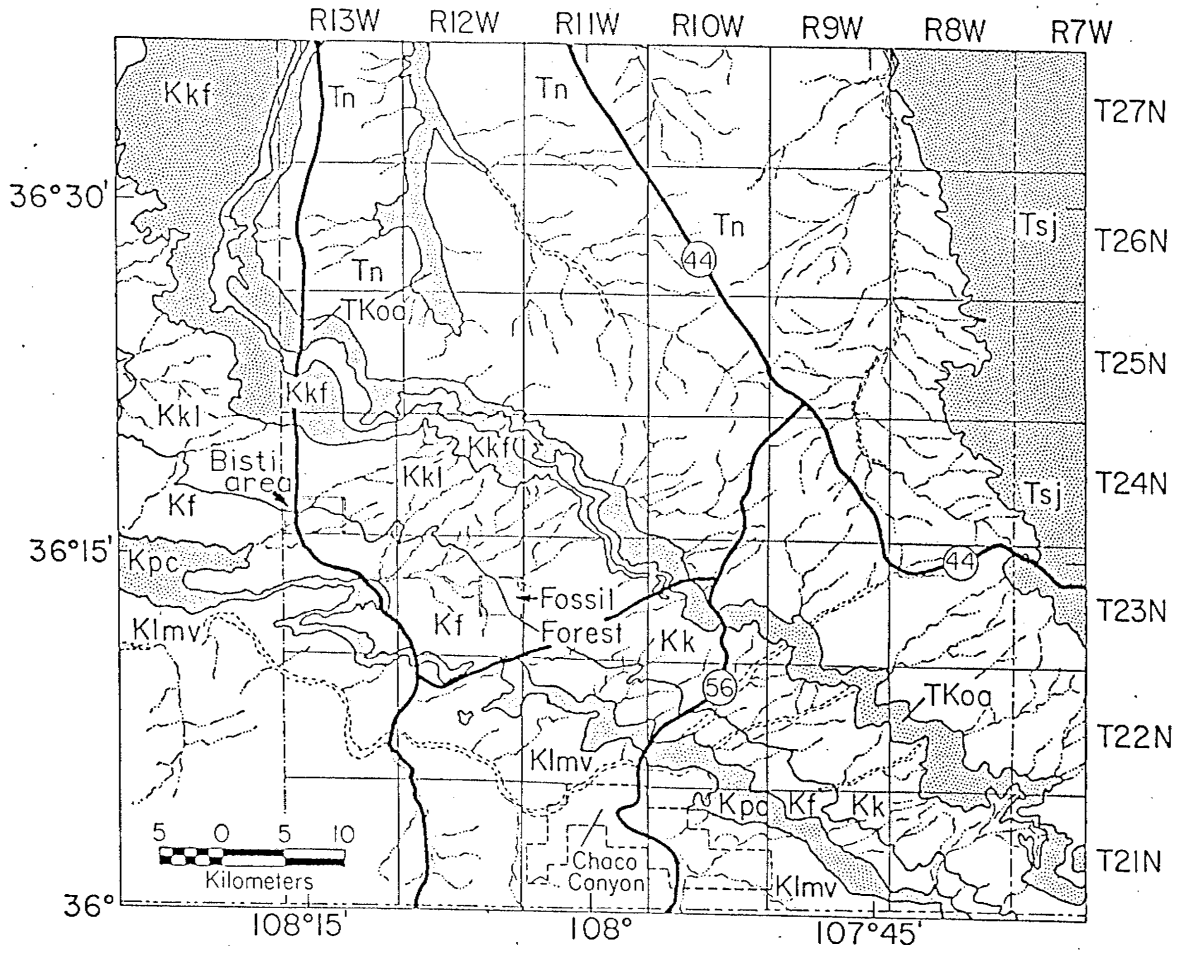


Figure 48. Location of Bisti area in relation to the Fossil Forest study area. For key see Figure 1.

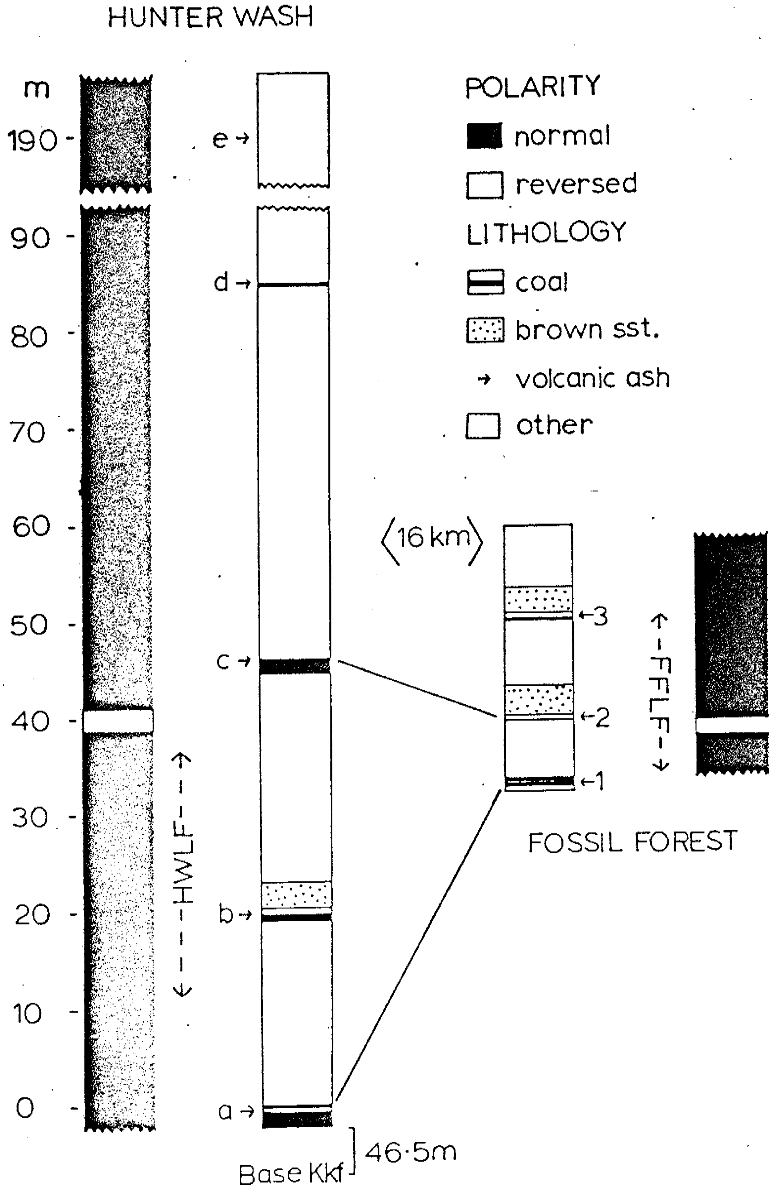


Figure 49.

Magnetostratigraphic and lithostratigraphic correlation between Hunter Wash and Fossil Forest. Kf, Fruitland Formation, HWLF, Hunter Wash Local Fauna (Clemens, 1973), FFLF, Fossil Forest Local Fauna. Partly after Hutchinson (1981) and Lindsay et al. (1981).

sequence of fluvially deposited rock. Stratigraphy above the lowest ash is a short zone of reversed magnetic polarity above which lies a second ash (ash (c) at Hunter Wash and (2) in the Fossil Forest area). Above the second ash in Hunter Wash is a sequence of ashes whereas in the study area there is only one other, due to lack of outcrop of stratigraphically higher units. A correlative of ash (3) has yet to be found in Hunter Wash. Ash (b) is found at Hunter Wash, but no correlative is found in the study area. It is presumed that ash (b) was eroded away by the downcut complex occurring immediately above the main coal in the study area. The base of this complex is demonstrably unconformable (Chapter II).

In each area the rocks show a progressive change, upward from the tonstein bearing coal. Mudstones become less grey and more grey-green in colour. Siltstones are increasingly important, volumetrically, at the expense of mudstones. The carbonaceous content of beds decreases and siderite concretions become less numerous.

On the basis of lithologic similarity, presence of a reversed magnetozone in a part of the magnetostratigraphic section where only one such magnetozone is found (Lindsay et al., 1981) and a similar sequence of volcanic ashes, the two areas are correlated, as shown in Figure 50. The thin coals/carbonaceous shales associated with ashes (a) and (b) have been traced, in outcrop, approximately 4 km from Hunter

Wash towards the Fossil Forest. However, correlation of coal zones rather than of individual coal beds is proposed between the two areas.

Based on lithostratigraphy and the relationship of ashes to carbonaceous layers, a preferred correlation would match ash (a) to ash (1), ash (b) to ash (2), ash (c) to ash (3). This interpretation would contradict the magnetostratigraphic zonation for the Fossil Forest given above, but that zonation is equivocal. Application of the the criteria of Lerbekmo et al. (1979) to the raw data would give a reversed polarity zone above ash (2) which would give the desired correlations.

