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Late Proterozoic and Early Cambrian structural setting of western Montana and the stratigraphy and depositional environment of the Flathead sandstone in west-central Montana

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LATE PROTEROZOIC AND EARLY CAMBRIAN STRUCTURAL SETTING OF WESTERN MONTANA AND THE STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT OF THE FLATHEAD SANDSTONE IN WEST-CENTRAL MONTANA

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The Cambrian Flathead Sandstone lies unconformably on Middle Proterozoic Belt Supergroup sedimentary rocks in western Montana, and records the first major Paleozoic marine transgression across the North American continent. The unconformity beneath the Flathead provides a way to determine the pre-Flathead structural setting of the underlying Belt rocks in western Montana; and provides clues for interpreting Late Proterozoic and Early Cambrian structure of western North America.

The Flathead generally lies disconformably or with low-angle unconformity on Belt rocks in western Montana. Paleogeologic and subcrop maps of Belt units beneath the Flathead indicate that before Flathead deposition, Belt rocks in western Montana dipped gently west. The lack of a repeating pattern of Belt rocks beneath the Flathead, and the general lack of high angle unconformity indicate Belt rocks in western Montana were not intensely folded by proposed Late Proterozoic compression and regional metamorphism (Leach and others, 1988) before Flathead deposition. Local pre-Flathead deformation is recorded by high-angle unconformity near Helena, Montana; and by changes in paleogeologic map patterns in the southern Flint Creek Range.

Recent research has shown that the Paleozoic transgressive sandstones may record several distinct depositional environments (Dott and others, 1986). In west-central Montana, the Flathead is a fine- to coarse-grained, well to poorly sorted quartz sandstone which coarsens upward and interbeds with overlying marine shale; and records continuous marine deposition. Grain size, bedding characteristics, and crossbedding styles provide a basis for separating the Flathead into upper and lower stratigraphic units. The lower unit contains separate fine- and medium-grained lithofacies. The medium-grained facies of the lower unit contains 5 to 20 cm-thick tabular sets of high-angle crossbeds deposited by 0.25 to 1 m tall straight-crested sandwaves; and grades into the overlying coarse-grained upper unit. The upper unit contains 0.4 to 2 m-thick tabular sets of high-angle crossbeds with mud drapes on the crossbed laminae and rare glauconite grains. The upper unit grades upward into overlying marine shale. The Flathead Sandstone in west-central Montana then records marine deposition in a deepening marine environment similar to the modern North Sea off the Dutch coast.

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INTRODUCTION

The Flathead Sandstone lies at the base of the Sauk Sequence and is part of a thin Cambrian sand blanket which covers most of North America (Sloss, 1963; Lochman-Balk, 1972). Widespread Phanerazoic continental sand sheets are poorly understood because no modern environment completely models their depositional setting (Hereford, 1977; Brenner, 1980; Klein, 1982; Dott and others, 1986) and their uniform quartz composition makes distinguishing sedimentary structures difficult. These thin sand sheets have been the subject of several recent studies (Hereford, 1977; Dott and Byers, 1981; Klein, 1982; Dott and others, 1986), and have been interpreted as braided stream and eolian deposits (Bell, 1970; Bell and Middleton, 1978; Dott and others, 1986) and nearshore marine deposits (Deiss, 1941; Seeland, 1969; Hereford, 1977). Although the Flathead has been studied in southern Montana (Shearer, 1981) and near Helena, Montana (Wittman, 1982), the stratigraphy and depositional environment of the Flathead in west-central Montana have not been studied in detail.

Throughout North America, the Flathead and the basal Sauk sequence sandstones lie unconformably on Pre-Cambrian rocks; and the unconformity beneath the Flathead in west-central Montana reflects the Late Middle Proterozoic to Early Cambrian structural history of western North America. Western Montana is a key area to study the Middle Proterozoic to Early Cambrian North American history because it lies near the western edge of the North American craton, where Belt Supergroup sedimentary rocks record much of the Middle Proterozoic regional history.

The western edge of North America underwent at least two pulses of rifting during the latest Proterozoic (Pell and Simony, 1987), and drifted about 570 million years ago (Bond and Kominz, 1984). A number of proposed tectonic events may have affected the western craton during the Late Proterozoic (Deiss, 1935; McMechan and Price, 1982; Harrison, 1986; Walker and others, 1986; Leach and others, 1988). If Late Proterozoic tectonic events deformed rocks in western North America, the structural setting of the rocks lying unconformably beneath the Flathead should reflect those events. By evaluating the record of these events, we can develop a more complete understanding, and better evaluate and constrain the Late Proterozoic and Early Cambrian history of western North America.

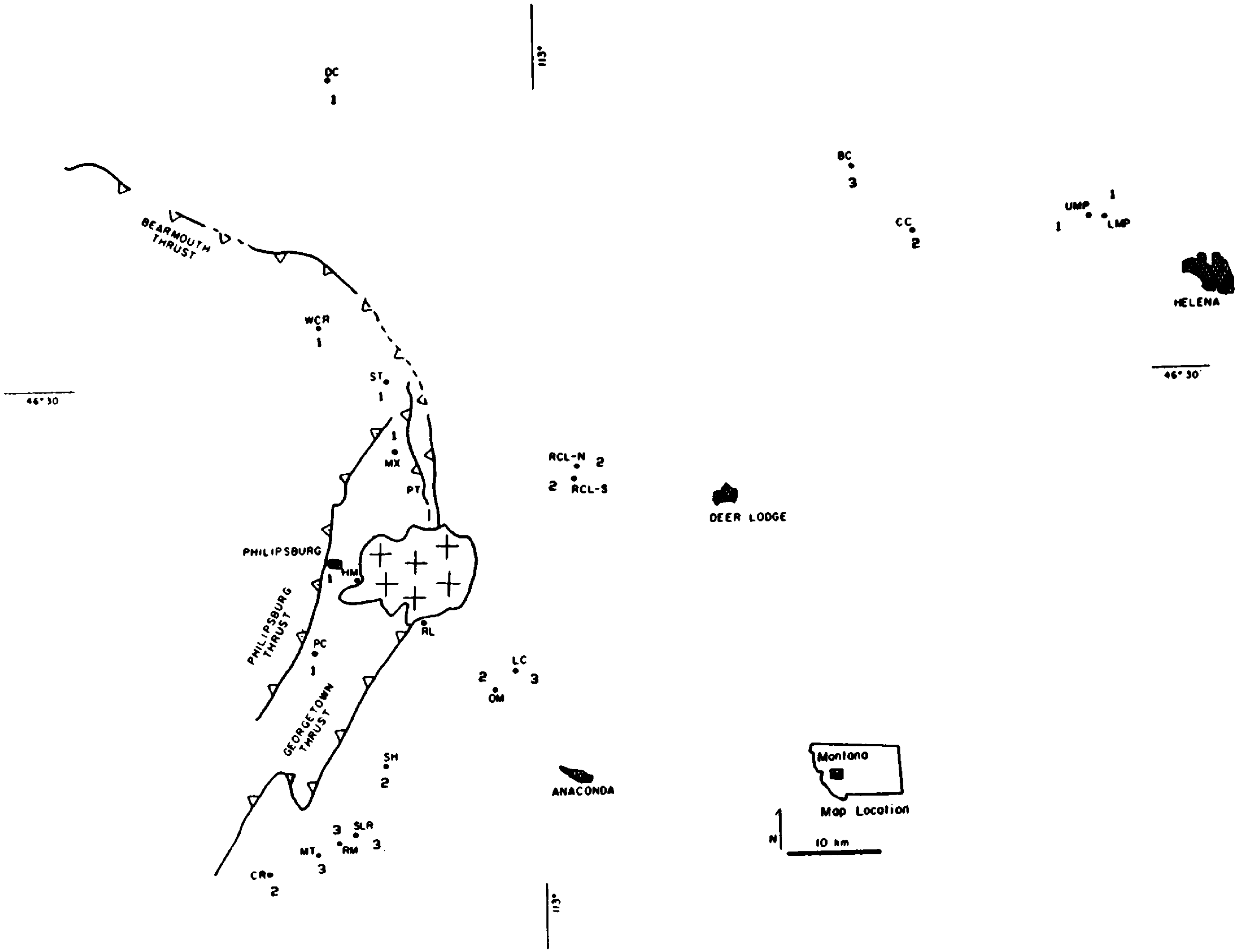
To address the problems of the blanket sandstones and the pre-Flathead tectonic history of western North America, this thesis is divided into two sections. Part 1 analyzes the structural setting of the underlying rocks before Flathead deposition and interprets the tectonic history of western North America as recorded by the unconformity beneath the Flathead. Part 2 analyzes the stratigraphy and depositional environment of the Flathead Sandstone from a process-oriented approach.

Widespread Mesozoic metamorphism in western Montana has obscured many of the detailed sedimentary structures within the Flathead, and stratigraphic interpretation is largely limited to a few well exposed, relatively unmetamorphosed sections at Willow Creek Reservoir, Maxville, Porter's Corner, Deep Creek, and Mullan Pass near Helena, Montana (fig. 1). Several additional measured sections provide control on the stratigraphy through the Flint Creek and Anaconda Ranges. To determine the structural attitude of the Belt rocks before Flathead deposition I measured the attitudes of both the Flathead and underlying rocks where the Flathead contact with underlying Belt rocks outcrops. Figure 1 shows the boundaries of the study area, section locations, and the types of data collected throughout the area.

CURRENT STRUCTURAL SETTING OF WESTERN MONTANA

Mesozoic to early Tertiary compression has folded and thrust rocks in west-central Montana. Sections in the Flint Creek Range, at Mullan Pass, and in the Garnet Range have undergone little tectonic transport relative to each other (Rupple and others, 1981). The Willow Creek Reservoir, Stone and Maxville sections lie west of the Philipsburg thrust near the north-west edge of the Philipsburg thrust plate, and the Porter's Corner and Hasmark sections lie on the Georgetown thrust plate (Rupple and others, 1981) (fig. 1). Rocks carried on the Philipsburg and Georgetown plates are part of the Sapphire plate and have been displaced to the east relative to rocks east of the thrusts, but have undergone little transport relative to other rocks on the plates (Hyndman, 1980; Rupple and

Fig. 1. Location map of study area. 1 = detailed section. 2 = thickness measurement. 3 = measured structural data. 4 = structure data from map references. BC = Blackfoot City CC = Clarks Canyon CR = Carpp Ridge DC = Deep Creek HM = Hasmark LMP = Lower Mullan Pass MT = Mount Tiny MX = Maxville OM = Olson Mountain PC = Porter's Corner PT = Philipsburg thrust RCL-N = Rock Creek Lake (North) RCL-S = Rock Creek Lake (South) RL = Red Lion SH = Silver Hill SLR = Storm Lake Ridge ST = Stone UMP = Upper Mullan Pass WCR = Willow Creek Reservoir. See appendix B for locations and detailed sections.



DC 1
113°
BC 3
CC 2
UMP 1
LMP 1
HELENA
46° 30'
BEARMOUTH THRUST
WCR 1
ST 1
46° 30
MX 1
PT
RCL-N 2
RCL-S 2
DEER LODGE
PHILIPSBURG
HM 1
RL
PHILIPSBURG THRUST
PC 1
LC 3
OM 2
GEORGETOWN THRUST
SH 2
ANACONDA
Montana
Map Location
N
10 km
SLR 3
RM 3
MT 3
CR 2
113°

others, 1981) (fig. 1). As noted by Calkins and Emmons (1915), the Gerogetown and Philipsburg thrusts are complementary. In the south, the Georgetown thrust accomodates most of the regional shortening, and displacement on the Philipsburg thrust is relatively small. To the north, near the Maxville section, the Georgetown thrust dies out, and the Philipsburg thrust takes up most of the regional shortening (Calkins and Emmons, 1915). The Maxville section lies near the eastern-most edge of the Philipsburg thrust, west of where the Philipsburg thrust trace is repeated by a high angle reverse fault (fig. 4) (Calkins and Emmons, 1915; McGill, 1959, 1965).

PART I

STRUCTURAL SETTING OF THE PRE-FLATHEAD SURFACE

INTRODUCTION

Over most of the North American continent, Cambrian and early Paleozoic sandstones lie unconformably on Precambrian rocks; and the absence of a depositional record across the unconformity forces us to infer late Precambrian and Early Cambrian history by interpreting the geologic record beneath the Cambrian unconformity. In western Montana, the unconformity beneath the Flathead reflects at least 330 million years of western North American history (Obradovich and others, 1983) and the structural setting of Middle Proterozoic Belt sedimentary rocks lying unconformably beneath the Cambrian Flathead Sandstone reflect the structural configuration of western North America during the Late Proterozoic and Early Cambrian. The purpose of this section is to examine the structural configuration of Belt rocks recorded by the unconformity, and evaluate and constrain the magnitude, timing, and record of any events which deformed Belt rocks before Flathead deposition.

The Late Proterozoic and Early Cambrian history of western North America is poorly understood, and a number of proposed and inferred tectonic events may have affected the western continental margin during the Late Proterozoic and Early Cambrian (Deiss, 1935; Harrison, 1972; Harrison and others, 1974; McMechan and Price, 1982; Harrison, 1986; Walker and others, 1986; Pell and Simony, 1987; Leach and others, 1988). If Belt rocks were intensely compressed and folded before Flathead deposition, the Flathead would lie on beveled folds with distinct angular unconformity. Throughout western Montana there is no apparent change in metamorphic grade across the Belt-Flathead contact, and Belt rocks generally lie disconformably or dip beneath the Flathead less than 5°. Therefore, Belt rocks in west-central Montana experienced only limited deformation during the Late Proterozoic, and were not intensely folded before Flathead deposition.

GEOLOGIC SETTING

In western Montana, the Belt Supergroup lies beneath the Flathead Sandstone and forms a thick package of sedimentary rocks deposited in a basin which covered most of western Montana during the Middle Proterozoic (Harrison, 1972; Harrison and others, 1974; Winston, 1986) (fig. 2). Belt rocks are reported to reach a maximum thickness of up to 20 km in northwest Montana (Harrison, 1972) and generally thin towards the stable Archean North American craton along the eastern basin margin (Harrison, 1972; Harrison and others, 1974; Winston, 1986). Along the southern basin margin, Middle Proterozoic faulting uplifted Archean crystalline rocks of the northern Wyoming Province Dillon Block (Harrison, 1972; Harrison and others, 1974; O'Neill and others, 1986; Winston, 1986). Proterozoic faulting also has been proposed for a zone along the Hope and Osborne faults (Harrison and others, 1974; Winston, 1986); and other basin growth faults may have controlled sedimentary thickness patterns within the basin throughout the Proterozoic. Faulting which controlled Belt sedimentation patterns and possibly continued after Belt deposition snould be recorded by the unconformity beneath the Flathead (Winston, 1986). Figure 3 summarizes the generalized west-central Montana Belt stratigraphy.

Following Belt deposition the western margin of North America underwent extension and prolonged rifting before continental separation (Stewart, 1976; Devlin and others, 1985; Bond and others, 1984; Miller, 1987; Pell and Simony, 1987). Dating of initial rifting and the end of Belt sedimentation relies on 850 Ma K-Ar dates of relatively unaltered Huckleberry Formation basalts which lie unconformably above Belt rocks in eastern Washington (Stewart, 1976). The Huckleberry basalts provide the only direct evidence which establishes the absolute timing of the end of Belt sedimentation and initial rifting (Miller and others, 1973; Stewart, 1976; McMechan and Price, 1982; Devlin and other, 1985). However, Devlin and others (1985) demonstrated that the Rb-Sr system in the Huckleberry Formation basalt has been disturbed, and so the 850 Ma K-Ar dates are suspect. Therefore, the date of basalt extrusion, initial rifting, and the end of Belt sedimentation is largely unconstrained. Complete continental separation and drifting may not have occurred until 570 Ma (Bond and Kominz, 1984).

Several workers propose that from the Middle Proterozoic to Early Cambrian western North America was tectonically compressed and metamorphosed (McMechan and Price, 1982; Leach and others, 1988; Deiss, 1935, 1941; Harrison, 1972, 1986; Harrison and others, 1974). An alternate hypothesis proposes that western North America underwent no compressional deformation during the Proterozoic, but

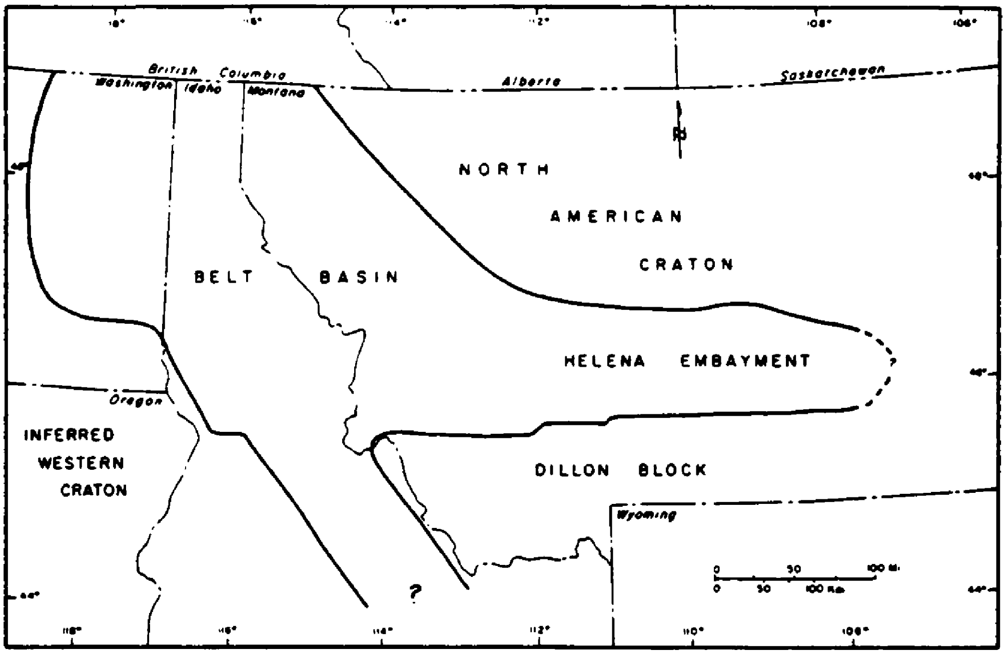


Fig. 2. Postulated limits of Middle Proterozoic Belt Basin, partially restored to pre-thrusting position, but unrestored for later normal faulting (after Winston, 1986).

