Carbonate petrology of the "upper Hasmark" Cambrian of southwestern Montana

Monte Laurence Pearson

*The University of Montana*

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CARBONATE PETROLOGY OF THE "UPPER HASMARK",
CAMBRIAN, OF SOUTHWESTERN MONTANA

by

Monte L. Pearson

B. A., University of Montana, 1972

Presented in partial fulfillment of the requirements for the degree of

Master of Science

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Interpretations of the Cambrian "upper Hasmark" carbonate facies in southwestern Montana are based on data from 6 measured sections, more than 420 thin sections, and 1480 polished slabs. In southwestern Montana, Cambrian carbonate deposition occurred across a subtidal shelf area, while to the east laterally-equivalent tidal to supertidal carbonates of the Pilgrim and Park formations were deposited. This study divided the "upper Hasmark" into two units, representing different depositional environments; phase (A) initial transgression across the shelf by the Cambrian sea to the craton, phase (B) regression of the Cambrian sea off the craton.

Phase (A) represents a transgressive subtidal phase during which extensive accumulations of algal stromatolite beds and finely laminated carbonate mud were deposited. The facies relationships, patterns, and sediment accumulation were controlled by current energy and water depth.

Phase (B) represents a regressive phase, with influx of clastic sediments from small positive areas to the west. Westward-flowing streams also transported clastic sediment from the craton into the Cambrian sea. This quartz blanketed the carbonate sediments of phase (A), producing the phase (B) low-energy sandy carbonate units. Minor amounts of laminated carbonate mud, algal stromatolites, and carbonate intraclasts were also deposited.

Upper Hasmark sediments were altered by stylolitization, dolomitization, and cementation. Two stages of stylolitization occurred. Early in the diagenesis and cementation history, horizontal stylolites developed, parallel to the carbonate lamination and algal stromatolite laminations. The laminations, natural zones of weakness, facilitated the stylolite development, and served as a passageway for high Ca/Mg solutions. Abnormally high Ca/Mg solutions, produced by dissolution of the carbonate sediments and decay of the algal sheaths, facilitated early dolomitization. Massive dolomitization of the laminated boundstone and bedded algal boundstone was hindered by the network of early cementation and horizontal stylolites. The second phase of stylolite development was produced during late diagenesis, related to extreme overburden and intense tectonic activity. This phase of stylolitization, vertical-inclined (horizontal) crosscutting and interconnected network, caused selective massive dolomitization of the "upper Hasmark".
ACKNOWLEDGMENTS

Many people were involved in all phases of this thesis work. However, special thanks and great appreciation are extended to my advisor and good friend, Dr. James A. Peterson, for his invaluable help in field work, thin section analysis, and providing thoughtful questions throughout this thesis. Special thanks are extended to Dr. Don Winston for the many hours of help with the thin section analysis and all the suggestions on environmental interpretation. Thanks are also extended to Dr. Robert Weidman, Dr. James Cox, and Col. Julien LePage for their subjective review of the manuscript, Russ Tysdal for mailing his thin sections and detailed notes on his measured sections, and special thanks to the Cadre of the Army R.O.T.C. Department for the special momento of inspiration during difficult periods, especially Lt. Col. Clearman and fellow armor officer, Captain Moreland.

Finally, special thanks are saved for my wife, Lois, who helped in all phases of the thesis, carrying rocks from the field, watching for wood ticks, note taking, and especially all of the many hours she spent typing the manuscript.
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CHAPTER I
INTRODUCTION

The purpose of this investigation was to define and interpret the depositional environments of the "upper Hasmark" member of the Hasmark Formation, Upper Cambrian, in southwestern Montana (Figs. 1 & 2). Work completed by Tysdal (1970) formed a basis for detailed study of the "upper Hasmark", and the lithofacies and lithologic units used in his work were employed whenever possible.

Hanson (1952, Plate 8) illustrated the correlation between the Hasmark Formation of western Montana and the Meagher Formation, Park Shale, and the Pilgrim Formation of central Montana. The Meagher and Pilgrim formations are predominately limestone, and have received considerably greater study than the Hasmark which is a dolomite. This thesis study was undertaken as an attempt to determine if detailed petrographic work would provide sufficient information to make reasonable environmental interpretations of the Hasmark Formation.

Study Method

The "upper Hasmark" member, which includes the interval between the Park Shale and the base of the Red Lion Formation (Fig. 3), was measured, sampled and described at six localities in western Montana (Fig. 1 & Appendix B) during the summer and fall of 1972 and 1973. Field descriptions were somewhat generalized and were mainly for the
Fig. 1. Location Map of Study Area and Measured Sections.
Fig. 2. General Regional distribution of Cambrian rocks and paleogeologic features modified from Lochman-Balk 1970, Palmer (1970), Tysdal (1970), Grant (1965).
purpose of referencing outcrop samples to the thin sections. The measured section descriptions in Appendix C were compiled entirely from thin section and polished slab descriptions. Four hundred and twenty-one thin sections and one thousand four hundred and eighty-one polished slabs were cut from two thousand four hundred and ninety field samples, and the thin sections were petrographically examined and described. Polished slabs were submerged in ten percent HCl, then bathed in H$_2$O and examined under a binocular microscope.

Dunham's (1962) classification of carbonate rocks was used in this study. Table 1 shows this classification, which places major emphasis on depositional textures, sorting and depositional fabric, and minor emphasis on energy indicators, cementation and recrystallization. Dunham defined the term "mud" as carbonate crystals of less than 20 microns and "grains" as carbonate constituents of greater than 20 microns.

The following features were emphasized in thin section and slab examination:

a. Structure - lamination, burrowing, etc.
b. Texture - relationship of the dolomite rhombs to matrix
c. Alterations - such as dolomitization, stylolites
d. Algal Structures - mats, domes, columns
e. Mottling - solution effects, cementation

The measured section information combined with published information were used in the palinspastic considerations and in attempting to determine facies belts within the "upper Hasmark".

Method of Lithofacies Correlation

Stratigraphic correlations and lateral facies interpretations are
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### Fig. 3. Correlation chart for Middle and Upper Cambrian rocks in Montana.

Positioning of formation contacts is approximate because of limited data and recent revision of faunal zones. Sources of data include Howell and others (1944), Hanson (1952), McMannis (1955), Alexander (1955), McGill (1958), Kauffman (1963, 1965), Robinson (1963), Grant (1965), Tysdal (1966, 1970), Deiss (1938), Maxwell (1959), Calkins and Emmons (1915), and this report.
normally based on established time horizons. Due to the dolomitization of the Hasmark, establishment of faunal zones and detailed stratigraphic correlations are not possible. However, using Walther's Law (e.g., Visher, 1965) which states that lateral positioning of sedimentary facies tends to be similar to that of their vertical superposition, an interpretation of facies position was possible.

**Previous Work**

Previous studies of the Upper Cambrian strata, including the Hasmark Formation, in southwestern Montana have been conducted by numerous authors. Most of these early works dealt with ore deposits, structural considerations, plus general mapping, and only a few with the general stratigraphy of the Hasmark.

Willis (1912) in a paper entitled, "Index to the Stratigraphy of North America" included a condensed discussion of the Cambrian of the Philipsburg area. This discussion was based on an earlier manuscript on the ore deposits of the area by Calkins (1911), who named the formation. Calkins' manuscript, however, was not published until 1913, and in the same year Calkins and Emmons (1915) published a folio which included a map and a discussion on the general stratigraphy of the Philipsburg Quadrangle. The Hasmark Formation (Calkins, 1913), was named after a nearly abandoned settlement located about three miles southeast of Philipsburg, Montana.

Clapp's (1932) map also includes part of this area. The Anaconda Company has an unpublished map, by Grimes and Rosenkranz (1919), reported by Maxwell (1965), that includes the study area, but was not available for this present reporter. The remaining parts of the Philipsburg
and Drummond areas were mapped during the late 1950's and early 1960's by Poulter (1958), Maxwell (1959), Gwinn (1961) and Kauffman (1963). Nelson and Dobell (1961) mapped the Bonner Quadrangle which includes some outcrops of the Hasmark. McMurtrey and others (1965) mapped the Missoula Basin which includes mainly Tertiary and younger sediments. Wells, of the U.S.G.S., is currently mapping the Alberton Quadrangle, and the preliminary results are expected to be published in the summer of 1974. Hall (1969) mapped the area generally south and southwest of the Alberton Quadrangle. Several areas of southwestern Montana have not yet been mapped in detail, so the possibility remains that other outcrops of the Hasmark may yet be found. Hanson (1952) published a comprehensive report on the Cambrian stratigraphy in southwestern Montana, and most subsequent studies have expanded on the basic material of his paper. Earlier work by Charles F. Deiss (1933, 1935, 1936, 1938) and others provided the initial foundations for understanding the Cambrian stratigraphy of western Montana.

Cambrian Nomenclature

Cambrian rocks recognized in southwestern Montana are Middle and Upper Cambrian in age. In the study area, the Cambrian units from oldest to youngest are the Flathead Sandstone, Silver Hill Formation, Hasmark Formation, and Red Lion Formation. Several correlations have been proposed for the Cambrian rocks of this and adjacent areas: Emmons and Calkins (1915), Howell and others (1944), Lochman and Duncan (1944), Deiss (1939) and Lochman (1940). As paleontological information was added to Cambrian stratigraphic data, the correlations proposed by Sahinen (1950) and Hanson (1952, 1957) were further verified and became more or less the standard for later investigations. Lochman-
Balk (1958) agreed with Sahinen and Hanson and her recent works have helped to update the standard. Figure 3 is a chart showing current usage of nomenclature in the study area and correlations with other areas in Montana. The chart also shows the major faunal zones of the Cambrian and how they correlate with the Cambrian rock units.

The name, "Hasmark Formation", was assigned to the thick dolomite section of southwestern Montana at a time when Cambrian nomenclature and correlation were as yet unresolved. At that time, the middle shale unit was thought to occur only locally. The work completed in this thesis shows that the middle shale unit is found over most of the study area and the rest of southwestern Montana.

The Montana Bureau of Mines and Geology has published a chart, "Stratigraphic Correlations for Montana and Adjacent Areas" (1971), edited by C. A. Balster, which provides the complete correlation of all rocks in Montana.
CHAPTER II
GENERAL CAMBRIAN STRATIGRAPHY

The basal Cambrian unit, the Flathead Sandstone, rests unconformably on Precambrian strata. Within the study area, the Flathead ranges from about 15 feet near Alberton, Montana, (Peterson, 1974, personal comment, and Hall, 1969), to 100 feet thick in the southeastern portion. Light brown and various shades of purple are typical colors. Grain size ranges from fine to coarse, but typically the Flathead is medium-grained (Hanson, 1959). Beds range up to 3 feet, but beds of 6 inches to 1 foot are common and outcrops appear well-stratified.

In southwestern Montana the Flathead Sandstone is overlain by the Silver Hill Formation which is normally 250 to 350 feet thick. The Silver Hill consists of three units, a lower shale unit normally characterized by greenish-gray, fissile, micaeous shale containing a high percentage of interbedded limestone, and ranging in thickness from 100 to 150 feet. At several locations worm tubes and loadcasts are observed. At the Alberton section the lower shale expands from the normal thickness of 100 feet to over 300 feet. The middle unit is a fine to medium bedded, medium to dark-gray dense dolomite approximately 100 to 150 feet thick, which also thickens at the Alberton section, to 247 feet. The uppermost shale unit, about 50 feet thick, is lithologically similar to the lowermost shale. The Hasmark Formation ranges from 1000 to 2000 feet in thickness and forms massive cliffs throughout southwestern Montana.
Lithologically, it is a medium to thick bedded unfossiliferous, light-gray weathering, medium-gray to dark-gray sacchroidal dolomite. The weathered surface is extremely rough and pitted, and outcrops commonly show depositional features such as thin laminations, algal laminations, intraformational conglomerates and small lenses of intraclasts, plus isolated occurrences of mottling. In fresh exposures the above features are not visible. The formation was divided by Emmons and Calkins (1915) into three members, present as the type section at Hasmark, Montana, in ascending order as follows:

- Magnesium limestone, mostly blue-gray, about 550 feet thick.
- Calcareous shale, coal-black which ranges from 25 to 100 feet in thickness.
- Magnesium limestone, mostly white to cream white, about 350 feet thick.