Three of the above mentioned volcanic ashes in Hunter Wash have been radiometrically dated:

Ash e:	64.6 + or - 3.0 m.y.	(Lindsay et al., 1981)
Ash d:	78.0 + or - 3.1 m.y.	(JKR-54 of Brookins and Rigby, 1982)
	69.0 + or - 2.6 m.y.	
Ash c:	68.3 + or - 5.0 m.y.	(Hutchinson, 1981b)
	72.7 + or - 3.0 m.y.	(JKR-62 of Brookins and Rigby, 1982)
	53.8 + or - 2.4 m.y.	
	76.5 + or - 3.1 m.y.	(JKR-4 of Brookins and Rigby, 1982; locality is incorrectly given as T24 instead of T23)

The locality of JKR-93 (T24N R12W) of Brookins and Rigby (1982) is too vague to allow relocation. The above ages suggest an absolute date for the rocks exposed in the Fossil Forest area of early Campanian to late Maastrichtian (Obradovich and Cobban, 1975), assuming that the Tertiary date of JKR-62 can be discounted on the basis of presence of dinosaurs. The reversed magnetozone, if indeed it represents that lying between normal zones 30 and 31 of the standard magnetic anomaly timescale (Lindsay et al., 1981), would have an absolute age of 69 to 69.11 m.y (Ness et al., 1980).

VII. AFTERWORD

The strata exposed in the Fossil Forest area represent a period of transition in the Upper Cretaceous of the San Juan Basin. Stratigraphically this transition is between the Fruitland Formation and the Kirtland Shale. Bauer and Reeside (1921) considered the formational boundary to pass through the study area, as does this report which uses as the top of the Fruitland Formation, the top of the highest "significant coal."

Sedimentologically the strata of the study area represent a transition from the grey mudstones and coals, with their associated iron concretions of the Fruitland Formation, to the grey green siltstones of the Kirtland Shale. This transition represents a regional increase in drainage associated with the retreat of the Pictured Cliffs Sea and a change in fluvial style associated with a change in sediment source. Channels B and D seem to reflect a first pulse of the new mode of sedimentation.

Taphonomically the sequence exposed in the Fossil Forest represents a short fossiliferous stratigraphic interval, which is also fossiliferous at Hunter Wash and elsewhere in the west Central Basin. In the Fossil Forest the fossilized biota is dominantly restricted to one downcut complex. The Fossil Forest area can be correlated with

Hunter Wash on the basis of lithostratigraphy and magnetostratigraphy.

APPENDIX I

Measured Stratigraphic Sections

ABREVIATIONS

- Bed No. ------------------------ Bed Number
- Bed Thck (m) ------------------- Bed Thickness (centimeters)
- Grain Size (after Wentworth)
    - vc ---------------------- very coarse sand
    - c ----------------------- coarse sand
    - m ----------------------- medium sand
    - f ----------------------- fine sand
    - vf ---------------------- very fine sand
    - sl ---------------------- siltstone
    - md ---------------------- mudstone
    - cl ---------------------- claystone
- Induration 1 ------------------- well Induarted
    - 2 ------------------- moderately Indurated
    - 3 ------------------- poorly Indurated
- Sorting 1 ---------------------- well sorted
    - 2 ---------------------- moderately sorted
    - 3 ---------------------- poorly sorted
- Smx ---------------------------- small scale crossbedding
- Lgx ---------------------------- large scale crossbedding
- Fossil ------------------------- fossil material
- Con ---------------------------- concretion
- Col ---------------------------- colour
    - gg ------------------------- grey green
    - y -------------------------- yellow
    - o -------------------------- orange
    - b -------------------------- brown
    - bl ------------------------- black
    - v -------------------------- very
    - d -------------------------- dark
    - l -------------------------- light
    - g -------------------------- grey

Locations of sections see Plate 2

All sections measured by A. Hunt or A. Hunt and J. Menack (1980-1981) using Brunton compass, and Jacob staff.

AAA

Bed No.	Bed Thck (cm)	Col.	Grain size vc	c	m	f	vf	sl	md	cl	Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
001	36	vlg			|	|					2	2			carb. plant remains up to >.5cm in length occur concent. in laminae and scattered	Siderite band 10cm from base d.brown	sinuous irreg. bedding often picked out by plant fragments
002	10	ygg				|					1	2			carb. plant remains 1% by volume		
003	20	gg								|	1	1			carb. plant frags. 1% by volume	Siderite conc. 18cm from base brown	
004	26	ygg				|					1	2					
005	61	gg			|						1	1			carb. plant remains <1.5mm in diam 5% by volume	Siderite conc 10cm from base brown	
006	22	dg							|		1	1			rare carb. plant fragments		
007	15	gg		|	|						3	1/2					lateral extent 4m. Grain size +sorting vary laterally
008	30	gg						|			1	1			large silicified wood frag. 12x10x8cm 5cm below top of bed		
009	33	gg							|		1	1					deeply weathered
010	10	gg								|	2	1					deeply weathered 15% silt sized grains

AAB1

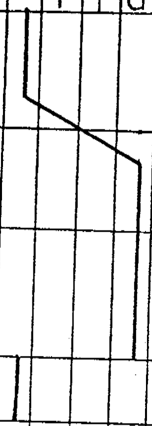
Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	56	vlg									1	1	common arcuate to planar	uncommon arcuate	carb. plant fragments 2-4mm in diam. 10% by vol. 2 horizons of shell fragments 5 + 10cm above base. most shell frags <5 sq.cm rare complete shells	siderite concs av. 60cm diam. 15cm above base become more continuous to west. maroon	
002	98	vlg									1	1	common arcuate	rare arcuate	carb. plant fragments 1% by vol. v.rare poorly preserved leaves	laterally discontin. hoodoos 7m apart and .3 thick, 2m in diameter. siderite conc band. 7cm above hoodos + 15cm higher	gradational upper and lower contacts
003	45	gg									1	2	ripples		carb. plant fragments 10% by vol. v.rare seeds		forms 45° slope cf. 002 30°
004	30	gg									1	1			carb. plant fragments <2mm in diam.		
005	34	gg									1	1			carb. plant fragments poorly sorted linear up to 7cm long and 3% by vol. <4mm		
006	64	g									1	1			carb. plant fragments 20% by vol.	Siderite 7cm above base. d. brown	Plant remains particularly rich just above concretion
007	106	gg									1	1			carb. plant fragments 5% by vol.	siderite 20cm above base maroon	deeply weathered
008	10	vlg									1	1	common		carb plant fragments 10% by vol. <2mm in diam. scattered →3 sq.cm		<5% clay pebbles c1cm in diameter

AAB2

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	si	md	cl							
009	12	vlg									1	1	common arcuate		carb. plant fragments <2mm in diam in 2 distinct laminae where 10-20% by vol.	whole layer is hoodo	occasional clay pebbles
010	90	vlg									1	1	common planar to arcuate	common planar	carb plant. fragments 5-10% by vol. rare large >5cm fragments		5% clay pebbles
011	36	ygg									1	2			carb. plant fragments 5-10% by vol.		

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	18	dg							│		1	1			carb. plant fragments 15% <4mm in size		
002	88	ygg				│					1	2			carb. plant fragments <5% by vol		
003	50	lg							│		1	1			carb. plant fragments <4mm in diam scattered	Siderite d.brown	
004	84	g				│			│		2	2			shale: 30% carb. plant fragments by vol.	Siderite d.brown	Interlaminated mudstone + sandstone laminae <1cm thick
005	48	vlg			│						1	1	common		carb. plant fragments 20% by vol		uncommon yellow weathering laminae
006	48	gg							│		1	1					
007	50	g						│			1	1			carb. plant fragments 20% by vol		grades up
008	52	g						│	│		1	1			carb. plant fragments poorly sorted up to 8sq.cm 40% by vol.		grades up
009	42	g							│		1	1			carb. plant fragments up to 5% by vol		
010	44	gg						│			1	1			carb plant fragments		
011	44	gg				│					1	2			carb. plant fragments 10% by vol. up to 9sq.cm poorly sorted		
012	61	ygg				│					2	2	uncommon				
013	15	g						│			1	1			carb. plant fragments 10% by vol.		
014	33	ygg						│			1	1					grades up
015	30	g						│	│		1	1			carb. plant fragments 10% by vol		grades up

AAC2



Bed No.	Bed Thck (cm)	Col.	Grain size vc	c	m	f	vf	si	md	cl	Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
016	30	lg/ygg									1	1	uncommon		carb. plant fragment 10% by vol		grades up colour upword changes ygg to lg
017	30	db									3	3			>60% carb. plant fragments		fissile M2 carbonaceous mudstone
018	89	lg									1	1			carb plant fragment 10% by vol		
019	15	ygg									2	1					

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	si	md	cl							
001	51	ygg									2	2	common			Siderite maroon 20cm from top	clay pebbles up to 5mm×3mm aligned with long axis sub parallel to horizontal
002	54	ygg									1	2	common 3cm thick sets associated laterally + vertically with clay laminae				locally 5% clay pebbles up to 5cm× ·25cm. 3cm thick clay-rich laminae Lateral extent 4m
003	116	lg									siltstone 1 mudstone 3	3	2		carb. plant fragments 10-20% by vol	siderite maroon 50×70 cm in X section	Interbedded siltstone (80%) and mudstone (20%)
004	55	dg									1	1			carb. plant fragments 15-20% by vol.		