MISSOULA GROUP	PILCHER
	GARNET RANGE
	MACNAMARA
	BONNER
	MOUNT SHIELDS
	SHEPARD
	SNOWSLIP
	HELENA
	EMPIRE
	SPOKANE
	GREYSON
	NEWLAND
	CHAMBERLAIN

Fig. 3. Generalized Belt Supergroup stratigraphy in west-central Montana (after Winston, 1986).

instead block faults cut Belt rocks during and after Belt deposition (Winston, 1986, 1988).

McMechan and Price (1982) proposed that the compressional East Kootenay orogeny and associated metamorphism terminated Belt and Purcell sedimentation, and accompanied intrusion of the Hellroaring stock in southern British Columbia and other felsic plutons in western North America about 1300 to 1350 Ma (Evans, 1986). McMechan and Price (1982) also infer the later extentional Goat River orogeny at 850 Ma, and constrain the timing of the Goat River orogeny on basis of K-Ar dates from Huckleberry Formation basalts discussed above.

A second interpretation of pre-Flathead compressional deformation of western North America proposes that compression metamorphosed and intensely folded Belt rocks in the Coeur d'Alene district following the end of Belt sedimentation (Harrison, 1972; Harrison and others, 1974; Leach and others, 1988). In the Coeur d'Alene district, lead-bearing veins in folded Belt rocks yield lead model dates ranging from 850 to 1350 Ma (Zartman and Stacey, 1971); although zircons from nearby migmatites contain inherited old lead componenets (Grauert and Hoffman, 1973). Axial planar sericite in Coeur d'Alene district folds give K-Ar dates of about 850 Ma, which Leach and others (1988) interpret as recording regional metamorphism and compressive deformation associated with the tectonic event that led to extrusion of the Huckleberry Formation basalts (Harrison, 1972; Leach and others, 1988).

Deiss (1935, 1941) and Harrison (1986) proposed Belt rocks were compressed into open, gentle, folds in western Montana before Flathead deposition. Deiss estimated that 30,000 feet of Belt rocks were eroded near Neihart, MT, before Flathead deposition. However, his estimates of pre-Flathead erosion and uplift are based on the incorrect assumption that Belt units do not thin eastward across the basin, and on miss-correlations of several Belt units (Harrison, 1972; Harrison and others, 1974; Winston, 1986). Folds diagramed by Deiss (1935) in the Neihart area probably reflect Middle Proterozoic basin block faulting (Winston, 1986).

METHODS

Data used to determine the pre-Flathead attitudes of Belt rocks at the unconformity are included in appendix A. To determine the angular discordance of the rocks underlying the Flathead, I measured the bedding attitudes of Belt rocks and overlying Flathead, and stereographically restored the Belt rocks to their Early Cambrian attitude by rotating the Flathead to horizontal. These rotations assume the rocks are unaffected by regional or local structural plunge, the rocks have not undergone tectonic rotation, and that Flathead bedding approximates a horizontal depositional surface.

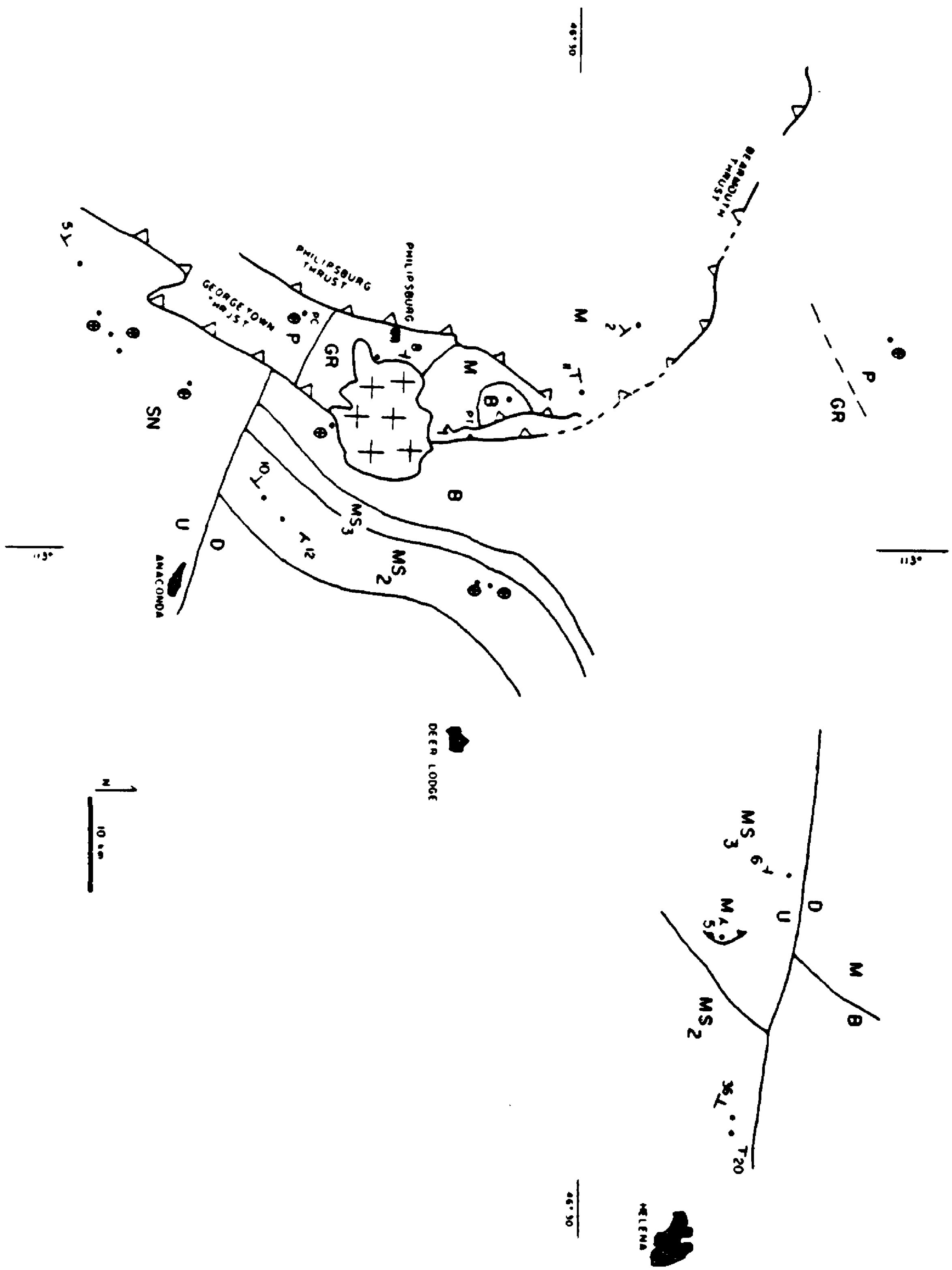
In west-central Montana, regional plunge is less than 10° and does not significantly alter the results of sterographic rotation (Sears, personal communication). Local structural plunge in the Flint Creek Range affects the strike of the pre-Flathead restoration, although the magnitude of pre-Flathead dip is not affected. In the Flint Creek Range, the Olson Mountain section lies in a structurally complex area (Calkins and Emmons, 1915; Csejtey, 1963; Wallace 1987); and the Lost Creek section lies in the hinge of a fold. Local structural plunge may also affect the Rock Creek Lake and Red Lion sections where the rocks crop out on overturned limbs of folds. The amount of plunge at these sections is unknown and so the data cannot be corrected for inaccuracies resulting from local plunge.

Tectonic rotation during Mesozoic and Tertiary thrusting may have affected the rocks where they have acted as cohesive blocks. However, rocks within the Montana thrust belt do not appear to have rotated during thrusting except where rigid buttresses deformed plate margins (Elston, 1983; Eldredge and Van der Voo, 1985).

The data shown in figure 4 and appendix A generally agree with observations at outcrops, where clear angular discordance between the Flathead and underlying Belt units are rare. Stereographic rotation of Belt and Flathead bedding at Stone indicate Belt rocks dipped 10° before Flathead deposition. However, no angular discordance is apparent at outcrop.

Identification of Belt units at a single outcrop is subject to interpreation because of repeated facies patterns during Belt deposition (Winston, 1986), and the identifications of underlying Belt rocks presented here (figs. 4, 5, appendix A) do not agree with those of Wallace (1987) where he has mapped a series of younger-over-older thrust faults. No localized deformation or changes in bedding attitudes are apparent across many of the younger-over-older thrust faults Wallace (1987) mapped in Belt rocks below the Flathead; and lithology changes mapped as thrust faults are interpreted here as normal stratigraphic contacts. Previous mapping in the area does not indicate these faults (Calkins and Emmons, 1915; McGill, 1959; Poulter, 1956; Mutch, 1960; Csejtey, 1963; Maxwell, 1965); and have not been reported from mapping to the north near Choteau, Montana (Mudge and others, 1982), and to the south in the Anaconda Range (O'Neill, personal communication). The identifications of Belt rocks used here are based on measured sections starting at a known stratigraphic datum (Winston, 1986; Winston, unpublished data; Baldwin, unpublished map data).

Fig. 4. Subcrop map of Belt rocks beneath the Flathead in west-central Montana. See figure 1 for section abbreviations, appendix A for structural data. P = Pilcher GR = Garnet Range M = McNamara B = Bonner MS = Mount Shields SN = Snowslip



PHILIPSBURG THRUST
GEORGETOWN THRUST
PHILIPSBURG
BEARMOUTH THRUST
ANACONDA
DEER LODGE
HELENA
10 km
N
46°30
113°
GR
SN
MS3
MS2

RESULTS

Throughout most of west-central Montana, Belt rocks lie disconformably or dip gently beneath the Flathead (fig. 4). The low angle of unconformity beneath the Flathead has long been noted by workers in western Montana (Calkins and Emmons, 1915; Deiss, 1935, 1941; Nelson and Dobell, 1961; McGill, 1959; Csejtey, 1963; Maxwell, 1965; Illich, 1966; Mutch, 1960). Only locally at Mullan Pass near Helena, Montana, and near Olson Mtn. in the southern Flint Creek Range does the Flathead overlie Belt rocks with significant angular unconformity.

Belt units subcrop below the Flathead in zones bounded by Mesozoic thrusts and structures (figs. 4, 5). Upper Missoula Group rocks lie beneath the Flathead on the southern parts of the Philipsburg plate and on the Georgetown plate in the west part of the study area; and north of the Clark Fork River in the western Garnet Range. In the northeast part of the Philipsburg thrust plate the Flathead lies on the middle Missoula Group McNamera and Bonner Formations. Middle Missoula Group Bonner and the underlying Mt. Shields lie beneath the Flathead east of the Philipsburg and Georgetown thrust faults in the Flint Creek Range and the eastern Garnet Range near Helena, MT. Throughout the Anaconda Range in the southern part of the study area, the lowest Missoula Group Snowslip Fm. underlies the Flathead. In the Highland Mountains south of the Anaconda Range, the Flathead lies on the lowest part of the Snowslip Formation and the underlying Helena Fm. (O'Neill, personal communication).

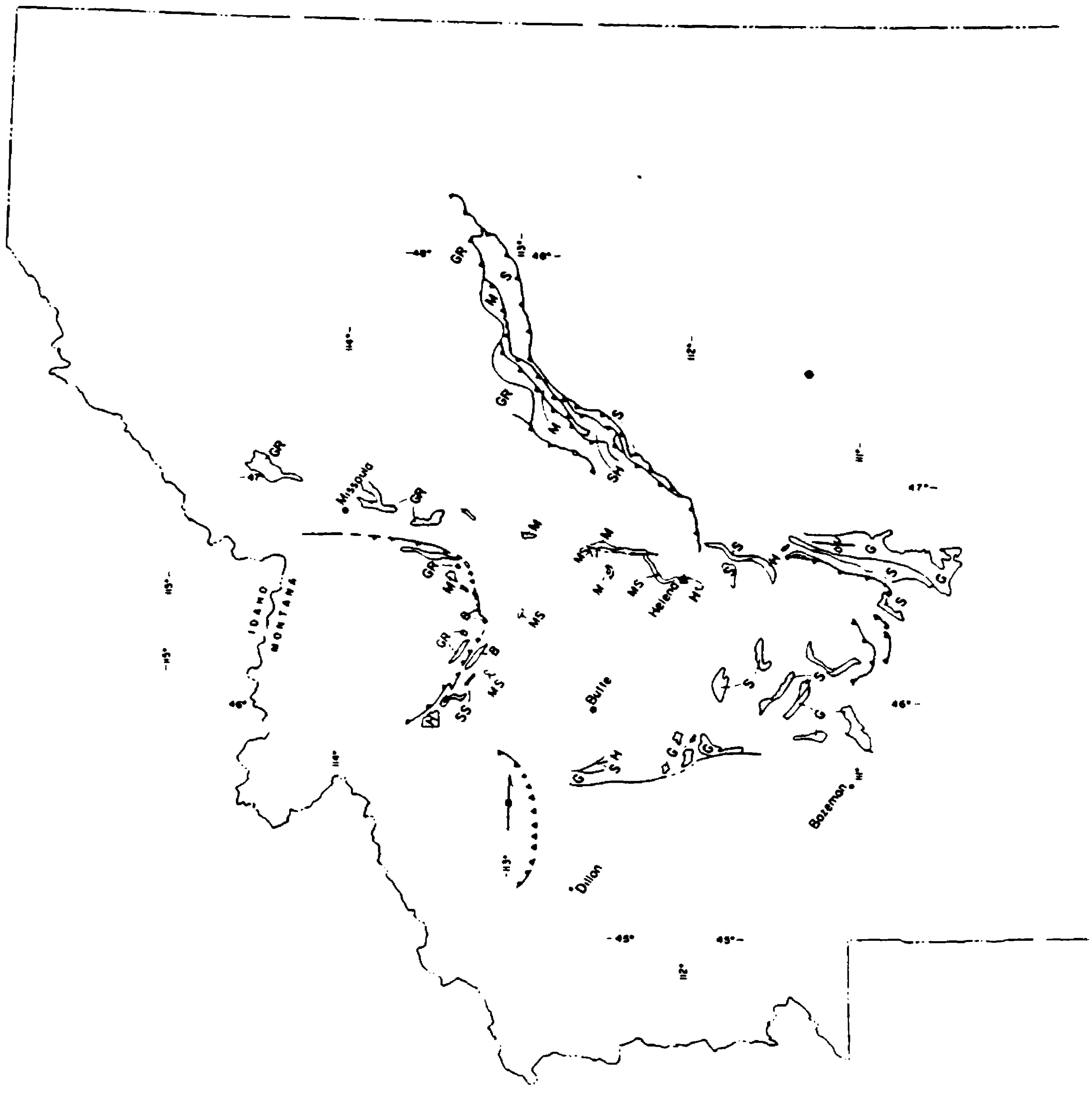


Fig. 5. Subcrop map of Belt rocks beneath the Flathead in western Montana (modified after Winston, 1986).

To the north in the Choteau, MT, area the Belt-Flathead contact is exposed on a series of north-striking thrust sheets, and mapping at the 1:250,000 scale indicates a low angle truncation of Belt rocks beneath the Flathead Sandstone (Mudge and others, 1982). The uppermost Missoula Group rocks outcrop in the west near the Idaho border, and the unconformity cuts progressively to the southeast, reaching the lower Belt Empire and Spokane Formations on the eastern-most thrust plates near Helena, Montana. On some thrust sheets individual Belt units subcrop beneath the Flathead more than 100 km. along strike (Mudge and others, 1982). East of the study area the unconformity beneath the Flathead cuts the lower Belt Spokane and Grayson formations. (fig. 5) (Winston, 1986).

DISCUSSION

Although the low angle of unconformity between the Flathead and underlying Belt rocks indicates that proposed Late Proterozoic regional metamorphism and intense folding and compression in the Coeur d'Alene district (Harrison and others, 1974; Leach and others, 1988) did not metamorphose or intensely fold Belt rocks in west-central Montana before Flathead deposition, the unconformity reflects local areas of pre-Flathead deformation.

Zones of distinct angular unconformity occur in the Flint Creek Range, and at Mullan Pass near Helena, MT; and define areas of local pre-Flathead deformation. The Upper and Lower Mullan Pass sections are separated by a thrust fault (Winston, 1986). At Lower Mullan Pass 36 m of Flathead overlie Mt. Shields member 2 which dipped 25° south-southwest during the Early Cambrian; while at Upper Mullan Pass, 2 km east of the Lower Mullan Pass section, 12 m of Flathead lie above Mt. Shields member 2 which dipped 36° northeast (fig. 4). Although the thickness variation in the Flathead probably reflects topography on the pre-Flathead surface, the differing pre-Flathead structural attitudes of the underlying Belt rocks may define a local northwest trending fold with steep limbs, or result from faulting and rotation of Mt. Shields Fm. before Flathead deposition. However, a northwest trending fold would trend nearly perpendicular to the general pre-Flathead strike of Belt rocks at Clarks Canyon, Blackfoot City, Olson Mtn., and Lost Creek; and therefore seems unlikely.

The Mullan Pass sections lie along the proposed Garnet line (Winston, 1986), a zone of down to the north normal faulting during the Middle Proterozoic. Continued faulting along this structural zone during the Late Proterozoic and Early Cambrian (Winston, 1986) may have rotated the Mt. Shields before Flathead deposition; although the opposing attitudes of the Mt. Shields at the Mullan pass sections may conceivably result from pre-Flathead slumping or other non-tectonic deformation.

At the Olson Mountain and Lost Creek sections in the southern Flint Creek Range, the Flathead lies with distinct angular unconformity on Mt. Shields Formation. At Olson Mountain, the Mt. Shields dipped 10° northwest during Flathead deposition (fig. 4) (Csejtey, 1963). Nearby at Lost Creek, the Mt. Shields dipped gently to the east-southeast; and the discordance of pre-Flathead structural attitudes at these sections may reflect either pre-Flathead faulting or localized gentle folding of Belt rocks before Flathead deposition.

Previous mapping in the Flint Creek and Anaconda Ranges also indicates local areas pre-Flathead Belt deformation. Calkins and Emmons (1915) documented an angular unconformity along Carpp Ridge in the Anaconda Range, although later workers have not located that unconformity (this study; O'Neill, personal communication). Ten km east of the Olson Mountain and Lost Creek sections, Calkins and Emmons (1915) and Csejtey (1963) described a wedge-shaped conglomerate at the base of the Flathead which may have been shed from a fault scarp, but its origin is uncertain.

