1984

Bivalve associations of the Cannonball Formation (Paleocene, Danian) of North Dakota

Rosanne M. Lindholm
University of North Dakota

Recommended Citation

Lindholm, Rosanne M., "Bivalve associations of the Cannonball Formation (Paleocene, Danian) of North Dakota" (1984). *Theses and Dissertations*. 175.
https://commons.und.edu/theses/175

BIVALVE ASSOCIATIONS OF THE CANNONBALL FORMATION
(PALEOCENE, DANIAN) OF NORTH DAKOTA

by
Rosanne M. Lindholm
Bachelor of Science
University of North Dakota

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements
for the degree of
Master of Science

Grand Forks, North Dakota

May
1984

This thesis submitted by Rosanne M. Lindholm in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

Alan M. Cvancara
(Chairperson)

F. D. Holland Jr.

Richard D. LeFever

This thesis meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

____
Dean of the Graduate School

Permission

Title Bivalve Associations of the Cannonball Formation (Paleocene, Danian) of North Dakota

Department Geology

Degree Master of Science

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the Library of this University shall make it freely available for scholarly purposes and may be granted by the professor who supervised my thesis work or, in his absence, by the Chairman of the Department or the Dean of the Graduate School. It is understood that any copying or publication or other use of this thesis or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any scholarly use which may be made of any material in my thesis.

Signature [illegible]

Date [illegible]

TABLE OF CONTENTS

APPENDICES

LIST OF ILLUSTRATIONS

Figure

Figure

LIST OF TABLES

Table

ACKNOWLEDGMENTS

I would like to express my gratitude to Dr. Alan M. Cvancara for acting as chairman of my thesis committee, for providing guidance in and out of the field, and for his patience throughout this project. I would also like to thank the other members of my thesis committee: Dr. F. D. Holland, Jr., who provided a great deal of help in editing the manuscript, and Dr. Richard D. LeFever, whose knowledge and assistance in the world of computers and cluster analyses were invaluable.

I also wish to thank Edward C. Murphy, North Dakota Geological Survey, who provided transportation into a nearly inaccessible field area.

Special thanks are due to my fellow graduate students at the University of North Dakota: in particular, Charles L. LoBue for being my sounding board and for providing constant support; Brian P. Wallick for his enthusiasm and willingness to share his thoughts about Paleocene geology; and Stephen C. Thompson whose geologic insight and friendship were always appreciated.

I would like to acknowledge the Department of Geology, University of North Dakota, for providing the facilities and funding for this project. Partial field support was provided by the Beta Zeta Chapter of Sigma Gamma Epsilon and is gratefully acknowledged.

Finally, I would like to thank my parents for their love and endless encouragement.

ABSTRACT

The Cannonball Formation (Paleocene, Danian) is best exposed in southwest-central North Dakota. Here, two major lithotypes, mudstone and sandstone, occur. In this area, the Cannonball can be informally subdivided into four lithologic units: lower (primarily thinly-bedded sandstone and mudstone), lower-middle (sandstone), upper-middle (mudstone), and upper (sandstone). The Cannonball is also exposed in southwestern North Dakota where it occurs as two mudstone tongues (upper and lower).

During July and August, 1982, thirteen Cannonball outcrops were studied. Bivalves, along with other macrofossils, were collected quantitatively in an attempt to determine fossil species dominance. Rock samples were also collected and analyzed for textural characteristics and organic carbon content. In addition, R-mode and Q-mode cluster analyses were done using the reported occurrences of 20 bivalve species, along with other macrofossils, from 97 localities in North Dakota.

Five bivalve associations are defined: *Ostrea*-*Corbula*-*Corbicula*, *Crassostrea*-*Corbicula*-*Corbula*, *Isognomon*, *Glycymeris*-*Arctica*, and *Crassatella*-*Nucula* associations. One sub-association, the modified *Crassatella*-*Nucula* association, and a biotic association of *Ophiomorpha*-Crab-Driftwood-Shark Teeth, are also defined. These associations aid in the interpretation of the relationships of Cannonball lithologic units and depositional environments.