Emmons and Calkins' informal members correspond with the "lower", "middle", and "upper Hasmark" members which are characterized by the following general lithologic aspects within the study area.

The "lower Hasmark" member ranges in thickness from 860 feet in the southern portion of the study area to approximately 1000 feet in thickness in the northwest. This member maintains a fairly consistent lithologic nature throughout the area, characteristically a medium to dark gray sucrosic dolomite, with local occurrences of irregular chert lenses and finely crystalline dolomite. At several locations the weathered surface shows very fine laminations which may represent stromatolitic algal structures (Photo Plate 1a & b). At some outcrops obscure textures such as oolites, intraclasts and mottling can be observed. However,
because these and other textural and structural features are poorly expressed in the outcrop it is very difficult to make detailed outcrop correlations at the present time. As pointed out later, petrographic studies offer significantly greater data with which to attempt such correlations, especially in the case of the carbonate members.

The "middle" member is a calcareous shale and siltstone, ranging in thickness from 40 feet to approximately 100 feet. Its color varies from coal-black to rust-red at the Lower Willow Creek section to greenish-gray at Cramer Creek. The lithologic character is also quite variable and according to Emmons and Calkins (1915), ranges from fine silty dolomite with beds of greenish fissile micaeous shale at Lower Willow Creek to the typical greenish-gray, purplish-gray fissile shale with lenses of carbonate at Cramer Creek and in the Princeton area. At the Alberton section and Dry Gulch area near Nimrod this member is not exposed and may not be present.

The "upper Hasmark" member ranges from 484 feet in the northwestern portion of the area to 375 feet in the southernmost sector, at the type section near Hasmark, Montana. The type section, as Emmons and Calkins (1915) state, is not representative of its general regional characteristics, because only the outcrops in the area of Hasmark, Montana and Cable Mountain (Fig. 1) fit their description. Because of a contact with igneous intrusion at Silver Hill, the unit has a similar appearance. Throughout the rest of the area and in the extreme southwestern Montana, the "upper Hasmark" is a light to medium gray, cliff-forming, massive dolomite which from bottom to top is divided into the following four identifiable rock types.
1. Fine to medium crystalline dolomite.
This unit comprises the mass of the exposures of "upper Hasmark" within the study area. It may comprise up to 50% of any one section and range from 5 feet to over 100 feet in thickness. Prominent thin layers of finely laminated algal dolomite are commonly interbedded with the finely laminated, fine to medium, crystalline dolomite, giving the sections a cyclic appearance. The unit is a light to medium (locally dark) gray dolomite with generally no distinct surface textures or sedimentary features (Photo Plate 1 c). Recurring features are "calcite twig" type structures, chert and magnesium nodules (Emmons & Calkin, 1915 and Kaffmann, 1963), which are most prevalent at the Lower Willow Creek and Cramer Creek sections. The "calcite twig" type structures have been noticed by all Cambrian workers in western Montana, but their origin and identification is still unknown (Photo Plate 1 d). At rare locations within the unit, faint oolitic structures, mottling, and fine laminations were observed. On weathered surfaces which were characterized by a rough and highly pitted nature, this rock locally appears similar to that of both the fine laminated algal dolomite and finely laminated, fine-medium, crystalline dolomite. Stylolites could be identified locally within the fine crystalline dolomite.
2. Finely laminated algal dolomite.

This outcrop type is noticeable at all measured sections, but is most prevalent at the Cramer Creek and Lower Willow Creek sections. This algal mat unit is traceable laterally for the extent of the outcrop and is medium gray to tannish-yellow in color. It consists of thinly laminated, wavy-bedded, algal units and underlying fine-grained dolomite. Howe's (1968) "planar stromatolite" (Photo Plate 1a & b) is a typical form found in most Cambrian strata throughout Montana and adjacent areas. The laminated algal unit interval ranges from less than a foot up to tens of feet in thickness. Contact between the wavy-bedded, algal unit and the underlying, fine-grained dolomite is very distinct and quite sharp. Algal layers stand out in relief and give the unit a distinctive differentially-weathered outcrop appearance. At Cramer Creek, chert nodules, up to 2 feet long, and continuous beds are interbedded with the stromatolites. Algal structures in this outcrop unit appear similar to those illustrated by Gebelein and Hoffman (1968, 1973), Ginsburg and others (1954), and Kepper (1966, 1968).

3. Finely laminated-fine to medium crystalline dolomite.

This outcrop unit is visible throughout the area. It occurs at random within the sections and produces a rhythmic nature interbedded with the fine to medium crystalline dolomite and finely laminated algal dolomite, mentioned above. Thickness ranges from 10 feet to over 100 feet. It is light to medium
gray weathering, crystalline dolomite, dark gray on fresh exposure. Laminations range from .1 to 5 mm and are generally traceable for the length of each outcrop (Photo Plate 2a), although at most locations sedimentary structures are also visible on fresh exposure. Locally, some beds contain intraclast chips of coarser crystalline dolomite. The intraclasts appear as stromatolitic algal or finely laminated, fine crystalline dolomite chips and occur in intraclast/intraformational beccia beds only 1 inch to 3 inches in thickness. Chert and magnesium nodules (Photo Plate 2b & d) are present, and bedding is observed to extend through the chert nodules (Photo Plate 2c).

4. Sandy crystalline dolomite.

This outcrop unit occurs only at the top of the "upper Hasmark". It ranges in thickness from 30 feet in the northwestern portion to 50 feet in the south, with best exposures located at the Six-Mile, Cramer Creek, Princeton and Dry Gulch localities. Outcrops generally are of light yellow-tan to pale reddish-brown, medium crystalline, sandy dolomite. Locally, quartz grains appear to float in the dolomite matrix, resulting in a rough and distinct surface texture with no apparent bedding. When bedding does occur, it ranges from 2 to 10 cm and is traceable laterally only a few feet. Locally, thin laminations of fine to medium quartz grains stand in relief over the crystalline dolomite (Photo Plate 3a). In the top portion of this lithologic unit, silt and shale become dominant.
The Red Lion, which overlies the Hasmark throughout the area, can be divided into two members. The lower limestone member is a drab or blue-gray siliceous limestone which weathers to a rust-red. The deep reddish-purple siliceous layers of this unit contrast sharply with the light to medium gray nonsiliceous layers giving the unit a banded or well bedded appearance. The upper "Shaly Member" of Emmons and Calkins (1915), later named the Dry Creek Shale by Lochman (1950), is locally a coal-black shale of fine-grained texture, but within the study area is a light tan fissile shale with local lenses of limestone. Hall (1969) describes an unnamed dolomite unit above the Red Lion Formation west of Missoula which has not been reported at other localities in southwestern Montana.

Geologic History During "Upper Hasmark" Deposition

The major part of the Hasmark dolomite was deposited in the Cordilleran miogeosyncline which was dominant during most of Paleozoic time. According to Krumbein and Sloss (1963, p. 418), "the Cordilleran miogeosyncline is characterized by a series of alternating negative marginal basins and mildly positive marginal uplifts." During Middle and Upper Cambrian time central and eastern Montana and adjacent areas were the site of a broad stable shelf. The miogeosyncline bordering this area, to the west, extended through northwestern to southcentral Idaho, and southward. During the Dresbachian, the shoreline was stabilized in the eastern Dakotas. According to Lochman (1957), sedimentation was slow, and shoals and small low islands were prevalent, especially in south-central Montana and western Wyoming. Straddling the Montana, Idaho and Canadian borders during this time was "Montana Island" a
positive area named by Walcott (1915), and later renamed "Montania" by Deiss (1941). According to Palmer (1969) an "outer detrital belt" was located in south-central Idaho and was apparently a source area for clastic sediments during the Middle and Upper Cambrian. On the craton margin or outer shelf, immediately landward of the hinge line, carbonate sedimentation was generally dominant during deposition of the "upper Hasmark". Stromatolite banks and associated lagoons dominated this outer shelf area. According to Lochman-Balk (1970), lagoons varied in depth from shallow to moderate (3-100 m.) and were crossed by subtidal channels. Lagoon floors were not exposed for prolonged periods of subaerial exposure and desiccation structures have not been found within the "upper Hasmark". Deposits of lime mud and faecal pellets, and large areas of algal mat growth covered the lagoon floors. This environment produced a rhythmic interbedding of the following major rock types; finely-laminated algal dolomite, finely-laminated, fine-medium crystalline dolomite, and medium bedded, fine to medium crystalline dolomite.

During the later stage of "upper Hasmark" deposition an influx of clastics, including quartz sand, occurred and intermixed with the carbonate sediments. According to Palmer (1971), this clastic sediment was derived from the "outer detrital belt", a small positive area in south-central Idaho. The Cambrian sea was apparently in a progressive stage of regression at the close of the Dresbachian.

Lochman-Balk (1970) published a series of paleogeologic environmental maps of each of the major faunal zones of the Cambrian of North America. These maps are included in Appendix D along with her lithologic
descriptions, and environmental interpretations, for the four faunal zones that relate to the "upper Hasmark". Lochman-Balk's maps provide a useful framework as background for the type of detailed depositional analysis attempted in this thesis study.

**Palinspastic Consideration**

Post-depositional structural movements must be considered in reconstructing the depositional geometry of the "upper Hasmark" member. Intricate folding along with compression and strike-slip faults, plus thrust plates characteristic of southwestern Montana have displaced some of the outcrop sections eastward as much as twenty miles or possibly more. Several thrust plates are present in the area around Hall and Philipsburg, Montana within the Philipsburg Thrust and Georgetown Thrust (Fig. 4), which has a northeastward direction of movement (Scholten, 1957).

Scholten (1957) proposed that some thrusting or overriding of the plates in the Philipsburg and Georgetown Lake area resulted from gravity sliding of plates off the Idaho Batholith during emplacement. Talbot (1973, personal comment) supports this overriding theory.

A series of strike-slip faults are present in the Alberton and Six Mile areas and southeast to the Drummond area, whose movement is to the northwest. This belt of faulting has been named the Montana Lineament, the southern side of which has moved toward the southeast. The Montana Lineament forms the major trend, but the possibility of additional movement on both sides is considerable and highly probable (Fig. 4). The amount of movement along this structural element has not been precisely measured, and the lateral movement includes some thrusting components.
Fig. 4. General structure map and locations of Cambrian outcrops within the study area. Modified from the Montana State Geologic Map, and the tectonic map of the United States.
In constructing the palinspastic map (Fig. 5) the sections associated with the Philipsburg Thrust and Georgetown Thrust, (Lower Willow Creek, Princeton and Hasmark sections), have been relocated twenty miles to the southwest. Outcrops located along the Montana Lineament, (the Alberton, Cramer Creek, and Six Mile sections), have been relocated twenty-five miles to the northwest (Fig. 5). The palinspastic isopach map of the "upper Hasmark"-Pilgrim unit includes the sections measured during the study, and in addition those published by Hanson (1952), Hall (1969), and Tysdal (1970) were used as control points for the reconstruction. The sections west of the eastern limit of the Disturbed Belt were similarly relocated.

