



Fluvial systems of the Upper Jurassic Morrison Formation, northern Beartooth and Gallatin Ranges,
southwest Montana
by Jonathan Todd Cooley

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

The Upper Jurassic Morrison Formation of southwest Montana contains dinosaur remains discovered by paleontologists from the Museum of the Rockies in Bozeman, Montana. Analysis of sedimentology and alluvial architecture suggests the sediments which contain these bones are the deposits of a northeast flowing, low gradient, mud-and-sand dominated anastomosed fluvial system. Characteristic deposits found in the Morrison include low width-to-thickness ratio channel deposits encased in extensive overbank-derived mudstone, crevasse channel and splay deposits, and coal-and-back swamp deposits.

Morrison deposits compare closely with deposits of modern anastomosed fluvial systems, as well as with ancient deposits interpreted as having been deposited by anastomosed fluvial systems. Ancient fluvial channels in the Morrison were laterally stable and changed position through the process of avulsion. This, combined with the delivery of fine-grained, suspended sediment to the mid and distal floodplain through crevasses in levees, resulted in high overall mudstone-to-sandstone ratios and isolated channel deposits. Taphonomic analysis of a bone bed contained within a channel sandstone suggests the fluvial system may have been subject to rapid fluctuations in discharge.

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NORTHERN BEARTOOTH AND GALLATIN RANGES, SOUTHWEST MONTANA

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APPROVAL

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Jonathan Todd Cooley

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

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Signature

Jonathan Cook

Date

11/16/93

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For Ward, who loved rocks.

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ABSTRACT

The Upper Jurassic Morrison Formation of southwest Montana contains dinosaur remains discovered by paleontologists from the Museum of the Rockies in Bozeman, Montana. Analysis of sedimentology and alluvial architecture suggests the sediments which contain these bones are the deposits of a northeast flowing, low gradient, mud-and-sand dominated anastomosed fluvial system. Characteristic deposits found in the Morrison include low width-to-thickness ratio channel deposits encased in extensive overbank-derived mudstone, crevasse channel and splay deposits, and coal-and-back swamp deposits.

Morrison deposits compare closely with deposits of modern anastomosed fluvial systems, as well as with ancient deposits interpreted as having been deposited by anastomosed fluvial systems. Ancient fluvial channels in the Morrison were laterally stable and changed position through the process of avulsion. This, combined with the delivery of fine-grained, suspended sediment to the mid and distal floodplain through crevasses in levees, resulted in high overall mudstone-to-sandstone ratios and isolated channel deposits. Taphonomic analysis of a bone bed contained within a channel sandstone suggests the fluvial system may have been subject to rapid fluctuations in discharge.

INTRODUCTION

Purpose

The goal of this study is to determine the depositional environment of the Upper Jurassic Morrison Formation in the northern Gallatin and Beartooth Ranges of southwest Montana. This includes determination of the paleogeographic setting during Morrison deposition, and types of depositional systems and environments in which Morrison sediment was deposited. More specifically, questions to be addressed in this study include: 1) Which types of depositional environments characterized the Morrison alluvial depositional systems? 2) Which alluvial architecture models compare most closely with the Morrison strata? 3) What were the hydrodynamic characteristics of the specific processes of sediment transport and deposition at work within these systems?

Determining depositional environment is important for two reasons. First, in the last three years the Museum of the Rockies has found numerous dinosaur remains in the Morrison Formation in the study area. Yet to date, no work has been done on the paleoecology of these dinosaur sites. A detailed analysis of the depositional environments and sedimentology of these sites will provide information pertinent to understanding Late Jurassic dinosaurs and the ecosystems they inhabited. Second, this study will allow paleoenvironmental characteristics of dinosaur sites in southwest Montana to be compared with other sites, regional and international, providing a better understanding of dinosaur ecology. Similar studies of Late Cretaceous dinosaur nesting sites in west-central Montana (Lorenz and Gavin, 1984) have provided valuable

information concerning dinosaur behavior (Horner, 1987). Additionally, sedimentologic studies focusing on deciphering the depositional setting of Morrison strata have recently been conducted directly to the west (Malone, 1991), and to the north (Meyers and others, 1992) of the study area. This study provides information that will complement these studies and broaden the understanding of Late Jurassic depositional systems in southwest Montana.

By determining the hydrodynamic characteristics of sediment transport and delivery processes, the study addresses a long standing question concerning the Morrison Formation in Montana. Precisely how were the sediments that comprise the Morrison delivered? Peterson (1966) noted a lack of coarse-grained channel bodies and an abundance of mudstone in deposits he interpreted as fluvial. This led to the proposition that much of the mudstone originated as ash fall. This inference, however, was not supported by exhaustive petrographic work by Suttner (1969), who proposed that Morrison fluvial systems were of such low gradient that coarse sand facies were not formed. This study is focused on an area where coarse-grained sandstone bodies, such as those sought by Peterson (1966), crop out. Thus, understanding the origin of these sandstone bodies and the physical processes that linked them to the fine-grained sediments at the time of deposition are primary objectives of this study.

Study Area

Exposures of Jurassic rocks exist along the north flank of the Beartooth and Gallatin ranges (Figure 1) in southwest Montana. The Morrison Formation is exposed in folds produced by late Mesozoic and early

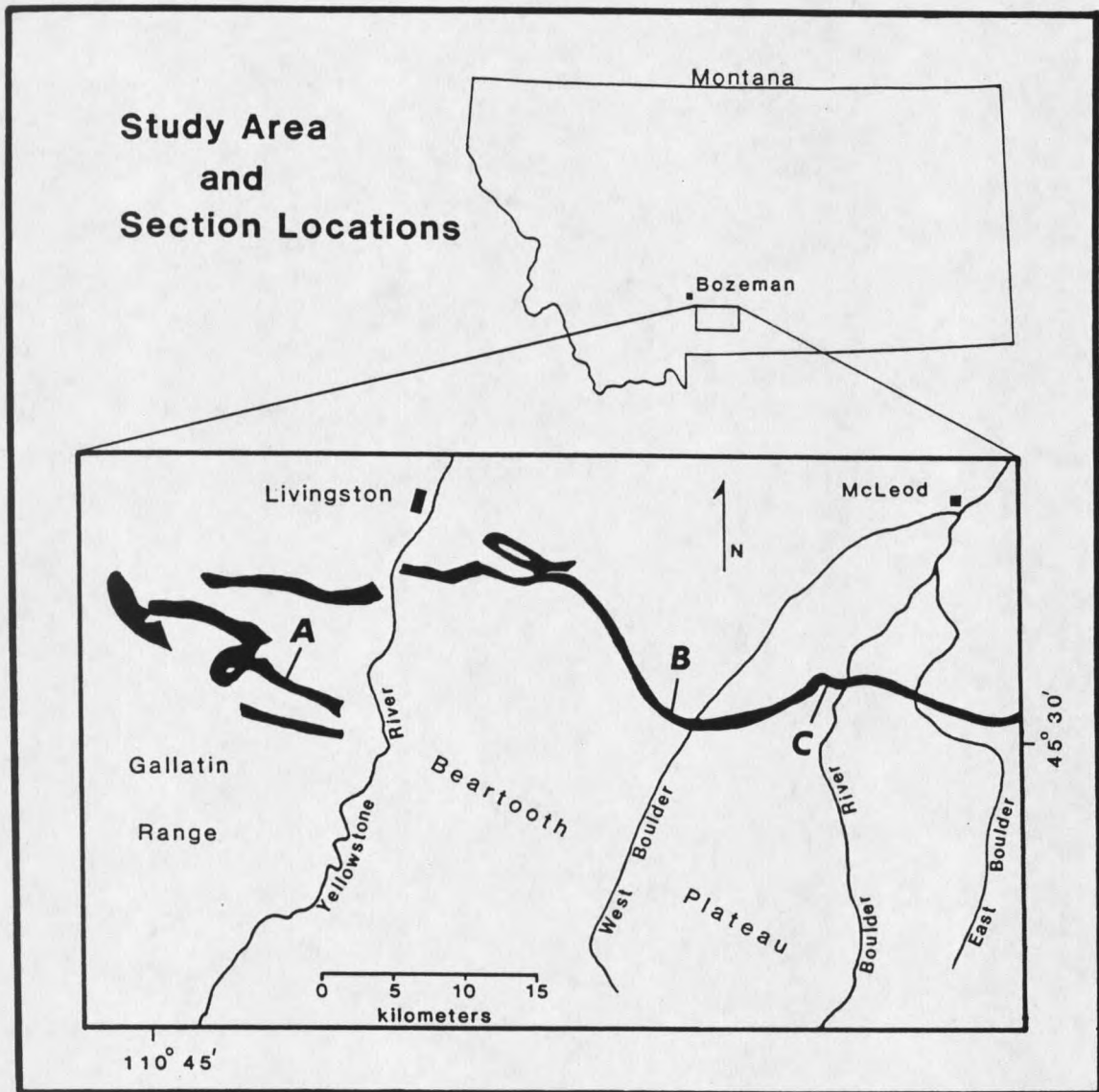


Figure 1. Map of study area, showing location of measured sections and extent of Jurassic rock. A-Strickland Creek (NW1/4, Sec. 29, T3S, R9E, Chimney Rock quad., Mt.), B-West Boulder River (SE1/4, Sec. 26, T3S, R9E, Mt. Rae quad., Mt.), C-Boulder River (NE1/4, Sec. 27, T3S, R12E, McLeod Basin quad., Mt.). Adapted from Ross and others, 1955.

Cenozoic uplift. Locations for measured sections were chosen based on quality of exposure and proximity to the Museum of the Rockies quarry. The study area contains three measured stratigraphic sections (A-C, Figure 1).

The Strickland Creek section (section A, Figure 1) is the site of the Museum of the Rockies quarry. The quarry exposes an otherwise covered part of section A. Measurement of a section through the quarry places the bone-bearing unit in its proper stratigraphic context.

The West Boulder River section (section B, Figure 1) contains laterally continuous outcrop of the upper Morrison Formation that was exposed in landslide scarps. In addition, this section provides sedimentologic and stratigraphic information between the Strickland Creek and Boulder River sections.

The Boulder River section (section C, Figure 1) was chosen because it provides excellent lateral exposure of Morrison strata and contains a dinosaur fauna similar to the Strickland Creek section. The presence of dinosaur bones in the Boulder River section allows depositional environment interpretations to be directly associated with dinosaur remains. The majority of the data used to interpret depositional environment was gathered at the Boulder River section.

MORRISON FORMATION

Local and Regional Stratigraphic Context

Previous sedimentologic, stratigraphic, and paleontologic studies of the Morrison Formation and its equivalents, both regional (Imlay, 1952; Moberly, 1960; Walker, 1974; Peterson and Turner-Peterson, 1987), and local (Suttner, 1969; Malone, 1991), concluded that the Morrison Formation in Montana is entirely non-marine and almost entirely fluvial in origin, with lacustrine and eolian processes playing minor roles. In Montana, the Upper Jurassic Morrison Formation records the Late Jurassic onset of terrestrial sedimentation, which followed the rapid northward withdrawal of the Middle Jurassic Sundance Sea (Imlay, 1952). These non-marine conditions continued until transgression of the Cretaceous Western Interior seaway in Albian time.