Along the north side of Warm Spring Creek, 7 km southwest of the Olson Mountain section, the sub-Flathead unconformity cuts down to the lowest Missoula Group Snowslip Formation; and up to 1 km of Snowslip, Shepard, and lower part of the Mt. Shields Formation were eroded from the southern section before Flathead deposition. These two sections may be separated by a zone of pre-Flathead down-to-the-north normal faulting. The pre-Flathead attitudes of nearby rocks at Rock Creek Lake 20 km northeast of Olson Mtn., and Red Lion 11 km west of Olson Mtn. indicate that deformation near Olson Mtn. was locally restricted, and the subcrop pattern of rocks cut by the unconformity precludes extensive folding exposing older Belt rocks in the core of a fold (figs. 4, 5) (appendix A). Pre-Flathead faulting or gentle folding of Belt rocks may also be recorded at the Stone, Willow Creek Reservoir and Maxville section at the northeast edge of the Philipsburg plate where the McNamera and Bonner Formations underlie the Flathead (figs. 4, 5) (appendix A).

Although localized pre-Flathead deformation is apparent at Mullan Pass and near Olson Mtn., the low angle of unconformity beneath the Flathead and the general Belt subcrop pattern indicate Belt rocks in west-central Montana were not intensely folded or deformed during the Late Proterozoic and Early Cambrian. Throughout western Montana the general subcrop pattern of Belt rocks beneath the Flathead Sandstone indicates that rather than having been intensely folded and compressed during the Late Proterozoic, Belt rocks dipped nearly monoclinaly to the west before Flathead deposition (figs. 4, 5) (appendix A) (Mudge, 1982).

A gentle west dipping monocline in western Montana during the Late Proterozoic and Early Cambrian apparently conflicts with hypothosized intense compressional deformation and regional metamorphism in the Coeur d'Alene district (Harrison and others, 1974; Harrison, 1986; Leach and others, 1988). If Late Proterozoic compressional tectonics did deform rocks in the Coeur d'Alene district, those events should be recorded by angular unconformities and folded rocks beneath the Flathead in western Monanta. Rather than recording intense Late Proterozoic compressional deformation, the unconnformity beneath the Flathead reflects only local extentional deformation.

PART II

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT

INTRODUCTION

The Middle Cambrian Flathead Sandstone is a widely recognized unit in Montana and Wyoming (Peale, 1893; Weed, 1900), and lies at the base of the transgressive Sauk sequence. In western Montana, the Flathead lies unconformably on beveled Precambrian Belt sedimentary rocks (Deiss, 1935, 1941; Illich, 1966). Although the transgressive sand deposits may include nearshore, and alluvial and eolian depositional environments (Deiss, 1941; Lochman-Balk, 1972), we know little about the stratigraphic details and the interplay of depositional environments in west-central Montana. The purpose of this section is to interpret the stratigraphy and depositional environment of the Flathead Sandstone in west-central Montana.

Metamorphic overprints limit the detail of stratigraphic and crossbed interpretation through much of western Montana. Partial and complete, moderately- to well-exposed, unmetamorphosed Flathead outcrops at Lower and Upper Mullan Pass near Helena, MT, Deep Creek in the Garnet Range; and near Philipsburg, MT, at Willow Creek Reservoir, Stone, Maxville, and Porter's Corner (fig. 1). These sections form the basis for interpreting the stratigraphy and depositional environments of the Flathead, but observational and limited stratigraphic evidence from poorly exposed and metamorphosed sections support this framework (fig. 1) (appendix B).

The lower Flathead in west-central Montana lacks fossils, and so the age of its base is constrained only to post-Middle Proterozoic.

However, its gradational relationship to overlying trilobite-bearing shales indicates a Middle Cambrian age for the upper part (Hanson, 1952; Lochman-Balk, 1972). In west-central Montana, the Flathead ranges from 9.5 to 48 m thick (appendix B); and thickness variations probably reflect topography on the beveled pre-Flathead surface (Hanson, 1952; Lochman-Balk, 1972).

During the Cambrian marine transgression, invading seas formed a large re-entrant in western Montana (Lochman-Balk, 1972) (fig. 6); and moved across a surface covered with a veneer of eolian and fluvial sediments (Bell, 1970; Hereford, 1977; Bell and Middleton, 1978; Shearer, 1981; Wittman, 1982; Dott and others, 1986). Sand accumulated nearshore and on the coastal plain, were covered by marine mud and carbonate offshore as the Cambrian shoreline advanced to the east. The re-entrant probably created a large, partially protected bay along the Montana coast, and offshore carbonate platforms also protected the shore from the open ocean.

In Wyoming, where the Flathead has been studied in detail, it contains a lower fluvial member and an upper marine and tidal facies (Bell, 1970; Bell and Middleton, 1978). Near Townsend, MT, Wittman (1982) interpreted the Flathead as containing a lower eolian and upper tidal facies; and Shearer (1981) interpreted a fluvial origin for the lower Flathead. Graham and Suttner (1974) implied a marine origin for the Flathead in southwest Montana, and identified islands in the Cambrian sea formed by hills on the pre-Flathead surface. Other studies indicate that braided stream and eolian deposits comprise most of the lower Paleozoic sheet sandstones, and these

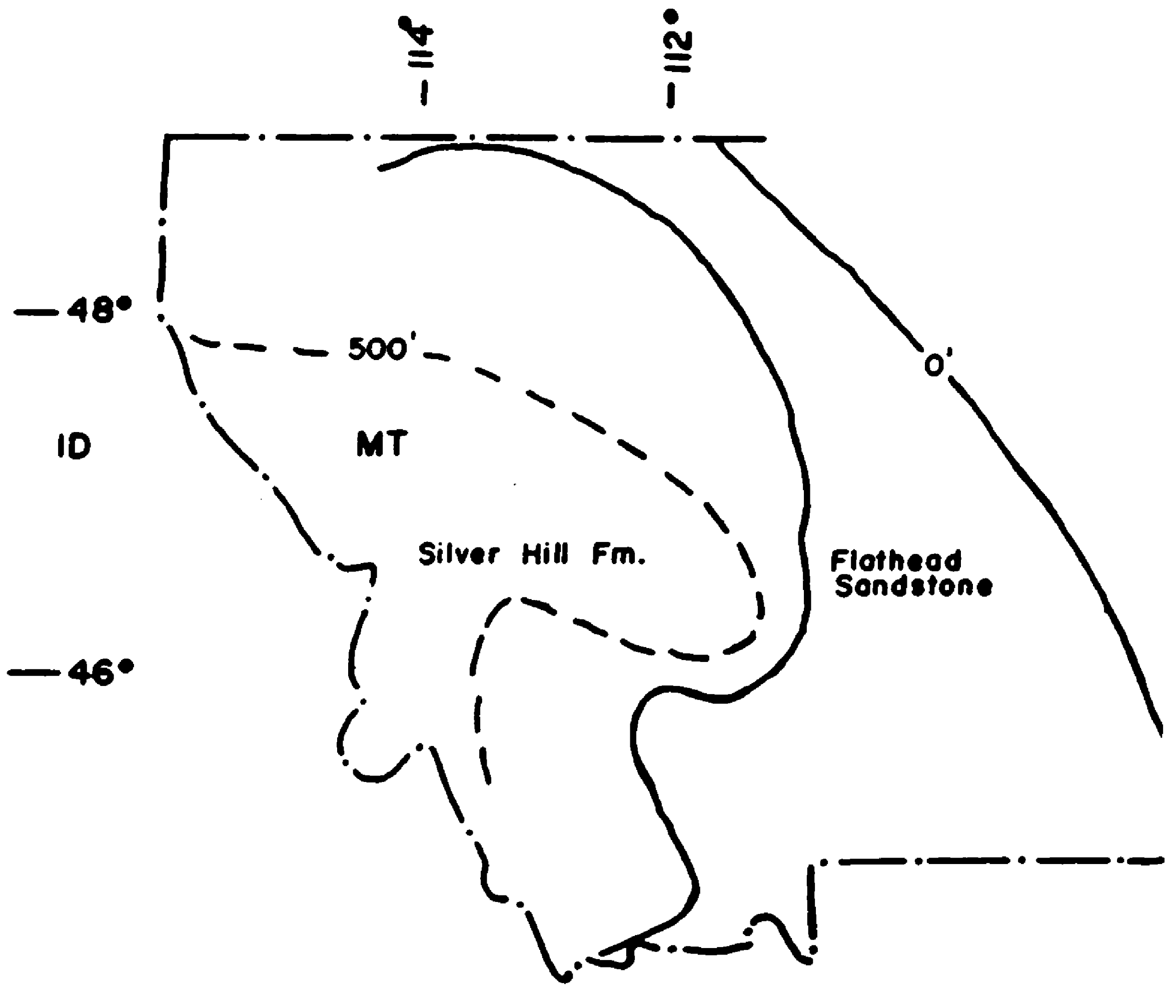


Fig. 6. Restored thickness and lithofacies of lower part of the Middle Cambrian in western Montana (after Lochman-Balk, 1972).

deposits were only partially reworked by the marine transgressions (see review by Dott and others, 1986).

The Flathead Sandstone in west-central Montana contains an upper and a lower stratigraphic unit. The two units form a coarsening upward sequence of fine- to coarse-grained quartz arenites and wackes which becomes thicker bedded and more complexly crossbedded near the top. As shown in this thesis, the coarsening and thickening upward sequence records deposition in a continuously deepening marine environment. The lower part of the Flathead was deposited on a scoured surface by straight-crested bedforms in a shallow marine environment. As the transgression progressed, larger bedforms migrating in deeper water deposited complexly crossbedded medium-and coarse-grained sand above the nearshore deposits.

LOWER AND UPPER STRATIGRAPHIC UNITS

Differences in grain size, bedding characteristics, and crossbed types provide the basis for separating the Flathead sandstone in west-central Montana into lower and upper stratigraphic units (figs. 7, 8). Together the two form an overall coarsening upward sequence. The cliff-forming lower unit is well developed throughout the area and ranges from 10 to 25 m thick. The lower unit consists of even and continuous, occasionally wedge shaped, 0.4 to 0.8 meter thick beds. Some beds are well indurated and others are slabby. The lower unit contains separate fine- and medium-grained lithofacies, referred to as the fine-grained and medium-grained facies. The fine- and medium-grained facies of the lower unit share similar even, continuous bedding and stratigraphic position below the upper unit, but are separated on the basis of their grain sizes and crossbedding.

The upper stratigraphic unit varies in thickness throughout the area. At Stone the upper unit is 27 m thick, and 24 m thick at the Willow Creek Reservoir section (figs. 7, 8). At the Maxville section 7 km southeast of Stone, and at Porter's Corner east of the Philipsburg thrust, the upper unit thins to 1 m (figs. 7, 8). Near Helena at Mullan Pass the upper unit ranges from 1 to 10 m thick (figs. 7, 8). The upper stratigraphic unit is generally thick-bedded and coarser grained, less well indurated, and more argillaceous than the lower unit. The upper unit consists of medium- to coarse-grained, occasionally argillaceous quartz sandstone with occasional mudchips, glauconite grains, and clay

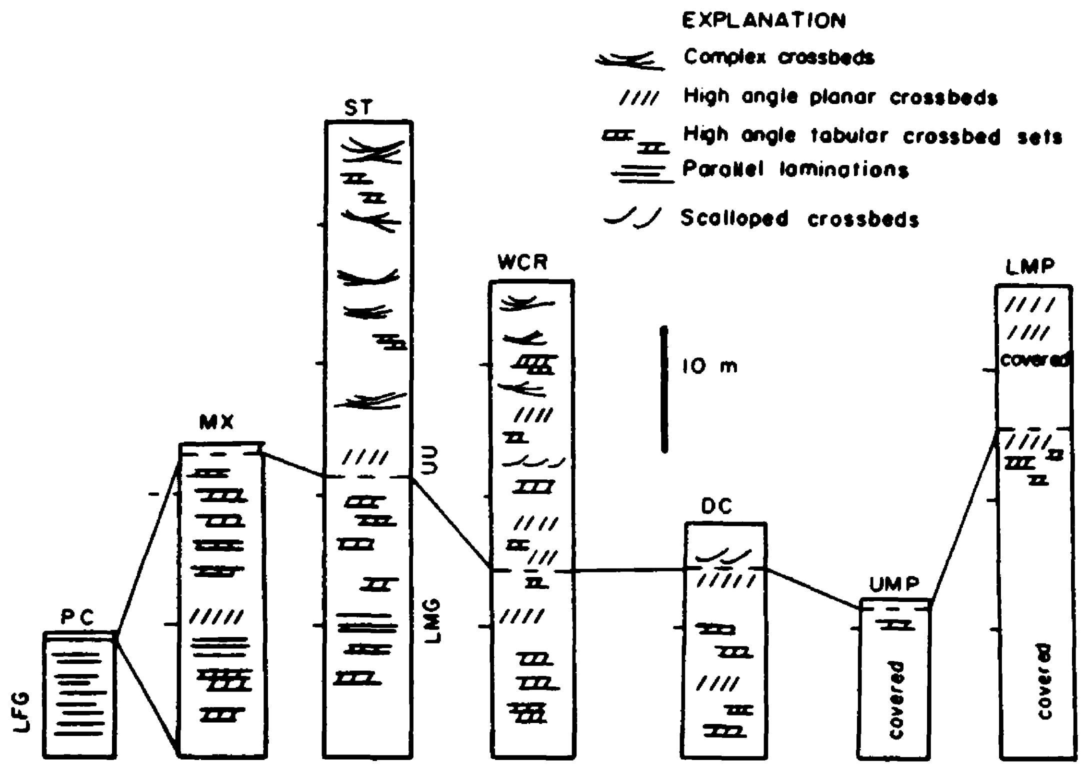
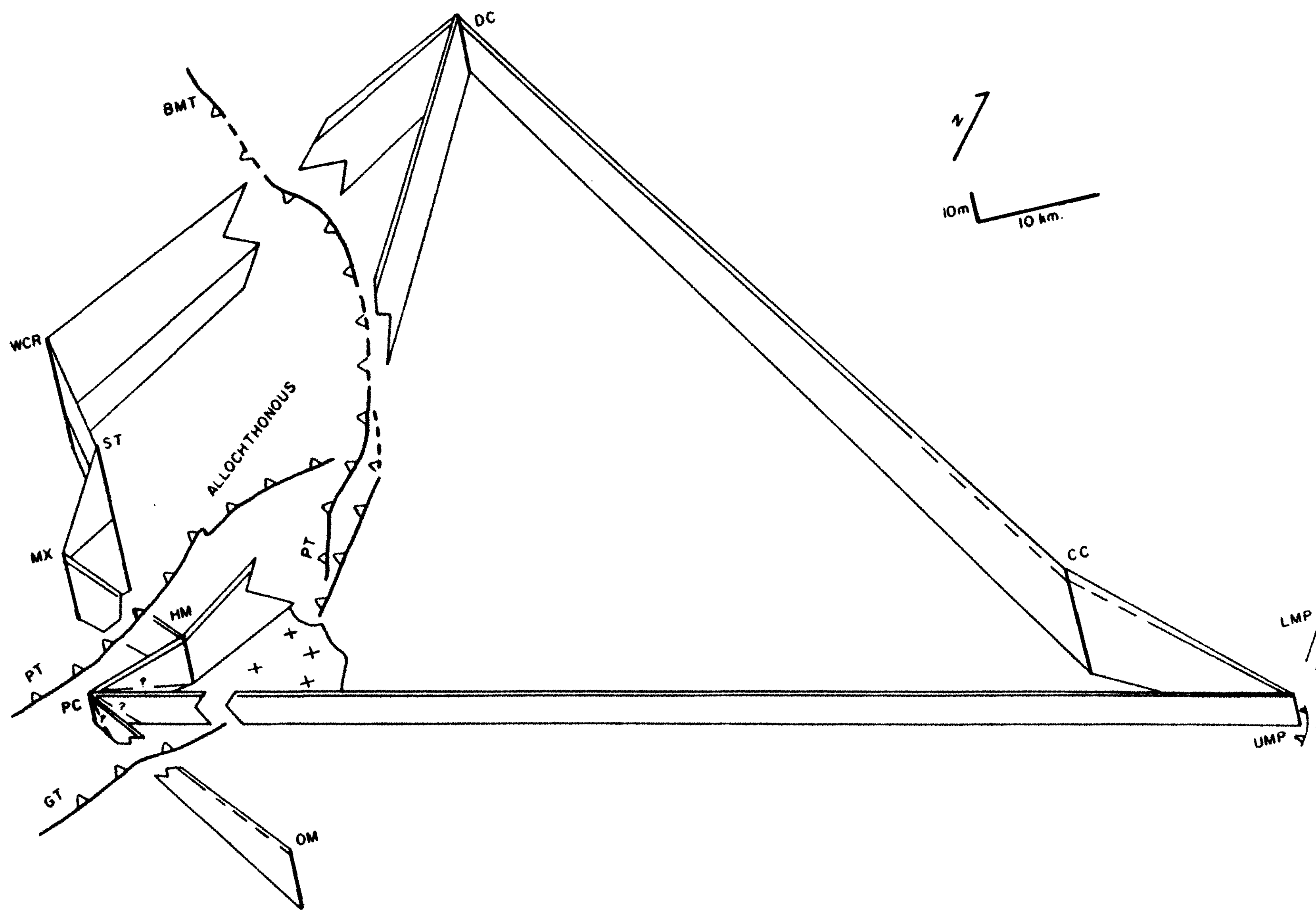


Fig. 7. Stratigraphic sections and unit correlations based on crossbedding at detailed sections and Hasmark. See fig. 1 for locations. LMF = Lower medium-grained facies, LFG = Lower fine-grained facies, UU = Upper unit.

Fig. 8. Flathead facies relationships in west-central Montana. Note that the Stone, Willow Creek Reservoir, Maxville and Lower Mullan Pass sections are allochthonous and not at true locations. See fig. 1 for section abbreviations and true locations.


DC
BMT
WCR
ST
ALLOCHTHONOUS
MX
PT
HM
PT
PC
GT
OM
CC
LMP
UMP
N
10m
10 km.

drapes on bedding surfaces and crossbed laminae. Crossbedding within the upper unit consists of both tabular high-angle crossbed sets and thicker, more complex crossbed sets.