BAB

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	61	ygg				│					2	2					fractures subparallel to bedding
002	69	dg						│			1	1			carb. plant fragments 15-20% by vol.		
003	36	gg						│			1	1			carb plant frags. <3% by vol		grades laterally into ygg fine grained sst. with 5% carb plant frags.
004	81	g								│	1	1			carb. plant. frags. 20% by vol.		
005	79	ygg				│					1	1			carb plant frags <5% by vol		60° topographic slope
006	15	ygg						│			1	1			carb plant frags 20% by vol.		
007	18	db							│		3	2			>60% carb plant frags. 30% of surface covered in carb. wood		carbonaceous mudstone M1 very friable scattered amber blebs
008	15	lg							│		1	1			carb plant frags 15% < 10mm in diam		
009	10	vdg							│		3	2			carb. plant fragments c 50% by vol av. <·25cm ⇒ ·75sq cm.		thinly laminated very friable
010	15	g							│		1	1			carb. plant fragments 15% by vol. <10 mm in diam.		

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	si	md	cl							
001	76	bl			c	oa	l										10cm from top is 3-4 cm tonstein. abundant amber. subbituminous. small lenses (mm) of plant rich sandstone
002	76	dg						|			1	1			carb. plant fragments 20% by vol.		
003	211	vlg			|						1	1	common tabular	common low angle planar		Several bench forming hoodoo layers	laterally cuts down into coal. ygg sandstone laminae near top. grades up
004	71	gg				|					1	2	common tabular				scattered clay pebbles up to 2.5cm in diam.
005	23	gg						|			1	1			carb plant fragments scattered up to 3cm x .5cm c 1% by vol.		
006	46	ygg				|					2	2					
007	30	gg							|		1	1					
008	30	vlg				|					1	1			carb. plant fragments 15% by vol. up to 1cm x .2cm		
009	114	vlg			|						1	1	common	common low angle			scattered clay pebbles at base up to 10cm x 6cm. 38cm from top are two 2.5cm thick interbedded sst + >50% plant rich sst. grades up
010	15	ygg				|					3	3	uncommon				
011	13	dg-bl							|		3	2			>60% carb. plant fragments		Carbonaceous mudstone M1 grades up
012	10	dg							|		1	1			carb. plant fragments poorly sorted 5%. up to .8cm in diam		
013	30	gg						|			1	1					

BAE

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	61	bl			c	o	a	l									abundant amber pockets of plant rich poorly indurated sst.. 2cm tonstein 8cm from top. subbituminous
002	38	dg							|		1	1			carb. plant fragments 10% by vol.		
003	76	gg							|		1	1			carb. plant. fragments 10% by vol.		
004	86	g							|		1	1			carb plant fragments 10% by vol.		weathers grey cf. 003 weathers light khaki
005	86	dg							|		1	1			carb. plant fragments 10-20% by vol		
006	10	vlg				|					1	1			carb. plant fragments 2-3% by vol. <1mm in diam	siderite maroon 10cm from base.	

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	s	md	cl							
001	20	gg									1	1			carb. plant fragments 15-20% by vol		
002	41	vlg									1	1	common planar		carb. plant fragments 10% by vol.		
003	15	vlg									1	1			carb. plant fragments 5% by vol.	hoodoo development	
004	15	vlg									1	2	common planar		carb. plant fragments → 20% by vol. up to 2mm in diam.	locally iron staining siderite 30cm wide 20cm thick at top	scattered clay pebbles up to 3.75cm in length
005	28	g									1	1			carb. plant fragment <5% by vol.		scattered laminae of very fine vlg sand. grades up
006	43	vlg									2	2			carb. plant fragments 10% by vol.	locally iron staining particularly in 5cm band. 10cm from base	scattered clay pebbles up to 2cm in length 002 - 006 have a lateral extent of 15m
007	71	lg									1	1			carb. plant fragments 5% by vol. <2mm in diam		small lenses of very fine sand containing 20% carb. plant fragments
008	30	dg									1	1			carb plant fragments 10-20% by vol including *in situ* roots?		comparitively fissile along laminae where most carb. plant fragments occur
009	46	vlg									1	1	common		carb. plant remains 20% by vol		coal lenses locally up to 5cm x ·5cm. 009 pinches out laterally into 008
010	36	vdg									3	2			> 50% carb. plant remains		carbonaceous mudstone
011	36	lg									1	1			no plant remains	-	
012	10	dg									1	1			carb plant fragments 20% poorly sorted up to 3.75cm		
013	46	lg									1	1			carb. plant fragments 10% by vol		
014	20	dg									1	1			carb. plant fragments scattered up to 2x·2cm		

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
015	15	dg									1	1			carb. plant fragments 20% by vol.		
016	33	gg g									1	2			20% carb plant remains on some laminae		interlaminated g and gg mudstone. lamination sinuous
017	10	lg									1	1					
018	15	lg									1	1			Scattered carb. plant remains up to 4.5cm in length		

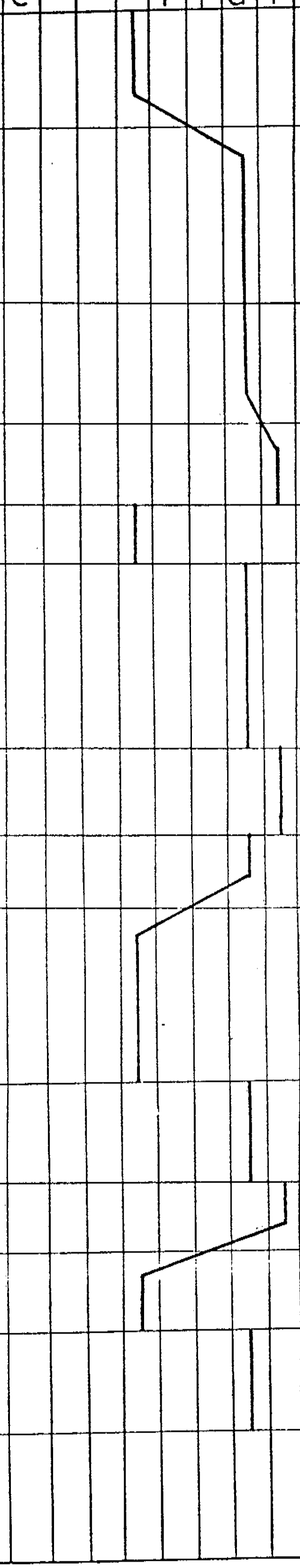
BAG1

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	264	vlg				│					1	1			carb. plant fragments 15-20% by vol. <2mm in diam laterally equivalent x bedded sandstone has less (5%) plant fragments +smaller and better sorted	siderite maroon band 15 cm from base. not horizontal	grade laterally (ESE) in x-bedded vlg medium grained sandstone with less plant material and more scattered. grades WNW 36m into dg mudstone with c10% carb. plant material
002	5	lg							│		1	2			carb. plant fragments <5% by vol +<2mm in diam		some laminae contain larger plant fragment up to 1sq.cm. 20% silt
003	20	gg							│		1	2			carb. plant fragments 5-10% + scattered large linear fragments up to 1.1cm long × 2mm		20% silt
004	12	dg							│		2	2			>50% carb. plant fragments <2mm in diam. scattered large frags. up to 2sq cm		small lenses of coal 2x2cm small quantity of amber.
005	10	b			coal												5% amber blebs up to 4.25 sq.cm. interlaminated are dg. mudstone up to 1cm thick locally up to 50% of rock. M1
006	61	dg							│		1	1			scattered carb linear fragments up to 1.3x2.5 mm		
007	61	gg							│		1	1			rare compressed plant material		
008	61	dg							│		1	1			carb. plant fragments <5% by vol. fine sand size. rare -2sq cm		
009	96	dg-lg			│	│					2	2	common		<5% carb. plant fragments 7. thick bands (1cm) >50% carb plant fragments	Siderite maroon 30x15cm in xsection spaced every 2m. from base to 45cm from base Laterally hoodoos	Laterally sandstone is better indurated Interbeded medium and fine sandstone
010	30	lg							│		1	1			<1% carb plant fragments		
011	5	dg								│	1	1					

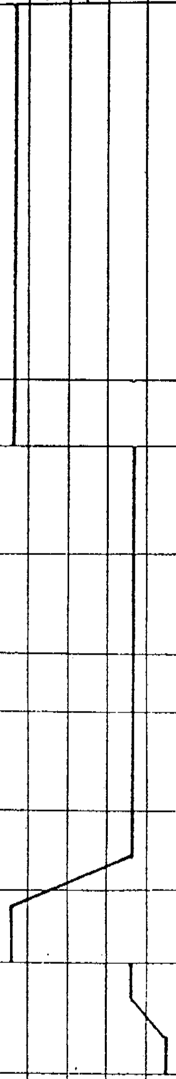
BAG2

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
012	61	dg								│	1	1			carb. plant fragments 10-20% <1.5mm in diam scattered large fragments up to 3ycm		differs from 011 in plant content
013	30	gg							│		1	1					deeply weathered
014	30	dg							│		1	1			carb. plant fragments 5% by vol	siderite maroon-brown. cays hillock	deeply weathered