The Morrison Formation in Montana consists of generally poorly exposed, interbedded mudstone and lenticular sandstone bodies, and is recognized largely by stratigraphic position. These strata overlie the marine Upper Jurassic Ellis Group and are overlain by resistant basal Cretaceous sandstone and conglomerate. The Morrison is correlative with the Kootenay Formation north of the Canadian border. The Kootenay interfingers with the marine Fernie Group farther north (Walker, 1974). The Fernie Group is the only Morrison-equivalent marine deposit known in North America (Walker, 1974), with the possible exception of marine beds known from well logs in the Williston Basin (Francis, 1957). In eastern Idaho and western Wyoming, the Morrison appears to be correlative with the lower Ephraim Formation of the Gannett Group based on biostratigraphy

(Eyer, 1969) and petrographic work by Furer (1970).

The Morrison Formation in the study area, and to the north and west, rests conformably on glauconite-bearing sandstone beds deposited by the retreating Sundance Sea (Walker, 1974; Malone, 1991). This glauconitic, cross-bedded quartz sandstone is known regionally as the Swift Formation and is the uppermost member of the marine Ellis Group (Cobban, 1945). The Ellis Group is correlative with the San Rafael Group in Utah, Stump Sandstone in eastern Idaho (Furer, 1970), and Sundance Formation of Wyoming (Imlay, 1952).

The Morrison is overlain by the Kootenai Formation in Montana. The Kootenai Formation is an equivalent of the Cloverly Formation of central Wyoming and south-central Montana. Both the Cloverly and Kootenai contain a basal, black chert clast-bearing sandstone or conglomerate (Moberly, 1960; Suttner, 1969), which is in unconformable contact with the underlying, poorly indurated mudstones of the Morrison. The precise amount of time represented by this unconformity is unknown.

Age

Until recently the age of the Morrison Formation was based on biostratigraphy using vertebrate and invertebrate fossils with broad ranges (Kowalis and others, 1991). This led to much controversy, as ages ranging from Oxfordian to Neocomian have been proposed for the Morrison (Simpson, 1926; Baker and others, 1936; Stokes, 1944; Yen, 1952; Imlay, 1980). Recent $^{40}\text{Ar}/^{39}\text{Ar}$ dates obtained from bentonites in the Morrison on the Colorado Plateau, however (Kowalis and others, 1991), constrain most of the formation to the Kimmeridgian and Tithonian (153 to 145 Ma \pm 1-2

Ma). Unfortunately, this does not resolve whether the Jurassic/Cretaceous boundary lies at the upper contact of the Morrison, because the youngest dated sample was taken more than 20 m below the top of the Morrison.

The age of the Morrison Formation in Montana is not constrained by radiometric dates, although a Late Jurassic-Early Cretaceous age has been tentatively proposed for the upper Morrison of the Big Horn Basin in Wyoming, based on magnetostratigraphy (Swierc, 1990). Indeed, it seems likely that a formation with such great areal extent could be time transgressive; a concept that has been previously noted (Bowman and others, 1986). Despite the lack of age data, the Morrison Formation in southwest Montana is generally considered to be Late Jurassic in age, with the Jurassic/Cretaceous boundary conveniently placed at the contact between the Morrison and the Kootenai.

METHODS

Measured Sections

Vertical stratigraphic sections were measured in areas of best exposure (Figure 1). Measurements were made at all three localities using a Jacobs Staff and standard techniques of description (Tucker, 1982, p. 9-19). All outcrops between measured sections were walked to search for lithofacies exposure. Lithofacies are classified using Miall's (1985) scheme, and therefore have only a hydrodynamic interpretation associated with them.

Architectural Element Analysis

The distribution and interconnectedness of alluvial sandbodies within finer-grained deposits has been termed "alluvial architecture" (Allen, 1978, Leeder, 1978). This concept has been further developed and formalized as an interpretive method, and labeled "architectural element analysis" by Miall (1985). Architectural elements (original term, Allen, 1963) were defined by grain size, types of bedforms present, internal lithofacies sequence and, most critically, by external geometry. The combination and distribution of these elements within the deposit were used to interpret depositional environment because architecture reflects processes occurring on the scale of floodplain or basin, and this is the scale on which fluvial styles are recognized. Stratigraphic sections were measured not only to record vertical changes in lithofacies and allow the application of Walther's law, but to serve as a framework for recording lateral lithofacies changes. This then allowed the construction of

architectural elements. The analysis and interpretation of these elements is the next step towards interpretation of depositional environment. Architectural elements constructed from lithofacies described in the Morrison Formation can be compared to various models as well as other studies which have used this method. These will be discussed below in the Anastomosed Fluvial Systems section.

Photomosaics and Mapping

Photomosaics were used to document lateral changes in lithofacies. Photomosaics are single or composite photographs, generally taken orthogonal to the outcrop, which are used as a base for definition of architectural elements which were sketched on overlays (Miall, 1985). In this study, photomosaics at the scale of individual outcrops were used to record lateral changes in lithofacies geometry and vertical sequence, and sedimentary structures. These features are often difficult to see on the photographs themselves but are recorded on the photomosaic to provide data on spatial relationships of architectural elements. Photographs and overlays covering up to 2 km of outcrop record lateral changes in architectural elements.

In other studies using photomosaics, photographs are generally taken from an opposing canyon wall. Due to the orientation of the two section locations which contain extensive lateral exposure (Boulder River and Strickland Creek), aerial photography was the only way to obtain photographs suitable for producing photomosaics. Air photos were taken from approximately 2000 ft. and have scale of 1:4770.

Modern Comparisons

To interpret the depositional environment of an ancient deposit, it is often useful to compare the deposits of ancient rivers with unknown morphology to the deposits of modern rivers, where morphology can be observed. For example, Smith (1983) found that by coring a modern floodplain, the thickness and width of channel deposits laid down by a river of known morphology could be determined. These data are often expressed as the ratio of width to thickness of channel sandstone bodies. In addition, the distribution of channel deposits within overbank sediments has been determined for modern flood plains (Smith and Smith, 1980; Smith and others, 1989) and can be compared with spatial distributions in the Morrison Formation.

In order to compare the dimensions of sand bodies identified as channel deposits in the Morrison Formation of southwest Montana with those of modern fluvial systems, several measurements were made. Multiple thickness measurements were taken along the outcrop where sandstone bodies were of non-uniform thickness. Where sandstone lenses pinched out completely into covered section, trenches were dug to confirm the limits of lateral extent of the sand bodies. The widths of the channel deposits were measured along outcrop; however, since the true width of a channel is measured perpendicular to flow, it follows that the width of a channel deposit must be measured perpendicular to paleoflow. This is not always possible because outcrop faces do not always form perpendicular to paleoflow. To correct for this, paleocurrent directions were determined and trigonometric corrections were made to provide width dimensions closer to the true widths of Morrison alluvial channels.

Paleocurrent Measurements

Paleocurrents were measured to calculate width to thickness ratios of channel sandstone bodies. These values were compared to data from modern alluvial systems as well as ratios published in studies of other ancient deposits. In addition, paleocurrent measurements provide knowledge of sediment transport direction and allowed for interpretations of source area location, local drainage patterns, and paleo-topography.

Paleo-flow data were taken from trough cross bedding, dinosaur bone long-axis orientation, and aligned heavy mineral stringers. These latter structures result from small scale current vortices aligned parallel to transport direction which deposit stringers of heavy mineral sand, usually in a trough or on a horizontal bed (Miall and Smith, 1989). Other measurements were taken from two dimensional exposures of trough cross-bedding. Although it can be difficult to accurately determine paleo-flow direction from two dimensional outcrops, DeCelles and others (1983) showed it was possible to obtain reasonable paleo-flow measurements (± 25 percent) by using limb truncation angles to recognize the obliquity of the outcrop cut, and correct for it qualitatively. In addition, comparisons were made with computer generated models of cross bedding (Rubin, 1987) which allowed recognition of bedding structures cut at various angles.

LITHOFACIES

Lithofacies were delineated on the basis of grain size and sedimentary structures, and to a lesser extent, induration and color. The lithofacies codes used in this section are those of Miall (1985), and in some cases have been modified. Lithofacies are divided into mudrock and sandstone lithofacies. Hydrodynamic interpretations accompany each description. Broader, depositional environment interpretations will be presented in the next section when these lithofacies are compiled into lithofacies assemblages or architectural elements.

Mudrock

Massive clay and silt (Fm)

Description: This lithofacies makes up the majority of strata in all measured sections. It is poorly indurated and often covered but was observed in slump scarps, steep slopes, and trenches. Weathered exposures are often fissile but fresh material (trenches) is massive. Thin (1 to 3 mm), laterally discontinuous, sandy silt stringers are sometimes present. Grain size ranges from silty clay to sandy silt.

Color varies from light green and red to light and dark grey. Purple horizons were found at the Strickland Creek section. At the West Boulder section the grey mudstone is slightly petroliferous. Flakes of carbon of unknown origin and small leaf fragments are common in several horizons of the green and grey mudstone. Zones 0.5 m thick with small (1 to 5 cm diameter) iron-bearing nodules occur within this lithofacies.

Interpretation: Structureless mud is deposited when fine-grained sediment settles out of suspension with little variation in settling rate

and grain size (Collinson and Thompson, 1982, p. 57). The environment of deposition is one of very low energy. Red and brown zones are interpreted to have been oxidized, likely as a result of pedogenic processes (Kraus and Bown, 1988). Green and grey zones represent primary or diagenetic reducing environments. The presence of a reducing environment is indicated by preserved plant material.

Laminated clay and silt (F1)

Description: This lithofacies is similar to Fm in grain size, color, and induration but has fine laminations that are typically 1 to 3 mm thick. These laminations are often accompanied by a change in grain size, from clay to silt or sandy silt. Uncommonly, the laminations are wavy with the waveform height ranging from 1 to 2 cm and the wavelength ranging from 5 to 10 cm.

Interpretation: This lithofacies is also the result of low energy suspension deposition. Laminations of this scale are the result of fluctuations in the supply of different sizes of suspended sediment (Collinson and Thompson, 1982, p. 56). Wavy lamination may result from soft sediment deformation or drapes on underlying ripple cross-laminated sediment.

Silty limestone (Fc)

Description: This lithofacies occurs as small lenses of light grey, silty, micritic limestone. Lenses range from 1 to 5 m in width and 5 to 20 cm in thickness. Small stringers of sparry calcite 1 to 3 mm thick are common. Upper and lower contacts are sharp and uniform.

Interpretation: These limestone lenses are interpreted to be the

result of carbonate precipitation in shallow floodplain ponds or backswamps. Shallow water environments were responsible for creating similar deposits found in the Lower Cretaceous Peterson Limestone of western Wyoming and southeastern Idaho (Glass and Wilkinson, 1980). The limited lateral extent and uniform contacts preclude the possibility of these deposits being interpreted as calcretes or caliches as these pedogenic features are usually laterally extensive and nodular (Blodgett, 1988).

Coal and woody material (C)

Description: This lithofacies occurs as a zone at the transition between mud lithofacies of the Morrison Formation and sand lithofacies of the overlying Kootenai Formation. The zone varies in thickness laterally from 0.5 m to 10 cm. Coal occurs as partings up to 1 cm thick and 40 cm long, encased in medium to coarse-grained sand. The impressions of woody material are up to 1 m long and have the third dimension slightly preserved although all fragments were clearly crushed.

Interpretation: The poor quality of the preserved coaly material precluded identification (W. Tidwell, pers. comm., 1992). No in situ stumps or roots were found and fragments were all aligned parallel to one another. This, along with the fact that coal is sparse and not developed in seams indicates that trees grew upstream and were likely transported during flood events. Transport of the logs is further corroborated by their worn nature observed in the impressions. In all cases the logs had been crushed.