The lower unit generally grades into the upper unit as crossbeds become larger and more complex, and as grain size and mud content increase slightly. On the allochthonous Philipsburg plate at Stone and Willow Creek Reservoir, the lower medium-grained facies grades into thick sequences of the upper unit through a 5 m-thick zone (fig. 7). At Hasmark and Maxville, the boundary between the two units is gradational and the upper unit is poorly developed and is a complexly crossbedded argillaceous, medium- and coarse-grained layer less than 1 m thick. At Porter's Corner, the coarse-grained facies is less than one meter thick and sharply overlies the lower fine-grained facies along an apparent erosional surface. In the Flint Creek and Anaconda Ranges, metamorphic overprints obscure the stratigraphic relationships. However, at Silver Hill in the Anaconda Range a 1 m-thick bed of coarse-grained sand overlies 41 meters of fine-grained, welded quartzite; and is overlain by metamorphosed Silver Hill shale (appendix B).

LOWER FINE-GRAINED FACIES

The fine-grained lower Flathead facies outcrops only at Porter's Corner where it is a 9 m-thick, pink, medium- to thick-bedded, homogeneous, fine-grained, very well sorted and rounded, well indurated quartz sandstone. Very rare medium-fine sand grains form layers a single grain thick throughout the section which increase in frequency up section, and indicate a coarsening upward sequence within the lower fine-grained facies. The degree of induration and uniform grain size makes most crossbedding within the lower fine-grained facies difficult to recognize. However, the beds commonly contain distinct low-angle crossbeds or parallel laminations. Isolated high-angle, sweeping 5 to 10 cm-thick crossbeds bounded by parallel laminae occur scattered throughout the outcrop. The high angle crossbeds only rarely form well defined sets, and 25 cm-wide, 10 cm-deep scour surfaces occasionally cut the sets and bedding surfaces (fig. 9). Asymmetrical small ripples 2 cm tall and 10 cm long appear near the top of one bed (fig. 10). Pockmarks or dimple-like depressions 3 cm in diameter and 1 cm deep cover some bedding planes. Rare green clay layers up to 0.5 cm thick cover some pockmarked surfaces, and faint very thin (<1 mm) green clay layers also appear within some beds.

The lower 10 m of the Hasmark, Maxville and Stone sections contain beds with bedding-parallel laminations and low-angle crossbeds similar to the crossbeds within the massive, pink fine-grained beds at Porter's Corner. However, at Hasmark, Maxville, and Stone the parallel laminated zones are medium- and medium- to fine-grained and are included in the medium-grained facies; although their similar crossbedding form indicates that the same processes deposited the fine-grained facies and the parallel-laminated zones of the medium-grained facies.

LOWER MEDIUM-GRAINED FACIES

The medium-grained facies of the lower stratigraphic unit consists of well defined 40 to 80 cm-thick beds of moderately and poorly

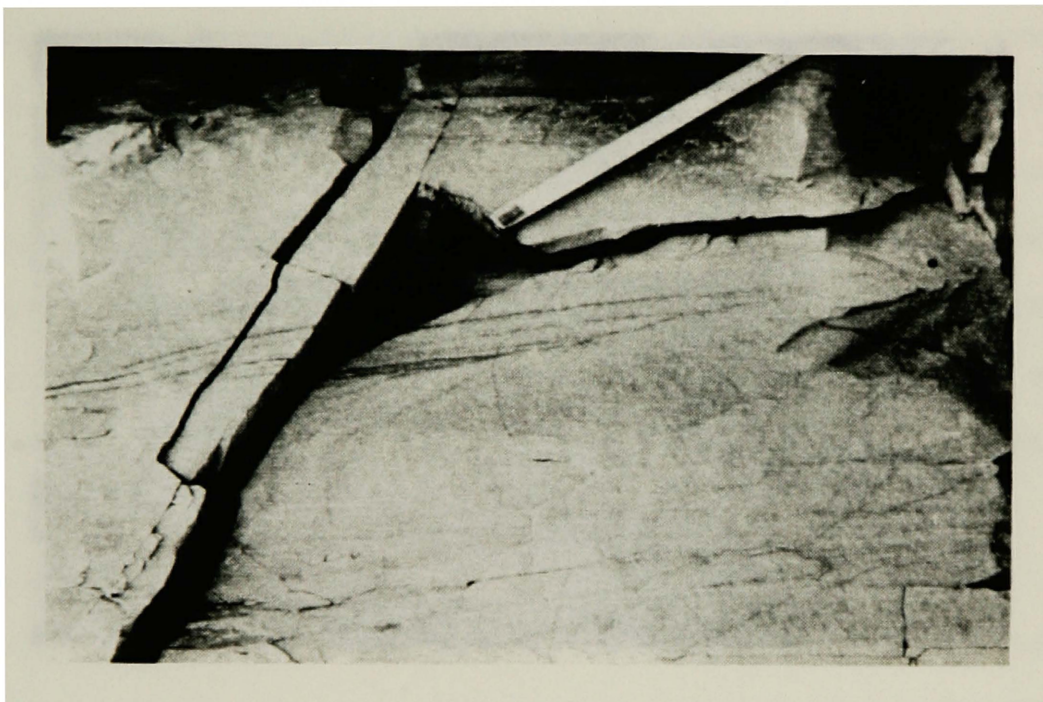


Fig. 9. Scour cutting high angle crossbeds in lower fine-grained facies at Porter's Corner. 18 cm. of tape exposed.

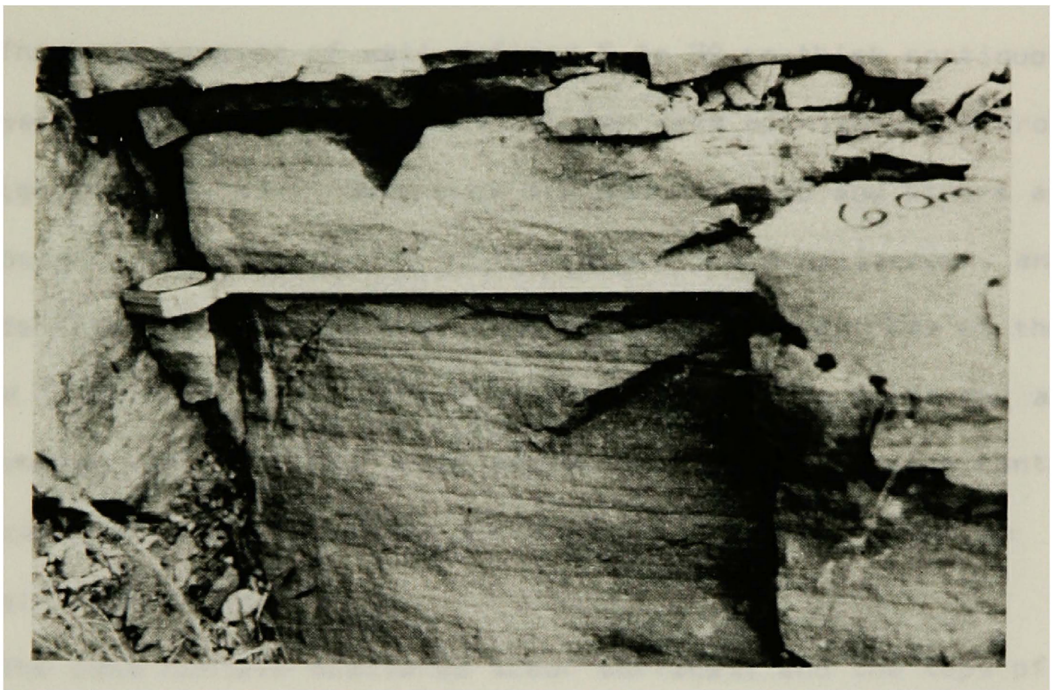


Fig. 1Ø. Ripples near top of bed in lower fine-grained facies at Porter's Corner, 5.9 m. above base. Note parallel laminations below tape. About 25 cm. of tape exposed.

sorted, medium-fine- to medium-coarse-grained sand; and outcrops at all sections except Porter's Corner (figs. 7, 8) (appendix B). Where it outcrops, the lower medium-grained facies ranges between 25 and 17 m thick.

The beds consist of well defined 5 to 30 cm-thick continuous layers containing one or more tabular sets of high-angle crossbeds (figs. 11, 12, 13). Some beds are wedge shaped and others are tabular. The lower parts of some slabs are argillaceous, and the beds lack distinct grading. Coarse grains concentrate at the tops and bottoms of beds, along crossbed set bounding surfaces, and along crossbed laminae. The lower medium-grained facies also contains occasional green mud chips and thin (<1 mm) mud laminae in argillaceous zones.

The beds contain scattered scour surfaces, and the tops of most beds undulate. Near the top of the lower medium-grained facies, some beds have strikingly planar upper and lower bedding surfaces. Thin clay layers, which become more common up section, and 2 cm-thick layers of coarse argillaceous sand separate many beds. Frequent slabby, argillaceous, medium- to coarse-grained sand layers 5 to 10 cm thick layers also separate the beds (figs. 12, 13).

The dominant crossbeds in the medium-grained lower facies are tabular 5 to 20 cm-thick continuous sets of high-angle crossbeds with steep, tangential toes and nearly bedding-parallel bounding surfaces; and were probably deposited by migrating waves of straight-crested bedforms. The sets generally thicken up section from 5 to 10 cm near the base to 10 to 20 cm at the top of the unit.

Fig. 11. Tabular high angle crossbeds at Willow Creek Reservoir, 10 m above base. Staff divisions 10 cm.

Fig. 12. Slabby lower medium-grained facies beds at Willow Creek Reservoir, 7 m above base. Note more massive bedding above slabby beds. Staff divisions 10 cm.

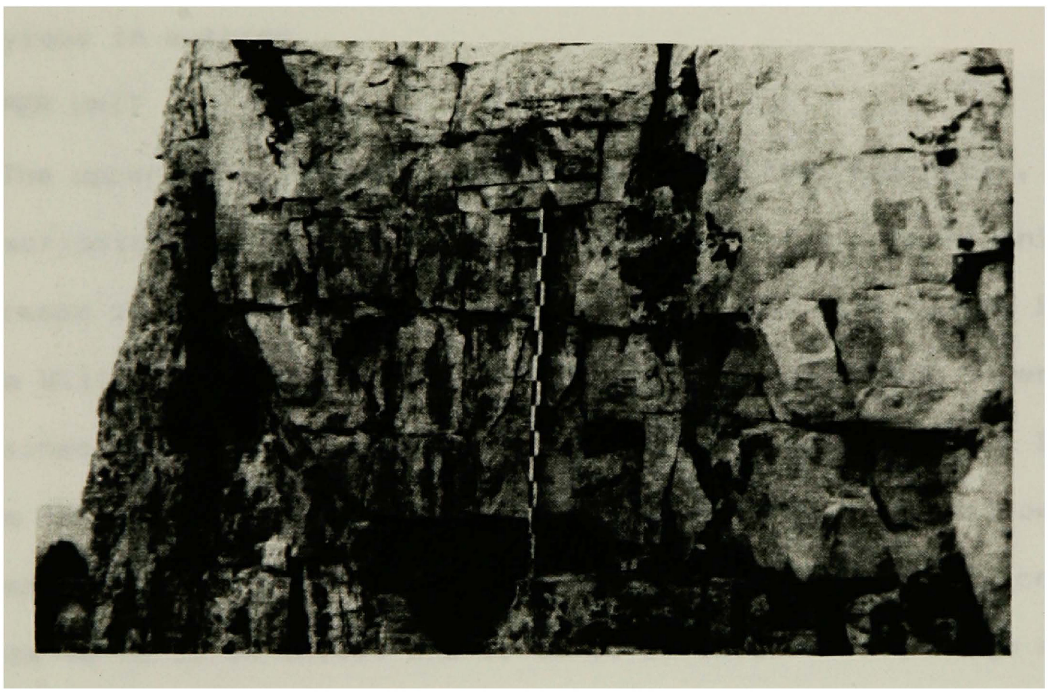


Fig. 13. Wedge shaped lower medium-grained facies beds at Willow Creek Reservoir. Note slabby bed at top of staff. Base of staff 7 m above base. Staff 1.5 m.

Similar layers which lack high-angle crossbeds, or contain thin (2 mm) parallel laminae interbed with the high angle crossbed sets, but the laminae occasionally include faint sweeping crossbeds. The lower medium-grained facies also contains rare 40 cm-thick sets of planar high-angle crossbeds which were probably deposited by bars or record preserved bedforms, although the bedform shapes are not obvious in outcrop.

UPPER UNIT

The upper unit is best exposed at Willow Creek Reservoir, and the description and depositional interpretation of the upper unit focuses on the Willow Creek Reservoir section. The lowest 14 m of the Willow Creek Reservoir section are included in the lower medium-grained facies. The upper unit includes the interval from 14 m to the top of the Flathead at 36 m. From 14 to 20 m the Willow Creek Reservoir section contains wedge-shaped high-angle planar crossbed sets 40 to 50 cm thick, and 10 to 30 cm-thick sets of high angle crossbeds similar to the dominant crossbeds in the lower medium-grained facies.

Scalloped crossed sets which form repeated or cyclic arcs on their lower bounding surfaces lie above 10 cm-thick high angle crossbed sets and are exposed at 20 m (fig. 14). A 1 m-thick, well indurated bed of high-angle 10 cm-thick crossbed sets overlie the scalloped crossbeds from 21 to 22 m.

The crossbeds from 24 to 28 m at Willow Creek Reservoir form 80 cm thick sets with repeated wedge-shaped bundles of tangential-toed cross-laminae (fig. 15). The thick tabular crossbed sets are

Fig. 14. Scalloped crossbeds in upper unit at Willow Creek Reservoir, 18 m above base. Note the repeated scalloped scour surfaces (arrows) above slabby layer. Staff 1.5 m.

Fig. 15. Thick crossbeds in upper unit at Willow Creek Reservoir, 24 m above base.

bounded above and below by bedding surfaces. The crossbed laminae are normally graded up the lee slope and also normally graded across the laminae. Clay drapes, which are thickest at the laminae toes and pinch out up slope, cover some crossbed laminae. At the bottom of the crossbed laminae, repeated thin opposing crossbed laminae intertongue with the major crossbed laminae. At 29 m, 0.5 m-thick high-angle crossbeds overlie 10 cm-thick high-angle, tabular crossbed sets.

From 31 to 33 m, a 2 m-tall slipface of a straight-crested bedform is preserved and dips nearly due west. Laminae at the bedform crest are 2 cm thick and extend parallel to the crest for at least 3 meters, and the laminae lack internal cross-stratification (figs. 16, 17). At the base of the slipface, the bedform trough has 10 to 15 cm of relief, and crossbed laminae drape over the topographic irregularities in the bedform trough. At the bedform toe, west dipping crossbeds envelope an opposing north-east dipping crossbed package; and the toes of the opposing bunches intertongue (fig. 17). The thick, complex crossbed sets and the scalloped crossbed sets may record either cyclic flow variations, or scour pits migrating through the troughs of bedforms, or a combination of both processes.

The stratigraphic sequence at the Stone section is similar to the sequence at Willow Creek Reservoir (fig. 7, 8) (appendix B). The lower 24 m of the Stone section are included in the lower medium-grained facies; and the upper unit includes the interval from 24 m to the top of the Flathead at 48 m. At 25 m, 50 cm-thick, high-

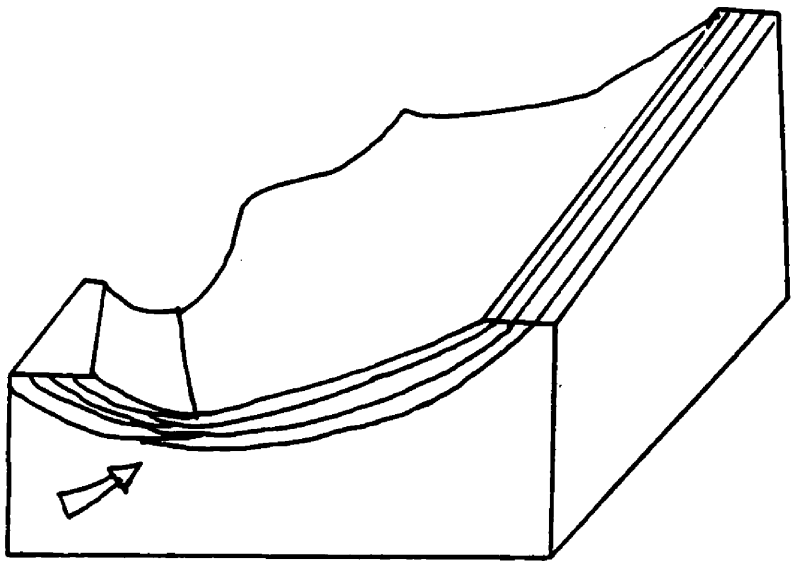


Fig. 16. Schematic drawing of preserved 2 m tall bedform at Willow Creek Reservoir, 33 m above base. Arrow points to location of figure 17.