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	249	vlg			|						1	1	common planar to arcuate	occur low angle	carb. plant fragments 5-10% by vol. Zone 15 cm thick, 15cm from base has 20% carb. fragments scattered shell fragments just above base		grades up to 002
002	25	vlg				|					1	2	ripple marks picked out by plant rich laminae		15% carb. plant fragments up to 1cm².		weathers yellower than 001
003	30	b-vdg-gg							|		3	2			g. mudstone 5% carb plant fragments		⅓ lignite ⅓ subbituminous coal 1/6 dg mudstone 1/6 gg mudstone amber pieces <2.5mm in diam. M1
004	30	gg								|	1	1			scattered carb. plant fragments		
005	68	lgg						|			1	1			10-20% carb. plant fragments		004 + 005 laterally thin to a combined 30cm as the two enveloping sandstones tend to convergence.
006	48	vlg				|					1	2			15% carb plant. fragments individual laminae up to 60%. most frags 2-2.5mm in diam		
007	122	vlg			|						1	1	medium to low angle planar to arcuate	low angle planar to arcuate	5-10% carb. plant fragments some over 2mm in diam.	Siderite band almost continuous overlies hoodoo layer	
008	53	gg							|		1	1			scattered compressed plant material → 3.75cm x 2.5mm		weathers khaki
009	33	dg							|		1	1			carb. plant fragments 10% up to 2.5mm in diam		weathers lg
010	46	gg							|		1	1			→ 20% compressed plant remains. most <2mm in diam rare →15cm.	siderite red brown up to 30x30cm in xsect.	

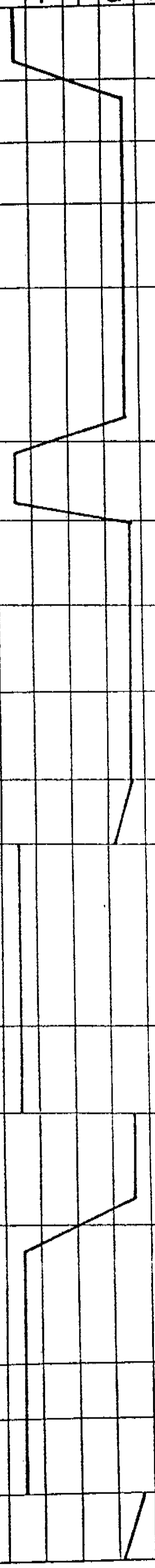


Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	127	v/g									1	2	common planar to arcuate	low angle	discontinuous laminae of plant carb. 25%		10% mudstone 15cm from base lens of dg mudstone 2x9cm grades up
002	71	dg									1	1			Base 30% carb. plant fragments middle 20% Top 5%. Gradation fragments <2.5mm in diam		
003	15	vdg									1	1			>60% carb. plant fragments		carbonaceous mudstone. laterally grades into coal. vertically grades up to 004 Ml
004	76	gg									1	1			scattered plant fragments <2.5mm in diam		
005	15	v/g									1	1					
006	15	dg									1	1			20% carb. plant fragments → 2.5mm in diam. scattered large pieces up to 2x1cm		
007	15	gg									1	1			15% plant fragments <6mm in diam		
008	23	dg									1	1			15% carb. plant fragments		grades up to 009
009	76	v/g									1	1			5-10% carb. plant fragments. irregular laminae >30%.	Laterally grades into 15cm thick houdou layer which is immediately overlain + underlain by siderite	Basal 15cm lenses of dark grey mudstone
010	15	dg									1	1			5% carb. plant fragments 20% in scattered laminae		
011	15	gg									1	1					grades up into 012
012	61	v/g									1	1	low to medium angle arcuate		5% carb plant fragments		ledge former grades up into 013
013	46	gg									2	1			10% carb plant fragments.		laterally pinches out into a sandstone more fissile than other mudstones in this section



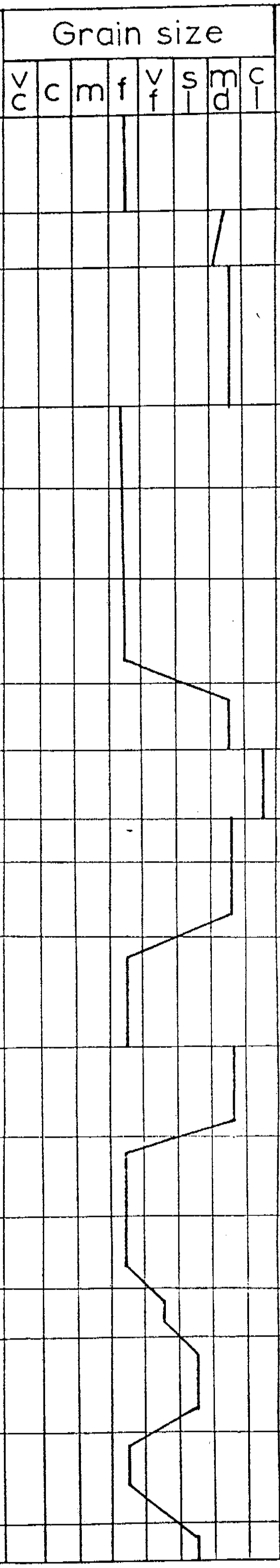
Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	241	vlg									1	1	low angle planar to arcuate	low angle planar to arcuate sets separated by plano parallel sets. low angle planar in hoodoo layer		1·3–2m above base is hoodoo forming sst in the form of 2 cylindrical 4m long and 60cm thick parallel trending 340°. Hoodoos laterally become red-brown capping sst.	15cm above base y medium grained sand, grades up to lgg sand which has horizontal intermittent bands of 15% carb. plant remain sst. 1·5m above base is iron stained band (2.5cm thick) above this is 1·25m interval with laminae with >30% carb. plant remains.
002	15	ylg									2	1			20% carb plant fragment		
003	7	lg									1	1			scattered carb. plant fragments 5%. up to 1cm²		
004	147	gg									1	1			<5% of carb. plant fragment of fine sand size	siderite brown. discontinuous 15cm thick 1·1–1·24m above base	
005	8	lg									1	1					20% clay
006	10	vdg									1	1			5–10% carb plant fragments 7 .6cm²		grades up to 007
007	8	gg									1	1			no plant remains		grades up to 008
008	50	ygg									2	2			5% carb. plant fragments		
009	94	gg									1	1				siderite dark brown caps hillock	fines up after 23cm to muddy claystone

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	61	vlg				│					1	1	common in top 40cm medium to low angle slightly arcuate		5% av. carb. plant fragments		Basal 23cm interlaminated lg + dk bands -colour caused by carb. plant fragments (>40%) Laterally (12m) below 001 is a mollusc rich horizon
002	10	vlg				│					1	1			1% plant fragments		
003	109	lg-dg				│					2	2					circa every 15cm are 2.5cm bands of organic rich laminae (>30% carb. plant frags. These bands less common in top 60cm grades up to 004
004	30	lg							│		1	1			10% carb. plant fragments < .5x.25cm	siderite d. brown 5cm thick concretion 10cm above base	
005	68	vlg				│					1	1					planar lamination picked out by carb. plant fragments.
006	10	ygg						│			1	1					
007	79	gg							│		1	1					
008	66	lg-dg							│		1	1			lg - 1% carb. plant fragments dg → 20% → 2cm in diam		interlaminated lg and dg mudstone
009	43	yg				│					2	2					
010	44	gg							│		1	1			scattered carb. plant fragments → 1.5x 2.5mm	siderite brown scattered through 010	deeply weathered



Bed No.	Bed Thck (cm)	Col.	Grain size vc	c	m	f	vf	sl	md	cl	Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
001	79	yg									2	2			<5% carb. plant fragments		grades up into 002
002	91	gg									1	1					grades up into 002
003	15	dg									1	1					
004	137	gg									1	1					60cm from base is 15cm layer with 40% very fine sand
005	10	dg									1	1			15% carb plant fragments <2.5mm in diam. fragments increase in size upward		grades up into 006. gradational zone alternating sst. and claystone.
006	91	vlg									1	1			<5% carb. plant fragments		grades up into 007
007	36	vdg									1	1			carb plant fragments → 4.5cm x 25mm		grades up into 008
008	38	gg									1	1			<5% plant. fragments c.5cm²		
009	50	dg									1	1			10-20% carb plant fragments		
010	61	gg									1	1			10-20% plant fragments		coarsens upward
011	76	vlg									1	1	low angle planar		10% carb. plant fragments		30cm from base is 2.5cm band of dg discontinuous shale with pieces of coalified wood → 2cc grades up into 012
012	8	vlg									1	2			25% carb plant fragments		
013	30	db/bl									3	3			>80% carb. and compressed plant fragments		friable grades up into 014. M2
014	25	yg									2	2			carb. plant fragments decrease upward from 10 - 1%		grades up into 015
015	61	vlg									1	1					grades up into 016
016	25	yg									2	2			5% carb. plant fragments		
017	28	gg									1	1			scattered carb. plant fragments → 1.5cm²		coarsens upward into sst/mudstone interlamination. thin laminae 10% carb. in top 8cm

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss.	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
018	86	yg				|					2	2			carb. plant fragments 5-10%		grades up and becomes yellower and carb. fragments increase
019	25	lg							|		1	1			10% carb. plant fragments $>.5 cm^2$		