SandstoneTrough cross-bedded sand (St)

Description: Fine to coarse-grained, well sorted, moderately to well indurated trough cross-bedded sand is the dominant sand lithofacies. Cross beds occasionally occur as sets 30 to 60 cm thick, 0.5 to 1.5 m wide, and always appear as cosets. Indistinct normal grading can be seen within some of the individual foresets. Cement is often calcareous.

Color is generally light yellowish brown. Dark, heavy mineral sand layers are occasionally present at the base of troughs and were exposed under overhanging exposures. The composition of this lithofacies is typically that of a sublitharenite (Folk, 1968).

Interpretation: Trough cross bedding results from the down-current migration of large sinuous crested and isolated sand dunes. As dunes migrate across and fill hollows in the substrate, concave up bedding results (Harms and Fahnstock, 1965). The dunes are created and maintained by unidirectional flow in the upper part of the lower flow regime. They form in water depths greater than twice the thickness of the individual sets (Harms and others, 1975). As such, the presence of the structure is not indicative of water depth.

Ripple cross-laminated sand (Sr)

Description: This lithofacies consists of very fine- to medium-grained, moderately well indurated sand. Ripple forms typically have an amplitude of 1 to 3 cm and wavelength of 3 to 10 cm. This lithofacies occasionally exhibits load and fluid escape structures when overlain by lithofacies St. Limonitic partings are also present. The color is

yellowish brown to brown. The composition of this lithofacies ranges from sublitharenite to litharenite.

Interpretation: Ripple cross-lamination results from the down current migration of small scale bedforms (height < 3 cm, wavelength < 50 cm), produced by lower flow regime flow (Collinson and Thompson, 1982, p. 59). Ripple laminations can have various cross-sectional geometries. The ripple forms found in this lithofacies exhibit sigmoidal morphologies. Based on flume and sedimentologic studies, Jopling and Walker (1968) concluded that sigmoidal morphology represented preservation of lee side laminae with no preservation of stoss side laminae. This reflects low aggradation rates as a result of low suspended load/traction load ratios.

Scours with mudclast conglomerate (Sei)

Description: This lithofacies is a moderately well indurated, matrix-supported, mud-pebble conglomerate which always overlies an erosional scour. The clasts are predominantly 0.5 cm to 1 cm in length, but clasts up to 10 cm were found; they are grey to green, calcareous, and subangular.

The matrix is a greenish-grey to yellow, medium-grained, poorly-sorted, calcareous sand. Dinosaur bones are typically found within or closely associated with this lithofacies. Disarticulated sauropod post-cranial bones up to 1 m in length were found at the Strickland Creek site by staff from the Museum of the Rockies, along with the hind limb elements of an allosaur and several turtle scutes. The bone bed at Strickland Creek lies just below the base of a 3 m thick channel sandstone mostly contained within in a 0.2 m grey green siltstone although several poorly preserved bones were found within a 0.4 m thick unit of lithofacies Sei which lies

directly above the siltstone unit. Sauropod caudal vertebrae and a cervical vertebrae of a Stegosaurid were found at the Boulder River location within this lithofacies. Impressions of woody material are also locally common.

Interpretation: This mudclast conglomerate appears to have formed in a low energy environment. The mudclasts likely formed when cohesive mudbanks collapsed into the channel as a result of bank erosion. The majority of mudclasts found at all three sections are angular and therefore could not have been transported far, or in a high energy environment. In addition, dinosaur bones found at Boulder River in lithofacies Sei showed no evidence of wear.

ARCHITECTURAL ELEMENTS

Architectural elements were defined on the basis of grain size, types of bedforms present, internal lithofacies sequence (vertical and lateral), and external geometry. Three of Miall's (1985) eight original architectural element types were recognized: channel (CH), sand bedform (SB), and overbank fines (OF). The channel element type CH has been subdivided to include three different channel classes. Fifteen individual elements were identified in the Morrison outcrops and are listed in Table 1. They can be seen best on air photos (Figures 2 and 3). Relative dimensions of element types CB and SB are graphically presented in Figure 4. Representative sketches, showing lithofacies composition and external geometry of element types CH and SB are presented in Figure 5. Element OF does not show noticeable lateral or vertical changes in the above mentioned defining parameters and was not sketched.

Channel Elements

Primary Channels (CHp)

Description: This channel element is characterized by a concave-up erosional base and the predominance of lithofacies St and Sei. Element CHp is also the largest channel element (largest cross sectional area perpendicular to paleoflow) of all the channel elements recognized (Table 1D).

Primary channel deposits have a moderately low width to thickness ratio relative to other CH elements (Table 1C). Ratios of 5.5 and 10.7 were determined for the two channel elements (1 and 11) classified as

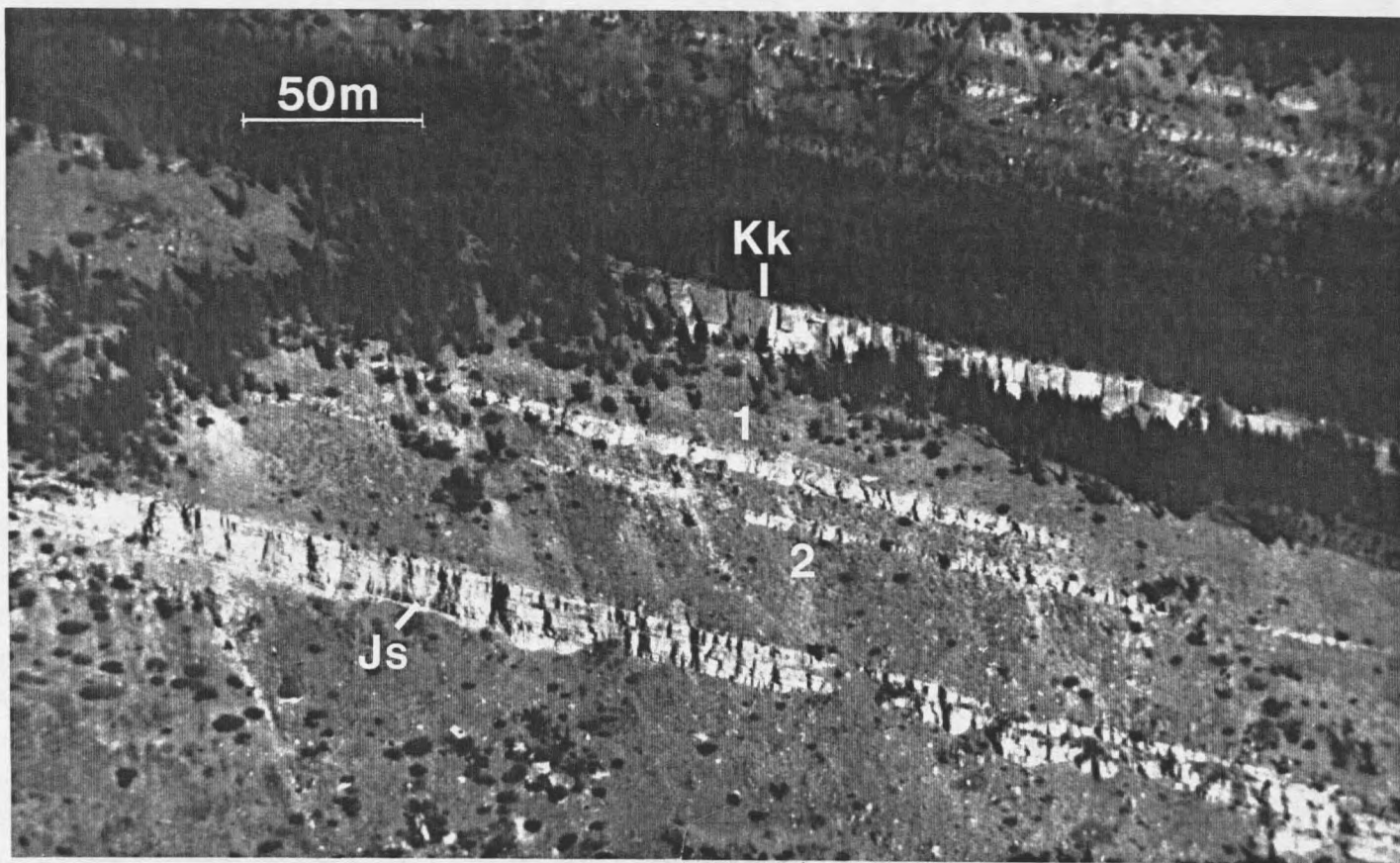


Figure 2. Air photograph taken orthogonal to outcrop of elements 1 (CHp) and 2 (CHs). Outcrop face is 17 degrees from paleoflow mean azimuth. Overlying Lower Cretaceous Kootenai formation (Kk) and underlying Jurassic Swift (Js) Formation labeled.

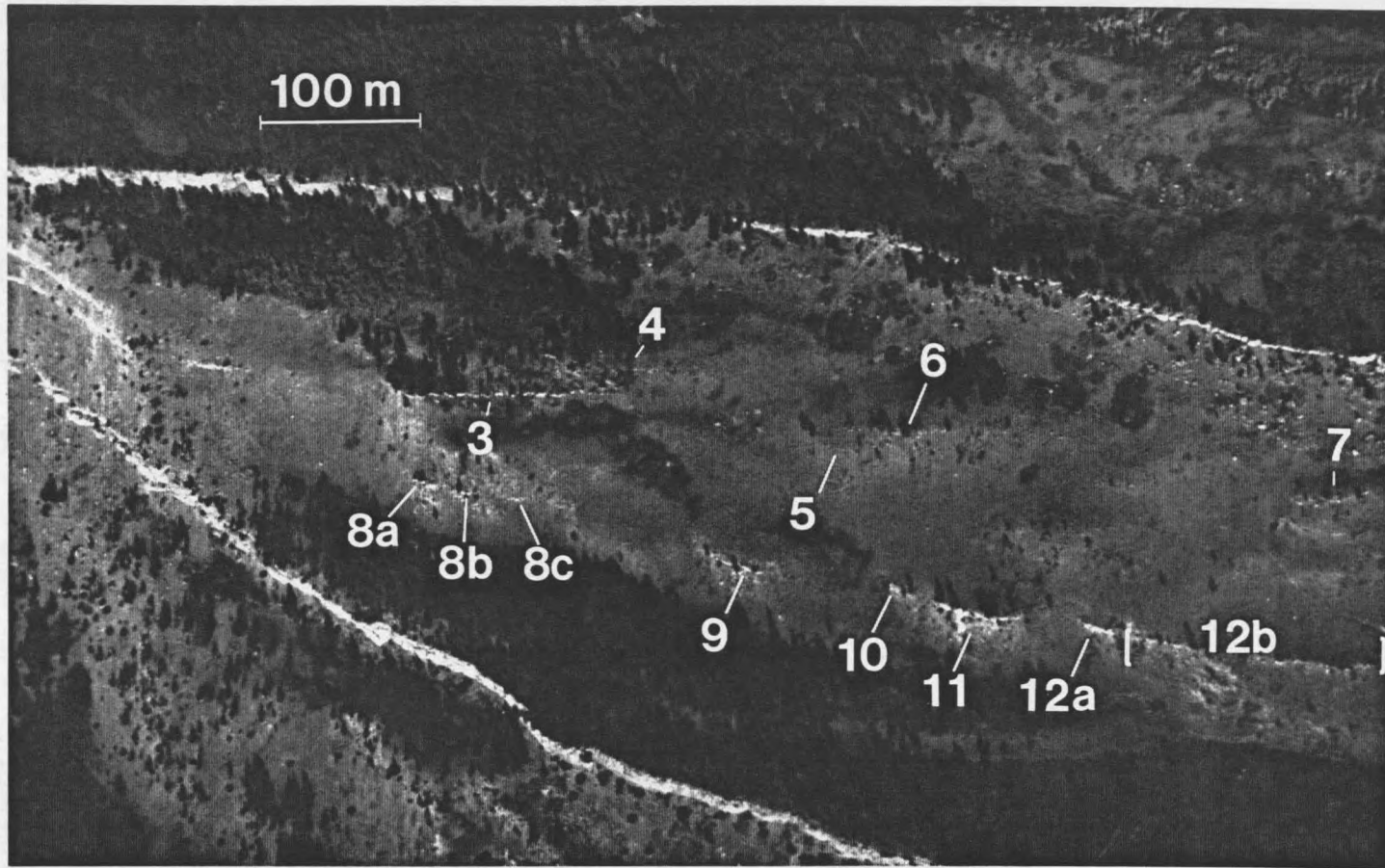


Figure 3. Air photograph of Boulder River location (section D) showing elements CHp (11), CHs (12a, 8a, 8c, 10, 8b, 9), CHcr (3) and SB (5, 4, 7, 6, 12b), encased in element OF. Numbers refer to specific elements described and listed in Table 1. Note lenticular nature of channel bodies and dimensions of CH elements compared to SB.