The palinspastic work resulting in the isopach map (Fig. 5) broadens the craton in a westerly direction, plus a broadening out of the "upper Hasmark"-Pilgrim unit isopach map of southwestern Montana published by Hanson (1952). Reconstruction of the geometry of the western portion of the craton shows the area of sedimentation to be larger than previously considered.
Fig. 5. Palinspatic Isopach Map of the "upper Hasmark"/Pilgrim Formation of southwestern Montana. The unit is projected westward 25 miles.
CHAPTER III
LITHOFACIES OF THE "UPPER HASMARK"

The following lithofacies were identified solely from thin sections with no reference to field lithologies, although there was some correlation noted between the two (discussed under Cambrian Stratigraphy, p.9). Only five identifiable lithofacies of the "upper Hasmark" were noted in the study, the limited number probably related to the obscuring of original sedimentary features by dolomitization. Two other units are identifiable from the thin section work, but because of the extent of recrystallization, their original nature was indecipherable. The identifiable lithofacies are described, and their environment and stratigraphic position are discussed below (Figs. 6 & 7).

Intraclastic Crystalline Dolomite--Rocks of this lithofacies are comprised mainly of fine to medium crystalline dolomite (30 to 100 microns) with minor amounts of fine quartz sand. The intraclasts appear as laminated units normally with patches of quartz sand ranging from 0.1 to 1.0 mm. Fine to medium sized dolomite rhombs appear in the matrix and are overgrowing the crystal mosaic. The clasts are chips of finely-laminated dolomite and algal boundstone (Photo Plate 3 b). They range in size from 0.5 to 1.5 cm. and are normally subrounded.

Environment--This lithofacies is interpreted as subtidal, occurring either near wavebase, or as storm deposits. The quartz sand occurs in
patches or lenses and is subangular to round and is larger sized than
the quartz sand of the other lithofacies. Also, the associated finely-
laminated intraclasts could not conceivably have remained intact if
transported any distance by strong currents. The poorly sorted nature
of the lithofacies helps to support this interpretation.

Stratigraphic position--This rock type is always associated with
rocks of the laminated boundstone or algal boundstone lithofacies.
Figures 6 and 7 show the interpreted facies pattern.

Sandy-Laminated Crystalline Dolomite--Thin laminations of silt and
sand size quartz occur in a matrix of fine to medium (30 to 100 microns)
crystalline dolomite (Photo Plate 4 a). Randomly, clear rhombs of
dolomite occur overgrowing the crystalline dolomite mosaic (25 to 75
microns). Stylolites are common and dolomite crystals decrease in size
as the distance increases from the stylolites. The quartz grains are
subround to round.

Environment--The environment postulated for rocks of this litho-
facies is subtidal to intertidal. The relationship of quartz and
laminations is similar to that which Kendall and Skipwith (1969) described,
associated with intertidal flats and stromatolite mat algae from the
Persian Gulf area. The lack of desiccation features within the litho-
facies supports its position near the top of the subtidal zone and/or
near the base of the intertidal zone. The mixture of quartz grains
reflects high energy conditions and/or rapid deposition (Tysdal, 1970).
Energy changes could be a reflection of tidal activity, but generally
below normal tidal range.

Stratigraphic position--This facies is normally associated with the
laminated boundstone lithofacies (Figs. 6 & 8).
Laminated Boundstone Crystalline Dolomite--The dolomite of this lithofacies ranges from fine to medium (30 to 100 microns). Laminations are 0.1 to 1.0 cm. thick and are alternating light to dark tan in color, with medium crystals occurring in the light colored laminations (Photo Plate 4 b). Dolomite rhombs and the crystalline mosaic show the same overgrowth relationship as the other lithofacies. Stylolites follow the laminations and clear medium dolomite crystals are associated within them (Photo Plate 4 b). Occasionally, fine quartz sand and pelletal mud occurs and follows the lamination (Photo Plate 5 a). Often, calcisphere-like features are identifiable (Photo Plate 5 b).

Environment--A subtidal origin is postulated for this lithofacies. Conditions, transitional from slightly oxidizing to slightly reducing, are suggested by the color difference. According to P. Hoffman (personal comment to Winston, 1973), the laminations could also represent a particular stromatolite algal form with a sticky mucilaginous sediment-trapping sheath which results in the rapid accumulation of a relatively thick laminae. Eventually, however, the rapid sedimentation rate, along with bottom traction and abrasion by particles, exceeds the tolerance of the stromatolite algal form and carbonate mud deposition supervenes. The movement of sediment could be related to wavebase and proximity to subtidal channels, as described by Gebelein (1969). The lack of desiccation features provides additional support for subtidal deposition. Winds or sealevel fluctuations could have caused the variation in influx of bottom sediments.

Stratigraphic position--This rock type is always associated with the algal boundstone. The positioning will vary due to the forementioned factors. Figures 6 and 7 show the interpreted facies patterns.
Bedded Algal Boundstone--This lithofacies is composed of thin fine-grained dolomite beds of stromatolite mat algal (Photo Plate 6 a). The dolomite is a fine mosaic with only occasional rhombs. The laminations range from less than 0.5 to 4.0 mm. Laminations are wavy, but domes or column structures are not present. Fine-grained quartz sand and small intraclasts of fine crystalline dolomite are interbedded with the mat algae. Horizontal stylolites are closely associated with the stromatolites (Photo Plate 6 a).

Environment--The Algal boundstone lithofacies of the "upper Hasmark" is characteristic of lithofacies forming presently in the subtidal zone (3 to 25 feet) in the Bermudas (Gebelein, 1969; Neumann, Gebelein and Scoffin, 1970). Most algal workers have studied supertidal and intra-tidal forms and their relationship to the dolomite problem, and only recently have efforts been directed toward the subtidal algal mats.

Surface sediments in the subtidal algal zone may be bound into a cohesive mat, and in some locations three or four mat layers occur, one on top of the other (Gebelein, 1969). "Upper Hasmark" algal mat structures are flat or gently undulating, and in this respect are very similar to those described by Gebelein from modern subtidal environments. According to Bathurst (1971), the mats cover stable bottoms and have a high degree of cohesiveness and primary cementation allowing them to break into flat chips, some of which exceed 1 inch in diameter. In the subtidal facies in Bermuda the mat algal forms are dominant over the dome and biscuit forms. In the Hasmark only mats are present, suggesting that surface current and sediment movement exceeds the tolerances of the other forms, Gebelein (1969). The stromatolites of this lithofacies may not have
sticky mucilaginous sheaths, so sediment was not trapped, and mat
growth is purely algal sheaths. As the sediment influx increased due
to lower sea level, storms, etc., the nonsticky species tolerance was
reached.

Stratigraphic position--The algal boundstone is generally in close
association with the laminated boundstone lithofacies (Fig. 6).

Sandy Crystalline Dolomite--Rocks of this lithofacies conform to the
description of Tysdal (1970). Dolomite comprises 40-60%, with quartz
40-50% and small amounts of feldspar and hematite. Tysdal reported
fossil fragments from this lithofacies, but probably because of the
dolomitization, none were observed in my rocks. Dolomite crystals range
from fine to medium (30 to 125 microns), and the quartz grains are of sand
size. The quartz sand is subangular to rounded (Photo Plate 4 a).

Environment--The environment inferred for this lithofacies is sub­
tidal to intertidal. Like those of Tysdal (1970), the sediments are
poorly sorted, and contain quartz sand with local intraclasts. The fine
to medium grained dolomite intraclasts occur in a matrix of medium
crystalline dolomite. This suggests deposition in an environment that
fluctuated from low to high energy conditions.

Stratigraphic position--This lithofacies occurs only at the top of
the "upper Hasmark", and is Phase B deposition. Figures 6 and 7 show the
interpreted facies patterns.

Recrystallized Dolomite--Dolomite crystals are generally subhedral
to euhedral in shape, ranging from fine to coarse (30 to 200 microns).
Rhombs of dolomite are fine to medium (40 to 80 microns) and all have
clear interiors. Rhomb to crystal relationship produces a tightly inter-
locking mosaic (Photo Plate 6 b). Some of the rhombs are overgrowing dolomite crystals. This relation exists where the dolomite crystals are small in size. Locally, quartz sand occurs ranging from silt to medium sand (30 to 300 microns), which is subangular to rounded and tends to form laminae in the non-laminated dolomite. Stylolites regularly occur within this unit, occasionally producing a lamination effect. Locally, lamination appears as a reflection of different dolomite crystal size (Photo Plate 7 a).

Environment--As a result of the complete recrystallization of the rocks of the unit the environmental positioning is impossible.

Stratigraphic position--It occurs randomly in vertical section.

Granular Mottled Dolomite--Dolomite also dominates this unit and is generally subhedral to euhedral in shape ranging from fine to coarse (30 to 200 microns). The rhombs of dolomite are randomly occurring and generally appear to overgrow the crystalline dolomite. The mottled (Photo Plate 7 b) nature of this unit sometimes forms either as a result of the stylolitization or as changes in the size relationship of the dolomite crystals. Quartz sand is also identified in this unit.

Environment--The extent of the dolomitization and stylolitization of rocks of this unit prevents identification of the environment of deposition.

Stratigraphic position--Like the rocks of the recrystallized lithofacies, it occurs randomly, but normally is associated with the recrystallized dolomite.
CHAPTER IV
PHASES OF DEPOSITION

To demonstrate the lateral lithofacies relationship (Figs. 6 & 7), the "upper Hasmark" was divided into two intervals that represent phases of deposition: (1) Phase A, (Cedaria and Crepicephalus faunal zones) representing the initial phase of transgression of the Cambrian seas across the craton from the outer shelf to the inner shelf until maximum transgression was reached. (2) Phase B, (Dunderbergia and Aphelaspis faunal zones) at which time the seaway regressed from the inner shelf to the outer shelf area. These form faunal zones are not recognizable in the Hasmark, probably because of dolomitization, and are used here for a stratigraphic framework only. The "upper Hasmark" phases of deposition are correlateable to Lochman-Balk's (1970) transgressive and regressive phases of sedimentation (Appendix D) by the occurrences of the Sandy Crystalline Dolomite at the top of the member, and because general accuracy and not absolute is the design of the phases.

Phase A

During Phase A (Fig. 6), the Cambrian seaway started to transgress from the craton (west to east) at the beginning of the Cedaria faunal zone. According to Lochman-Balk (1970), maximum transgression was reached during the time of the Crepicephalus zone. Throughout this phase, the study area was a subtidal zone of deposition and the lithofacies
<table>
<thead>
<tr>
<th>NAME</th>
<th>ENVIRONMENT</th>
<th>LITHOLOGY</th>
<th>CHARACTERISTICS</th>
<th>THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy Crystalline Dolomite</td>
<td>Intertidal to Subtidal</td>
<td>Dolomite with Quartz Sand</td>
<td>Medium Mosaic of Dolomite, with Quartz Sand, Locally Laminated</td>
<td>23-50 ft</td>
</tr>
<tr>
<td>Sandy Laminated Crystalline</td>
<td>Subtidal to Intertidal</td>
<td>Dolomite with Quartz Sand</td>
<td>Thin Laminations of Quartz in Dolomite Matrix, Dolo. Rhombs, Quartz Sub-rounded</td>
<td>1-3 ft</td>
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<tr>
<td>Dolomite</td>
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<tr>
<td>Interclastic Crystalline</td>
<td>Subtidal</td>
<td>Dolomite Mosaic</td>
<td>Laminated and Algal Chips w/ Quartz Patches</td>
<td>1-5 ft</td>
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<td>Dolomite</td>
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<tr>
<td>Laminated Boundstone</td>
<td>Subtidal</td>
<td>Dolomite Mosaic w/ Minor Quartz</td>
<td>Alternating Lamination of Dolomite Mosaic, Laminations Wavy and Fine Quartz Sand</td>
<td>1-50 ft</td>
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<tr>
<td>Crystalline Dolomite</td>
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<tr>
<td>Bedded Algal Boundstone</td>
<td>Subtidal</td>
<td>Dolomite Mosaic</td>
<td>Thin Way Stomatolite Algal Laminations with Some Chert</td>
<td>1-25 ft</td>
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Fig. 6 Interpreted lateral facies relationship compiled from thin sections, lithofacies, using Walther's Law (see text p.7), modified from Tysdal (1970).
Fig. 7. Interpreted lateral facies relationship compiled from thin sections, lithofacies, using Walther's Law (see text, p. 7), modified from Tysdal (1970).