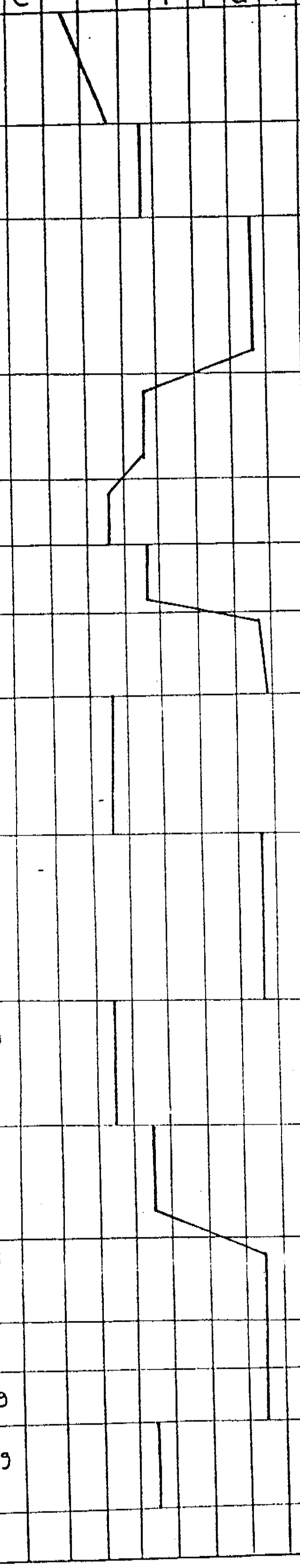


Bed No.	Bed Thck (cm)	Col.	Grain size vc	c	m	f	vf	sl	md	cl	Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
001	142	vlg											common low angle planar to arcuate	low angle planar	5% carb. plant fragments <1.5mm in diam		
002	30	dg									1	1					coarsens up grades into 003
003	178	g									1	1			bands of coalified plant fragments 2.5mm thick. and 10 cm lateral extent		
004	122	ygg									1	2			5% carb. plant fragments	siderite brown 15cm from top	
005	86	vlg									1	1	low angle arcuate		5-10% carb. plant fragments	siderite brown 10cm thick 15cm from top. laterally nodular	grades up into 006
006	43	vlg									1	1			scattered laminae >30% carb. plant fragments		grades up into 007 scattered laminae of gg mudstone some iron staining
007	109	gg									1	1			<5% carb plant fragments		
008	20	g									1	1			<5% carb. plant fragments		
009	23	gg									1	1					
010	10	lg									1	1			<5% carb. plant fragments		grades up into 011
011	38	ygg									2	2			5-10% carb. plant fragments. increase upward		g mudstone pebbles near base.
012	20	b									3	3			>90% carb. plant fragments		carbonaceous mudstone. grades up into 013
013	25	ygg									3	2			20-30% carb. plant fragments		
014	30	lg									1	1			5% carb. plant fragments		grades into 015
015	84	yg									1	2					5% clay fines upword grade into 016
016	61	dg									2	2			20-30% carb plant fragments <1.5cm^2	siderite brown at top	coarsens upword grades into 017
017	104	yg									1	1			15% carb. plant fragment decrease upward		fines upward into 018
018	48	lg									1	1			<5% carb plant fragment		plant fragments < 2.5mm in diam

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
019	66	ygg				|					1	2					
020	63	lg								|	1	1			<5% carb. plant fragments <2.5mm in diam.	siderite dark brown highly weathered	

BAN

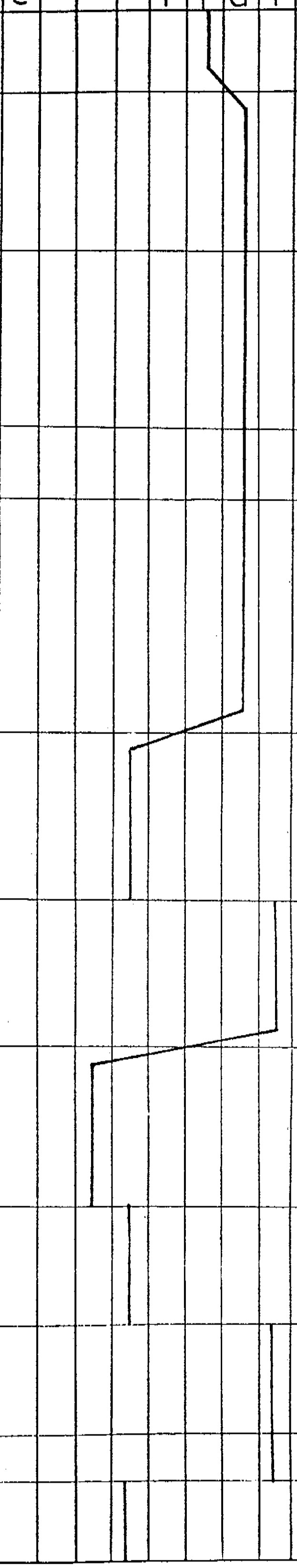
Bed No.	Bed Thck (cm)	Col.	Grain size vc	c	m	f	vf	s	md	cl	Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
001	122	gg						|			1	1				siderite dark brown top of bed continuous to discontinu	
002	33	lg							\						10%carb. plant fragments decreases upward		fines upward
003	66	gg				|					1	2				siderite up to 30x10cm laterally discontinous dk. brown	
004	46	gg						|			1	1					
005	63	lgg-lg				|				|	2	2			sandstone 10%carb plant remains claystone 5% plant remains. conifer fragment in claystone		1gg claystone + lg sandstone interlaminated scattered amber blebs
006	25	ygg			|						2	2			20%carb plant fragments → 8cm².		grades upward into 007
007	30	bl			coal	\											basal 10 cm 5% mud decreases upword. small lenses of fine grained grey. sandstone. abundant amber. yellow powdery mineral on surface on top 15cm.
008	8	dg							|		1	1			40%carb plant remains		grades downward into 007
009	10	gg								|	1	1			scattered compressed plant		



Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			v c	c	m	f	v f	s l	m d	c l							
001	91	vlg									1	1	common low angle	low angle	1% carb. plant fragment → 2.5cm × 2.5mm in area	hoodoos	scattered clay pebbles in basal portion. → 5mm in diameter
002	46	vlg									1	1	common			siderite dark brown. subcontinuous at top	
003	45	gg									1	1			5% carb plant fragments → 2.5mm in diam	siderite dark brown 15cm and 30cm above base, 13cm in diam.	grades up to 004
004	30	vlg									1	1			20% carb plant fragments < 2.5mm in diam		grades up to 005
005	33	vlg									1	1	occur				very well indurated
006	99	gg									1	1					grades up into 007
007	61	gg									1	1			5% carb plant fragments	siderite dark brown. near continuous top	fines upward from 10% silt to 5%
008	86	vlg									1	1	ripples troughs		fine laminations picked out by 10% carb plant fragments	locally hoodoos	
009	76	gg									1	1			< 1% carb. plant fragments scattered large fragments → 3cm × 2.5mm		
010	99	vlg									1	1	planar				2% clay pebbles (2cm²) scattered throughout. irregular sharp lower contact
011	15	yo									3	2			5% carb. plant fragments < 3mm in diam		grades up into 012
012	13	6-61									3	3			> 70% plant debris		< 1% amber blebs yellow powdery mineral on surface
013	15	gg									1	1					
014	23	lgg									1	1					
015	36	lygg									1	1			scattered plant fragments → 10cm²		

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	51	bl									2	2			>70% carb. plant fragments coalified wood fragments → tens of cc's		c1% scattered amber blebs. yellow powdery mineral on surface. carbonaceous mudstone
002	41	dg									1	1			large carb. plant fragments → 4cm² av. <2.5mm overall 20%		weathers lg deeply weathered
003	43	lb									3	3			carb. plant fragments increase upward to 80%		friable grades up into 004 carbonaceous mudstone
004	12	db									2	3			80% carb. plant fragments		carbonaceous mudstone
005	51	bl			Coal												abundant amber <2.5mm in diam. friable poorly indurated sandstone lenses (15% carb. plants) up to 10x10x10cm. sand has moved down fractures in coal. Top 10cm interbedded tonstein → 5cm thick band + lenses. Laterally 15m coal becomes clinker.
006	15	vlg									1	1	low angle. trough	laterally low angle	5% carb plant fragments At base locally carb. plant fragments → 12cm². At base large coalified logs 60x60 cm. in x section. Laterally dinosaur scrap and several poorly preserved dinosaur bones. Large silicified wood fragments → 15x15 cm in diam + up to 1.5m long		scoured base on coal. laterally cuts out coal. section near Bauer + Reeside (1921) section 510