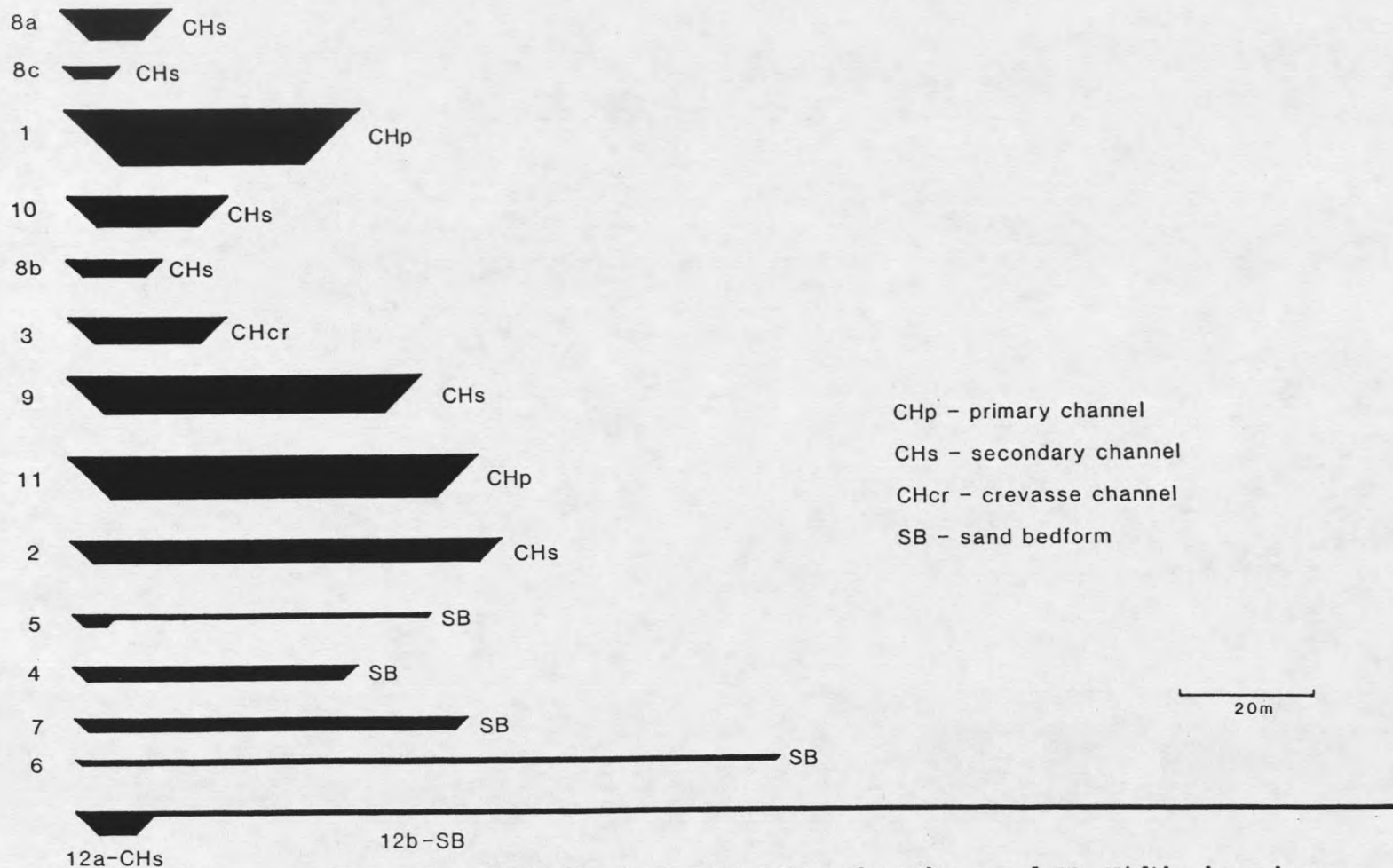


Figure 4. Cross sections of architectural elements Chp, Chs, Chcr, and SB. Widths have been corrected to account for outcrop faces which were oblique to paleoflow. Width to thickness ratios increase from top of diagram to bottom. Channel margins in the diagram are not representative of actual margins. Note difference in geometry between channel elements and sand bedforms. Refer to table 1 for dimension data. No vertical exaggeration.

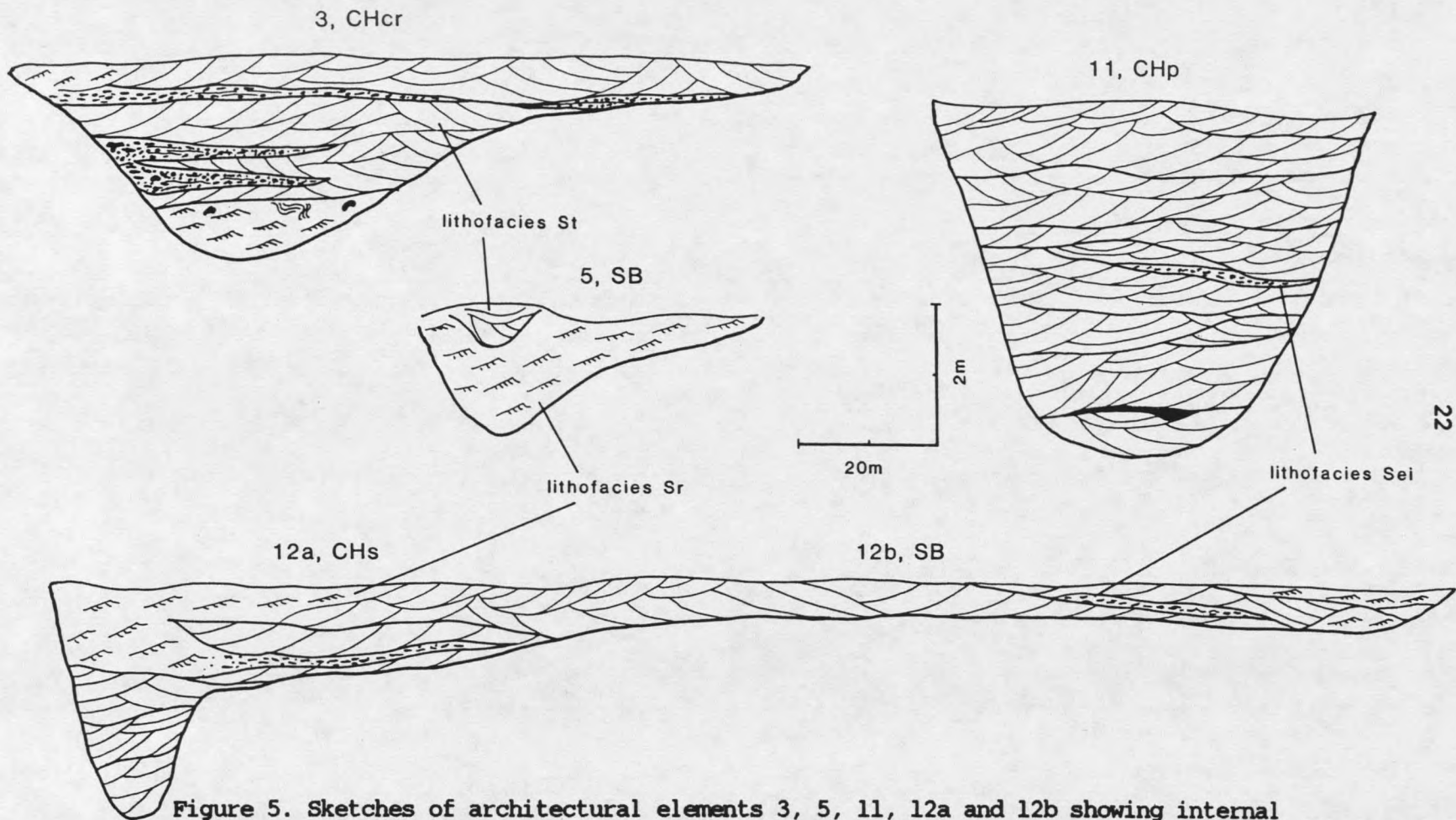


Figure 5. Sketches of architectural elements 3, 5, 11, 12a and 12b showing internal lithofacies relationships and external geometry. Although these sketches are of specific elements, they are also generally representative of element types CHs, CHcr and SB. Note vertical exaggeration (10x).

Table 1. Table of architectural element data (meters). The data are variously ordered: width, thickness, width to thickness ratio (W/T), and width multiplied by thickness (WxT).