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<td>Thin laminations of quartz in dolomite matrix dol. rhoms, quartz sub-round</td>
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<td><strong>Laminated Boundstone Crystalline Dolomite</strong></td>
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<td>Alternating lamination of dolomite mosaic laminations wavy and fine quartz sand</td>
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patterns (Fig. 6) migrated back and forth across the region because of fluctuations in current velocity and/or sediment influx. The sedimentary environments were constantly fluctuating as indicated by the inter-relationship between laminated boundstone, bedded algal boundstone, sandy laminated crystalline dolomite and interclastic crystalline dolomite (Figs. 6 & 7). According to Gebelein (1969), some of the modern algal mats, occurring in Bermuda, appear and disappear weekly, but the deeper water algal facies are generally of a permanent nature. The deeper subtidal zone algal mats have a substantial accumulation of stromatolitic material, whereas those in shallower water or affected by moderate to strong currents, and/or areas of high bottom traction have only thin accumulations. Due to the above mentioned factors, the subtidal floor lithofacies were constantly migrating back and forth.

Phase B

During Phase B (Fig. 7 & Appendix D) the Cambrian seaway was regressing off the craton (east to west) making the close of the Dresbachian of western Montana. Accompanying this regression, small positive areas to the west were exposed and shedding clastic sediment, which migrated into the study area during this phase. Nevertheless, some of the clastic sediments also could have been derived from the craton by westward flowing streams draining the craton.

This influx of quartz sand resulted in a blanketing effect which increased the effect of traction and abrasion by bottom sediment, and exceeded the tolerance of stromatolite algae (Fig. 7). As the Cambrian seaway regressed, the tidal zone also regressed causing an increase in energy environment thus producing the sandy carbonate deposition.
Fig. 8. Columnar Section
CHAPTER V
ALTERATIONS

For simplicity the alterations, which occurred during diagenesis of the "upper Hasmark", are treated in three distinct sections, but in reality they are interrelated events. They are stylolitization, cementation and dolomitization, not necessarily occurring in the above stated order.

Stylolitization

Stylolites are generally defined as a form of irregular discontinuity surface between or within rock units. According to Park and Schot (1968 a) the word "stylolite" comes from the Greek word "stylus" which refers to columns and/or pyramids. Stylolites can be confined to bedding planes or may transcend the whole rock. A stylolite is a complex interface between two rock units which appear to be interlocked and/or mutually related along this interlocking structure. Commonly insoluble residues remain on the surface and form seams composed of carbonate-rich clay material. Clear dolomite rhombs, associated with this solution process, are a recrystallization phenomenon due to chemical factors caused by changes in the physical parameters, causing pressure-solution to develop. According to Bathurst (1971) this process of pressure-solution depends upon the decrease of strain in the grain or lamination surface away from the place of contact. Such
features as microstylolites, and wavy clay seams in carbonate rock, are a result of the accumulation of insoluble material during dissolution of the rock.

![Diagram of stylolite types](image)

Fig. 9. Classification of stylolites in relation to the bedding plane. Modified from Park and Schot 1968, a. and b.

Park and Schot (1968 a & b) state that, "Stylolite features are defined in terms of rock-grain fabric relationships: intergranular and aggregate stylolites are differentiated." According to Park and Schot's (1968 a) genetic description classification, in which they consider the deviation of the stylolites from the bedding plane, two types are differentiated in terms of formation time: (1) diagenetic stylolites, which originate during early or late diagenesis, and (2) tectonic stylolites, which occur during tectonism of the host rock. The "upper Hasmark" contains three of the six different stylolite forms described by Park and Schot (1968 a), horizontal (Fig. 9a), interconnected network (Fig. 9 b), and vertical-inclined (horizontal) crosscutting (Fig. 9 c).
The horizontal forms observed in this study occur in laminated crystalline dolomite, algal boundstone and laminated crystalline dolomite. The amplitude or height of the "fingertips" of a stylolite is generally confined to one laminae (Photo Plate 7 a). The interconnected network stylolites occur predominately in the rocks of the intraclastic crystalline dolomite lithofacies. Dominant forms in the recrystalized and granular mottled dolomite units are the "vertical-inclined (horizontal) crosscutting" and "interconnected network" types (a & b). The nature of this form of stylolite gives some of the rocks a brecciated appearance (Photo Plate 8 a). Some of the granular dolomites appear laminated because of the interlayered relationship that exists between fine and medium crystalline dolomite. This crystal layering could have been formed by second generation stylolitization which was superimposed over first generation horizontal stylolites (Photo Plate 8 a). Rocks of these units appear mottled, but again this appearance is related to the stylolitization (Photo Plate 8 b).

Horizontal stylolites (Fig. 9 a, Photo Plate 4a) are generally parallel or nearly parallel to the bedding of the rock. According to Park and Schot (1968), horizontal stylolites are generally not produced or affected by tectonic activities. The controlling factor in their development, according to Rigby (1953), is the orientation of the linear stress axis which is generally vertical, being a simple factor of overburden. Dunnington (1967, from Bathurst, 1971) has found the horizontal stylolitization process operative in which limestone is buried only 300 m. Schlanger (1964), who found horizontal stylolites in the Alifan Limestone of Guam which had not been buried by overburden greater than
90 m., suggested that the special susceptibility of micrites and algal boundstones to pressure-solution may be related to their relatively high clay content. Both of these study areas have undergone only relatively minor tectonism, if any.

Vertical-inclined (horizontal) crosscutting stylolites are formed by extreme overburden and tectonic pressure during folding or vertical loading. Vertical-inclined (horizontal) crosscutting stylolites represent inclined stylolites that have been displaced by fractures which later developed into vertical stylolites. The inclined or horizontal stylolites formed first and the vertical ones later.

The interconnected network originates because of intense tectonic pressure (Park and Schot, 1968 a & b). Type A (Fig. 9 c) fingers are sometimes greater than amplitude of the bedding they are associated with. Type B (Fig. 9 c) represents a stylolite network within the rock that has usually been affected by intense tectonic pressure. They are characterized by low amplitude with undulating surfaces, and inclination to the bedding ranges from horizontal to vertical. Because of the recrystallization that occurred in the "upper Hasmark" this stylolite to bedding relation is not commonly viewed.

Rocks of the "upper Hasmark" lithofacies illustrate that there were two stages of stylolitization. First, the horizontal form developed early in the diagenesis and cementation of the sediments. The stylolite seams probably served as passages for the Ca/Mg rich solutions in the laminated sediment and the algal stromatolite sediment after the cementation process had started (discussed under Cementation, p. 36). Dolomitization of the study area is thought to be related to the passage of high Mg solutions
from the algal area caused by ion diffusion away from the vicinity of high Mg concentration to areas of less concentration (discussed under Dolomitization, p. 37). The horizontal phase of stylolitization is believed to have occurred in most rocks of the study area. Although horizontal forms are not recognizable in the recrystallized and granular dolomites, lamination type structures are observable, and I believe they are a result of first phase stylolitization.

A second phase of stylolitization, represented by intraconnected network and vertical-inclined (horizontal) crosscutting stylolites probably developed during later diagenesis under conditions extreme overburden and intense tectonism activity. The exact formation time for stylolitization in the Hasmark is not known. However, following the interpretations of Bathurst (1971), stylolites must be pre-complete cementation in origin (discussed under Cementation, p. 36).

Cementation

Due to the dolomitization of the rocks of the study area, the exact relationship between original grain and cement is not known. However, work by Ball (1967), Barrett (1964), Lucia (1968), Purdy (1964), Bathurst (1971), and others provide us with knowledge of early cementation of carbonate sediments. Subtidal algal mats from Berry Island illustrate that the top .25 cm. of the sediment tends to coalesce (Bathurst, 1971). These mats are suberially exposed, and even at extreme low tide they are under approximately 15 cm. of water. Nevertheless, the cementation is strong enough to withstand moderate to strong currents. Cementation can start during deposition, but the main phase begins during early
diagenesis. This is closely associated with the time of development of horizontal stylolites (discussed under Stylolites, p. 32). Rocks of the algal boundstone lithofacies best illustrate this process. The presence in the "upper Hasmark" of "birds-eye" structures, inferred to represent gas bubbles in soft sediment, suggests that cementation had started before decay of the algal sheaths. According to Bathurst (1958) and Heald (1956), stylolites provide a passageway for the carbonate cement within the partly cemented rock. According to Park and Schot (1968 a & b), the calcium/magnesium cement is produced by a volume reduction of 35 to 42% that accompanies stylolitization. This is enough material to provide cement for large areas of sediment. According to Bathurst (1971), stylolites must be pre-cementation in origin, beginning in sediments that are only partly or lightly cemented, such as the fine-grained carbonate muds and algal mats of the subtidal zone, with the cementation process carried on by a release of CaCO₃ from the carbonate muds. At this time, the magnesium is released from the algal sheath (discussed under Dolomitization, p. 37). The evidence of gas bubbles and the presence of horizontal stylolites provide (Photo Plate 9 b) support for an early stage of cementation for at least the laminated boundstone and bedded algal boundstone. The fact that desiccation features are lacking supports the subtidal submarine cementation process described by Friedman (1964). The known presence in recent sediments of cohesive algal mats, fine-laminated carbonate mud and oolites makes the process acceptable.

**Dolomitization**

The vertical sequence of dolomitized rock changes from section to section within the "upper Hasmark". This selectivity must have been
controlled by either the fluid source or the rock nature. Texturally the dolomite ranges from microcrystalline to coarse mosaic, with rhombs of dolomite well developed at the expense of the dolomite mosaic. For generations, geologists have been puzzled as to the origin of dolomite, and some earlier workers advocated a process of direct precipitation from sea water. However, the large body of research work accumulated on this subject of dolomitization since World War II has shown that direct precipitation of the dolomite mineral is highly unlikely. Theories resulting from this work have proposed an origin of dolomite which involves the replacement of aragonite or calcite by magnesium-rich brines soon after deposition.

Penecontemporaneous replacement may result from two main processes: (1) "capillary concentration" of the interstitial waters by intense evaporation in intertidal and spertidal areas causing a dolomite crust to develop on the carbonate mud flats, and (2) "Seepage-Refluxion" (Adams and Rhodes, 1960), which proposes that dolomitization is caused by dense hypersaline brines refluxing seaward under a barrier and through porous carbonate sediment to produce dolomite. Both processes have type areas and models, and whatever the mechanics involved, both methods can explain many of the dolomite sections in the geologic record. Although the two processes explain most of the thick-bedded or massive dolomites, they yield no satisfactory explanation for closely inter-bedded dolomite and limestone (Friedman and Sanders, 1967). In 1973, Gebelein and Hoffman proposed an explanation for the thin bedded dolomites, suggesting that the algal sheath material provided a location for the concentration of magnesium liberated during decomposition of the sheath.
and the excess magnesium caused dolomitization of the algal lime mud. Rocks of the "upper Hasmark" of the study area may have been dolomitized by this process rather than by an evaporitic process which would be required under the "capillary concentration" or "Seepage-Refluxion" theories. The "upper Hasmark" does not contain evidence of evaporite sequences, or a barrier system that would produce an area of hypersaline brine nor does it contain beds representing intertidal or supertidal zones. These facts, along with the abundant laminated lithofacies, support the hypothesis of Gebelein and Hoffman (1973).