BAQ



Bed No.	Bed Thck (cm)	Col.	Grain size vc	c	m	f	vf	sl	md	cl	Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
001	66	g									1	1			scattered carb. stems → 2.5mm x 6mm		weathers gg grades up into 002
002	15	bl-gg									3	3			<60% carb. plant fragments in mudstone		carbonaceous (gg) mudstone grades into coal (bl). amber blebs <2.5mm in diam locally yellow powdery mineral dust on surface.
003	43	lg									1	1			10% carb. plant fragments large stems → 3cm x 6mm dg portions 40% carb		grades up from 003 locally dg.
004	4	vdg									3	3			50% carb plant fragments		ml
005	20	gg									1	1			g. mudstone 20% carb plant fragments gg mudstone 20% carb plant fragments rare large pieces → 20cm² av <2.5mm		laminated. laminations picked out by g mudstone and carbonaceous material grades up into 006
006	79	lg-ygg									1	2			top 15cm increase in carb plant fragments from 15% to 20-30%		
007	15	gg									1	2			5% carb plant fragments <2mm scattered large fragments → 4cm²		10% silt grades up into 008
008	89	ygg									1	2			5% carb. plant fragments <2mm in diam. scattered fragments → 4cm²		grades up into 009
009	13	vlg									1	1			25% plant fragments → 4.8cm in length.	siderite dark brown at top	
010	246	lg									1	1			10% plant clasts <2.5mm in diam		< 1% amber blebs
011	51	gg									1	1					
012	20	ygg									1	2			< 3% carb plant fragments fine sand size [illegible]		

BAR

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	28	ygg					|				1	1			10% carb plant fragments →1×.5cm		grades into 002
002	33	lgg							|		1	1			10% carb plant fragments av. 2.5mm in diam →1×.5cm more carbonaceous upward (15%)		grades up into 003
003	38	dg							|		3	3			>60% carb plant fragments		carbonaceous mudstone
004	15	dg-bl							|		3	3			20% carb plant fragments range up to 80%		carbonaceous mudstone laterally coal. M2
005	20	vlg			|						1	1			5-10% carb. plant fragments <2.5mm in diam.		
006	127	gg							|		1	1			5% carb. plant fragments		
007	69	lg							|						<5% carb. plant fragments <1.5mm in diam	Laterally siderite up to 3m² and hoodoos	grade up into 008
008	86	gg							|		1	2					5% fine sand Laterally 007 and 008 cut out by medium grained cross bedded sandstone

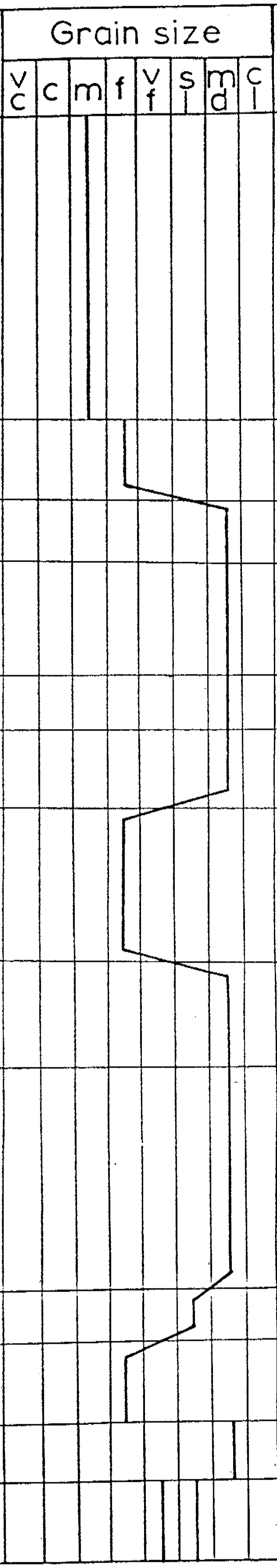
BAT1

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	80	61				c	oa	l									
002	100	vlg			|						1	1	planar low to medium angle troughs	low angle	<2% carb plant fragments 30cm long endless limb bone horizontal on basal undulatory erosion surface		12% mica basal 2cm contains 2cm diam. clay pebbles.
003	10	dg							|						10% carb. plant fragments <2mm in diam		grades up into 004
004	140	61				c	oa	l							Scattered carb. plant remains in ash bifurcating linear fragments		70-10cm from top are lenses of fine grained volcanic ash, vlg with euhedral mica crystals lenses coalesce upward. some gradation of lens into coal - dark grey outer margins. lenses from 3 x 2cm to form 70% of rock 20cm from top where coalesce
005	534	vlg			|						1	2	low angles + parallel lamination	low angle		10cm thick siderite zone - discontinuous subspherical concretions	basal 10cm - clay pebbles and plant rich laminae. laterally cuts out coal (004) overall stripy appearance due differential weathering of clay rich bands varying in width from 10-30cm forming 40% of volume. Some bands rich in carb. plant fragments. Top 200cm bands of finer dirtier (clay/carb. frags.) interlayered..
006	168	ygg			|						2	3			30% plant material abundant seeds partial leaves. Araucaria fragments particularly in lenses of cleaner sandstone in basal 30cm. most plant material broken up but large fragments several > cm² >10cm² coalified and compressed ?carnosaur femur - in vicinity 80 plant frags Bones laterally 30m in extent		occasional euhedral micas 10-20% clay

BAT2

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
007	25	lgg				|					2	2					clay rich laminae inter tongues with 006
008	15	lg						|	\		1	2			15-20% carb. plant fragments which is poorly sorted →8x2cm		grades up into 008
009	10	gg							|		1	1			poorly sorted plant material →3x1cm		
010	3	dg							|		1	1			30% carb. plant fragments <3½mm		
011	2	b							|		3	2			>60% plant fragments		fissile carbonaceous mudstone
012	5	bl							|	\	2	2			>80% plant debris		carbonaceous mudstone M1 grades up into 013
013	100	lg								|	1	1			10% carb. plant debris <5mm²		
014	30	lg							|		1	1			<5% carb. plant fragments <2mm in diam		East 30m from base of section
015	10	gg						|			1	1			<3% plant fragments		
016	2	gg							|		1	1			<5% plant fragment		
017	4	ygg				|					1	2			→40% plant fragments of clast size		
018	10	lg							|		1	1			10% carb. plant fragments →5mm in diam		
019	10	gg							|		1	2			<3% plant debris		10% silt
020	30	gg							|		1	1			<3% plant fragments		
021	90	ygg				/	/	/			1	1					coarsens upward siltstone → fine sandstone
022	20	vlg				|					1	1					
023	70	vlg				|					1	1	troughs	planar low angle cross beds troughs	<1% carb. plant fragments clast size		top 30cm weathers red brown. laterally extensive arkosic, tops hillocks very resistant. laterally up to very coarse grain size. scattered clay pebbles at base

BAU



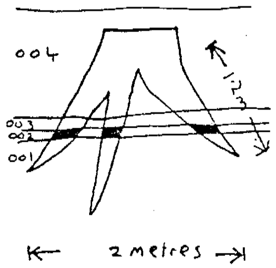
Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	376	vlg									1	1	low angle	low angle picked out by clayrich laminae. low angle picked out by carb. fragments	log 1·2m long 30x15cm in x-sect Hadrosaur partial skeleton ½ way up <3% carb. plant fragments	Discontinuous hardoos at 3 levels 1x·3m in xsection sideritic "whisps" follow carb. rich x-beds siderite stratiform 4cm and 10cm thick possibly follow mud laminae	10% micas 10% felspars interdigitating margin laterally
002	20	ygg									1	2			10% carb. plant fragment → ·5cm²		grades up into 003
003	4	b									3	2			>60% plant fragment		friable carbonaceous mudstone
004	8	bl									3	2			mudstone >60% carb. plant fragments		scattered amber. carbonaceous mudstone laterally coal M1
005	20	lg									1	1			10% linear carb. fragments		
006	15	dg									1	1			5% plant fragment ·5mm².		abundant slickensides grades up into 007
007	30	ygg									1	2			Turtle fragments up to 5cm² c10		top increasing muddy and contains 10% carb. plant debris mainly linear → 1x·2cm grades up into 008
008	8	dg									1	1			20% carb. plant debris mainly linear as 007		grades up into 009
009	30	lg									1	2			10% carb. plant debris decreases upward in quantity but increases in size → ·75cm² top 5cm devoid of plant fragments		becomes more clay rich higher. grades up into 010
010	4	gg									1	1					grades up int 011
011	10	ygg									1	1			top 5cm plant material increases 0-5%		
012	7	dg									1	1			15% carb. plant fragments		
013	10	dg									2	2			5% plant fragments		interlaminated siltstone and very fine sand