	ELEMENT AND CLASS	WIDTH (W)	THICKNESS (T)	W/T RATIO	WxT
A ORDERED BY WIDTH	8c-CHs	8.0	1.5	5.3	12.0
	12a-CHs	11.0	4.0	2.8	44.0
	8a-CHs	15.0	4.0	3.8	60.0
	8b-CHs	15.0	2.5	6.0	37.5
	3-CHcr	22.0	3.2	6.9	70.4
	10-CHs	23.0	4.0	5.8	92.0
	4-SB	40.0	1.8	22.9	70.0
	1-CHp	43.0	7.8	5.5	335.4
	9-CHs	50.0	5.0	10.0	250.0
	5-SB	51.0	2.5	20.4	127.5
	7-SB	55.0	1.8	31.4	96.3
	11-CHp	59.0	5.5	10.7	324.5
	2-SB	62.0	3.2	19.4	198.4
	6-SB	100.0	1.0	100.0	100.0
B ORDERED BY THICKNESS	12b-SB	179.0	0.8	223.8	143.2
	6-SB	100.0	1.0	100.0	100.0
	8c-CHs	8.0	1.5	5.3	12.0
	4-SB	40.0	1.8	22.9	70.0
	7-SB	55.0	1.8	31.4	96.3
	5-SB	51.0	2.5	20.4	127.5
	8b-CHs	15.0	2.5	6.0	37.5
	2-CHs	62.0	3.2	19.4	198.4
	3-CHcr	22.0	3.2	6.9	70.4
	8a-CHs	15.0	4.0	3.8	60.0
	10-CHs	23.0	4.0	5.8	92.0
	12a-CHs	11.0	4.0	2.8	44.0
	9-CHs	50.0	5.0	10.0	250.0
	11-CHp	59.0	5.5	10.7	324.5
1-CHp	43.0	7.8	5.5	335.4	
C ORDERED BY W/T RATIO	12a-CHs	11.0	4.0	2.8	44.0
	8a-CHs	15.0	4.0	3.8	60.0
	8c-CHs	8.0	1.5	5.3	12.0
	1-CHp	43.0	7.8	5.5	335.4
	10-CHs	23.0	4.0	5.8	92.0
	8b-CHs	15.0	2.5	6.0	37.5
	3-CHcr	22.0	3.2	6.9	70.4
	9-CHs	50.0	5.0	10.0	250.0
	11-CHp	59.0	5.5	10.7	324.5
	2-CHs	62.0	3.2	19.4	198.4
	5-SB	51.0	2.5	20.4	127.5
	4-SB	40.0	1.8	22.9	70.0
	7-SB	55.0	1.8	31.4	96.3
	6-SB	100.0	1.0	100.0	100.0
12b-SB	179.0	0.8	223.8	143.2	
D ORDERED BY WxT	8c-CHs	8.0	1.5	5.3	12.0
	8b-CHs	15.0	2.5	6.0	37.5
	12a-CHs	11.0	4.0	2.8	44.0
	8a-CHs	15.0	4.0	3.8	60.0
	4-SB	40.0	1.8	22.9	70.0
	3-CHcr	22.0	3.2	6.9	70.4
	10-CHs	23.0	4.0	5.8	92.0
	7-SB	55.0	1.8	31.4	96.3
	6-SB	100.0	1.0	100.0	100.0
	5-SB	51.0	2.5	20.4	127.5
	12b-SB	179.0	0.8	223.8	143.2
	2-CHs	62.0	3.2	19.4	198.4
	9-CHs	50.0	5.0	10.0	250.0
	11-CHp	59.0	5.5	10.7	324.5
1-CHp	43.0	7.8	5.5	335.4	

primary channels. The cross sectional area perpendicular to paleoflow of channel elements 1 and 11 is 335.4 m^2 and 325.5 m^2 , respectively (Table 1D).

Interpretation: The size and lithofacies associations (lithofacies representing uppermost lower flow regime) of element CHp indicates it represents areas of highest hydrodynamic energy on the floodplain. Channel elements 1 and 11 are considered deposits of primary channels (Table 1, Figures 4 and 5). This element is also classified as a primary channel because it exhibits the most cycles of aggradation and erosion (>20). These cycles are the result of cutting and filling of previous, lower flow regime deposits and can be seen in the form of numerous laterally extensive scour surfaces which truncate underlying St lithofacies, and which form the base for overlying St lithofacies. These surfaces also form the base for mudclast conglomerates, which make up lithofacies Sei. A primary channel deposit contains up to 25 such cycles.

Secondary Channels (CHs)

Description: Element CHs, like element CHp, is characterized by a concave-up erosional base and relatively coarse grain size. This element, however, is typically smaller in cross-sectional area than element CHp (Table 1D), and while still dominated by lithofacies St, contains fewer units of lithofacies Sei. Width to thickness ratio ranges from 2.8 to 19.4 (Table 1C), and cross sectional area ranges from 12 m^2 to 250 m^2 (Table 1D). Elements interpreted as secondary channels include: 12a, 10, 9, 8a, 8b 8c, and 2 (Table 1 and Figure 3).

Interpretation: This element also represents areas in the system with relatively high hydrodynamic energy. Channels classified as element

CHs are the result of cycles of aggradation and erosion as they contain cut and fill structures similar to element CHp. These deposits, however, contain fewer cycles (<20), which may be the result of shorter channel life. They are laid down by smaller, yet established channels which carry lesser flows than the primary channel. This likely results in lesser amounts of bank erosion or channel scour, which could account for lithofacies Sei being a minor component of this element.

Crevasse Channels (CHcr)

Description: Element CHcr is also characterized by a concave-up erosional base and relative coarse grain size (medium to coarse sand), although fine-grained sand is more abundant than in CHp or CHs. This fine-grained sand is present as lithofacies Sr, which is a major component of element CHcr. Lithofacies Sei is also common in this element. Element CHcr exhibits more lateral lithofacies variation than element CHp and CHs. One element (3, Figure 5) representing this stage of channel development is present in the study area. The width to thickness ratio is 6.9 (Table 1C) and cross sectional area is 70.4 m^2 (Table 1D).

Interpretation: This element, like CHp and CHs, also represents areas of high hydrodynamic energy in the system; however, the replacement of much of St with Sr indicates lower energy levels than those represented by element CHp and CHs. This element is deposited by channels smaller than primary and secondary channels. It has formed as the result of levee breaching, or crevassing along primary or secondary channels. The crevasse channel often begins with the deposition of a crevasse splay deposit (element 5, Figure 5), which results from the delivery of sediment laden water to the overbank environment through the levee crevasse (Reading,

1978 p 41-42, 120). If the incision is not plugged, and through-going water returns to the primary channel at a point down stream, the splay deposit may become incised, and a minor channel established. On modern floodplains, this process often deposits a coarsening then fining upward lithofacies sequence due to its progradational nature (Smith, 1983). This process of channel evolution is well documented on modern floodplains (Smith and Putnam, 1980; Smith and others, 1989). If the crevasse channel is not choked and abandoned, these channels often become secondary or primary channels.

Floodplain Elements

Sand Bedforms (SB)

Description: This element is characterized by a more flattened concave-up erosional base, medium grain size, and sheet-like geometry (Figure 4 and 5). This element is dominated by lithofacies Sr, with minor amounts of St and rarely, Sei. Elements identified as crevasse splay deposits include: 4, 5, 6, 7, and 12b. Width-to-thickness ratio ranges from 20.4 to 223.8 (Table 1C), and cross sectional area ranges from 70.0 to 143.2 m² (Table 1D).

Interpretation: This element represents an environment lower in hydrodynamic energy than that represented by CHcr as evidenced by the predominance of lithofacies Sr which represents lower flow regime flow. This lithofacies represents the initial deposits of the crevasse splay process. The deposits contain few, if any, internal scour surfaces. This, along with the fact that the element is rarely thicker than 1.5 m, indicates deposition by one or two flood events, closely spaced in time

(Miall, 1985). The sheet-like geometry is reflected in width-to-thickness ratios as high as 223.8 (element 12b, Figure 4, Table 1C), and results from unconfined flow carrying suspended and entrained sediment into the mud-dominated environment of the adjacent floodplain. On modern floodplains this process results in sand sheets and wedges ranging in thickness from 40cm to 2m (Miall, 1985; O'Brien and Wells, 1986).

Overbank Fines (OF)

Description: This element is dominant and is characterized by a sheet-like geometry and lateral truncation by elements CHp, CHs, and CHcr. Element SB often occurs as conformable lenses within element OF. Measured sections comprise between 70 and 100 percent of element OF. Typically, element OF is made up of lithofacies Fl, Fm, and C. Element OF encases all other architectural elements.

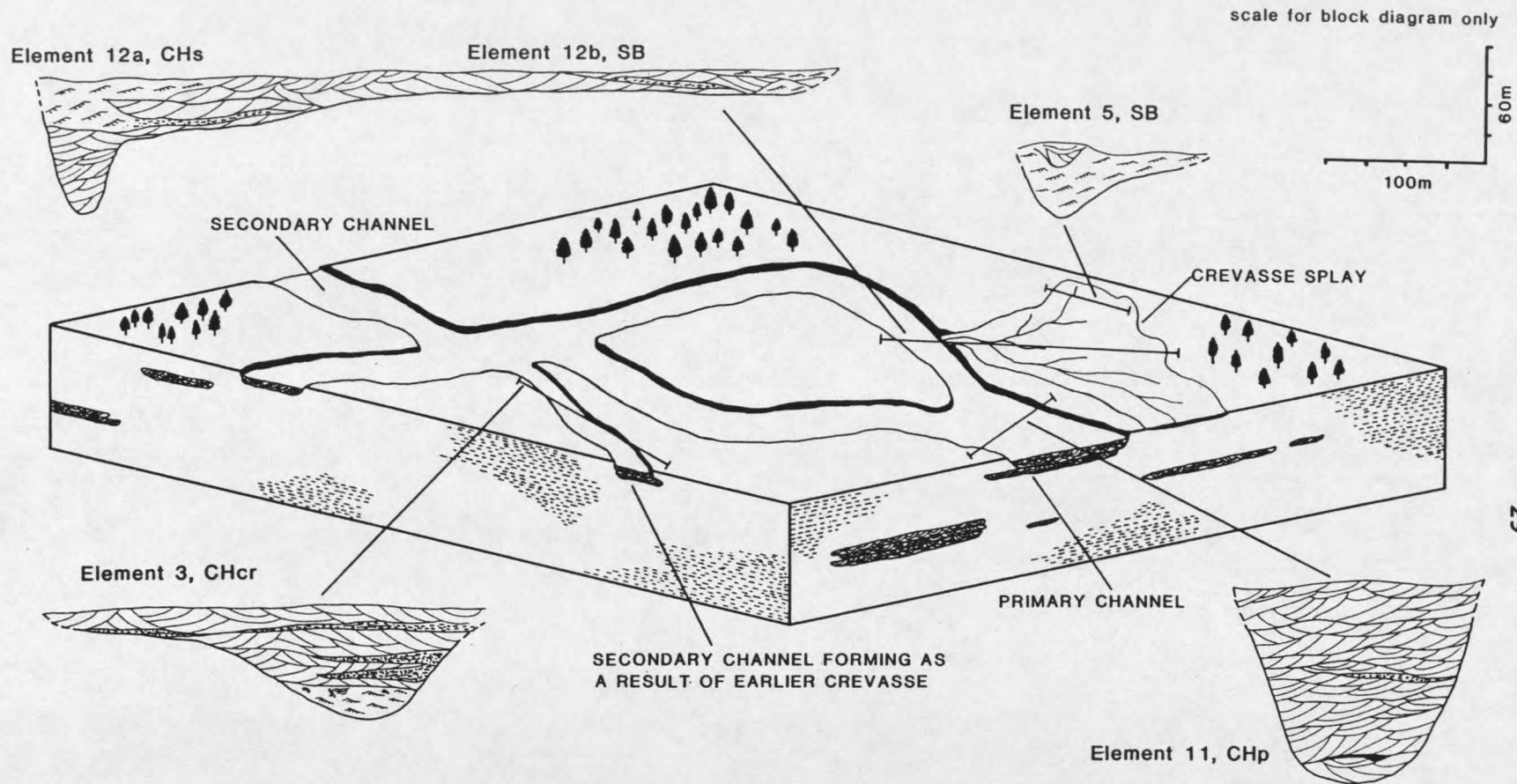
Interpretation: This element is deposited predominantly by flood waters which reach the floodplain, become still, and drop suspended sediment. In some modern floodplains, water delivered to this environment through levee crevasses can affect areas up to 500 km² (Smith and others, 1989). In some rapidly aggrading fluvial systems, architectural elements representing single events such as crevasse splaying, are soon covered by element OF (Smith, 1983). This element comprises 100% of the Morrison between the measured sections.