The recrystallized dolomite probably represents later diagenesis and/or tectonism, which formed the granular and recrystallized dolomites during second stage stylolitization. Because of the early development of cement in the laminated boundstone and bedded algal boundstone, and the resulting development of a complex network of horizontal stylolites (Photo Plate 7 a & b), the total recrystallization and dolomitization of these beds may have been hindered. There are other factors besides cementation and stylolitization related to the selective massive dolomitization, such as permeability, particle size and chemical factors, and the relative solubility of the carbonate minerals, (e.g., as Friedman (1964) pointed out, high-magnesium calcite particles are easily replaced by low-magnesium calcite even when aragonite is retained). This process would reverse the relative solubility of the particles, leaving the relatively more soluble aragonite available for dolomitization. This reversal could have taken place during early diagenesis of the area, causing selective dolomitization to occur. The stylolitization and the solubility could have caused the later massive recrystallization of some of the "upper Hasmark".
CHAPTER VI
SUMMARY AND CONCLUSIONS

The "upper Hasmark" was deposited during a complete transgressive/regressive cycle.

The absence of desiccation features, such as curled algal mats, polygonal type features, etc., supports the subtidal environment postulated for this area.

Carbonate muds and stromatolite algal mats dominated deposition during the transgressive phase (Cederia and Crepicephalus faunal zones) of the early "upper Hasmark".

During the regressive phase (Aphelaspis and Dunderbergia faunal zones) positive areas to the west, and westward flowing streams draining the craton provided an influx of quartz sand throughout late "upper Hasmark" deposition.

During "upper Hasmark" deposition the study area was a subtidal zone of deposition, crossed by subtidal channels, the area was subject to occasional storms. Across the area, the depositional environments were constantly fluctuating, and thus providing a non-definable cyclic pattern of deposition for the lithofacies of the "upper Hasmark" because of the selective massive dolomitization.

The origin of the dolomite is thought to be related to the decomposition of algal sheaths, releasing Mg, this solution moved along horizontal stylolites which developed during the early stage of cementation.
During later diagenesis, the second phase of stylolitization occurred causing selective massive dolomitization. These stylolites were related to overburden and tectonism.

Throughout most of the study area, the middle shale is an identifiable member of the Hasmark Formation.
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PHOTO PLATE 1

Figure A. The thinly laminated, wavy-bedded, algal unit.

Figure B. A contact between a finely-laminated, algal, dolomite unit and a medium crystalline dolomite.

Figure C. The fine to medium crystalline dolomite which normally exhibits no distinct surface features.

Figure D. The "calcite twig" like structures that occur in the fine to medium crystalline dolomite.
PHOTO PLATE 2

Figure A. The finely-laminated crystalline dolomite, with laminations that range from .1 to 5 mm.

Figure B. A common chert nodule that is found in the fine to medium crystalline dolomite.

Figure C. A chert nodule within the finely-laminated crystalline dolomite with laminations.

Figure D. Magnesium nodule which is commonly found in the fine to medium crystalline dolomite.
PHOTO PLATE 3

Figure A. Thin lamination of fine to medium quartz grains standing in relief over the crystalline dolomite, from the sandy crystalline dolomite.

Figure B. Clast from intraclastic crystalline dolomite lithofacies, the clasts are chips of finely-laminated dolomite and algal boundstone.
PHOTO PLATE 4

Figure A. Thin laminations of silt and sand size quartz occurring in a matrix of medium crystalline dolomite. A horizontal stylolite occurs below the quartz lamination.

Figure B. Alternating light to dark tan colored laminations related to crystal size, dark lamination, fine crystalline dolomite and the light lamination is of medium crystalline dolomite. The white crosscutting lines are stylolites.
Figure A. Pelletal mud occurring between the laminations, and some fine quartz sand. This is from the laminated boundstone crystalline dolomite.

Figure B. A calcisphere-like feature which is occasionally found in the laminated boundstone crystalline dolomite lithofacies.
PHOTO PLATE 6

Figure A. Thin laminations of stromatolite mat algae, composed of fine crystalline dolomite, with horizontal stylolites associated with the lamination. The stylolites are the white line-like features.

Figure B. The common crystalline dolomite mosaic with dolomite rhombs overgrowing the dolomite mosaic. This is common of recrystallized dolomites.
Figure A. The lamination of this rock occurs because of the size relationship of the crystalline dolomite. Note the network of stylolites that has developed within the rock.

Figure B. The mottled nature of the granular mottled dolomite unit is related to the stylolitization.
Figure A. Granular dolomite appears brecciated because of the development of the interconnected network of stylolites. They are the white line-like features.

Figure B. This algal boundstone shows the gas bubbles which are formed by the decomposition of the algal sheaths. Horizontal stylolites formed during the early stage of cementation: are the white line-like features.
APPENDIX B

MEASURED SECTIONS

The following is a list of measured sections used in this report. The sections were measured during the summer and fall of 1972-1973 (Fig. 1). A five foot Jacob staff and brunton compass were used, and the sections were numbered with paint at 10 to 15 foot intervals.

1. Alberton NE$\frac{3}{4}$ SW$\frac{1}{4}$ sec. 1 T. 15 N. R. 23W.
2. Six-mile NE$\frac{3}{4}$, NE$\frac{3}{4}$, sec. 34, T. 15N. R. 22W.
3. Cramer Creek NW$\frac{3}{4}$, Sec. 3, T. 12 N, R. 15W.
4. Lower Willow Creek SW$\frac{1}{4}$, sec. 36, T. 10 N, R. 14W.
5. Princeton SW$\frac{1}{4}$, sec. 14, SE$\frac{3}{4}$ sec. 15, T. 8N, R. 13W.
6. Hasmark sec. 30, T. 7N, R. 13W.
Appendix C

Alberton Section Location; NE 1/4 SW 1/4 sec. 1T. 15N. R. 23W.

**Cambrian:**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Lion dolomite: would be the next unit, above the Hasmark at the Alberton Section. The upper portion of the Hasmark and Red Lion formations were removed by erosion.</td>
<td>489'10&quot;</td>
</tr>
<tr>
<td>1. Sandy crystalline dolomite: medium to large (90 to 200 microns) crystalline dolomite. Coarse dolomite rhombs (130-150 microns). Quartz is angular sand size. Sand lamination occur in the dolomite matrix, in the upper and lower few feet.</td>
<td>30'</td>
</tr>
<tr>
<td>Covered Interval</td>
<td>31'0&quot;</td>
</tr>
<tr>
<td>2. Laminated boundstone crystalline dolomite: fine crystalline (30 to 50 microns) dolomite. Fine dusty rhombs of dolomite are overgrowing the matrix. Dolomite rhombs appear to produce medium sized laminations, and horizontal stylolitic generally follows the lamination.</td>
<td>6'0&quot;</td>
</tr>
<tr>
<td>3. Bedded algal boundstone: algal mat units ranging from .05 to 3.0 mm. Dolomite matrix is fine (40 to 60 microns) crystalline algal laminated. Horizontal stylolites follow the algal inter-facies.</td>
<td>5'6&quot;</td>
</tr>
<tr>
<td>4. Laminated boundstone crystalline dolomite: fine crystalline (40 to 60 microns) dolomite. Very fine clear rhombs of dolomite are overgrowing the dolomite matrix. Birdseye structures occur along with the dolomite rhombs produces fine lamination, appearance and horizontal stylolites following these lamination.</td>
<td>6'0&quot;</td>
</tr>
<tr>
<td>5. Recrystallized dolomite: coarse (140 to 200 microns) subhedral dolomite. Clear dolomite rhombs medium (60 to 80 microns). Crystal and rhombs are tightly interlocked. Quartz medium (60 to 80 microns) sand, subangular with no lamination. Stylolites are randomly located within the unit.</td>
<td>23'6&quot;</td>
</tr>
</tbody>
</table>
Covered Interval

6. Laminated boundstone crystalline dolomite: fine crystalline (30 to 60 microns) dolomite. Very fine to fine clear rhombs of dolomite overgrowing the matrix. Horizontal stylolites produce a finely laminated appearance, with the clear dolomite rhombs occurring along the lamination.

7. Sandy laminated crystalline dolomite: medium (80-100 microns) crystalline dolomite, patches of dusty medium (60 to 90 microns) dolomite rhombs occur. Horizontal stylolites produce the fine lamination, along with the dolomite rhombs.

8. Laminated boundstone crystalline dolomite: same as unit number 6.

9. Interclastic crystalline dolomite: medium crystalline (80 to 100 microns) dolomite. Fine (30 to 50 microns) quartz sand are intermixed with medium (80 to 100 microns) dusty dolomite rhombs. Subrounded clasts of laminated boundstone are randomly located within the unit.

10. Recrystallized dolomite: same as unit number 5 only the quartz sand only appears in the upper 10 feet of the unit.

11. Granular mottled dolomite: coarse (150 to 200 microns) subhedral dolomite, with medium (80 to 120 microns) dusty and clear dolomite rhombs. Medium (80 to 100 microns) subrounded quartz occur within this unit. Interconnected network stylolites are abundant with this unit. Ghost clast features are present in the lower few feet.

Covered Interval

12. Granular mottled dolomite: similar to unit number 11, the ghost clast features are present throughout unit, and no quartz was identified in this unit.
Covered Interval

12. Laminated boundstone crystalline dolomite: 5'0"
   Same as unit number 6.

14. Recrystallized dolomite: coarse (130 to 200 microns) subhedral dolomite, clear dolomite rhombs fine to medium (40 to 80 microns). The rhombs and matrix are completely interlocked. Interconnected network type stylolites are randomly located within this unit. No quartz was identified.

15. Laminated boundstone crystalline dolomite: 13'7"
   Fine crystalline (30 to 60 microns) dolomite. Fine clear rhombs are overgrowing the dolomite matrix. Birdseye structures and oolites are present in the upper two feet of the unit. Both features are horizontal to the finely laminated bedding. Horizontal stylolites generally follow the bedding.

Covered Interval

16. Granular mottled dolomite: similar to unit number 11, the only difference is the medium (80 to 100 microns) quartz only appear in the upper top 3 feet of unit. 36'1"

17. Laminated boundstone crystalline dolomite: 5'0"
   Medium (80 to 100 microns) dolomite. Medium clear rhombs are overgrowing the dolomite matrix. Fine lamination occur and horizontal stylolites generally follow the bedding.

Covered Interval

18. Recrystallized dolomite: same as unit number 14. 1'6"

19. Laminated boundstone crystalline dolomite: 5'6"
   Similar to unit number 17, with pellets and oolite structures occurring along the fine lamination.
20. Bedded algal boundstone: algal mat units ranging from .05 to 3.5 mm. Dolomite matrix is fine (40 to 50 microns) crystalline algal laminated. Fine (30 to 60 microns) quartz sand occurs along the algal surface. Horizontal stylolites follow the algal interfacies.

21. Laminated boundstone crystalline dolomite: similar to unit number 19. In the upper 2 feet dolomite is fine (30 to 60 microns) crystalline with fine clear rhombs overgrowing the matrix. Fine (30 to 60 microns) quartz is abundant in the upper 2 feet.

22. Recrystallized dolomite: Same as in unit number 14.

Covered Interval.

23. Recrystallized dolomite: same as in unit number 14.

24. Laminated boundstone crystalline dolomite: medium (80 to 100 microns) dolomite. Medium clear rhombs are overgrowing the crystalline dolomite matrix medium lamination occur and horizontal and some vertical-inclined (horizontal) cross-cutting stylolites occur.