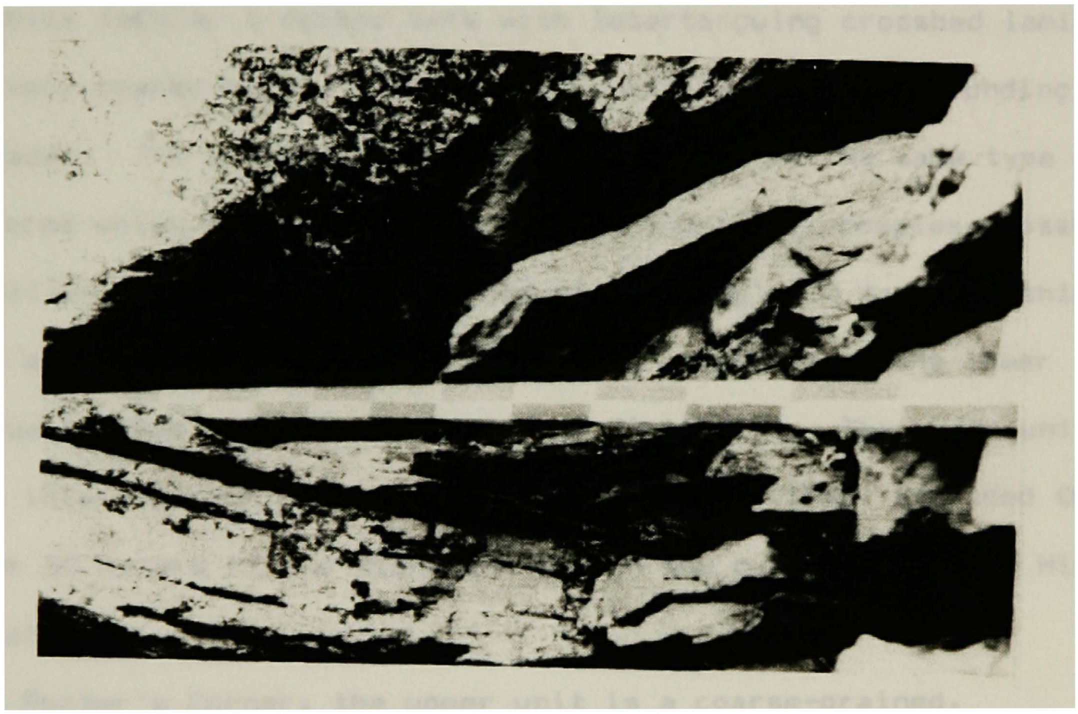


Fig. 17. Complex intertonguing crossbeds in upper unit at Willow Creek Reservoir, 33 m above base. Dominant crossbeds dip west (left). Divisions on staff 1Ø cm.

angle planar crossbeds overlie the lower unit. The interval from 26 m to 48 m contains zones of 1 to 2 m-thick, recessive weathering medium- and medium- to coarse-grained sandstone beds separated by 2 to 5 m-thick covered shaley intervals. The beds contain 10 to 40 cm-thick tabular crossbed sets with intertonguing crossbed laminae and very coarse sand grains along the bedding parallel bounding surfaces. The crossbeds were probably formed by the same type of bedforms which deposited the scalloped and thick, complex crossbeds at Willow Creek Reservoir. A bed of high-angle 10 to 15 cm-thick high angle crossbed sets similar to the crossbeds of the lower medium-grained facies crops out from 30 to 31 m. The upper unit beds interbed with green shale, and so Illich (1966) included the upper 30 meters of the Stone section in the overlying Silver Hill Formation.

At Porter's Corner, the upper unit is a coarse-grained, argillaceous, well sorted quartz sandstone bed 0.5 m thick (figs. 7, 8) (appendix B). The single bed contains high-angle tabular crossbed sets; and even green mud veneers cover some crossbed laminae.

At Deep Creek the upper unit crops out from 13 to 17 m and is poorly developed. The lower 13 m of the section contain rare 5 to 10 cm-thick high angle crossbed sets and are included in the lower medium-grained facies. The interval between 13 and 15 m contains 0.5 m thick high angle planar crossbeds. The interval between 15 and 17 m contains well indurated medium-grained sandstone with intertonguing crossbeds.

At Maxville the upper unit forms a moderately indurated, argillaceous, recessive weathering 0.5 m thick coarse-grained sandstone bed with intertonguing crossbeds above the well indurated lower unit (fig. 7, 8) (appendix B). At Lower Mullan Pass the upper unit outcrops from 30 to 36 m and contains 0.5 m thick, high-angle and planar crossbeds above a covered interval (fig. 7).

DEPOSITIONAL PROCESSES

INTRODUCTION

A bedform migrates and deposits crossbeds as material moves from its stoss side and accumulates on the lee slope (see review by Rubin and Hunter, 1982). During net deposition, the generalized bed surface must rise or climb; and the depth of erosion in the bedform troughs rises for each successive bedform (fig. 18). As bedforms migrate, they deposit crossbed sets, or translatent strata, as thick as the un-eroded layer, and bounded by scoured bounding surfaces (Rubin and Hunter, 1982). Because bedforms migrate at an angle to the horizontal surface, crossbed dips must be corrected to the surface they migrate on rather than bedding to determine their true migration directions.

With increasing flow velocity at constant depth, straight-crested bedforms develop sinuous crests; and separate into isolated, discontinuous-crested lunate and lingoid bedforms. A sinuous-crested bedform with a sinuosity migrating along the bedform crest, or a straight-crested bedform with topographic relief along its trough, deposit crossbeds identical to bedforms with scour-pits migrating parallel to the bedform crest, or to trough shaped crossbeds deposited by a discontinuous-crested bedform (Rubin, 1987a, 1987b).

The present confusion surrounding bedform nomenclature requires a note concerning bedform terminology used in this paper. This terminology is based on the system used by Costello and Southard (1981). The terms ripple, dune, and sandwave here are strictly

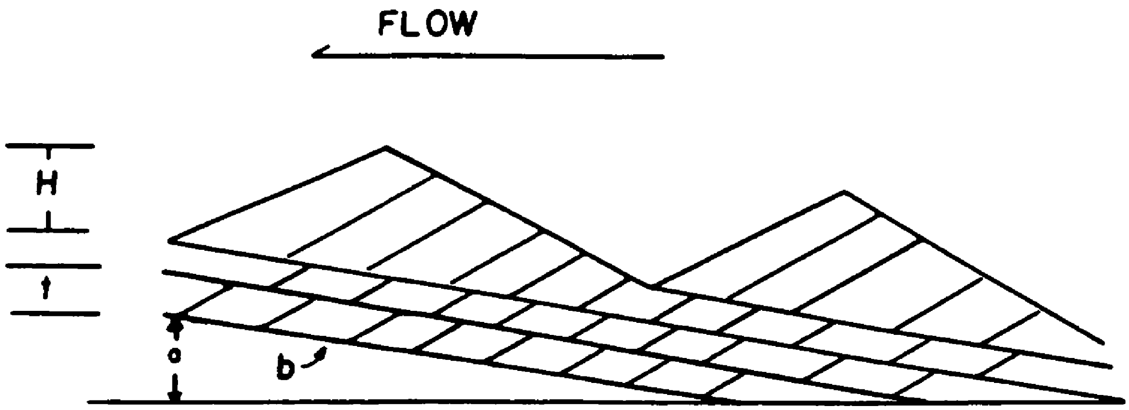


Fig. 18. Schematic diagram showing bedform climbing. H = bedform height, t = thickness of translatent strata, b = crossbed set bounding surface, a = angle of bedform climb (after Rubin and Hunter, 1982).

descriptive and should not be interpreted as genetic terms. Ripples refer to the smallest bedforms observed (<10 cm long). Dunes refer to straight-, sinuous-, and discontinuous-crested bedforms larger than ripples. The term sandwave refers only to bedforms larger than dunes in any environment. Costello and Southard (1981) did not use the term "bar", which here refers to a separate type of bedform which progrades by adding material to its slipface without eroding the stoss side, and deposits planar crossbed sets.

LOWER MEDIUM-GRAINED FACIES

The coarse grain concentrations along bounding surfaces and laminae, mud chips, occasional mud layers separating the beds, moderate sorting, and lack of definite eolian structures indicate subaqueous deposition of the medium- and thick-bedded lower medium-grained Flathead facies (Hunter, 1977, 1985). Trains of straight-crested climbing bedforms probably deposited the 5 to 20 cm-thick, bedding parallel sets of high-angle rarely trough-shaped crossbeds. (Costello and Southard, 1981; Rubin and Hunter, 1982, 1983; Hunter and Rubin, 1983; Rubin, 1987a, 1987b).

Some of the tabular crossbed sets continue for at least 30 m, and so the migrating bedforms which deposited the sets were probably long lived. The bounding surfaces and lack of repeated larger crossbeds indicate these bedforms were not superimposed on steeply dipping larger scale bedforms. Although climbing bedforms may have migrated up gently dipping lee slopes of larger bedforms whose bounding surfaces created bedding, they are not apparent at outcrops, and so they are unlikely to have generated bedding. The wedge-shaped beds and undulations on bedding surfaces may record the preserved shapes of bedforms. The undulations may also record scour of the substrate by migrating bedforms or record later modification of the substrate topography or compaction of the sediment.

If the bedforms which formed the tabular crossbed sets were nearly perfect sediment traps, the bedform height can be calculated using the equation:

$$H=(TD/I)^{1/2} \quad (1)$$

where H is height of the bedform, T is the thickness of the translatent strata, D is the horizontal distance over which the strata can be traced, and I is the bedform ripple index (height/wavelength) (Rubin and Hunter, 1982).

Ripple index values for small dunes and sandwaves in flumes and natural systems generally range between 20 and 50 (Allen and Friend, 1976; Reineck and Singh, 1980; Rubin and McCulloch, 1980; Costello and Southard, 1981; Dalrymple, 1984; Terwindt and Brouwer, 1986). The crossbed sets in the lower medium-grained facies average 10 cm thick; and some sets continue for at least 30 m without thinning.

The lack of preserved stoss slopes indicate the rate of bedform migration relative to suspension deposition was high, and implies the bedforms were good sediment traps. Terwindt and Brouwer (1986) argue that the variable currents and flow conditions of tidal environments precludes using bedform height and wavelength to predict flow conditions. However, their data may not reflect the maximum bedform wavelengths and heights. Allen and Friend (1976), Rubin and McCulloch (1980), and Boersma and Terwindt (1981) showed that bedforms at equilibrium with the dominant tidal current in intertidal and subtidal environments is consistent with data from unidirectional equilibrium flume studies.

For maximum and minimum values of T, D, and I in equation 1, calculated bedform heights range from 0.17 to 1.22 m (table 1). Bedforms 0.17 m tall, the minimum predicted height, could not deposit the thicker crossbed sets; and probably did not produce the thin extensive sets if no new sediment was supplied to the system. No translatent strata were traced for more than 30 m, and 0.20 m-thick sets are rare. Therefore 1.22 m probably overestimates the average bedform height. The bedforms which deposited the crossbed sets are probably best estimated by intermediate parameter values, which predict bedforms between 0.25 and 1.0 m tall.

Straight-crested bedforms between 0.25 and 1.0 meters tall and composed of medium-grained sand are stable in unidirectional, equilibrium flows between 1.25 and 5 m deep, and flowing between 0.70 and 0.90 m/sec. (Rubin and McCulloch, 1980; Costello and Southard, 1981).

Rare sets of apparently planar laminae within the lower medium-grained facies may record very low angles of bedform climb (Rubin and Hunter, 1982). The laminae are parallel to bedding and bounding surfaces of the high-angle crossbed sets; and faint, thin, crossbed toes appear in some laminae, and indicate that bedforms climbing at low angles produced these laminae. Although trains of climbing straight-crested dunes probably deposited the crossbeds within the lower medium-grained facies, climbing straight-crested dunes

TABLE 1. Calculated bedform heights using equation 1. T = thickness of translatent strata, D = distance strata can be traced, I = Ripple index, H = calculated bedform height. All measurements in meters.

T	D	I	H
.05	30	50 [1]	.17
.10	30	50 [1]	.24
.30	100	20 [2]	1.22
.10	30	35 [3,4,5]	.30
.10	30	20 [2]	1.00

TABLE 2. Calculated bedform heights for postulated large scale bedforms. Abreviations as for Table 1a. All heights in meters.

T	D	I	H
.5	200	30[2]	1.85
.5	100	100[2]	.71
.5	100	50[2]	1.00
.5	300	30[2]	2.23

References:

[1] Dalrymple (1984)
[2] Reineck and Singh (1980)
[3] Terwindt and Brouwer (1986)
[4] Allen and Friend (1976)
[5] Boersma and Terwindt (1981)

superimposed on larger bedforms could also create the observed bedding and crossbedding within the lower medium-grained Flathead facies. If larger bedforms did generate bedding, their height can also be calculated using equation 1. Beds continue without thinning for nearly 100 m, and average 0.5 m thick. The predicted bedform height for the hypothesized bedforms then ranges between 0.71 and 2.23 m (table 2). Bedforms between 1.5 and 2 m tall exist in flows 10 to 20 m deep moving between 75 and 150 cm/sec. (Rubin and McCulloch, 1980). Larger scale bedforms with east dipping slipfaces may have migrated through the system in response to onshore directed currents. Because of limited exposure and outcrop quality, both trains of climbing straight-crested dunes, or straight-crested dunes climbing up the lee slopes of larger bedforms must be considered possible. The lower medium-grained Flathead facies also contains rare tabular sets of 0.50 m-thick, planar crossbeds interstratified with the tabular high-angle crossbed sets. Five cm-thick sand layers cap some planar crossbeds, and the planar crossbed sets probably record preserved bars (Reineck and Singh, 1980; Crowley, 1983; Dalrymple, 1984) or preserved bedforms which deposited the tabular crossbed sets.

At Willow Creek Reservoir, the high-angle crossbeds dip northwest, while bounding surfaces dip gently east and southeast (fig. 19). Most crossbeds from the lower medium-grained facies at Willow Creek Reservoir, Stone, and Lower Mullan Pass dip within 90° of due west (fig. 20).

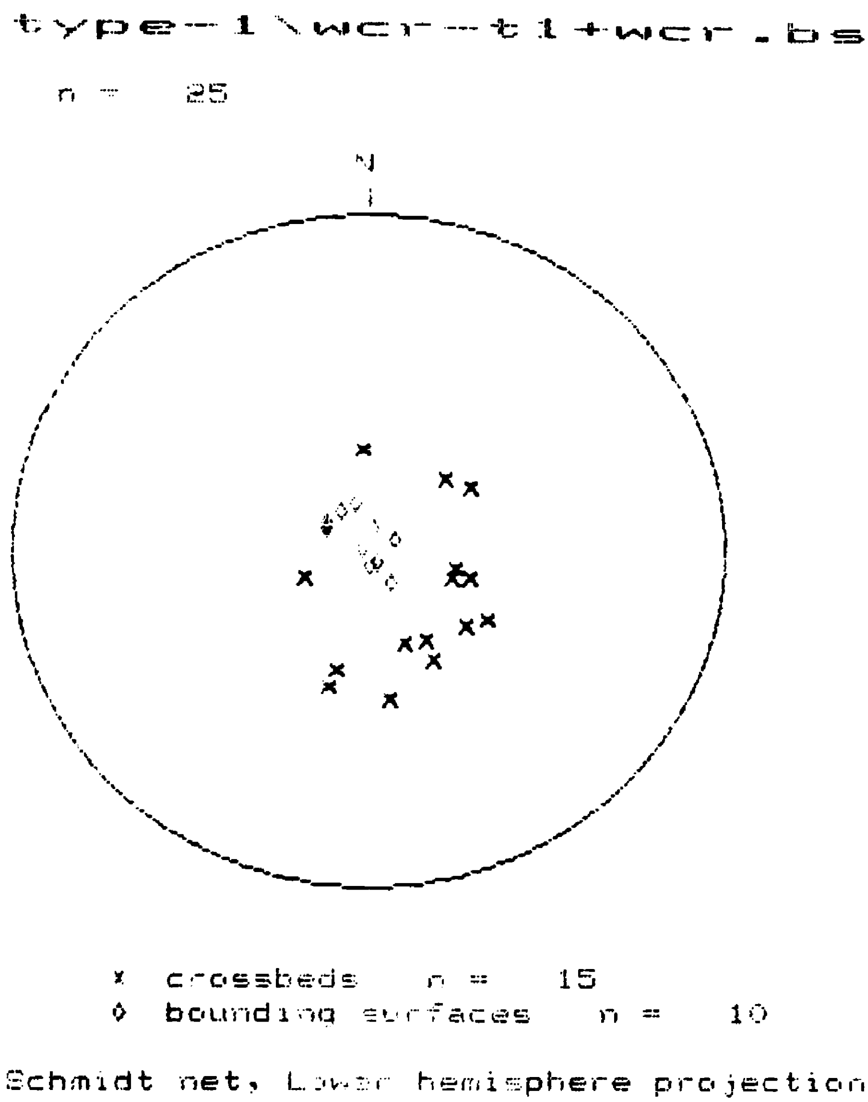


Fig. 19. Lower medium-grained facies crossbeds and bounding surfaces at Willow Creek Reservoir. Crossbeds corrected to bounding surfaces, bounding surfaces corrected to bedding.

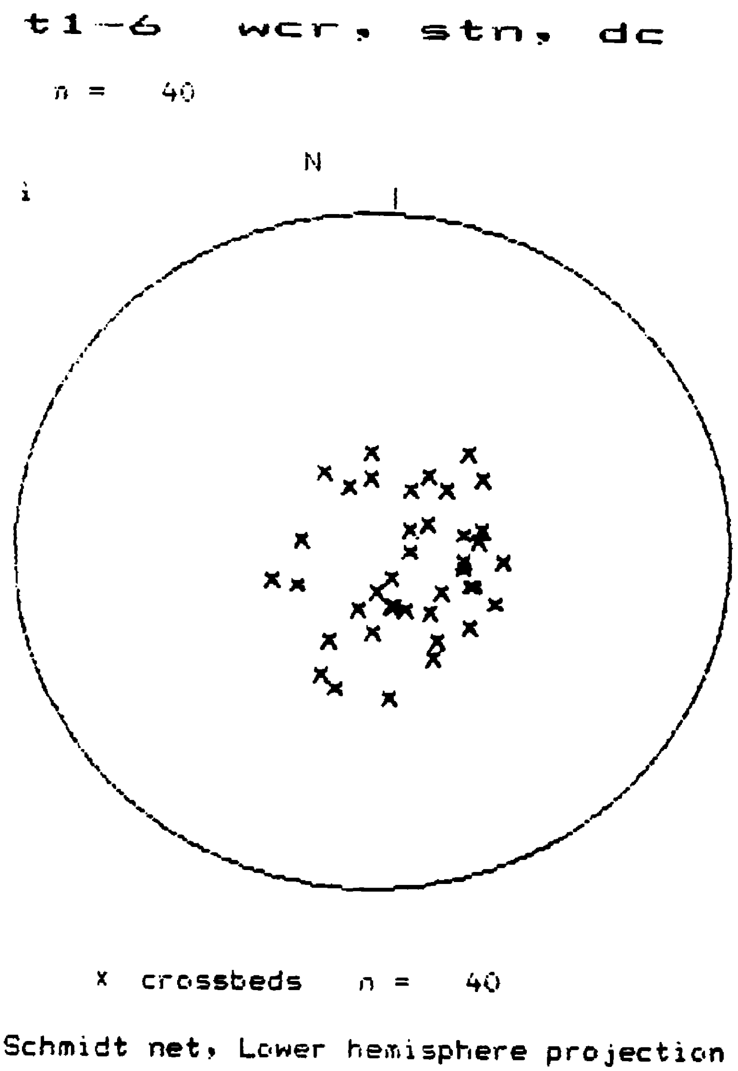


Fig. 20. Poles to combined lower medium-grained facies high angle crossbeds at Willow Creek Reservoir, Stone, and Deep Creek. Crossbeds corrected to bounding surfaces.