ANASTOMOSED FLUVIAL SYSTEMS

The type of fluvial system responsible for depositing the Morrison Formation is determined by the geometry, composition, and organization of the various architectural elements. While no single, observed sedimentologic or stratigraphic feature is diagnostic of a particular fluvial style, consideration of all features present leads to the conclusion that the sediments studied were deposited by an anastomosed fluvial system. Figure 6 represents such a system and places the sketched architectural elements of Figure 5 in the context of an anastomosed fluvial system. Braided and meandering depositional models were considered but were eventually rejected after criteria for identifying fluvial systems were compared. Note similarities between Morrison deposit characteristics and those of modern anastomosed systems (Table 2).

Definition

The American Geological Institute Glossary of Geology (Gary and others, 1972, p. 25) defines anastomosing stream as "braided stream"; however, several authors have made important distinctions between the two. In trying to clarify terms used to describe multiple channel fluvial systems, Schumm (1968a) distinguished anastomosing from braided systems by noting that in Australia the term "anastomosing" referred to laterally stable channels. Following the same basic theme, Smith and Smith (1980, p. 157) used the term "anastomosed river" to refer to "an interconnected network of low-gradient, relatively deep and narrow, straight to sinuous channels with stable banks composed of fine-grained sediment (silt/clay) and vegetation". These criteria have subsequently been useful in



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Figure 6. Block diagram showing an hypothetical anastomosed fluvial system with associated deposits. Architectural elements representing transitional channels and splay deposits described in the Morrison are here placed in a paleoenvironmental context. Note vertical exaggeration.

Table 2. Criteria for interpreting fluvial style based on deposit characteristics with Morrison characteristics compared (from Jackson, 1978; Smith and Smith, 1980; Smith and Putnam, 1980; Rust, 1981; Smith and others, 1989; Gavin, 1986).

Criteria	Meandering	Braided	Anastomosed	Morrison
Epsilon cross beds	common	absent	rare	absent
Total mudstone to sandstone ratio	moderate	low	high	high
Width to thickness ratio	>40	>40 often >300	<20	2.8-19.4
Splays and avulsions	rare	absent	common	common
Multistory channel deposits	rare	common	common	common
Lateral migration	common	common	common	common
Abrupt lateral contacts	rare	absent	common	common
Lenticular sand body geometry	rare	absent	common	common
Coal	rare	absent	common	common
Coeval channels	rare	rare	common	present

distinguishing among a wide spectrum of fluvial systems in both modern and ancient environments. Since the definition of an anastomosed system was proposed, several modern anastomosed systems of various scales have been studied in detail. The definition proposed by Smith and Smith (1980) has largely remained unchallenged, but more importantly it has become clear that at least two of the criteria are common to all anastomosed systems.

Fixed Channels

In modern anastomosed systems, fixed channels are always present and in part define the system. Fixed channels are considered laterally immobile or restricted. Initially this was thought to be due to the rip-rap effect of vegetation roots in channel banks (Smith, 1976). Erosion tests found banks containing thick mats of roots to be 20,000 times more stable than banks without roots (Smith, 1976). While rooted banks may restrict lateral channel migration in wet temperate zones, where early studies of anastomosed systems were conducted (Smith and Smith, 1980; Smith and Putnam, 1980), the cohesive nature of the clays in the bank appear to be responsible for restricted channel migration in anastomosed systems in arid central Australia (Rust, 1981). The idea that clays are responsible for bank stabilization in arid areas was corroborated by studies of an anastomosed system in the semi-arid savannah of Columbia (Smith, 1986), where fine mud deposited in an overbank setting served to stabilize subsequently incised channels. The bank stabilizing effect of fine sediment has been observed in meandering systems as well (Schumm, 1968b). Whatever factor, or combination of factors which restricts lateral channel migration in modern anastomosed systems, evidence of fixed

channels in ancient deposits is required to identify an anastomosed system.

Distinctions between fixed and laterally mobile channels can be made in several ways. Direct evidence of lateral migration is the presence of lateral accretion surfaces or epsilon cross-bedding (Allen, 1963). Moody-Stuart (1966) recognized the significance of these structures in Devonian stream deposits in Spitzbergen and used the presence or absence of them, in part, to infer high and low channel sinuosity, respectively. Well preserved examples of these structures have been documented in the Middle Jurassic Scalby Formation of Yorkshire, England (Nami and Leeder, 1978) and the Morrison of Colorado (Evanoff, 1992). No epsilon cross beds were found in the channel elements of the Morrison. This suggests that the channels themselves were fixed within the floodplain. However, while the presence of epsilon cross-bedding (Miall, 1985) indicates lateral channel migration, the absence of such structures does not necessarily mean the channel was restricted laterally. Corings of modern floodplains indicate that lateral accretion surfaces are not always found in deposits of mobile channels (Jackson, 1981). In addition, lateral accretion deposits have been found in laterally restricted channel deposits (Gibling and Rust, 1990), and while the channel did shift laterally, migration was not significant, as evidenced by low width-to-thickness ratios. Thus, while the absence of epsilon cross-bedding does not alone confirm lateral channel stability, when considered in conjunction with width to thickness ratio, the absence of epsilon cross-bedding is viewed as significant.

Width-to-Thickness Ratios

The width-to-thickness ratio of a channel deposit quantifies that element's cross sectional geometry perpendicular to channel paleoflow (Table 1C, Figure 4). There is an important distinction between width-to-thickness ratio and width-to depth-ratio. Width and depth are dimensions commonly used by geomorphologists to quantify the cross sectional area of water flowing in a channel. While it is possible to calculate paleochannel dimensions and paleo bankful discharge (Schumm, 1972), particularly if lateral accretion deposits are well preserved, such calculations are inaccurate and misleading (Miall, 1985), and are not used in this study. Width-to-thickness ratio does, however, approximate the dimensions of the actual paleochannel, particularly the width, if there is little lateral channel migration. Therefore deposit widths are considered indicative of paleochannel width while deposit thicknesses are regarded as independent of paleo water depth.

Width-to-thickness ratios of channel deposits are useful in predicting channel stability. Anastomosed channels that are laterally stable tend to accrete vertically, as demonstrated in floodplain coring studies (Smith and Smith, 1980; Smith and Putnam, 1980; Smith, 1986). As the depositional basin subsides, floodplain deposits aggrade vertically during overbank flooding. The channel also fills vertically by stacking of stories which represent erosional and depositional cycles. The channel remains laterally "locked" within the cohesive overbank fines (Smith, 1983). This serves to decrease the width-to-thickness ratio of the deposit by decreasing the width of the deposit relative to the thickness. Sandstone ribbons or stringers are the result of this process and width-

to-thickness ratios are typically 20 or less in modern deposits (Smith, 1986). Observed channel elements must have low width-to-thickness ratios if an anastomosed system interpretation is to be considered.

This parameter has been used in other studies of ancient fluvial deposits to infer channel stability. Friend and others (1979) classified sandstone bodies in the Ebro Basin of Spain by assigning the name "ribbon" to bodies with a width-to-thickness ratio less than 15, and "sheet" if the ratio was greater than 15. Ribbon-shaped channel sandstones were attributed to deposition by laterally stable rivers with cohesive or cemented banks. Blakey and Gubitosa (1984) and Friend (1983) used the same cut-off of 15 to distinguish between laterally stable and laterally unstable channels. Gavin (1986) measured width-to-thickness ratios of channel deposits in the Upper Cretaceous Two Medicine Formation of western Montana that he interpreted as anastomosed. The ratios ranged from 2.9 to 3.8. In addition, ratios of less than 15 were attributed to deposition by fixed channel rivers in Campanian strata of the Green River Basin (Shuster and Steidtmann, 1987), and Eocene strata in the Big Horn Basin of Wyoming (Kraus and Middleton, 1987). Currie and others (1991) found lenticular sandstone bodies in the Upper Cretaceous St. Mary River Formation of Alberta and used low width-to-thickness ratios (8-40) to interpret anastomosed channels. Similarly, Kirschbaum and McCabe (1992) inferred the existence of an anastomosed system in the Cretaceous Dakota Formation of Utah based, in part, on width-to-thickness ratios ranging from 7 to 20.

The width-to-thickness ratios of channel deposits (elements CHp, CHs, CHcr) found in this study range from 2.8 to 19.4 (Table 1C, Figure 4). They are consistent with ratios measured in modern anastomosed

systems, and with those found in ancient systems interpreted as anastomosed or fixed channel. Ratios of unchanneled or sheet flow deposits range from 20.4 to 224 (Table 1C, Figure 4). These elements (SBcr) are the result of crevasse splays, a process common to anastomosed systems.

Crevasse Splays

As discussed in the Architectural Elements section, crevasse splays result in the deposition of element SBcr. These deposits are found on modern flood plains where levees separate the channel from the overbank environment (Coleman, 1969; O'Brien and Wells, 1986; Smith and others, 1989). Crevasse splay deposits are commonly associated with anastomosed fluvial systems and have been studied in detail on modern flood plains in western Canada (Smith 1983; Smith and others, 1989). The sequence of depositional events observed in this modern environment is recorded in vertical and lateral lithofacies sequences of elements described in the Morrison.

The Cumberland Marshes in east-central Saskatchewan exhibit at least three stages (I-III) of crevasse splay evolution (Smith and others, 1989). The first stage (I) after levee breaching is characterized by deposition of clay and silt on the floodplain, followed by deposition of silt and fine sand; thus, this stage is also characterized by a coarsening upward sequence. The deposit is wedge-shaped, thinning in the direction of progradation, and lens-shaped transverse to progradation. Stage II represents development of a network of channels across Stage I deposits. The geometry of the channel deposits ranges from "continuous sheets to

disconnected elongated pods". Some channels incise underlying floodplain mud as a result of flow concentration into a few dominant channels. In Stage III, flow becomes more localized as Stage II channels coalesce and concentrate flow. The sandstone bodies resulting from this stage exhibit ribbon geometry, low width-to-thickness ratios, and are most similar to sand bodies described in other modern anastomosed systems (Smith and Smith, 1980).

Elements described in the Morrison Formation can be directly compared to the above described Cumberland Marsh deposits of east-central Saskatchewan. Element 5 (Figure 5) has the geometry and internal lithofacies composition of Stage I or early Stage II deposits. The small amount of lithofacies St at the upper left of the diagram may represent incipient channelization of the splay deposit which is represented by lithofacies Sr (Figure 5). Levee deposits composed of lithofacies Sr were found at the margins of elements 8a and 12a. Further evidence of Stage I deposition in the Morrison in the form of a coarsening upward sequence can be seen at the base of element 3 (Figure 5). Subsequent progression of Stage II and III, across Stage I deposits, produced this coarsening-up then fining up sequence. Similar vertical sequences have been noted in other modern splay deposits (Smith, 1983), and in ancient units interpreted as crevasse splay deposits (Tyler and Ethridge, 1983; Rust and Legun, 1983; Bridge, 1984; Shuster and Steidtmann, 1987).

In other studies, thin "wing" structures (terminology of Friend and others, 1979) extending laterally from the margins of more massive main channel deposits have been noted and interpreted as splay deposits (Stear, 1983). A similar geometry can be seen in element 12 (Figure 5), and is

likewise interpreted as a splay deposit or representative of Stage I and II of Smith and others (1989).