25. Recrystallized dolomite: same as unit number 14 and 23.

26. Laminated boundstone crystalline dolomite: same as unit number 24.

27. Recrystallized dolomite: same as unit number 14, 23 and 25.

Base of unit is covered by general slope covered with grass and pine trees
2. Six-mile Section: Location NE 1/4, NE 1/2, Sec. 34, T. 15N. R. 22W

Cambrian:

Red Lion Dolomite. Dark to Medium Purple
Mottled Silty Dolomite.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sandy Crystalline Dolomite: medium crystalline (80 to 110 microns) dolomite, large patches of clear dolomite rhombs, (60-100 microns). Medium subangular quartz sand grain. Some appearance of bedding by the quartz stringers.</td>
<td>26'6&quot;</td>
</tr>
<tr>
<td>2. Laminated Boundstone Crystalline Dolomite: medium crystalline (80 to 100 microns) dolomite. Clear dolomite rhombs overgrowing crystalline dolomite. 20 to 30% fine quartz sand. Clast of shale like or laminated and pelletal fine crystalline dolomite. Highly stylotized, horizontal only inter-connecting network types.</td>
<td>96'0&quot;</td>
</tr>
<tr>
<td>3. Granular Mottled dolomite: coarse (150 to 200 microns) subhedral dolomite. Patches of clear medium dolomite rhombs. Unit has a very mottled appearance, relates to the stylolite pattern which occurs. Medium to fine quartz sand occurs in lenses type patterns.</td>
<td>10'</td>
</tr>
<tr>
<td>4. Recrystallized Dolomite: medium to coarse (80 to 200 microns) crystalline dolomite. Clear medium dolomite rhombs over growing the coarser crystalline dolomite matrix.</td>
<td>18'</td>
</tr>
<tr>
<td>5. Laminated Boundstone Crystalline dolomite: medium (80 to 90 microns) subhedral dusty dolomite, laminations 0.5 cm thick with alternating light to dark colored. Light colored lamination have abundant clear medium dolomite rhombs, and horizontal stylolites. Laminations and rhombs show horizontal and/or vertical relationship to the stylolites, generally horizontal to the laminations.</td>
<td>5'</td>
</tr>
</tbody>
</table>
6. **Intraclastic crystalline dolomite**: medium (90 microns) crystalline dolomite, patches of fine (40 to 50 microns) dusty dolomite rhomb occur randomly in the matrix. Locally patches of fine quartz sand is abundant. Abundant rounded clasts of finely laminated dolomite and algal-like boundstone.

7. **Laminated boundstone crystalline dolomite**: similar to the unit number 5 above.

8. **Interclastic crystalline dolomite**: similar, but the clast are subrounded some of the dolomite rhombs are generally clear.

9. **Laminated boundstone crystalline dolomite**: fine (40 to 50 microns) subhedral dolomite. Laminations 0.5 to 1.0 cm thick. Alternating light and dark coloring. The stylolite - lamination relation similar to unit 5 above. Fine quartz sand present in only small amounts.

10. **Recrystallized dolomite**: mostly coarse (140 to 200 microns) crystalline dusty dolomite, only local patches of medium to fine crystalline dolomite. Well developed network of interconnecting stylolites. Fine to medium clear and dusty dolomite rhombs. Fine quartz sand randomly located within unit.

11. **Laminated boundstone crystalline dolomite**: similar to unit number 2.

12. **Bedded algal boundstone**: 

Base - covered interval - but still "Upper Member" of the Hasmark.
Cram er Creek Section Location: NW 1/4, Sec. 3, T. 12, N, R. 15W.

Unit Total

Cambrian:

Red Lion Formation, rust red silty dolomite

Covered Interval 27'0" 443'6"

1. Sandy crystalline dolomite: medium to large
   (90 to 200 microns) crystalline dolomite.
   Coarse dolomite rhombs 140-150 microns. Quartz
   is subangular to angular sand size. Sand
   lamination occurs in the dolomite matrix,
   in the upper and lower few feet. Pellets/oolite
   features occur in the middle 4 feet of unit.

Covered Interval 31'0"

2. Laminated boundstone crystalline dolomite:
   fine crystalline (30 to 50 microns) dolomite.
   Fine dusty rhombs of dolomite overgrowing the
   matrix. The rhombs are generally located on
   the laminated surface and occur with horizontal
   stylolites.

3. Recrystallized dolomite: coarse (120 to 200
   microns) subhedral dolomite, with sparcely
   occurring clear dolomite rhombs medium (60 to
   90 microns). The rhombs and matrix are inter-
   locked with interconnected network type
   stylolites.

4. Bedded algal boundstone: algal mat unit ranging
   from .05 to 2.5 mm. Dolomite matrix is fine
   (50 to 50 microns) crystalline algal laminated.
   Fine (30 to 60 microns) quartz sand occurs
   along the algal surface. Horizontal stylolites
   follow the algal interfacies.

5. Laminated boundstone crystalline dolomite:
   fine crystalline (30 to 60 microns) dolomite,
   very fine clear and dusty rhombs of dolomite
   and overgrowing the matrix. A small amount of
   microcrystalline chert occurs throughout the
   unit. Birdseye structures also occur in the
   middle 4 feet, along with clast of fine laminated
   fine crystalline dolomite. Lamination is 0.5 to
   2.5 cm and horizontal stylolites are abundant and
   generally follow the laminations.
6. Bedded algal boundstone: fine to medium crystalline (30 to 60 microns) dolomite with algal bound laminae 1.0 to 4 mm. Patches of dusty medium dolomite rhombs are randomly located with the unit, horizontal stylolites follow the algal laminae.

7. Laminated boundstone crystalline dolomite: similar to unit number 5. No birdseye structures are present and horizontal stylolites only occur in the lower foot.

8. Bedded algal boundstone: same as unit number 6. 13'8"

9. Laminated boundstone crystalline dolomite: same as unit number 7 with subangular quartz sand occurring throughout the unit.

10. Bedded algal boundstone: fine crystalline (30 to 60 microns) dolomite with algal bound laminae 1.5 to 2 mm. Patches of clear medium (60 to 80 microns) dolomite rhombs randomly located with the laminae. Patches of oolite/pellets are within the laminae.

11. Granular mottled dolomite: coarse (150 to 200 microns) subhedral dusty dolomite, patches of fine, clear dolomite rhombs. Interconnecting cross-cutting horizontal stylolites occur in the unit.

12. Laminated boundstone crystalline dolomite: similar to unit numbers 7 and 9 only no quartz sand occurs within the unit, and the stylolites occur in the lower part of the unit.

13. Bedded algal boundstone: same as unit numbers 6 and 8. 3'8"

14. Laminated boundstone crystalline dolomite: similar to unit number 9, only there is no quartz present within the unit. Horizontal stylolites are abundant throughout the unit.
15. Bedded algal boundstone: fine to medium crystalline (30 to 60 microns) dolomite with algal bound laminae 10 to 4 mm. Patches of dusty medium dolomite rhombs are randomly located within the unit, generally horizontal stylolites follow the algal laminae.

16. Granular mottled dolomite: coarse (140 to 200 microns) subhedral to euhedral dusty dolomite. The coarse crystalline matrix gives the unit an enterlocking mosaic nature. Fine quartz sand is present in minor amounts.

17. Interclastic crystalline dolomite: fine to medium (50 to 100 microns) crystalline dolomite, patches of fine, clear dolomite rhombs. Fine clast patches of laminated fine crystalline dolomite. Patches of pellets/oolite features occur in the middle of the unit.

18. Laminated boundstone crystalline dolomite: similar to unit number 12.

19. Interclastic crystalline dolomite: fine to medium (50 to 100 microns) crystalline dolomite, patches of fine, clear dolomite rhombs. Fine clast patches of laminated fine crystalline dolomite. Patches of pellets/oolite features occur in the middle of the unit. Fine quartz sand is present throughout the unit.

20. Recrystallized dolomite: similar to unit number 3

21. Bedded algal boundstone: algal mat unit range from 0.5 to 3.5 mm. The dolomite is fine grained with fine (40 to 70 microns) crystalline algal laminations. Only a few horizontal stylolites occur between the laminations.

22. Recrystallized dolomite: coarse (150 to 200 microns) dusty crystalline dolomite, fine to medium dusty and clear dolomite rhombs showing evidence of overgrowing the coarser matrix.
23. **Intraclastic crystalline dolomite**: fine to medium (50 to 100 microns) crystalline dolomite, patches of fine clear and dusty dolomite rhombs. Fine clast patches of laminated fine crystalline dolomite occur in the unit.

24. **Bedded algal boundstone**: fine crystalline (30 to 70 microns) dolomite with algal bound laminae 1.5 to 2.5 mm. Patches of clear and dusty dolomite rhombs randomly located within laminae. Fine subrounded quartz size sand occur along laminae, in the middle 2 feet of unit. Horizontal stylolites generally follow laminae.

25. **Laminated boundstone crystalline dolomite** similar to unit numbers 12 and 18.

26. **Recrystallized dolomite**. Coarse (120 to 200 microns) subhedral dolomite, with sparcely occurring clear and dusty dolomite rhombs medium (60 to 90 microns). Interconnected network type stylolites are abundant within the unit.

27. **Bedded algal boundstone**: similar to unit number 24, the fine subrounded quartz size sand occurs randomly throughout the unit.

28. **Laminated boundstone crystalline dolomite**: similar to unit number 9.

29. **Bedded algal boundstone**: similar to unit number 27, pellets/oolite patches occur throughout the unit.

30. **Granular mottled dolomite**: coarse (150 to 200 microns) subhedral to hedral dolomite, with medium (80 to 120 microns) dusty dolomite rhombs. Interconnected network stylolites are abundant in this unit. Medium (60 to 100 microns) quartz only appears in the upper 3 feet of unit.

**Covered Interval** along with a change in slope.

**Base**
Lower Willow Creek Location: SW 1/4, Sec 36, T. 10 N. R. 14 W.

Cambrian:

Upper Hasmark: Has been removed by erosion and faulting, reported by Maxwell (1959).

Unit Total

1. Sandy crystalline dolomite: medium crystalline (80 to 120 micron) dusty dolomite, with random patches of dusty fine dolomite rhombs. Angular medium quartz grains, form bedding or laminations in the lower half. Near the middle of unit medium clast of fine crystalline dolomite. Pellets/oolite type structures appear in the lower third of the top third. 48'7" 394'11"

2. Sandy laminated crystalline dolomite: fine to medium (40 to 100 microns) dusty crystalline dolomite angular to subangular fine quartz grains form laminar surface. 6'2"

3. Bedded algal boundstone: fine crystalline (30 to 60 microns) dolomite with algal bound laminae 2.0 to 4.0 mm. Patches of clear and dusty fine dolomite rhombs randomly located within laminae. Horizontal and interconnecting stylolites abundant generally following laminae. The top half of the unit contains fine grained quartz. Fine and medium sized clast of algal material are present within the upper 3 feet and middle of the unit. Pellets/oolites features near the top and bottom of the unit. 55'4"

Covered Interval 25'0"

4. Granular mottled dolomite: coarse (150 to 200 microns) subhedral to euhedral dusty dolomite, patches of fine dusty dolomite rhombs, the unit has a mottled appearance because of the rhombs to matrix appearance even without the stylolites. 10'0"
5. Laminated boundstone crystalline dolomite: fine crystalline (30 to 60 microns) dolomite, very fine clear and dusty rhombs of dolomite overgrowing the matrix. A small presence of microcrystalline chert occurs in the upper 5 feet of unit. Birdseye structures some collapsed also occur in the upper 3 feet along with clast of fine laminated fine crystalline dolomite. Lamination is 0.5 to 3.0 cm and horizontal stylolites are abundant generally following the laminations.