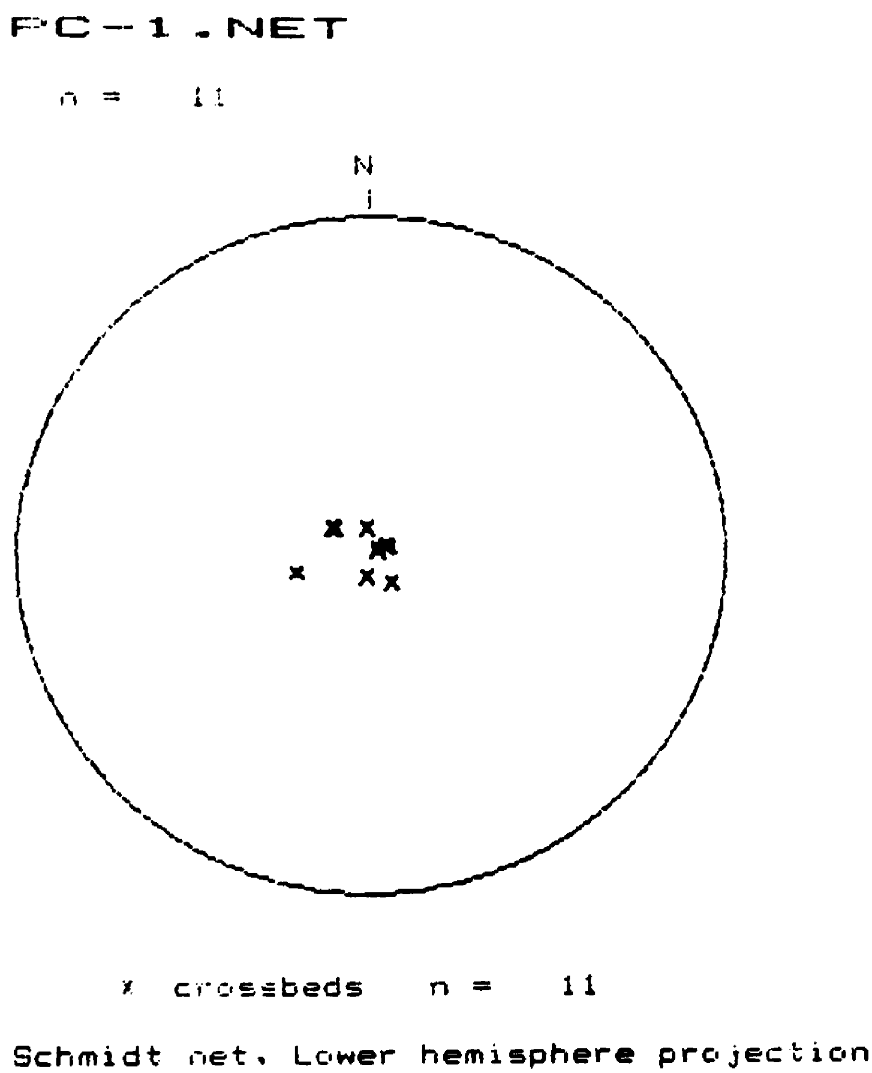


Fig. 21. Low angle crossbed orientations in lower fine-grained facies at Porter's Corner. Poles to bedding.

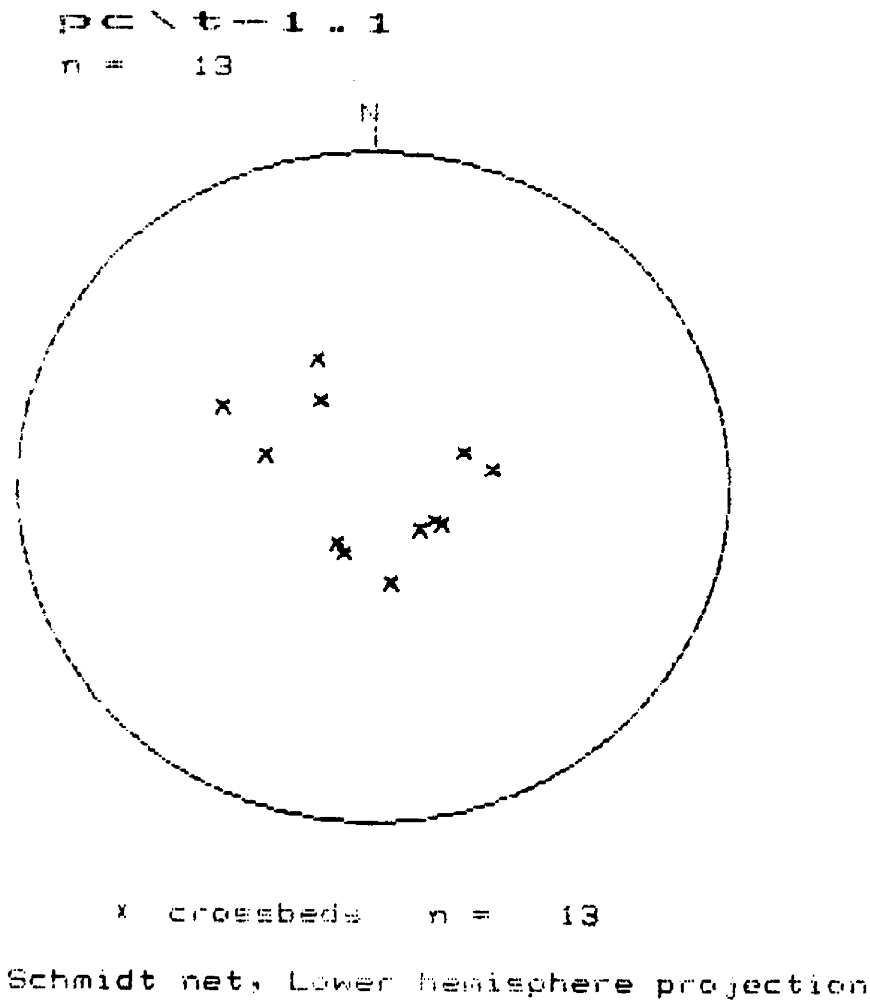


Fig. 22. High angle crossbed orientations in lower fine-grained facies at Porter's Corner. Poles to bedding.

The occasional planar bedding surfaces of the lower medium-grained facies with coarse grain concentrations in the upper parts may record planar subaerial or subaqueous erosion surfaces or upper flow regime plane beds. For 0.5 mm sand, plane beds develop in 2 to 5 m-deep flows when velocity exceeds about 1.25 m/sec. (Rubin and McCulloch, 1980); and floods, extreme tides, or storm generated currents could produce plane beds. However, data for distinguishing the plane beds from other erosion surfaces are not available.

LOWER FINE-GRAINED FACIES

As opposed to the well-defined layers and crossbed laminae of the lower medium-grained facies, crossbeds in the lower fine-grained facies are faint, and the beds only rarely separate into slabs and layers.

The most striking internal features of the fine-grained facies are the 2 to 5 cm-thick, gently-dipping, parallel laminae defined by red layers, rare heavy mineral laminations, or medium- to fine-grained sand laminae (figs. 9, 10). The prominent parallel layers do not dip in any preferred direction (fig. 21). Discontinuous and isolated crossbeds recording large bedforms appear within some laminae throughout the section, and the crossbeds have a weak bimodal, bipolar distribution (fig. 22). Rare climbing ripple sets appear near the top of one bed. The poor three-dimensional exposure of these crossbeds prevents estimating the sizes of their parent bedforms or interpreting the flow conditions which created the bedforms.

Accreting plane bed deposition in upper regime flow alternating with lower flow regime large scale bedforms could produce parallel laminae and high angle crossbeds. However, low angle bedform climb could also produce the parallel laminae by depositing thin translatent strata. With no variation in grain size or other features to define the sets, strata would appear only as parallel bounding surface laminations.

Ripples near the top of one bed (fig. 10) and occasional green mud drapes on bedding planes probably indicate that flow slowed, producing small ripples and rapid deposition. Flow then stopped, allowing mud to settle from suspension.

UPPER UNIT PROCESSES

In the upper unit, the association of clay drapes on beds and crossbed laminae, large bedforms and sets of complex high angle crossbeds, rare glauconite grains, and gradational contact to overlying trilobite-bearing shale indicate the upper facies was deposited in an intertidal to subtidal marine environment. Within the lowest part of the upper unit at Willow Creek Reservoir, the high angle crossbeds probably record bars or preserved bedforms which migrated through the depositional system (Reineck and Singh, 1980; Visser, 1980; Crowley, 1983; Dalrymple, 1984). Migrating straight- to sinuous-crested bedforms deposited the 10 to 30 cm-thick, tabular, high-angle crossbed sets which occur throughout the upper unit.

At Willow Creek Reservoir, the scalloped crossbeds within the upper unit, the complex crossbeds which overlie the scalloped crossbeds, and the bedforms recorded by the 2 m-tall slipface exposed between 31 and 33 m probably record similar depositional processes, because each has small opposing crossbed laminae or cyclic repetitions.

The complex and scalloped crossbeds in the upper facies may have formed by fluctuating unidirectional flow or reversing flow (De Raaf and Boersma, 1971; Terwindt, 1971, 1981; Visser, 1980; Boersma and Terwindt, 1981; De Mowbray and Visser, 1984); or by superimposed scour pits or topographic irregularities moving through the troughs of large bedforms under uniform flow (Rubin and Hunter, 1982, 1983; Hunter and Rubin, 1983; Rubin, 1987 a,b).

Intertidal sandwaves migrate during a dominant tide and cyclically change form during neap- to springtide cycles. During springtide flow the bedform trough deepens and the avalanche face becomes steeper as thin laminae are deposited in the bedform trough. As neaptide approaches, the avalanche face slacks; and thicker laminae and opposing crossbed laminae accumulate in the bedform trough (fig. 22) (De Raaf and Boersma, 1971; Terwindt, 1971, 1981; Visser, 1980; Boersma and Terwindt, 1981; De Mowbray and Visser, 1984). Mud drapes deposited during stillstand cover the crossbed laminae (Boersma and Terwindt, 1981; De Mowbray and Visser, 1984).

Hunter and Rubin (1983), Rubin and Hunter (1983), and Rubin (1987a) describe criteria for differentiating crossbeds produced by superimposed bedforms from those generated by fluctuating flow. Scour pits or topographic relief migrating through a bedform trough would produce asymmetrically distributed crossbed orientations and a

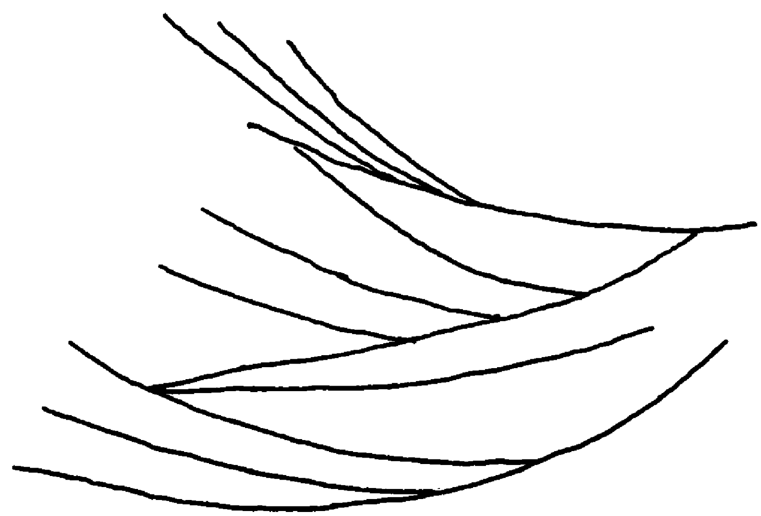


Fig. 23. Diagramatic sketch of crossbed bundles generated by fluctuating flow (after Hunter and Rubin, 1983).

linear distribution of bounding surface orientations; but crossbeds deposited by fluctuating flow would be symmetrically distributed (fig. 24). For both the complex and scalloped crossbeds, the crossbed and bounding surface relationships which Rubin (1987 a, b) uses to distinguish fluctuating flow and superimposed bedform origins, are clearly neither symmetrically nor asymmetrically distributed. Therefore, it is possible to credit neither as the sole depositional process, and they may have operated together to form the complex crossbeds. The opposing and intertonguing crossbeds oppose the larger crosssbed sets by less than 180° (fig. 25). These data may indicate that the opposing laminae record spurs on larger bedforms, or smaller bedforms which did not migrate opposite to the larger bedforms, but migrated along the bedform trough.

Using the 2 m-tall straight-crested bedforms at 31 to 33 m at Willow Creek Reservoir as a model, the bedforms which deposited the complex upper unit crossbeds must have been at least two meters tall, and possibly much taller (Rubin and Hunter, 1982, 1983). Mud drapes on crossbed laminae, and mud layers on the scalloped crossbed bounding surfaces indicate flow periodically stopped. Therefore, if superimposed bedforms deposited the crossbeds, they probably migrated sporadically, possibly in response to strong, storm generated currents or extreme tides.

The complex intertonguing crossbeds within the upper unit at Stone, Deep Creek, and Maxville probably record depositional processes similar to the process interpreted for Willow Creek

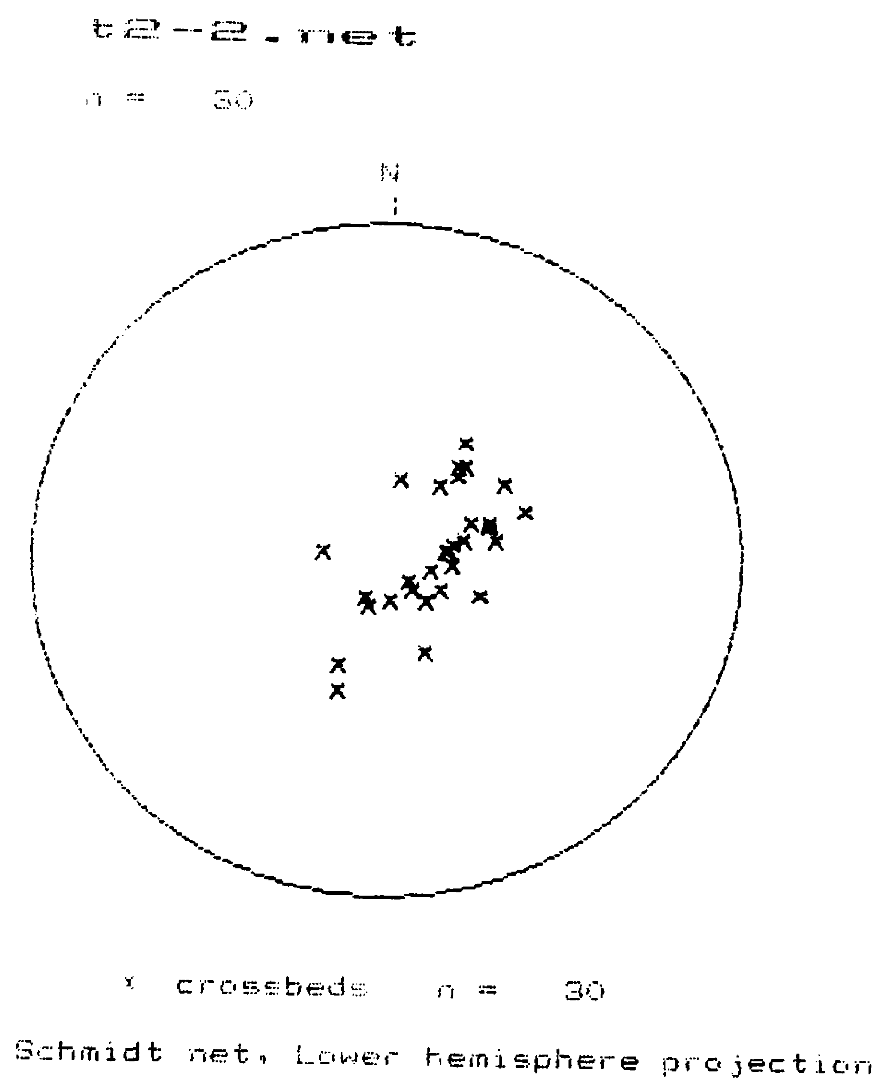
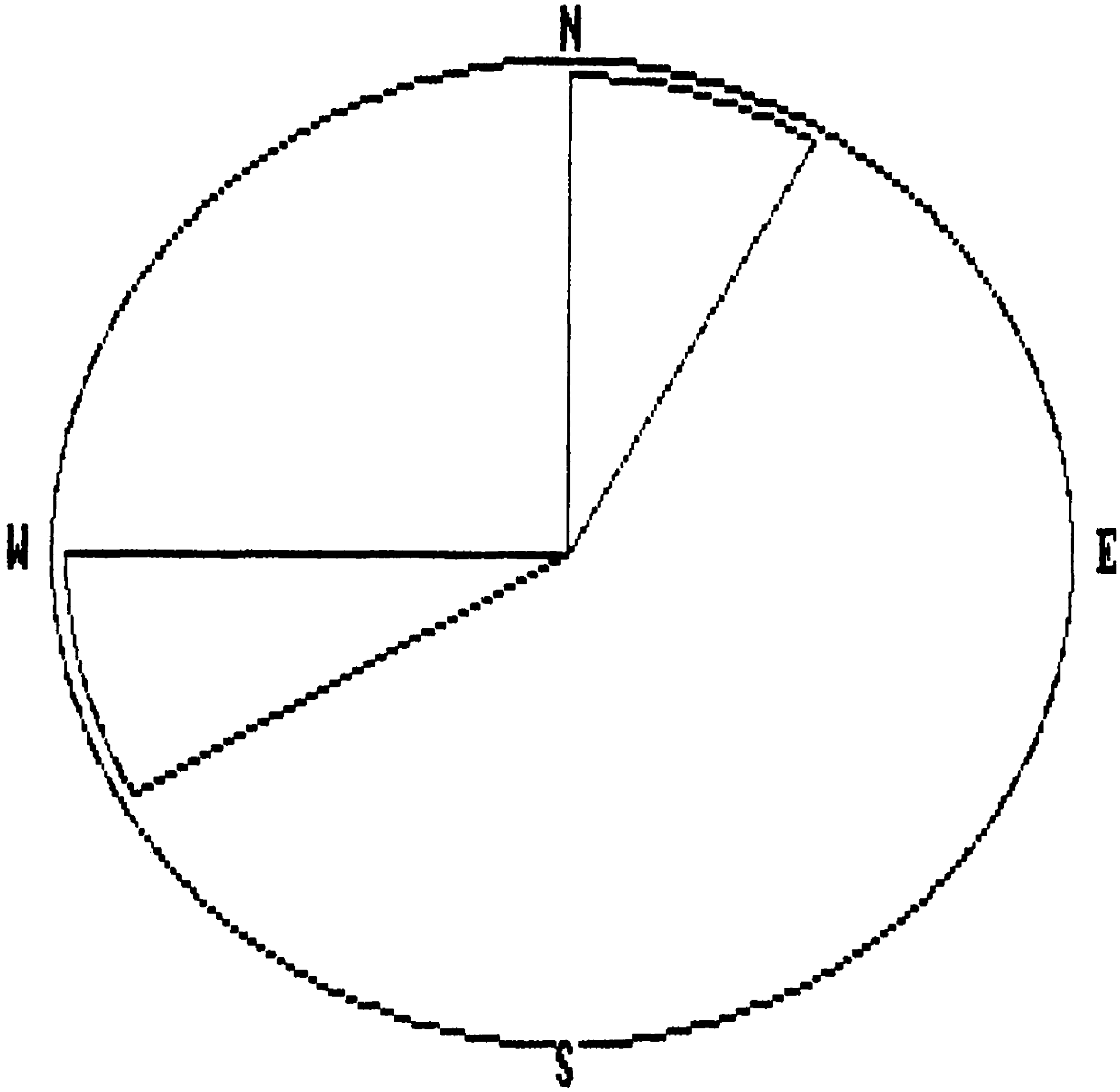


Fig. 24. Poles of combined upper facies crossbeds at Willow Creek Reservoir, Stone, Porter's Corner, corrected to bounding surfaces.