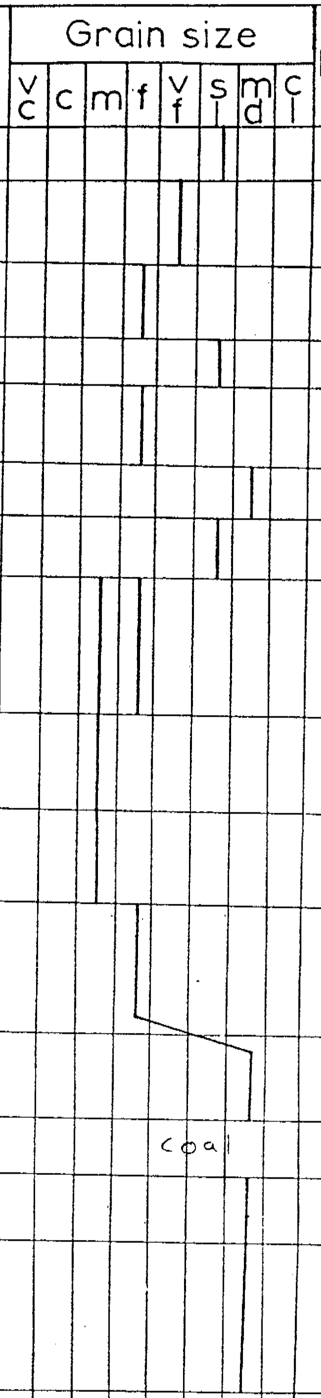
BAV

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	10	gg							│		1	1			10% plant fragments <2mm in diam		
002	18	gg							│		1	1					finely laminated. laminations of macerated and non macerated leaves 1–3mm thick Extends only 2m laterally
003	45	gg							│		1	1			subvertical linear carb. fragments numerous bones from contact with 002 upward. lose bones laterally laterally less plant material		Dinosour Quarry Areal extent of quarry 5x5m Base is 72cm above M1
004	15	gg						│			1	1					
005	18	gg							│		1	1			3% plant fragments >1.5×2mm		
006	15	ygg				│					1	2			top 5cm carb. plant material 10–25%		top 5 cm becomes finer grained
007	8	dg							│		1	1			20% carb. plant material		

BAW

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	40	gg									1	1					tree roots extend into
002	5-8	dg									1	1			30% carb. plant fragments		tree roots extend into. 002 and are coalified laterally bed coally
003	8	lg									1	1					tree roots extend into
004	60	ygg									1	2			20% linear carb. fragments -> 3cm seem to trend 340°c coal fragments -> .5cm²		covers stumps
005	5	dg									2	1			50% carb. plant fragments		
006	5	bl				Coal											3% amber blebs M1
007	2	dg									1	1			10% plant fragments		
008	8	lg									1	1			10% plant fragments poorly sorted		





Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	si	md	cl							
001	20	lg									1	1			"roots"		Forest Litter zone
002	32	vlg									1	1			30% carb. plant fragments		
003	15	ygg									1	1			3% carb plant fragments		
004	40	gg									1	1					
005	35	ygg									1	1			5% carb plant fragments	siderite Grown continuous at top 4cm thick	
006	15	dg									1	1					
007	10	lg									1	1					
008	16	vlg									1	2	low angle		middle 6 m contains 5mm thick plant rich (730%) laminae	basal 5cm hoodoo top 5cm hoodoo	
009	75	vlg									1	1			5-7% carb. plant fragment	siderite 25cm from top 12cm indian.	
010	93	lgg									1	2			55-63cm thinly laminated plant rich (80%)		basal 2cm scattered gg clay pebbles
011	28	ygg									1	2			3% carb. plant fragments more plant rich upward		grades up into 012
012	12	b									2	1			60% plant fragments		fissile grades up into 013
013	4	bl					coal										3% amber blebs MI
014	5	dg-b									3	1			>80% plant remains		fissile
015	20	gg									1	1			5% plant fragments av <1.5 mm in diam. but ⇒ 5mm long-linear		

Bed No.	Bed Thck (cm)	Col.	Grain size vc	c	m	f	vf	si	md	cl	Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
001	70	ygg									1	2	ripples low angle planar		layers up to .75cm thick -60% plant remains +8% amber Throughout plant material 20% → 1cm². At least 25 turtls and 30 coprolites laterally		weathers lg Turtle Heaven Extends laterally 50m
002	95	ygg									1	2			scattered carb. subvert. ?roots.		coarsens upward to fine sandstone
003	25	ygg									1	2			5% carb. plant fragments		
004	10	lg									1	1			20% carb plant fragments		
005	5	bl									3	1			>60% carb. fragments		carbonaceous mudstone M2
006	20	lgg									1	1			15% plant fragments		
007	105	ygg									1	2			10% carb plant fragments	siderite brown 18cm thick top	clay rich coarsens upward to medium from fine grained. Upwards "cleaner" -less plant material and clay

Bed No.	Bed Thck (cm)	Col.	Grain size vc	c	m	f	vf	si	md	cl	Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
001	30	gg							●		1	2			10% plant fragments		silty mudstone
002	25	vdg bl							●		2	2			mudstone		basal 8cm black carbonaceous mudstone 15cm coal 7cm vdg-bl carbonaceous mudstone. Thickens north. m 2
003	5	vlg							●		1	3					volcanic ash clayey mudstone with large <1mm euhedral mica crystals. grades up and down
004	20	gg							●		1	1					
005	340	vlg			●						1	1	low angle planar troughs	low angle planar troughs	<1%		top 60cm red brown (weathers) ridge former Basal is clay pebble conglomerate. gg pebbles in clay rich sandstone with 10% carb. fragments 40% clay pebbles plant fragments → 6 x 2cm. occasional euhedral mica crystals
006	70	ygg				●					1	1					East 70m from lower part of section
007	50	ygg						●			1	1					
008	30	lg							●		1	2					silty mudstone
009	30	ygg						●			1	1					
010	50	vlg				●					1	1				siderite brown 30cm in diam. every 2m laterally	
011	146	gg				●					1	2			laminae of 50% plant debris every 2cm		clay rich. euhedral biotite
012	50	ygg						●			1	1			10% plant fragments → 3x1mm		
013	50	ygg				●					1	1			10% plant fragments → 5x3mm		
014	40	lg						●			1	1			scattered plant fragments		
015	50	ygg						●			1	1			5% carb. plant fragments → 3x1mm		
016	15	lg							●		1	2			3% carb. plant fragments linear → 5x1mm		silty mudstone
017	30	gg						●			1	1					

BBA

Bed No.	Bed Thck (cm)	Col.	Grain size								Ind.	Sort.	Sm. X	Lg. X	Foss	Con.	Notes
			vc	c	m	f	vf	sl	md	cl							
001	6	bl							│		2	1			>70% carb. plant fragments		carbonaceous mudstone M1
002	450	vlg			│						1	1	trough planar	planar low angle trough Red brown cap is 50cm thick set of low angle planar.		Laterally Siderite at base.	basal 10-15cm clay pebble conglomerate with abundant molluscs. 50% clayey snd. clay pebbles 1-1.5cm in diam. 30% plant fragments. Quarry 4 Top 70cm red brown stained

APPENDIX II

Palaeomagnetic Data

Sample Designation	Demagnetisation (mT)	Inclination (Degrees)	Declination (Degrees)	Insensity (Amp/m)
FF001A	0	45.9	351.0	4.39x10-03
FF001A	10	49.5	345.2	3.10x10-03
FF001A	20	49.0	341.5	2.30x10-03
FF001A	30	50.4	343.2	1.89x10-03
FF001A	40	50.4	342.6	1.55x10-03
FF001B	0	64.4	346.2	3.50x10-03
FF001B	20	67.1	347.5	1.69x10-03
FF001C	0	56.9	303.3	2.83x10-03
FF001C	20	50.6	309.0	1.40x10-03
FF002A	0	62.9	229.8	5.82.10-03
FF002A	10	57.1	159.0	3.66x10-03
FF002A	20	60.9	194.7	2.84x10-03
FF002A	30	60.6	152.5	2.45x10-03
FF002A	40	58.9	147.1	2.04x10-03
FF002B	0	3.6	15.5	6.52x10-03
FF002B	20	49.4	359.6	3.35x10-03
FF002C	0	65.5	9.4	6.24x10-03
FF002C	20	62.2	349.9	3.72x10-03
FF003A	0	-3.6	344.9	2.87x10-03
FF003A	10	43.9	331.3	7.63x10-04
FF003A	20	-78.0	89.3	4.39x10-04
FF003A	30	-47.3	118.6	3.43x10-04
FF003A	40	-10.8	96.9	3.45x10-04
FF003A	50	50.7	72.1	4.19x10-04
FF003B	0	73.3	78.7	1.67x10-03
FF003B	10	21.1	112.6	5.80x10-04
FF003B	20	28.6	154.2	1.16x10-04
FF003B	30	-27.6	64.6	2.64x10-04
FF003B	40	-19.4	85.7	6.43x10-04
FF003C	0	81.5	84.0	3.58x10-04
FF003C	10	78.9	62.9	7.51x10-04
FF003C	20	67.1	237.0	3.43x10-04
FF003C	30	6.7	217.7	4.91x10-04