6. Bedded algal boundstone: fine to medium crystalline (30 to 80 microns) dolomite with algal bound laminae 2.0 to 4.0 mm. Patches of dusty medium dolomite rhombs randomly are located within the laminae. Horizontal stylolites follow algal laminae.

7. Granular mottled dolomite: coarse (150 to 200 microns) subhedral dolomite, with medium (80 to 120 microns) dusty and clear dolomite rhombs. Medium (80 to 120 micron) quartz subrounded integrated within the upper 5 feet and the lower 7 feet. Interconnected network stylolites are abundant within this unit.

8. Bedded algal boundstone: similar to unit number 6 with the addition of medium (80 to 120 microns) quartz subrounded located in the laminae along with the horizontal stylolites.

9. Recrystallized dolomite: coarse (120 to 200 microns) subhedral dolomite, with clear dolomite rhombs medium (60 to 90 microns). The rhombs and matrix are completely interlocked with interconnected network type stylolites located within the unit.

10. Interclastic crystalline dolomite: medium crystalline (80 to 100 microns) dolomite with medium (80 to 100 microns) dusty dolomite rhombs overgrowing the dolomite matrix. Clast of laminated boundstone subrounded to rounded and oolites are abundant. Lamination is 0.5 to 2.5 mm and horizontal stylolites are also present.
11. Bedded algal boundstone: fine crystalline (30 to 60 microns) dolomite with algal bound laminae 1.5 to 2 mm. Patches of clear medium (60 to 80 microns) dolomite rhombs randomly located within laminae. Patches of oolite/pellets are within the laminae. Horizontal stylolites generally follow laminae.

12. Laminated boundstone crystalline dolomite: similar to unit number 5. Quartz is randomly located throughout the unit.


14. Laminated boundstone crystalline dolomite: fine crystalline (30 to 60 microns) dolomite fine (30 to 60 microns) clear and dusty dolomite rhombs overgrowing the matrix. Horizontal stylolites produce a laminated nature and the dolomite rhombs are located along these laminations.

15. Recrystallized dolomite: similar to unit number 9 only medium (60 to 80 microns) quartz sand subhedral randomly occur within unit.

16. Interclastic crystalline dolomite: similar to unit number 10. Medium (60 to 80 microns) quartz sand subhedral randomly occurs within unit.


18. Granular mottled dolomite: similar to unit number 4 only the quartz appear in the lower 3 feet of unit.

19. Recrystalline dolomite: medium to coarse (80 to 180 microns) subhedral dolomite, clear and dusty medium (60 to 80 microns) dolomite rhombs. Matrix and rhombs are tightly interlocked. Quartz medium (60 to 80 microns). Sand, subangular with no apparent lamination. Vertical-inclined
(horizontal) crosscutting stylolites are randomly located within unit.

Base of section is grass and tree covered with no apparent slope brake.
Princeton Location SW 1/4, Sec. 14, SE 1/4 Sec. 15, T. 8N, R. 13W

Cambrian:

Red Lion Formation; rust red silty dolomite covered interval 50'

1. Sandy crystalline dolomite: medium to coarse (80 to 200 microns) crystalline dolomite, with randomly scattered patches of clear and dusty medium (60 microns) dolomite rhombs. Subangular fine quartz sand grains forming stringers or laminations in the crystalline matrix about the middle of the unit, plus medium clast of fine dusty crystalline dolomite. Also chert present.

2. Laminated boundstone crystalline dolomite: medium (60 to 100 microns) crystalline dolomite, fine to medium dusty rhombs of dolomite overgrowing the matrix. Fine size quartz sand forms laminations.

3. Granular mottled dolomite: coarse (140 to 200 microns) crystalline nature gives the unit an interlocking mosaic nature.

4. Recrystallized dolomite: coarse (150 to 200 microns) dusty crystalline dolomite, fine to medium dusty and clear dolomite rhombs showing evidence of overgrowth the coarser matrix. Medium to fine quartz is present. Fine, chert is present. Medium clast of medium crystalline dolomite occur randomly.

Covered Interval 30'6"

5. Bedded algal boundstone: the algal mat like units range from 1 to 2.5 mm. The dolomite is a fine with some very fine (10 to 35 microns) crystalline. Upper third of the unit the non-algal laminations contain oolite/pellet type structures. The middle third contains fine quartz sand grains within the non-algal laminations. Small algal laminated clast are present in the last 2 or 3 feet. Stylolites occur between all laminations.
6. Intraclastic crystalline dolomite: medium crystalline (80 to 100 microns) dolomite. Medium clast of laminated/bedded algal boundstone, plus minor amounts of fine grained quartz. The matrix of the medium crystalline and the clast gives the unit a mottled nature.

7. Recrystallized dolomite: similar to unit number 4, but without the quartz sand.

8. Bedded algal boundstone: similar to unit number 5. The small algal laminated clast are randomly occurring within the unit.

Covered Interval

9. Laminated boundstone crystalline dolomite: similar to unit number 2, only this unit within the upper 6 feet contains fine pellets/oolites structure along the lamination/bedded.

10. Bedded algal boundstone: identical to unit numbers 5 and 8. Small algal laminated clast are randomly occurring within the unit.

11. Sandy laminated crystalline dolomite: medium (80 to 110 microns) dusty crystalline dolomite. Minor amounts of angular quartz sand.

12. Laminated boundstone crystalline dolomite: similar to unit number 20 except no laminations, plus the present of small amounts of microcrystalline chert randomly located throughout the unit.

13. Sandy laminated crystalline dolomite: similar to unit number 11 except the laminations which range from 0.2 to 0.5 cm. in thickness. Interbedded are oolite/pellet like structures

<table>
<thead>
<tr>
<th>Unit</th>
<th>Total</th>
</tr>
</thead>
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<tr>
<td>5'0&quot;</td>
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<tr>
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</tbody>
</table>
14. Recrystallized dolomite: medium to coarse crystalline (120 to 200 microns) dolomite, subhedral to euhedral, which give the unit a mottled or interlocking mosaic. Fine to medium clear to dusty dolomite rhomb also for a smaller sized mosaic within the coarser matrix. The middle third contains fine grained quartz sand, also top and bottom foot of the unit. At the 20 foot interval pellet/oolite structure are present.

15. Bedded algal boundstone: identical to unit numbers 5 and 10.

16. Laminated boundstone crystalline dolomite: medium (50 to 100 microns) crystalline dolomite with fine clear dolomite rhombs overgrowing the matrix. Thin lamination (0.5 cm.) of alternating light/dark colored.

17. Bedded algal boundstone: similar to unit numbers 5 and 10. This unit contains no quartz sand.

18. Laminated boundstone crystalline dolomite: identical to unit number 16.


20. Laminated boundstone crystalline dolomite: fine crystalline (30 to 60 microns) dolomite, very fine clear and dusty rhombs of dolomite overgrowing the matrix. Birdseye structures are present, some collapsed along some laminations, clasts of fine laminated fine crystalline dolomite, within the 0.5 to 2.5 cm. laminations.

21. Granular mottled dolomite: identical to unit number 3.

22. Recrystallized dolomite: similar to unit number 7 except the upper half contains minor amounts of fine grain quartz sand.
23. Interclastic crystalline dolomite: medium crystalline (60 to 90 microns) dolomite, fine clast of laminated algal boundstone, with minor amounts of fine subrounded quartz grains.

24. Laminated boundstone crystalline dolomite: identical to unit number 12.

25. Sandy laminated crystalline dolomite: fine to medium (40 to 100 microns) dusty crystalline dolomite. Fine 0.5 to 1.0 cm. laminations with subangular quartz. Medium clasts to fine crystalline dolomite, minor amounts of fine crystalline chert.

26. Laminated boundstone crystalline dolomite: medium crystalline (70 to 100 microns) dolomite, fine dusty dolomite rhomb patches randomly overgrowing the matrix. Laminations are 0.5 to 1.0 cm. with pellets/oolite like structure interbedded, no alternating colored laminae.

27. Bedded algal boundstone: the algal mat like units range from 1.0 to 3.0 cm. The dolomite is fine crystalline with some very fine (10 to 30 microns) dolomite horizontal stylolites are well developed generally formed along the laminae surface. Small amounts of microcrystalline chert is interbedded with the algal material.

28. Laminated boundstone crystalline dolomite: similar to unit number 26, except fine grained quartz sand forms stringers.

29. Sandy laminated crystalline dolomite: identical to unit number 11.

30. Recrystallized dolomite: similar to unit number 17, except the upper 4 feet is laminated. Ranging from 0.5 to 1.0 cm.
31. **Granular mottled dolomite:** coarse (150 to 200 microns) subhedral dusty dolomite, patches of fine dusty dolomite rhombs. Fine quartz sand present in minor amounts. Interconnecting cross-cutting (horizontal) network stylolites gives the unit a mottled appearance.

32. **Laminated boundstone crystalline dolomite:** similar to unit number 26.

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0'0&quot;</td>
<td></td>
</tr>
<tr>
<td>Covered Interval</td>
<td>71'0&quot;</td>
<td></td>
</tr>
</tbody>
</table>
Hasmark Section Location Sec. 30, T. 7N. R. 13W.

Cambrian:

Red Lion Dolomite: Rust red silty dolomite covered interval below.

1. Sandy crystalline dolomite: medium (80-170 microns) 47'6" 375'
crystalline dolomite, patches of clear and dusty medium (60-80 microns) dolomite rhombs. Quartz is subangular to angular sand size. Sand stringers or like lenses within the dolomite matrix gives a bedded appearance. Larger quartz grain appear to flow in the crystalline dolomite matrix. Clast and pellets and/or oolites appear in the top third of the unit.

2. Recrystallized dolomite: coarse (130 to 200 microns) 57'6" dusty crystalline dolomite, fine to medium dusty and clear dolomite rhomb showing evidence of overgrowth of the crystalline dolomite matrix. Medium to fine quartz and appears in the upper two-thirds and is lacking from the bottom third. Pellet or oolites ghost-like features occur in the middle of the unit.

Covered Interval 23'

3. Laminated boundstone crystalline dolomite. Fine 26'
crystalline (30 to 60 microns) dolomite. Very fine clear rhombs of dolomite overgrowing the matrix. Birdseye structure present in the top half with only minor amounts in the upper few feet, collapsed birdseye structures producing medium size laminated clast. Lower third has abundant amounts of fine quartz sand following laminations. Horizontal stylolites generally follow laminations.

4. Sandy laminated crystalline dolomite: fine to medium 3'6" (50 to 100 microns) dusty crystalline dolomite. Fine 0.1 to 0.5 cm lamination with subangular to angular size quartz, sand stringers forms the lamination within the dolomite matrix. Oolite/pelletal like structures occur along lamination.

5. Laminated boundstone crystalline dolomite: 10'
similar to unit number 3, but lack the abundant birdseye structure.
6. Recrystallized dolomite: coarse (110 to 200 microns) dusty crystalline dolomite. Medium dusty dolomite rhombs showing a overgrowing. The dusty dolomite forms an interlocking pattern.

7. Bedded algal boundstone: algal mat units range from 1.0 to 2.5 mm. Dolomite is very fine grained (25 to 40 microns) crystalline matrix. In some of the laminae there are oolites/pelletal type structures, and fine quartz sand randomly occurs within the unit. Horizontal stylolites occur between all laminations.

8. Laminated boundstone crystalline dolomite: fine crystalline (30 to 60 microns) dolomite, fine clear rhombs of dolomite overgrowing the crystalline matrix. Pellets/ooolite type ghost structure present, also a few birdseye structures. Fine to medium clast of fine crystalline dolomite with very fine clear dolomite rhombs.


Covered Interval 15'

10. Granular mottled dolomite: similar to unit number 9, the lower third contains fine grained quartz, without appeared laminations.