Further similarities between the Cumberland Marsh deposits and Morrison elements are recognized in elements 8a, 8b, and 8c which are consistent in two dimensions with the three dimensional "discontinuous elongated pod" (Smith and others, 1989) geometry of Stage II deposits. In addition, the well developed, laterally discontinuous and isolated channel deposits of Stage III can be seen where element 1 crops out (Figure 2), and in outcrops of elements 9, and 11 (Figure 3).

The only dissimilarity between the Cumberland Marsh deposits and the Morrison elements is scale. The dimensions of active channels and recent deposits are 2 to 2.5 times larger than elements found in the Morrison. The processes which deliver sediment to the floodplain, however, appear to be scale independent, as evidenced by studies of other modern anastomosed systems (Rust 1981; Smith, 1983; Smith 1986). The Cumberland Marsh study, however, was chosen to compare to the Morrison because it described in detail deposits of transitional crevasse splay and channel stages. Deposits of these stages are observed in the Morrison. Another scale independent similarity between modern anastomosed river deposits and Morrison elements is mudstone to sandstone ratio, or ratio of element OF to CH + SB.

Mudstone to Sandstone Ratios

Deposits laid down by anastomosed fluvial systems have extremely high mudstone to sandstone ratios (Smith, 1986). The high ratios result from dominance of overbank mud sedimentation. Crevassing is the only way

in which coarse material can be delivered to the overbank environment, and relative to the size of the floodplain, these deposits cover a small percentage of the floodplain area. For example, the Magdalena River of northwest Columbia, which is the largest modern anastomosed system studied to date ($8800 \text{ m}^3 \text{ s}^{-1}$, bankful), has crevasse systems which cover 50 km^2 , crevasse deposits cover only 10 to 30 percent of the off-channel area (Smith, 1986). Percentages are remarkably similar in cores taken from modern anastomosed systems, where overbank deposits make up 80 to 90 percent of total accumulations (Smith and Smith, 1980). Sand percentages are even lower in arid region anastomosed systems, where channels carrying the sand comprise just 3 percent of the total area (Rust, 1981). Mudstone percentages are similarly high in the Morrison, ranging from 84 percent mudstone, to 97 percent mudstone in stratigraphic sections. Silty micrite deposits (lithofacies Fc) interpreted as backswamp and pond deposits are included as mudstone in these percentages. High mudstone to sandstone ratios can be seen in air photos (Figure 3), as well as stratigraphic section (Figure 7). In addition, the Morrison is entirely mudstone between measured sections. Thus, the anastomosed river model explains the large amounts of mudstone present in the Morrison of southwest Montana noted by Peterson (1966) and Suttner (1969).

Coeval Channels and Coal

Further similarities exist between the Morrison, modern, and ancient anastomosed systems (Table 2). One of the features which characterizes modern anastomosed systems is the existence of more than one active channel at any given time, which results from avulsive channel development

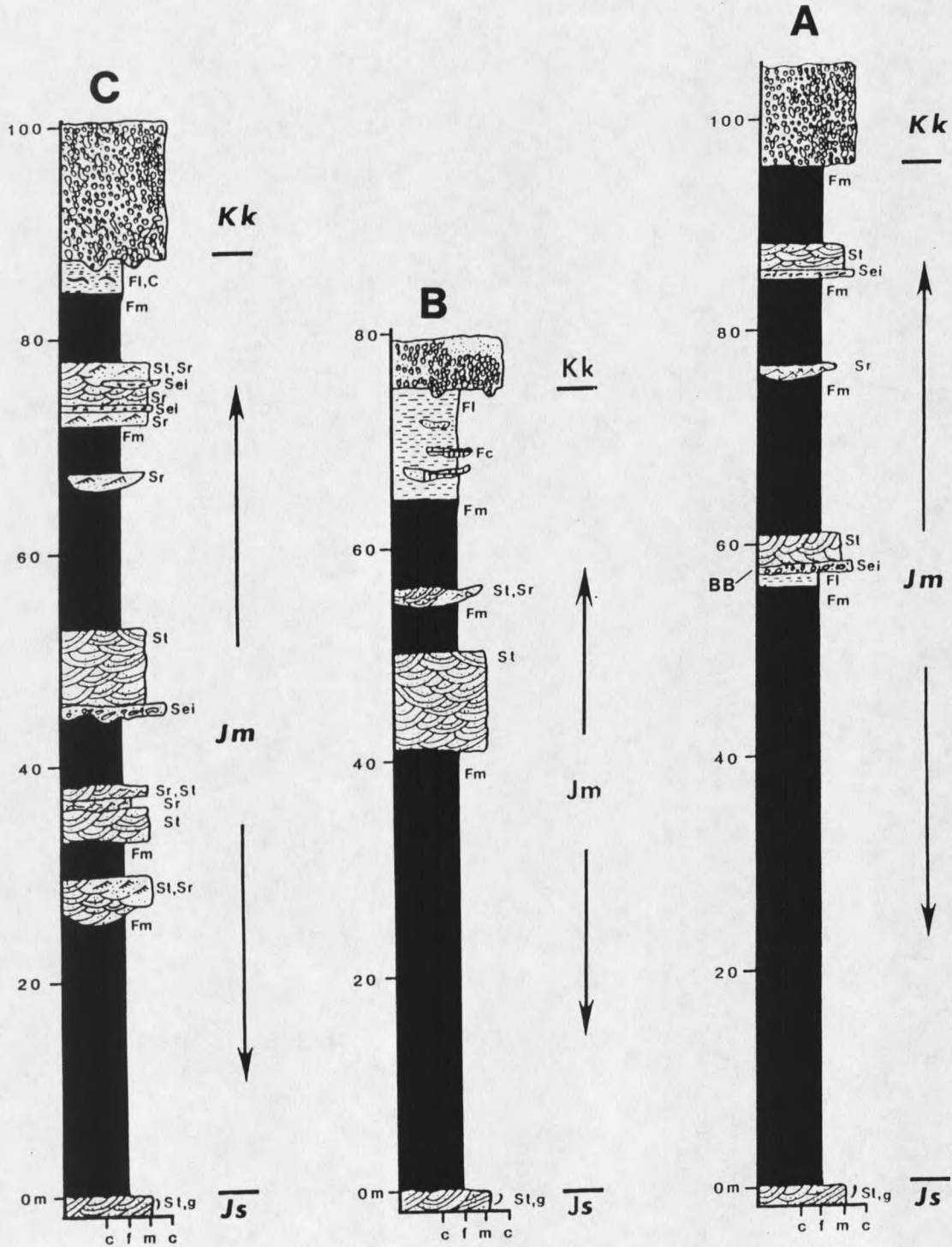


Figure 7. Composite stratigraphic sections from Strickland Creek-A (BB=bone bed), West Boulder River-B, and Boulder River-C (Figure 1). See Lithofacies section in text for descriptions and interpretations of lithofacies codes.

(Smith and Smith, 1980; Smith, 1986). In the geologic record, stratigraphically equivalent channel bodies should exist, and have been noted in other interpretations of anastomosed systems such as the Cretaceous Dakota Formation in Utah (Kirschbaum and McCabe, 1992) and the St. Mary River Formation in Alberta (Nadon, 1993). In the Morrison, channel elements 10, 11, and 12 (Figure 3) are on strike with one another, as are 8a, 8b, and 8c.

All modern anastomosed systems studied to date have plant material associated with them. Many contain large deposits of peat (Smith and others, 1989). Indeed, numerous ancient fluvial deposits interpreted as anastomosed contain coal. In some of these studies an anastomosed system/coal association was made by the original author (Smith and Putnam, 1980; Flores and Hanley, 1984; Rust and others, 1984; Kirschbaum and McCabe, 1992). Smith and Putnam (1980), however, re-interpret as anastomosed, some previously studied sequences, in part, because they contained coal. These studies include Jansa (1972), Eisbacher and others (1974), McLean and Jerzykiewicz (1978), Flores (1979), all of which concern deposits of the Western Interior foreland basin. Smith and Putnam (1980) also re-interpreted coal bearing sequences in the Karoo Basin of South Africa as deposits of an anastomosed fluvial system, which were originally studied by Le Blanc Smith and Eriksson (1979). Thin coal seams were also found associated with sandstone bodies interpreted to be left by an anastomosed fluvial system in the Carboniferous Clifton Formation of northern New Brunswick (Rust and Legun, 1983).

Jansa (1972) focused on the Elk member of the Kootenay (Morrison equivalent) Formation of southwestern Alberta which contains thin coal

seams and channel deposits with low width-to-thickness ratios. This may be the first inference, albeit a re-interpretation, of anastomosed systems in the Morrison Formation or Morrison equivalents. Isolated channel deposits with low width-to-thickness ratios have also been noted in the Morrison of Utah (Derr, 1974) and coal is common in the Morrison of central Montana (Walker, 1974). The Morrison in southwest Montana, while not containing coal seams, does contain coal-rich horizons (lithofacies C), further lending credence to an anastomosed fluvial system interpretation.

Section Correlation

The majority of data used in the above interpretations was gathered at the Boulder River section because of the quality and extent of exposure. Architectural elements CH and SB were found at all three localities, however, and none were found while walking the Morrison interval between the three sections. Much of this intervening section was grass covered but experience with the outcrop nature of the Morrison in this area, as well as trenching, indicates that if sandstones exist they will crop out. Siltstone lenses as thin as 10 cm are easily seen in grass covered section at Strickland Creek and Boulder River. At the West Boulder locality a 1 m thick sandstone crops out in dense forest and would certainly be noticeable in less vegetated areas. While differential cementation could produce intermittent outcropping of sandstones, this phenomena was not observed in areas where sandstone and mudstone were both well exposed. So while the three measured sections cannot be directly correlated, it is assumed that intervening section is dominated by mudstone. Furthermore, the sandstone lenses at all three sections are

thought to be deposits of the same anastomosed fluvial system. This conclusion is supported by consistency in paleoflow data gathered at all three sections (Figure 8) as well as similarities in architectural style.

Taphonomy

Dinosaur remains were found at the Boulder River section and the Strickland Creek site. Taphonomic analysis was possible only at Strickland Creek as quarrying allowed mapping of the bone bed. The taphonomy of this site aids in the interpretation of paleoenvironment and augments the sedimentologic data. The Strickland Creek bone bed contains 15 pre-sacral vertebrae, ribs, ilia and ischia, pubis, three caudal vertebrae, and partial skull of a small sauropod (Figure 9). In addition, a tibia, fibula, phalange and three metatarsals from an allosaur were found.