Sample Designation	Demagnetisation (mT)	Inclination (Degrees)	Declination (Degrees)	Intensity (Amp/m)
FF003C	40	23.6	210.3	3.70x10-04
FF004A	0	52.5	36.5	2.71x10-03
FF004A	10	61.1	47.9	6.69x10-04
FF004A	20	72.1	320.7	4.11x10-04
FF004A	30	43.2	343.1	5.26x10-04
FF004A	40	47.5	356.1	3.19x10-04
FF004B	0	72.7	62.1	1.28x10-03
FF004B	20	73.2	330.4	5.48x10-04
FF004C	0	80.2	90.4	1.09x10-03
FF004C	20	46.4	39.1	4.24x10-04
FF005A	0	36.9	109.5	1.13x10-03
FF005A	10	61.5	162.1	6.08x10-03
FF005A	20	64.9	182.7	3.94x10-04
FF005A	30	50.3	122.6	2.28x10-04
FF005A	40	56.3	143.6	2.02x10-04
FF005B	0	45.7	356.9	1.16x10-03
FF005B	20	48.6	339.7	4.88x10-04
FF005C	0	25.3	275.1	6.59x10-04
FF005C	40	47.3	346.8	-2.01x10-04
FF006A	0	32.7	245.9	-1.35x10-03
FF006A	10	-44.3	160.9	-5.69x10-04
FF006A	20	-21.3	188.9	-2.42x10-04
FF006A	30	-46.1	214.4	-2.76x10-04
FF006A	40	-58.0	229.7	3.37x10-04
FF006B	0	61.4	25.6	2.88x10-03
FF006B	20	49.2	118.1	5.65x10-04
FF006C	20	-19.2	330.0	6.77x10-04
FF006C	40	-27.2	309.4	2.07x10-04
FF007A	0	-11.2	100.4	2.57x10-03
FF007A	10	-32.8	102.9	9.99x10-04
FF007A	20	-18.9	100.6	5.87x10-04
FF007A	30	-28.9	115.3	4.10x10-04
FF007A	40	-13.7	99.8	2.16x10-04
FF007B	0	65.6	16.5	4.15x10-03

Sample Designation	Demagnetisation (mT)	Inclination (Degrees)	Declination (Degrees)	Intensity (Amp/m)
FF007B	20	63.4	309.6	1.56x10-03
FF007C	0	17.1	224.0	2.24x10-03
FF007C	20	21.7	357.2	8.88x10-04
FF008A	0	60.2	81.3	3.37x10-03
FF008A	20	2.7	356.0	1.43x10-03
FF008A	30	-16.5	349.9	1.03x10-03
FF008A	40	7.6	3.9	5.69x10-04
FF008B	0	-42.2	241.3	4.12x10-03
FF008B	20	-37.9	294.4	6.24x10-04
FF008C	0	-19.3	234.2	3.03x10-03
FF008C	20	-4.4	308.8	5.24x10-04
FF008C	40	55.0	8.8	4.47x10-04
FF008C	60	62.3	121.1	4.83x10-04
FF009A	0	-0.6	313.5	2.14x10-01
FF009A	10	-1.9	3.8	1.11x10-01
FF009A	20	8.7	346.4	3.90x10-02
FF009A	30	20.5	354.9	5.12x10-03
FF009A	40	18.1	354.9	5.12x10-03
FF009B	0	7.7	27.0	2.20x10-01
FF009B	20	8.3	30.1	3.54x10-02
FF009B	40	10.3	24.6	7.96x10-03
FF009B	60	13.9	30.9	1.30x10-03
FF009C	0	5.3	2.6	2.22x10-01
FF009C	20	7.9	6.6	4.41x10-02
FF009C	40	11.4	13.6	5.26x10-03

ABBREVIATION LIST FOR FISHER STATISTICS

Abbreviation	Meaning
Demag	Demagnetisation (mT)
Inclin	Inclination (degrees)
Declin	Declination (degrees)
Inten	Intensity (Amp/m)
n	number of samples
r	vector sum
k	Fisher precision parameter
sig	sigma (standard deviation)
a95	semi-angle of the cone of 95% confidence
VGP	Virtual Geomagnetic Pole Position
dp	95% confidence probability along palaeomeridian
dm	95% confidence probability at right angles to palaeomeridian

FISHER STATISTICS

Specimen Designation FF001	Demag	Inclin	Declin	Inten
FF001A	20 A	49.0	341.5	2.30000e-3
FF001B	20 A	67.1	347.5	1.69000e-3
FF001C	20 A	50.6	309.0	1.40000e-3
Mean of n = 3:		56.7	330.7	1.79667e-3

r = 2.92670 n-r = 0.07130 k = 28.1 sig = 0.02377 a95 = 23.73

Best VGP: N 66.7 E 172.7 dp = 24.94 dm = 34.40

Specimen Designation FF002	Demag	Inclin	Declin	Inten
FF002A	20 A	60.9	194.7	2.84000e-3
FF002B	20 A	49.4	359.6	3.35000e-3
FF002C	20 A	62.2	349.9	3.72000e-3
Mean of n = 3:		75.0	341.8	3.30333e-3

r = 2.60603 n-r = 0.39397 k = 5.1 sig = 0.13132 a95 = 61.63

Best VGP: N 62.2 W 126.5 dp = 102.72 dm = 112.52

Speciment Designation FF003	Demag	Inclin	Declin	Inten
FF003A	30 A	-47.3	118.6	3.43000e-4
FF003B	20 A	28.6	154.2	1.16000e-3
FF003C	40 A	23.6	210.3	3.70000e-4
Mean of n = 3:		4.2	164.9	6.24333e-4

r = 1.97993 n-r = 1.02007 k = 2.0 sig = 0.34002 a95 = 37.92

Best VGP: S 48.9 W 84.7 dp = 19.04 dm = 38.00

Specimen Designation FF004	Demag	Inclin	Declin	Inten
FF004A	30 A	43.2	343.1	5.26000e-4
FF004B	20 A	73.2	330.4	5.48000e-4
FF004C	20 A	46.4	39.1	4.24000e-4
Mean of n = 3:		57.9	3.1	4.99333e-4

r = 2.79406 n-r = 0.20594 k = 9.7 sig = 0.06865 a95 = 41.92

Best VGP: N 86.8 W 58.5 dp = 45.35 dm = 61.66

Specimen Designation FF005	Demag	Inclin	Declin	Inten
FF005A	30 A	50.3	122.6	2.28000e-4
FF005B	20 A	48.6	339.7	4.88000e-4
FF005C	40 A	47.3	346.8	2.01000e-4
Mean of n = 3:		67.2	9.3	3.05667e-4

r = 2.44598 n-r = 0.55402 k = 3.6 sig = 0.18467 a95 = 77.67

Best VGP: N 75.0 W 84.3 dp = 107.02 dm = 128.94

Specimen Designation FF006	Demag	Inclin	Declin	Inten
FF006A	30 A	-46.1	214.4	2.76000e-4
FF006B	20 A	49.2	118.1	5.65000e-4
FF006C	40 A	-27.2	309.4	2.07000e-4
Mean of n = 3:		-35.3	237.9	3.49333e-4

r = 0.72735 n-r = 2.27265 k = 0.9 sig = 0.75755 a95 = 180.00

Best VGP: S 37.0 E 164.0 dp = 120.14 dm = 207.96

Specimen Designation FF007	Demag	Inclin	Declin	Inten
FF007A	20 A	-18.9	100.6	5.87000e-4
FF007B	20 A	63.4	309.6	1.56000e-3
FF007C	20 A	21.7	357.2	8.88000e-4
Mean of n = 3:		38.8	27.4	1.01167e-3

r = 1.50168   n-r = 1.49832   k = 1.3   sig = 0.49944   a95 = 180.00

Best VGP: N 62.1 E 5.9   dp = 127.45   dm = 214.20

Specimen Designation FF008-1	Demag	Inclin	Declin	Inten
FF008A	30 A	-16.5	349.9	1.03000e-3
FF008B	20 A	-37.9	294.4	6.24000e-4
FF008C	20 A	-4.4	303.8	5.24000e-4
Mean of n = 3:		-21.1	318.7	7.26000e-4

r = 2.70347   n-r = 0.29653   k = 6.7   sig = 0.09884   a95 = 51.75

Best VGP: N 28.7 E 119.5   dp = 28.67   dm = 54.47

Specimen Designation FF008-2	Demag	Inclin	Declin	Inten
FF008A	40 A	7.6	3.9	5.69000e-4
FF008B	20 A	-37.9	294.4	6.24000e-4
FF008C	40 A	55.0	8.8	4.47000e-4
Mean of n = 3:		9.7	343.3	5.46667e-4

r = 1.99298   n-r = 1.00702   k = 2.0   sig = 0.33567   a95 = 41.03

Best VGP: N 54.9 E 101.7   dp = 20.96   dm = 41.47

Specimen Designation FF009	Demag	Inclin	Declin	Inten
FF009A	40 A	18.1	354.9	5.12000e-3
FF009B	40 A	10.3	24.6	7.96000e-3
FF009C	40 A	11.4	13.6	5.26000e-3
Mean of n = 3:		13.6	11.2	6.11333e-3

r = 2.93052   n-r = 0.06948   k = 28.8   sig = 0.02316   a95 = 23.41

Best VGP: N 58.6 E 50.1   dp = 12.21   dm = 23.91

Sample Designation	Inclin	Declin	Inten	n	k	a95
FF001	56.7	330.7	1.79667e-3	3	28.1	23.73
FF002	75.0	341.8	3.30333e-3	3	5.1	61.63
FF003	4.2	164.9	6.24333e-4	3	2.0	37.92
FF004	57.9	3.1	4.99333e-4	3	9.7	41.92
FF005	67.2	9.3	3.05667e-4	3	3.6	77.67
FF006	-35.3	237.9	3.49333e-4	3	0.9	180.00
FF007	38.8	27.4	1.01167e-3	3	1.3	180.00
FF008-1	-21.1	318.7	7.26000e-4	3	6.7	51.75
FF008-2	9.7	343.3	5.46667e-4	3	2.0	41.03
FF009	13.6	11.2	6.11333e-3	3	28.8	23.41

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