WCR-26.PRN CLASS SIZE = 30
WCR 33 m. MAX. RADIAL = 1

N=2

Fig. 25. Dip directions of intertonguing crossbeds at Willow Creek Reservoir, 33 m.

Reservoir. As the bedforms migrated, they deposited thick crossbed sets now bounded by bedding planes. The dominant west directed crossbeds in the upper coarse-grained facies probably indicate that the currents, either storm or tidal, moved towards the west (fig. 24). Crossbeds of the lower medium-grained facies dip in the same general direction as crossbeds from the upper stratigraphic unit (figs. 21, 22, 23). The gradational contact of the lower medium-grained facies into the upper unit, the general upward increase of lower medium-grained facies crossbed thickness from 5 to 10 cm near the base to 10 to 20 cm at the top and the common tabular high angle crossbed sets within the upper stratigraphic unit at Willow Creek Reservoir and Stone indicate that the parent bedforms of the tabular crossbed sets continued to exist in a deepening environment; and increased in size and complexity with increasing depth of the depositional environment.

DEPOSITIONAL RECONSTRUCTION

The Flathead was deposited shoreward of offshore marine shales and carbonate reefs (Lochman-Balk, 1972). Walther's Law of facies constrains the Flathead depositional environment to nearshore marine and delta environments; or to alluvial and eolian deposition on the beveled pre-Flathead surface. Modern mixed carbonate and clastic marine environments off Belize and eastern Australia, where carbonate platforms and reefs bound the seaward sides of clastic shorelines, probably model this setting in part (Sellwood, 1986). Troughs landward of the carbonate banks reach depths of up to 60 m, similar to the deepest parts of the southern North Sea Bight (Maxwell and Swinchatt, 1970; McCave, 1971; Dott and others, 1986).

Within this depositional framework, the Flathead Sandstone forms a sequence of lower medium- and fine-grained, medium-bedded sandstones with parallel laminations and tabular sets of high angle crossbeds, which grade into thicker-bedded, more complexly crossbedded, coarser-grained sandstones. The coarsening and thickening upward sequence records a progressive change from deposition by waves of straight-crested bedforms migrating in shallow nearshore marine environments, to deposition by migrating bars and large sandwaves in a deeper marine environment which was eventually replaced by deposition of offshore marine clastic shale (fig. 26).

Fine-grained sand, recorded by the lower fine-grained facies, accumulated locally. The coarsening upward sequence in both facies of the lower stratigraphic unit, and the overall coarsening upward sequence within the Flathead, indicates that the lower fine-grained

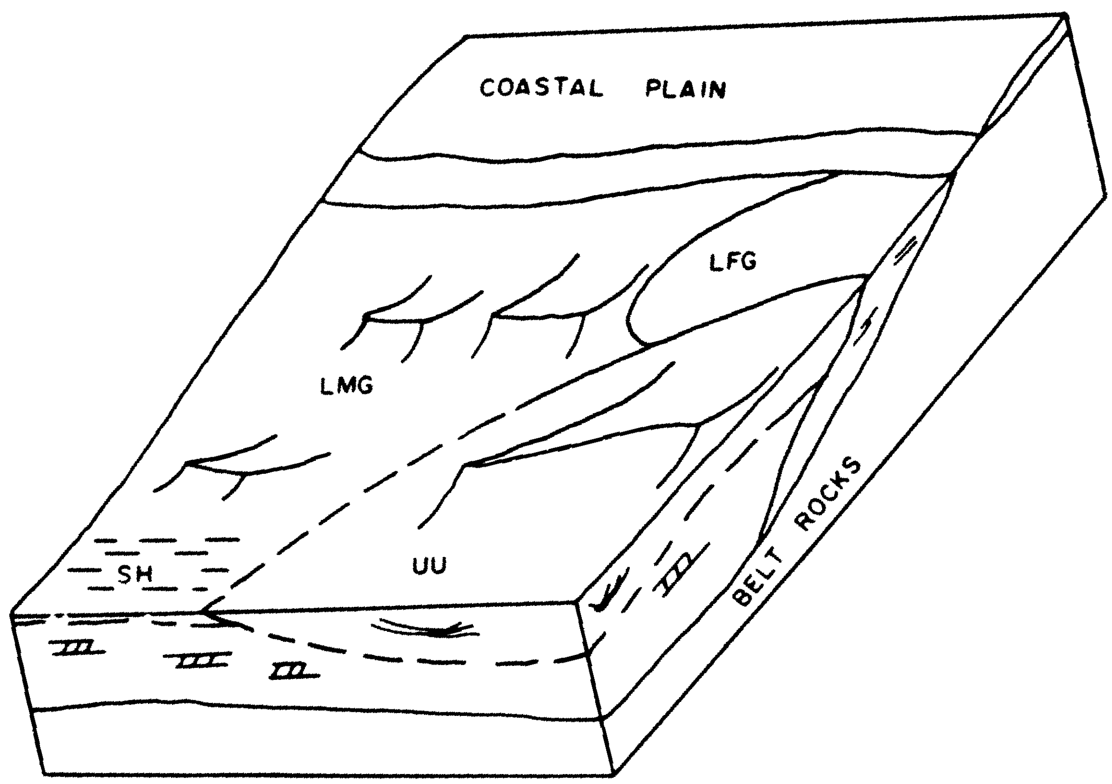


Fig. 26. Schematic diagram of depositional model. See text for explanations. LMF = Lower medium-grained facies, LFG = Lower fine-grained facies, UU = Upper unit, SH = overlying shales.

facies was deposited inshore of the lower medium-grained facies; and the weak bi-modal distribution of crossbeds within the lower fine-grained facies may indicate alternating currents controlled deposition (fig. 21). Erosion shoreward of the depositional strike of the lowest Flathead units removed the fine-grained nearshore deposits and the sediment veneer lying above the Precambrian rocks; and left only occasional lag concentrations of clay chips or clasts of underlying Belt rocks on the scoured surface. This erosion zone may record the shoreline of the transgressing Cambrian seas.

Bedforms similar to the straight-crested bedforms which produced the tabular sets of high angle crossbeds within the lower medium-grained facies develop in the North Sea (McCave, 1971) and bays (Salsman and others, 1966; Allen and Friend, 1976; Rubin and McCulloch, 1980); where tide generated currents often reach velocities between 0.5 and 1.7 m/sec. (Salsman and others, 1966; Rubin and McCulloch, 1980; Allen and Friend, 1976; De Mowbray and Visser, 1984; Terwindt and Brouwer, 1986). Long-lived sandwaves in St. Andrew Bay, Florida, migrate with the dominant tide and deposit cross stratified layers up to 10 cm thick (Salsman and others, 1966; Rubin and Hunter, 1982).

These bedforms are also common in fluvial systems (Smith, 1970; Reineck and Singh, 1980; Crowley, 1983), and intertidal areas (Reineck and Singh, 1980; Clifton, 1982). However, the lack of abundant well defined channels, fining upward sequences, and overbank deposits probably preclude braided stream deposition. In Wyoming and Arizona, fluvial facies of the Flathead and other cratonic sandstones contain abundant and distinct channels (Bell, 1970; Hereford, 1977; Dott and others, 1986). The paucity or absence of channels at outcrop also indicates that the lower unit does not record the upper reaches of intertidal sandflats or estuary deposits (Reineck and Singh, 1980; Clifton, 1982; Weimer and others, 1982).

West of the Philipsburg thrust at Stone and Willow Creek Reservoir, the locally thick upper unit records an isolated or only locally preserved offshore sandwave field. Although bedforms of the lower medium-grained facies generally graded into the larger, more complex bedforms of the upper facies, the large sandwaves occasionally scoured down into the lower unit and lie sharply on the lower fine-grained facies at Porter's Corner. As the transgression progressed, the limit of sand deposition moved eastward and marine deposition of the Middle Cambrian Silver Hill shale covered the inshore sand.

The lack of any body fossils in a marine sandstone may be unusual. However, the medium grain size and abundant crossbedding within the lower medium-grained facies indicate the environment experienced periodic high energy conditions. The tests of any animals living in such an environment would probably be rapidly abraded and removed from the system.

COMPARISON TO MODERN EXAMPLES

The stratigraphic sequence of coarsening upward, thickening upward sandstone beds recorded in the Flathead is modeled in the modern North Sea and some large bays. North of the Dutch coast and in San

Francisco Bay, sandwave height and sediment size increase away from shore (McCave, 1971; Rubin and McCulloch, 1980). Sediment size also increases offshore in the Bay of Fundy (Klein, 1970).

A preserved transgressive sequence formed by landward migration of North Sea bedforms would produce a coarsening upward, thickening upward sequence created by progressively larger bedforms, and overlain by marine terrigenous mud. That hypothesized sequence would be nearly identical to the sequence preserved within the Flathead in west central Montana.

The tallest sandwaves within 5 km of the Dutch coast are 2 m tall (McCave, 1971). Sandwaves do not appear closer than 5 km to the shore, or in water less than 15 m deep; probably due to wave action on the ocean floor (McCave, 1971). These data do not agree with the 0.25 to 1 m-tall bedforms migrating in water less than 5 m deep as predicted for the lower medium-grained facies of the Flathead. Smaller bedforms would probably develop closer to shore in an environment protected by offshore carbonate buildups, and in large semi-protected bays.

The thick planar crossbed sets within the lower medium-grained facies record migrating bars which exist in beach and nearshore environments (Hunter and others, 1979), or alternately could record preserved parent bedforms which deposited tabular crossbed sets in the lower medium-grained facies.

In the southern North Sea Bight, sandwaves up to 7 m tall occur in fields; and migrate along the ocean floor (McCave, 1971). Similar sandwaves migrate in the Bearing Sea (Field and others, 1981), off the east coast of North America, (Swift and others, 1979), and off the coast of Normandy (Berne and others, 1988). The large sandwaves probably deposit, thick, complex crossbeds similar to those in the upper unit of the Flathead (De Raaf and Boersma, 1971; McCave, 1971; Terwindt, 1971, 1981; Visser, 1980; Boersma and Terwindt, 1981; De Mowbray and Visser, 1984; Berne and others, 1988).

Within the North Sea, sandwaves migrate parallel to the shore in the direction of the dominant tide current (McCave, 1971), and on unprotected shelves sandwaves migrate with ocean, tide, or storm induced currents (Field and others, 1981; Swift and others, 1979). By analogy to these modern bedforms, the dominant westward orientation of crossbeds within the upper unit of the Flathead indicates that the currents were west directed. Periodic rapid sandwave migration during storms has been inferred for the large North Sea sandwaves (McCave, 1971), and it is reasonable to assume that mud accumulates on the sandwaves during inactive periods. Simlar mud accumulations may be recorded by mud drapes on the thick complex crossbeds at Willow Creek Reservoir.

ANCIENT EXAMPLES

Several studies have documented other coarsening upward, thickening upward sandstone sequences and interpreted as recording nearshore marine tide dominated deposition overlain by deeper, coarser grained, thicker and more complexly crossbedded sandbar or sandwave deposits (Nio, 1976; Hereford, 1977; Hobday and Tankard, 1978). Nio (1976) describes five examples of coarsening upward, thickening upward sequences in Europe and interprets them as nearshore tide deposits overlain by thick, complexly crossbedded sandstone beds which record tidal sandwaves up to 20 m-tall. Hobday and Tankard (1978) describe a similar sequence from the Pre-Cambrian Peninsula Fm. of South Africa. Hereford (1977) describes two facies within the Cambrian Tapeats Sandstone of Arizona which together form a coarsening upward sequence where crossbeds increase in size and complexity upward. Nio (1976) Hobday and Tankard (1978), Cotter (1983), Blakely (1984), and Soegaard and Erickson (1985) describe complex crossbed sets similar to those in the upper Flathead unit at Willow Creek Reservoir and interpret them as large, preserved tidal sandwaves.

SUMMARY

The Flathead Sandstone in west-central Montana consists of two stratigraphic units which record continuous deposition in a deepening marine environment. The lower Flathead records deposition by 0.25 to 1 m-tall bedforms with west-dipping slipfaces; and grade up into complexly crossbedded medium- and coarse-grained sand deposited further offshore. The upper, offshore sand interbeds with trilobite-bearing shales.

The trangressive sandstones were long thought to record exclusive nearshore marine depostion (Deiss, 1941), but recent research has demonstrated that the thin sand sheets record a complex association of eolian, braided stream and coastal plain deposits overlain by marine sediments (Bell, 1970; Hereford, 1977; Bell and Middleton, 1978; Klein, 1982; Dott and others, 1986). In west-central Montana, however, the Flathead Sandstone records marine sand deposition in a deepening marine setting.

APPENDIX A

PRE-FLATHEAD ATTITUDES OF BELT ROCKS

See figure 1 for section abbreviations and appendix B section locations.

Sec.	Flathead Attitude	Belt Attitude	Pre-Flathead Attitude	Belt Unit
BC	N10E 35SE N3E 39SE N1W 45NE	N1E 35SE	N9E 6NW	MT. SH. 2
CC	N15E 24NW N30E 29NW N19E 21NW	N20E 21NW N30E 18NW	N23E 5SE	MACNAMARA
CR	N20E 41NW N18E 54NW N21E 46NW	N23E 56NW N30E 54NW N30E 35NW N25E 55NW	N57E 5NW	SNOWSLIP
DC	N56W 7SW N43W 8SW	N30W 5SW N75W 7SW	HORZ.	PILCHER
HM	N65W 25NE N60W 30NE	N90W 26N N80W 35NE N70W 23NE N80W 25NE	N11E 8NW	GARNET R.
LC	N53E 60NW N54E 59NW N51E 51NW N60E 56NW	N57E 44NW	N38E 12SE	MT. SH. 2

LMP	N5E 22NW N11E 17NW N37W 12SW N15W 6SW N1E 22SW N15W 20SW N8E 17NW N7E 18NW N35E 25NW N12E 12NW N7E 22NW N5W 18SW N17W 20SW N15W 17SW	N50W 28NE	N85W 20SW	MT. SH. 2

Sec.	Flathead Attitude	Belt Attitude	Pre-Flathead Attitude	Belt Unit
MT	N75E 38NW	N70E 37NW N75E 40NW N77E 38NW	HORZ.	SNOWSLIP
OM	N25W 12NE N65W 10NE N45W 7NE N30W 10NE N56W 12NE N68W 10NE	N75W 14NE N85E 14NE N90W 16N N75E 9NW N85E 14NW N80W 14NE N89E 19NW N82W 16NE N89E 15NW	N49E 10NW	MT. SH. 2
PC	N45E 41NW N43E 45NW	N45E 41NW N45E 45NW N45E 43NW	HORZ.	PILCHER
RCL-N (OT)	N14E 29SE N6E 29SE	N2E 27SE	HORZ.	MT. SH. 2
RCL-S (OT)	N35E 15SE N30E 28SE	N30E 27SE	HORZ.	MT. SH. 2
RL(OT)	N55E 74SE N60E 76SE	N55E 71SE N55E 76SE N55E 71SE	HORZ.	BONNER
RM	N35E 65NW N43E 67NW	N45E 65NW N42E 64NW	HORZ.	SNOWSLIP
SH	N60E 25NW N50E 27NW	N50E 27NW N50E 23NW N45E 25NW	HORZ.	SNOWSLIP

SLR	N60E 36NW	N75E 30NW N60E 33NW N60E 30NW N53E 32NW	HORZ.	SNOWSLIP
STONE	N40E 40SE N39E 42SE N39E 47SE N29E 47SE N45E 55SE N35E 55SE N30E 38SE N30E 41SE N45E 31SE	N45E 55SE N43E 54SE N44E 52SE	N81E 11SE	MACNAMARA

Sec.	Flathead Attitude	Belt Attitude	Pre-Flathead Attitude	Belt Unit
UMP	N21W 34SW N35W 43SW N37W 36NW N50W 32SW	N43E 19NW	N68W 36NE	MT. SH. 2
WCR	N25W 9NW N15W 12NE	N45W 10NE N40W 12NE	N40W 2SW	MACNAMARA

APPENDIX B

Descriptions for detailed sections are presented here first. General section descriptions and locations of structural data control are presented at the end of the appendix.