The most readily transported of the sauropod bones should be the ribs and vertebrae according to flume studies with sheep and coyote bones by Voorhies (1969). In the Strickland Creek bone bed the 13 pre-sacral vertebrae are disarticulated but still in their proper order, (Figure 9) indicating minimal transport. In addition, the third cervical vertebra, which is one of the smallest, lightest and therefore probably one of the more easily transported elements, is no more than 1.5 m out of position relative to the other vertebrae. Furthermore, all the vertebrae, particularly the cervical vertebrae, have delicate processes extending from them making them extremely susceptible to breakage. The vertebrae, as well as the delicate ribs, show no signs of wear and all are close to their correct anatomical positions, again, indicating minimal transport from the location where the carcass came to rest. In addition, the

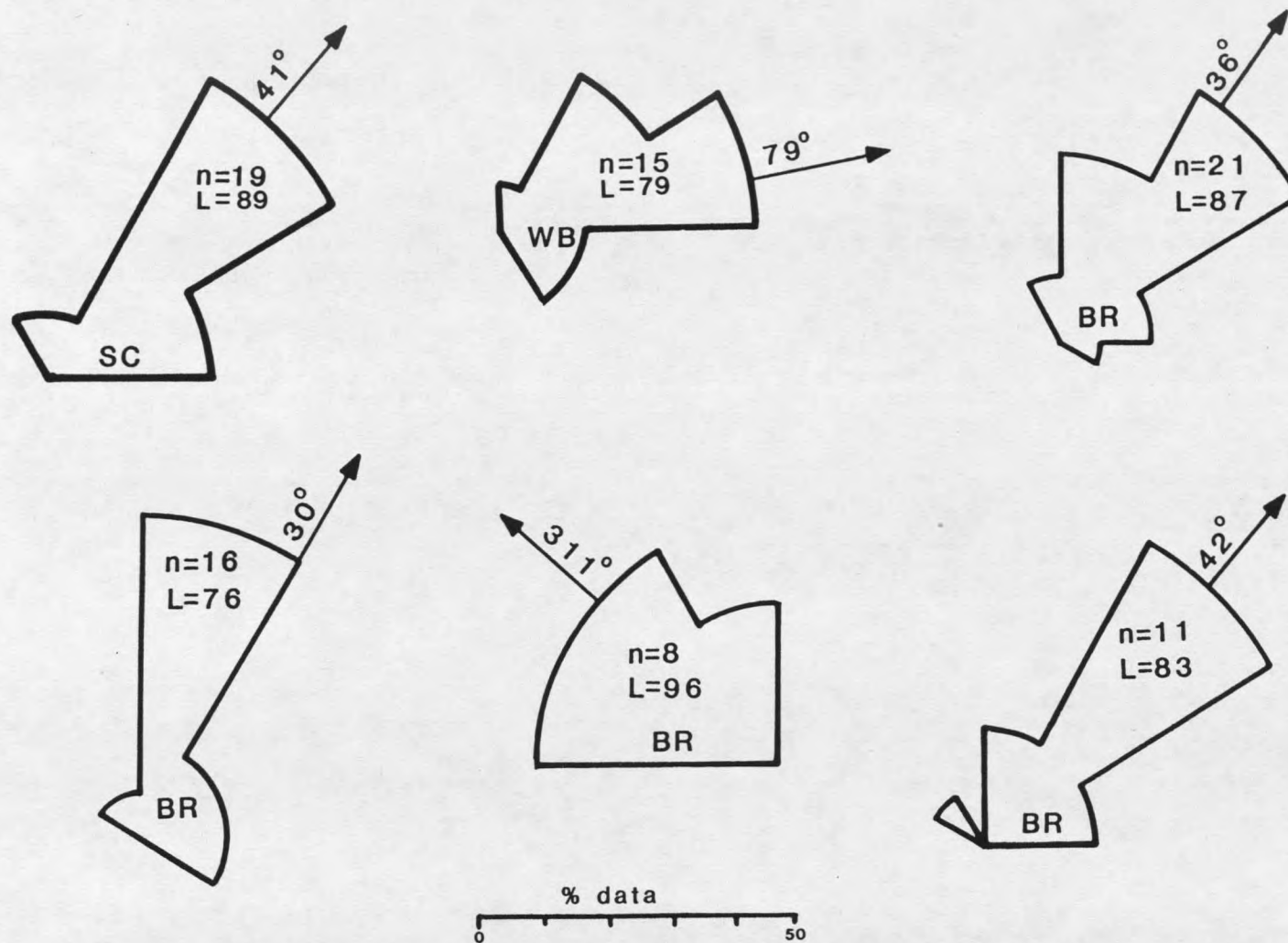


Figure 8. Rose diagrams of paleoflow data from channel sandstones. SC=Strickland Creek (bone long axes), WB=West Boulder, BR=Boulder River. See paleocurrent section text for sources of data.

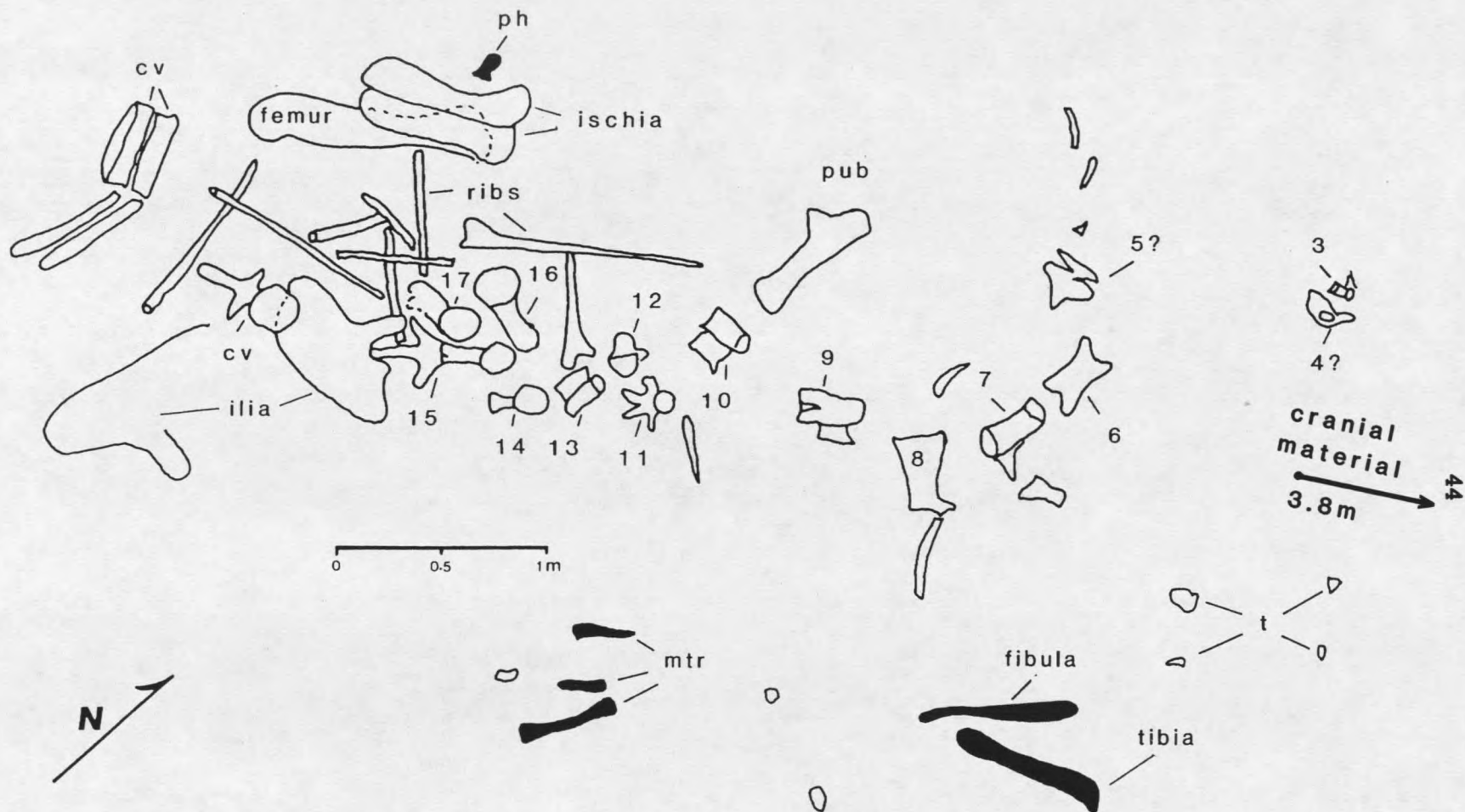


Figure 9. Map of Strickland Creek bone bed. Numbers refer to sauropod pre-sacral vertebrae, cv=caudal vertebrae, pub=pubis, t=turtle, ph=phalange, mtr=metatarsal. Solid black bones are allosaur. See text for taphonomy.

disarticulated sauropod skull elements which are similar in size to the small cervical vertebrae, have also only been transported several meters.

The fact that all but one leg element are missing may indicate that these elements were not at this site initially. A current capable of transporting leg elements should have completely removed ribs and vertebrae (Voorhies, 1969). This may indicate that there were higher flows while the body was still articulated, but that due to partial decay the limbs were carried away while the body remained anchored.

The allosaur leg elements occur within the same horizon as the sauropod bones and also appear to have been transported into the area while still articulated as indicated by the near anatomical positions of the metapodia, tibia and fibula (Figure 9). A low velocity current then moved the metatarsals and tibia/fibula apart, as indicated by the only slightly disarticulated state. It seems reasonable, however, that the metatarsals should have moved before the tibia and fibula because they are smaller, but if an ENE current existed, the tibia and fibula had to have moved first as they are downstream of the metatarsals. Alternatively, the tibia and fibula might move first if they were a unit and the metatarsals were a unit, with each unit possessing different hydrodynamic characteristics than individual elements. Still another explanation is that as flow waned, the partially disarticulated sauropod bones created a bar behind which ENE flowing main-stream water turned, creating a SE flowing eddy current responsible for the slight disarticulation of the allosaur leg. The intact leg was probably originally delivered via higher ENE flows, prior to the existence of the eddy at lower flows.

The allosaur phalange lying next to the paired sauropod ischia (Figure 9) probably came from the same allosaur carcass as the leg because the phalange articulates well with the medial metatarsal. Indeed, just as the sauropod could have lost fleshed legs while partially decayed, an allosaur carcass lying upstream could have lost this leg before the rest of the more easily transported elements such as vertebrae were disarticulated and available for transport to the sauropod site.

A summary of the above discussion and the proposed hydrodynamic events which produced the bone bed at Strickland Creek helps with interpretation of the paleoenvironment. Since the bone bed lies in the center of the channel deposit, the remains of both species were probably transported there; it is unlikely they both died in the center of a river channel, next to each other. The thickness of the bone bed bearing channel deposit is 2.8 m and therefore represents the maximum possible depth of the paleochannel, although multiple sets of trough cross bedding found in the channel deposit indicate bankful depths were less than 2.8 m. Bankful discharge or higher would have been required to transport this sauropod carcass. These flows would have needed to remain high for long enough so that by the time the allosaur had decayed to the point where a leg could be removed, the river would be capable of transporting it to the sauropod site. Decay to this stage would probably take no longer than a few weeks. If the disarticulation of the allosaur leg is to be explained by an eddy current, flow levels would need to have decreased to the point where the sauropod was nearly emergent, thereby creating the eddy. However the disarticulation of the allosaur leg is explained, flows capable of transporting a sauropod carcass were followed within a few weeks by flows

which could move the lightest elements only short distances. Such an interpretation suggests rapid fluctuations in discharge.

CONCLUSIONS

Analysis of the sedimentology and alluvial architecture of the Morrison Formation exposed in the northern Gallatin and Beartooth ranges of southwest Montana suggests these sediments were deposited by a north east flowing anastomosed fluvial system. Characteristic deposits found in the Morrison include low width-to-thickness ratio channel deposits encased in mudstone, crevasse channel and splay deposits, and coal and back swamp deposits. These deposits compare closely with those found in modern anastomosed fluvial systems as well as with ancient deposits interpreted as having been deposited by anastomosed fluvial systems. Ancient fluvial channels in the Morrison were laterally stable and changed position through the process of avulsion. This, combined with the delivery of fine-grained, suspended sediment to the mid and distal floodplain through crevasses in levees, resulted in high overall mudstone to sandstone ratios and isolated channel deposits. This fluvial system was likely subject to rapidly fluctuating discharges.

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