11. Laminated boundstone crystalline dolomite: similar to unit number 3.

12. Bedded algal boundstone: algal mat units range from .05 to 3.5 mm. Dolomite is of fine grained (40 to 70 microns). Fine quartz size sand only occurs in the upper 5 feet of unit.
<table>
<thead>
<tr>
<th>Unit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>13. Laminated boundstone crystalline dolomite: fine to medium (30 to 90 microns) crystalline dolomite, fine clear and dusty dolomite rhombs. Fine grained quartz sand randomly present in the lower half of the unit.</td>
<td>8'</td>
</tr>
<tr>
<td>14. Interclastic crystalline dolomite: fine to medium (50 to 100 microns) crystalline dolomite. Patches of fine clear dolomite rhombs. Fine clast patches of laminated fine crystalline dolomite.</td>
<td>2'</td>
</tr>
<tr>
<td>15. Granular mottled dolomite: similar to unit number 9, without the stylolites.</td>
<td>4'</td>
</tr>
<tr>
<td>16. Recrystallized dolomite: identical to unit number 2.</td>
<td>7'</td>
</tr>
<tr>
<td>17. Interclastic crystalline dolomite: identical to unit number 14.</td>
<td>1'</td>
</tr>
<tr>
<td>18. Laminated boundstone crystalline dolomite: fine crystalline (30 to 60 microns) dolomite, fine to medium dusty rhombs of dolomite, with small clusters of rhombs overgrowing the matrix, fine sized clast of very fine dolomite, with very fine clear dolomite rhombs.</td>
<td>1'</td>
</tr>
<tr>
<td>19. Bedded algal boundstone: similar to unit number 7. The oolites/pelletal type structures occur in the upper 3 feet of unit only.</td>
<td>5'</td>
</tr>
<tr>
<td>20. Laminated boundstone crystalline dolomite: fine crystalline (30 to 60 microns) dolomite, medium dusty rhombs of dolomite. Fine quartz sands which give the unit of laminated nature. Medium sized subround laminated clasts.</td>
<td>3'</td>
</tr>
<tr>
<td>21. Bedded algal boundstone: similar to unit number 7.</td>
<td>6'6&quot;</td>
</tr>
</tbody>
</table>

Covered Interval

22. Bedded algal boundstone: similar to unit numbers 7 and 21. | 5'6" |
23. Laminated boundstone crystalline dolomite: identical to unit number 20.

24. Bedded algal boundstone: the algal mat units range from 1.0 to 3.0 mm. Dolomite is fine crystalline with some very fine (10 to 30 microns) dolomite. Clear fine dolomite rhombs occur randomly within the unit. Horizontal stylolites are well developed generally follow the laminae. Small amounts of microcrystalline chert are inter-bedded with the algal material.

25. Recrystallized dolomite: similar to unit number 2 except no pellets or oolite ghost-like features. Small amounts of microcrystalline chert randomly occurs within the unit.

Base 0'0"

Covered Interval 82'
Appendix D

Lochman's Depositional Environments of the Cambrian of North America/U.S.

LEGEND--Figures 9-11 on the following pages. Genera known to date only in miogeosynclinal assemblages. Known or very probably lines of descent.

Time-stratigraphy of the Faunal Zones

<table>
<thead>
<tr>
<th>Series</th>
<th>Stage</th>
<th>Faunal Zone</th>
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</thead>
<tbody>
<tr>
<td>Upper</td>
<td>Trempealeauan</td>
<td>Saukia Zone</td>
</tr>
<tr>
<td>Cambrian</td>
<td>Franconian</td>
<td>Prosaukia Subzone</td>
</tr>
<tr>
<td></td>
<td>Dresbachian</td>
<td>Ptychaspis Subzone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Conaspis Zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elvinia Zone</td>
</tr>
<tr>
<td>Middle</td>
<td></td>
<td>Dunderbergia Zone</td>
</tr>
<tr>
<td>Cambrian</td>
<td></td>
<td>Aphelaspis Zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crepicephalus Zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cedaria Zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bolaspidella Zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bathyuriscus-Elrathinia Zone</td>
</tr>
</tbody>
</table>
Lateral and temporal relations of faunal zones to the transgressive and regressive phases of sedimentation.
(1A) Littoral—transgressive and lithotopy. A clean, well-sorted quartz sand, commonly with ripple marks and cross-bedding, is interpreted as a high energy beach environment. The thickness of the unit is highly variable and a quartz pebble conglomerate may be present at the base. In some of the thicker sections members of coarse granules and pebbles may alternate with sand members and occasionally red shales may appear (Templeton, 1950). The beds are unfossiliferous except for sporadic patches of innumerable comminuted inarticulate brachiopod valves.

(1B) Littoral—regressive sand lithotope. A clean, well-sorted, coarse-grained quartz sand with common cross-bedding is interpreted as a high energy beach environment. The unit is never more than about 60 metres thick and thins toward the outer shelf. The lower beds may contain patches of fossil fragments but otherwise the unit is entirely unfossiliferous.

(2A) Tidal (intertidal to infratidal)—sand lithotope. These sand flat deposits are characterized by thinly bedded, poorly sorted, glauconitic quartz sands grading vertically and laterally into lenses of silt, shale, granules, and dirty limes. Some areas are extensively burrowed and unfossiliferous, others have many lenses of fossil fragments. Intraformational pebble conglomerates may be few or numerous. The lithotope extended from the supratidal zone to the infratidal. The energy varied from low to high in tidal channels. Actual deposition was very sporadic and slight. Tides and currents reworked the material at the interface and slowly moved it toward the sublittoral zone.

(2B) Tidal (intertidal to infratidal)—mud lithotope. This environment of mud flats is characterized by silt and clay, thinly bedded and with fine glauconite grains, grading laterally into dirty limes and fine sand. The deposits are unfossiliferous except for rare inarticulate brachiopod valves. Intraformational pebble conglomerates may be few or numerous and very coarse. The lithotope extends from the supratidal zone to the infratidal and the energy is predominantly low with rare high-energy episodes. Actual deposition was sporadic and slow.

(2C) Tidal (lagoon)—sand/mud lithotope. Limited areal sites of fine-grained clastics trapped behind a barrier are located adjacent to the shore and characterized by few fossils, occasional carbonate debris, and thinly laminated beds. The energy is predominately low.

(2D) Tidal (algal shoals)—carbonate lithotope. Extensive shoals developed widely over the outer shelf and extended across the inner shelf nearly to the shore, depending upon the presence of clear normal sea water. Stromatolites occupied sites extending from the supratidal zone to the infratidal zone and ranging from low-energy lagoons to high-energy tidal channels. Fossil fragments were originally common, but have been destroyed by the prevailing early diagenetic dolomitization.
(2E) Tidal (intertidal to infratidal)--carbonate ooze lithotope. Lime mud flats with minor amounts of argillaceous clay and/or fine quartz sand or silt, as impurities or thin beds or lenses. Medium to fine glauconite grains are locally abundant. Rounded, medium-sized, flat-pebble conglomerates are usually common, as well as the thin micrite beds. Fossils are scattered, but of moderate abundance, often concentrated as a coquina matrix of the pebble conglomerates. The lithotope usually grades laterally into 2B with the increase in fine clastic material; and on the infratidal side may grade into 3C.

(3A) Sublittoral shelf--argillaceous sand lithotope. A moderately sorted, argillaceous or silty, quartz sand occurs as the seaward continuation of 2A. Glauconite may be abundant and calcareous cement is common. The clay may occur as matrix, as thin shale partings in thin-bedded sands, or uncommonly as shale sequences or lenses up to 3 or 4 meters thick. Scattered fossil debris is abundant. Ripple marks and current cross-bedding are present as well as thin layers of rounded pebble conglomerates. The water depth is within the infralittoral range and the environment passes seawards by gradual increase of carbonate beds and lenses into one of the carbonate environments, 2D or 3C.

(3B) Sublittoral shelf--sandy mud lithotope. This is an environment of relatively limited areal extent on the shelf which has a substrate of fine sand, silt, fine clauconite grains, clay, and occasional rounded frosted sand grains. It may develop seawards of 2B and represents areas where the water was quiet enough most of the time to accumulate predominately the winnowed fines. Trails, burrows, and scattered shells of inarticulate brachiopods may occur, but fossils are not abundant. It appears usually as local thin beds or lenses passing laterally by increase of lime into the dirty limes of 2D or 3C.

(3C) Sublittoral shelf--carbonate lithotope. Thin to medium-bedded limes, with small amounts of sand, silt, or clay, developed most frequently on outer shelf sites, but can extend close to the shore. Infralittoral water depths of medium to high energy are distinguished from 3A and 3B by the absence of most terrigenous-derived material and from 2D by greater water depths. Fossils may be absent, scattered, or locally very abundant, and oolite beds and lenses may be locally abundant. Size sorting of the organic debris may occur. The unit occurs now as crystalline limestones in which any dolomitization can be demonstrated to be late.

(3Ci) Sublittoral shelf--a variant of the carbonate lithotype. Brachiopod biostromes composed of numerous valves usually of Eoorthis and Billingsella occur most commonly during the Franconian. They appear to represent in-situ accumulations which developed in hard-bottom, clear, medium-energy areas, probably at depths close to 45 meters at which stromatolites did not or could not maintain themselves. The biostromes vary from 15 cms to as much as 3 meters in thickness.
(3D) Sublittoral shelf--swales--mud lithotope. These are sea bottom areas of variable size and shape which lie appreciably lower than the surrounding shelf floor. They may occur in either inner or outer shelf sites but appear to be more abundant in the latter. The low-energy, often stagnant waters of the bottoms permitted settling of the finest clastics in thin laminae, or the slow accumulation of organic debris as lag concentrates in 1-2 mm laminae. But slumping from the surrounding shelf shoals introduced pebble conglomerates, broken exoskeletons, and sand grains of varying sizes, often well rounded and mixed with well-rounded gluconite grains.
### ENVIRONMENTS OF DEPOSITION

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1A</td>
<td>Littoral--transgressive sand lithotope</td>
</tr>
<tr>
<td>1B</td>
<td>Littoral--regressive sand lithotope</td>
</tr>
<tr>
<td>2A</td>
<td>Tidal (intertidal to infratidal)--sand lithotope</td>
</tr>
<tr>
<td>2B</td>
<td>Tidal (intertidal to infratidal)--mud lithotope</td>
</tr>
<tr>
<td>2C</td>
<td>Tidal (lagoon)--sand/mud lithotope</td>
</tr>
<tr>
<td>2D</td>
<td>Tidal (algal shoals)--carbonate lithotope</td>
</tr>
<tr>
<td>2E</td>
<td>Tidal (intertidal to infratidal)--carbonate ooze lithotope</td>
</tr>
<tr>
<td>3A</td>
<td>Sublittoral shelf--argillaceous sand lithotope</td>
</tr>
<tr>
<td>3B</td>
<td>Sublittoral shelf--sandy mud lithotope</td>
</tr>
<tr>
<td>3C</td>
<td>Sublittoral shelf--carbonate lithotope</td>
</tr>
<tr>
<td>3C₁</td>
<td>Sublittoral shelf--carbonate lithotope variant</td>
</tr>
<tr>
<td>3D</td>
<td>Sublittoral shelf (swales)--mud lithotope</td>
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<tr>
<td></td>
<td>Shoreline</td>
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<td></td>
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</table>

Key to symbols used to indicate environments of deposition in the series of palaeogeographical maps.
Palaeogeography and palaeoecology—Upper Cambrian, early Aphelaspis Zone.

Palaeogeography and palaeoecology—Upper Cambrian, late Aphelaspis and Dunderbergia Zones.
Palaeogeography and palaeoecology—Upper Cambrian, early Cedaria Zone.

Palaeogeography and palaeoecology—Upper Cambrian, Crepicephalus Zone.