DEEP CREEK SECTION

LOCATION: NE NE Sec. 12, T. 12 N., R. 14 W., Granite County, MT.

29 to 30 m medium fine grained pink quartz sandstone, occasional 10 cm thick sets of high angle cross beds.

28.5 to 29 m medium to medium fine grained sandstone with .4 m thick sets of opposing high angle crossbeds.

28 to 28.5 m medium to medium fine grained sandstone, high angle .4 m thick set of high angle planar crossbeds,

27.5 to 28 m slabby medium to medium fine grained beds, 10-20 cm thick.

26 to 27.5 m medium to medium fine grained, well indurated sandstone, 10 cm thick laminae making up .4 m thick beds.

25 to 26 m medium fine grained, pink and purple well indurated quartzite, .4 m thick planer high angle crossbeds.

22 to 25 m medium to fine grained, moderately well sorted, well indurated pink, tan, purple quartz sandstone, rate crossbeds, occasional red grains.

21 to 22 m cleaved and fractured

18 to 21 m medium fine to medium grained pink to tan quartzite, .4 m thick beds, occasional 10-30 cm thick high angle crossbed sets, occasional red grains, very well indurated.

17 to 18 m medium to medium fine grained quartz sandstone, 40 cm thick sets of high angle planar crossbeds, very well indurated.

16 to 17 m fine to occasionally medium grained pink and buff, 10-20 cm thick crossbed sets.

15.5 to 16 m wedge shaped bed, medium to fine grained, well sorted, parallel internal laminae, very well indurated.

12 to 15.5 m medium to fine grained generally medium fine grained well sorted quartz sandstone, occasional medium grains, sets of

crossbeds 10 cm thick, purple and pink, beds .4 m thick, well indurated.

TOP OF PILCHER

0 to 12 m purple, medium to fine grained, well indurated, well sorted, rounded quartz sandstone, sightly micaceous on bedding planes, well defined purple and white 10 cm thick crossbed sets.

HASMARK SECTION

LOCATION: SE 1/4, SE 1/4, Sec. 30, T. 7 N, R. 13 W., Granite Co., MT

DESCRIPTION:

15 to 15.4 m medium-grained quartz sandstone, well indurated, vitreous, red stained, bedding 50 to 80 cm, coarse-grained sand at 15.4 m.

10.9 to 15 m coarse- and medium-grained sandstone, occasionally fine-grained, agrillaceous in upper 40 cm, bedding surfaces irregular, rare high angle crossbed sets.

9.5 to 10.9 m medium-grained quartz sandstone, as below, slightly recessive weathering.

6.5 to 9.5 m medium- to fine-grained quartz sandstone, well indurated, red and vitreous, iron stained, occasional 5 cm-thick high angle and trough crossbeds, occasional wedge-shaped beds, occasionally argillaceous (?).

6 to 6.5 m fine- to medium-grained quartz sandstone as below, massive, parallel laminations.

0 to 6 m medium-grained, occasionally fine- and coarse-grained, vitreous, clear to red and white, occasional intergranular iron stain, generally moderately to well sorted, very well indurated, hornfelsed quartz sandstone, beds 0.6 m thick, high angle crossbeds in poorly defined sets, lies above weathered zone with iron stained and dull green clasts.

LOWER MULLAN PASS

LOCATION: SE 1/4, NW 1/4, Sec. 1, T. 10 N, R. 5 W, Lewis and Clark Co., MT.

DESCRIPTION:

31 to 36 m medium- to coarse-grained, red and pink well indurated pure quartz sandstone, thick bedded, with common sets of 30 cm-thick planar crossbeds.

26.5 to 31 m covered

15 m to 26.5 m red and white, vitreous, medium-grained, well indurated, occasionally slabby, medium- to thick-bedded quartz sandstone with 5 to 10 cm-thick sets of high angle crossbeds.

0 to 15 m covered. Base of section marked by last occurrence of Mt. Shields Fm float. Base contains conglomerate with clasts of underlying unit.

MAXVILLE SECTION

LOCATION: NW 1/4 SE 1/4 Sec. 15, T. 8 N., R. 13 W., Granite County, MT

23.5 to 24 m medium to coarse grained moderately indurated, buff sandstone with opposing intertongueing crossbeds, weathers back.

21 to 23.5 m medium fine to medium coarse grained sand, occasional mud chips at 21.8 and 22.3 m, 10 cm thick high angle crossbeds, occasional coarse sand along bedding planes, well indurated, occasional slabby beds 10 cm thick.

20.5 to 21 m moderately sorted medium fine to medium coarse sandstone, well indurated, occasional clay along bedding surfaces, coarse sand along laminae.

17.8 to 20.5 m medium coarse to coarse grained sandstone, occasional strings of very coarse sand and granules parallel to and on bedding surfaces, occasional 5-20 cm thick sets of high angle crossbeds, occasional slabby beds 10 cm thick.

17.5 to 17.8 m gravely sand

13.5 to 17.5 m medium to medium-fine grained well indurated sandstone, well sorted with occasional strings of medium-coarse grained sand, clay partings on beds at 14.5, 15.5 m. Occasional high angle crossbeds, beds break into 5 to 20 cm thick slabs, occasional slabby 10 cm-thick beds, beds occasionally wedge shaped, rare concentrations of coarse sand grains on upper and lower bedding surfaces.

12.5 to 13.5 m medium coarse occasionally poorly sorted quartz sandstone, occasional 15 cm thick crossbeds.

10.8 to 12.5 m medium fine grained pink and buff sandstone, occasional 5-15 cm thick laminae, occasional high angle crossbeds, rare ripple in fine sand at 12.2 m

10.3 to 10.8 m medium fine grained well sorted sandstone, .5 m thick high angle planer crossbeds.

8.5 to 10.3 m medium to fine grained pink quartzite, .4-.6 m thick beds, occasional 5-10 cm thick sets of high angle crossbeds.

7.5 to 8.5 m covered

6 to 7.5 m vitreous white and red, fine- to medium-grained sandstone, well sorted, rare coarse sand grains in matrix, rare high angle crossbeds, occasionally moderately indurated, occasionally slightly friable.

4 to 6 m fine- and medium-grained quartz sandstone, vitreous, well indurated, low angle crossbeds, limonite stain, rare strings of medium grained sand parallel to bedding, occasionally moderately indurated.

3 to 4 m medium fine grained quartz sandstone, occasional 5--20 cm thick sets of high angle crossbeds, well indurated, occasional limonite stain.
2-3 m covered

1-2 m moderately sorted, medium to fine grained sandstone, red and purple, occasional high angle crossbeds 10 cm thick.

0-1 m covered

PORTER'S CORNER

LOCATION: SW 1/4, NE 1/4, Sec. 27, T.6 N., R.14 W., Granite County, MT.

9.2-9.7 m Coarse-grained, moderately to well indurated, rounded, well sorted, white to clear quartz sandstone, with green mud drapes within and covering beds and crossbed laminae, .3 m thick high angle crossbeds. Overlain by red shales and medium and fine qrained sandstone.

4.5-9.2 m Fine-grained, pink well sorted, rounded to well rounded, well indurated, homogeneous pink quartz arenite, common parallel laminae defined by dark minerals, oxidized (red) laminae, rare sweeping crossbed toes, rare layers of medium-grained sand, rare mud drapes between beds, rare green mud layers within beds, even bedded, more dark minerals than below.

0-4.5 m Fine-grained pink, well sorted, rounded to well rounded, very well indurated, homogeneous, quartz arenite with parallel laminae (1-5 cm spacing), rare sets of 5-10 cm parallel crossbeds. Rare green mud layers between beds, rare thin (<1 mm) overlain by bed with wide shallow scour, .5 m deep, 9 m long.

STONE SECTION

Location: NE 1/4, SW 1/4, Sec. 27, T. 9 N., R. 13 W., Granite County, MT Section is exposed in a small quarry visible from U.S. Highway 10 A.

110 to 114 m medium- and coarse-grained sandstone, occasional high angle crossbeds, occasional opposing crossbeds.

109 to 110 m covered

105 to 109 m medium- to fine-grained sandstone, occasional coarse grains defining crossbed laminae, slabby opposing crossbeds.

103.5 to 105 m covered

100 to 103.5 m medium- to fine-grained sandstone, rare 20 cm thick sets of high angle crossbeds, slabby, occasional slabby opposing crossbeds, coarse sand grains on crossbed laminae, rare mud chips.

98.5 to 100 m covered

95 to 98.5 m medium- to fine-grained sandstone, slabby beds separated by argillaceous layers and layers of very-coarse sand, beds slightly graded, mud chips at 96 m, occasional 10-20 cm thick sets of high angle crossbeds, recessive weathering.

93 to 95 m covered

89 to 93 m fine- to medium-grained sandstone, moderately sorted, occasional coarse grains in layers and stringers, poorly defined bedding, moderately indurated, 40 cm thick sets of opposing intertonguing crossbeds.

87 to 89 m covered

83 to 87 m medium- to fine-grained sandstone, slightly friable, opposing intertonguing crossbeds, rare clay drapes at toes of crossbeds.

81 to 83 m medium- to fine-grained sandstone, slightly friable, wedge shaped sets of 10-20 cm-thick high angle crossbeds, slightly recessive.

76 to 83 m medium- to fine-grained sandstone, .4 to .8 m thick beds, sets of 10-20 cm thick high angle cross beds.

71 to 76 m fine-grained well sorted quartz sandstone, cleaved, .4 to .8 m thick beds, some 10 cm thick layers within beds; some parallel laminations.

66 to 71 m poorly sorted fine- to coarse-grained vitreous quartzite, rare red mud chips at base, quartz pebble conglomerate at 69 m, .4 to .8 m thick beds, occasional 10 cm thick sets of high angle crossbeds, rare opposing crossbeds.

WILLOW CREEK RESERVOIR SECTION

Loction: NE SE Sec. 2, T. 9 N., R. 8 W., Granite County, MT

NOTE: Section measured on cliff above reservoir. There are three separate cliffs expose above the reservoir, each separated by down to the east normal faults.

DESCRIPTION:

64.5-74 m fine-grained to very coarse-grained sandstone, generally very well indurated where ledges form, irregular bedding, rare green mud chips throughout, occasional layers of well sorted very coarse sand, complex crossbeds, beds crudely graded, occasional limonite stain, weather buff and tan, rare green sandy shale exposed on ledges, crossbeds 0.2 to 2.0 m tall.

62-64.5 m well indurated very coarse to medium- and fine-grained sandstone, beds 0.2 to 0.6 m thick, occasionally distinct 0.2 to 0.4 m-thick crossbeds, bedding forms ledges, irregular bedding.

60-62 m complexly crossbedded, irregularly bedded, medium- to very-coarse-grained sandstone, moderately indurated, occasional green mud chips, slabby crossbed laminae, argillaceous ?, buff to tan, occasionally vitreous on fresh surfaces, laminae graded, recessive weathering.

49.5-60 m medium- to coarse-grained, very well indurated to slightly friable sandstone, red, white, and tan, occasionally vitreous, 0.4 to 0.8 m thick beds, occasional slabby units at 51, 53 m, beds occasionally wedge shaped, occasional large (30-40 cm) crossbeds.

46-49.5 m 0.5 to 0.8 m-thick beds, granules to medium-grained sand, tabular 20-30 cm thick slabs, occasionally with 5 to 20 cm thick sets of high angle crossbeds, becomes slabby towards top, well indurated, buff to tan weathering.

45.5-46 m moderately indurated, slightly argillaceous, buff-weathering, medium- to coarse-grained quartz sandstone, occasional mud chips, 5 to 10 cm-thick high angle crossbeds, occasionally pebbly, crossbeds graded.

38.6-45.5 m 0.3 to 0.8 m thick beds with 5-20 cm thick slabs, slabs generally normally graded, very well indurated, dull to vitreous, medium to very coarse grained, rare mud chips at 39.5, 42.0, 42.7, 44.0 m, slabby bed at 42 m, beds occasionally wedge shaped, scour surfaces (?) in slabby beds 42-44 m, occasionally limonite stained, dark oil (?) stain near base, occasional high angle crossbeds in layers and slabs, tops of beds often wavey and undulating.

38.1-38.6 m white, vitreous, red stained, medium- to coarse-grained, slabby, slabs with high angle crossbeds, slabs generally very well indurated, becomes more slabby at top, slabs normally graded, beds occasionally wedge shaped, occasional dark oil (?) stain, locally heavily cleaved, occasional channels(?) in slabby intervals.

37.3-38.1 m medium- to coarse-grained sandstone, high angle crossbeds capped by 10 cm thick slabby layer.

37.0-37.3 m 10 cm-thick slabby beds, as below.

36-37.0 m Coarse to fine grained, moderately sorted beds, rare mud chips, very well indurated, cream to tan, rare dark stain, beds 50 cm thick, made of 10 cm-thick slabs, rare green mud chips, layers occasionally slightly to strongly graded from v. coarse- to medium-grained sand, high angle planar and trough crossbeds in layers, vitreous to dull, rare limonite stain, occasionally slightly friable around jointing

UPPER MULLAN PASS

LOCATION: SE 1/4, NW 1/4, Sec. 2, T. 10 N, R. 5 W, Lewis and Clark Co., MT

DESCRIPTION:

7 to 12 m red and white, hornfelsed, medium- to very-coarse-grained rounded, moderately to poorly sorted, medium- to thick-bedded, quartz sandstone with 5 to 10 cm thick high angle crossbed sets.

0 to 7 m covered

BLACKFOOT CITY

LOCATION: NW 1/4, NE 1/4, Sec. 13, T. 11 N, R. 8 W, Powell Co., MT

This section was used for structural data only, presented in Appendix A.

CARPP RIDGE

LOCATION: UTM Grid 5100,500 N; 314,000 E Granite Co., MT

DESCRIPTION:

10.5 to 27 m heavily cleaved, very well indurated, white and vitreous, medium- to fine-grained quartz sandstone with red iron stain, occasional trough crossbeds and mud chips.

6.2 to 10.5 m medium- to fine-grained, white and vitreous quartz sandstone with occasional heavy mineral layers defining low angle crossbeds, rare discontinuous mud drapes, occasionally heavily cleaved, occasional high angle crossbeds.

3 to 6.2 m coarse- to occasionally medium-grained, well indurated, white and vitreous, iron stained, occasional pebbles and layers of very coarse sand grains.

0 to 3 m medium- to fine-grained white, vitreous very well indurated, iron stained moderately sorted quartz sandstone with green mudchip and quartz pebble conglomerate at base, quartz pebbles up to 4 cm in diameter, occasional high angle crossbeds.

CLARKS CANYON

LOCATION: SW 1/4, SW 1/4, Sec. 2, T. 10 N, R. 7 W, Powell Co. MT.

This section is covered and is 33 m thick as measured with a jacobs staff and contacts picked by last occurences.

LOST CREEK

LOCATION: NE 1/4, SE 1/4, Sec. 36, T. 6 N, R. 12 W, Deer Lodge Co., MT

This section lies in the hinge of a fold, and was used for structural data only, presented in Appendix A.

MOUNT TINY

LOCATION: UTM Grid 5103,400 N; 323,000 E; Granite Co., MT Located on ridge extending northwest from Mt. Tiny

This section was used for structural data only, presented in Appendix A.

OLSON MOUNTAIN

LOCATION: NE 1/4, SW 1/4, Sec. 2, T. 5 N, R. 12 W., Granite Co., MT

DESCRIPTION:

0 to 18 m fine- to medium-grained, white and red stained, vitreous, very well indurated, moderately sorted quartz sanstone, withh occasional 10 cm thick parallel layers or low angle crossbeds.

RAINBOW MOUNTAIN

LOCATION: UTM Grid 5102,450 N; 320,500 E; Granite Co., MT Located on ridge extending northwest from Rainbow Mountain.

This section was used for structural data only, presented in Appendix A.

RED LION

LOCATION: NE 14/4, SW 1/4, Sec. 13, T. 6 N, R. 13 W, Granite Co., MT

DESCRIPTION

13 to 18 m medium- to fine-grained white, vitreous, well sorted, hornfelsed white and limonite stained quartz sandstone.

12 to 13 m fine- to medium-grained, pure quatrz sandstone, generally vitreous, with green clasts of argillaceous fine-grained sandstone up to 12 cm floating in matrix and concentrated near bottoms of beds.

7.5 to 12 m fine- to medium grained, pure well sorted, well indurated, hornfeldsed, iron stained, thick-bedded, white, vitreous, quartz sandstone with occasional euhedral iron staining opaque minerals. Beds occasionally separate into 10 to 20 cm-thick layers and slabs.

2.5 to 7.5 m medium- to fine-grained, well sorted, moderately to well rounded occasionally limonite stained, pure quartz sandstone with parallel laminations and low angle crossbeds.

TOP OF BONNER FORMATION

0 to 2.5 m White vitreous and dull, slightly felspathic, fine-grained, hornfelsed, well to moderately sorted quartz sandstone with rare green micaceous partings on bedding surfaces.

ROCK CREEK LAKE-NORTH

LOCATION: NW 1/4, NW 1/4, Sec. 26, T. 8 N, R. 11 W., Powell Co., MT

This section was used for structural data only, presented in Appendix A.

ROCK CREEK LAKE-SOUTH

LOCATION: SW 1/4, SW 1/4, Sec. 27, T. 8 N, R. 11 W., Powell Co. MT.

This exposure was used for structural data only, presented in appendix A.

SILVER HILL

LOCATION: SW 1/4 NW 1/4, Sec. 33, T. 5 N., R. 13 W., Deer Lodge Co., MT

40.5 to 42 m coarse- to medium-grained, dull weathering, argillaceous (?), hornfelsed, buff and red to pale green, calcareous, poorly sorted sandstone.

6 to 40.5 m medium- to fine-grained, very well indurated, hornfelsed, buff to vitreous, occasionally limonite stained, cleaved, pure quartz sandstone, occasional bedding parallel red oxidized layers, occasional euhedral heavy minerals.

TOP OF SNOWSLIP FORMATION

0 to 6 m medium- to fine-grained, feldspatic, dull, white to pale green, well sorted, well indurated, slightly hornfelsed quartz sandstone, mica on bedding planes near base.

STORM LAKE RIDGE

LOCATION: UTM Grid 5104,100 N; 323,900 E; Deer Lodge Co., MT
Located on ridge extending north from Mount Tiny, west of Storm Lake.

This section was used for structural data only, presented in Appendix A.

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