The *Ostrea*-*Corbula*-*Corbicula* association (lower tongue) and the *Crassostrea*-*Corbicula*-*Corbula* association (upper tongue) contain low-diversity faunas that are characteristic of brackish-water environments associated with lagoons.

The *Isognomon* association, found in the lower Cannonball unit, occurs in muddy sandstone rich in organic material. The abundance of *Isognomon*, a large, thick-shelled, suspension-feeding bivalve, along with the lack of other macrofossils, suggests an environment where conditions were prohibitive to most organisms. A shallow-water environment associated with a tidal flat is proposed.

The *Glycymeris*-*Arctica* association, found in well-sorted sandstone in the lower-middle unit, is dominated by suspension-feeding bivalves. The presence of *Glycymeris*, a bivalve well adapted to high-energy conditions, indicates a nearshore, wave-agitated beach environment. The *Ophiomorpha*-Crab-Driftwood-Shark Teeth association also occurs in well-sorted sandstone but is not restricted to any Cannonball unit. The association of these nearshore inhabitants suggests a beach environment where deposition took place in the vicinity of the strandline.

The *Crassatella*-*Nucula* association occurs in the lower-middle unit in muddy sandstone. This association has high diversity and both deposit-feeding and suspension-feeding bivalves are present suggesting a stable, subtidal environment. The modified *Crassatella*-*Nucula* association contains bivalves similar to the veritable *Crassatella*-*Nucula* association but lacks the high diversity. The modified association occurs in variable lithology and is not restricted to any Cannonball lithologic unit. It also represents a subtidal environment; however, conditions were probably not conducive to high-diversity communities.

Two major transgressions and regressions occurred during Cannonball time. Based on the proposed associations, it seems likely that deposition of the brackish-water tongues in southwestern North Dakota is correlative with two major transgressive events in southwest-central North Dakota.

INTRODUCTION

General

The Cannonball Formation (Paleocene, Danian) is a marine unit of variable lithology in the Williston Basin in western North Dakota and northwestern South Dakota. The Cannonball probably occurs throughout the western half of the state but crops out primarily in southwest-central North Dakota and is best exposed in the drainage of the Missouri River and along three western tributaries, the Heart and Cannonball Rivers and Cedar Creek, particularly in Grant and Morton Counties. Almost everywhere else, it is concealed by younger bedrock or glacial drift. The notable exception to this occurs in southwestern North Dakota in the Little Missouri Valley. Here, two distinct units occur, both brackish-water tongues of the Cannonball Formation. These tongues are separated by approximately 100 feet (30 m) of nonmarine sedimentary rocks of the Slope Formation.

The Cannonball is composed primarily of mudstone and sandstone. However, many Cannonball sediments fall somewhere in the continuum between these two lithologies. Although the Cannonball lacks coal, it interfingers with the Ludlow and Slope Formations, Cannonball continental equivalents, both of which contain abundant lignite.

The marine fauna of the Cannonball has relatively low diversity (when compared to others, such as the fauna of the Cretaceous Fox Hills Formation), and fossils are not particularly common or abundant at the majority of Cannonball exposures. Previously, no paleoecological study of Cannonball macrofossils has been attempted. This investigation, though noting all observed macrofossil relationships, deals primarily with the paleoecology of one group, the bivalves.

Purpose of Study

The primary purpose of this thesis is to define the bivalve associations of the Cannonball Formation in North Dakota. Secondary purposes include: 1) to determine the trophic structure of these associations using functional morphology to reconstruct the niche of individual bivalve species; 2) to correlate these associations with different lithotypes of the Cannonball Formation; 3) to determine any organic carbon gradients among the Cannonball lithotypes in which these associations occur; and 4) using sedimentary characters and the above, to interpret the depositional environments of the Cannonball Sea.

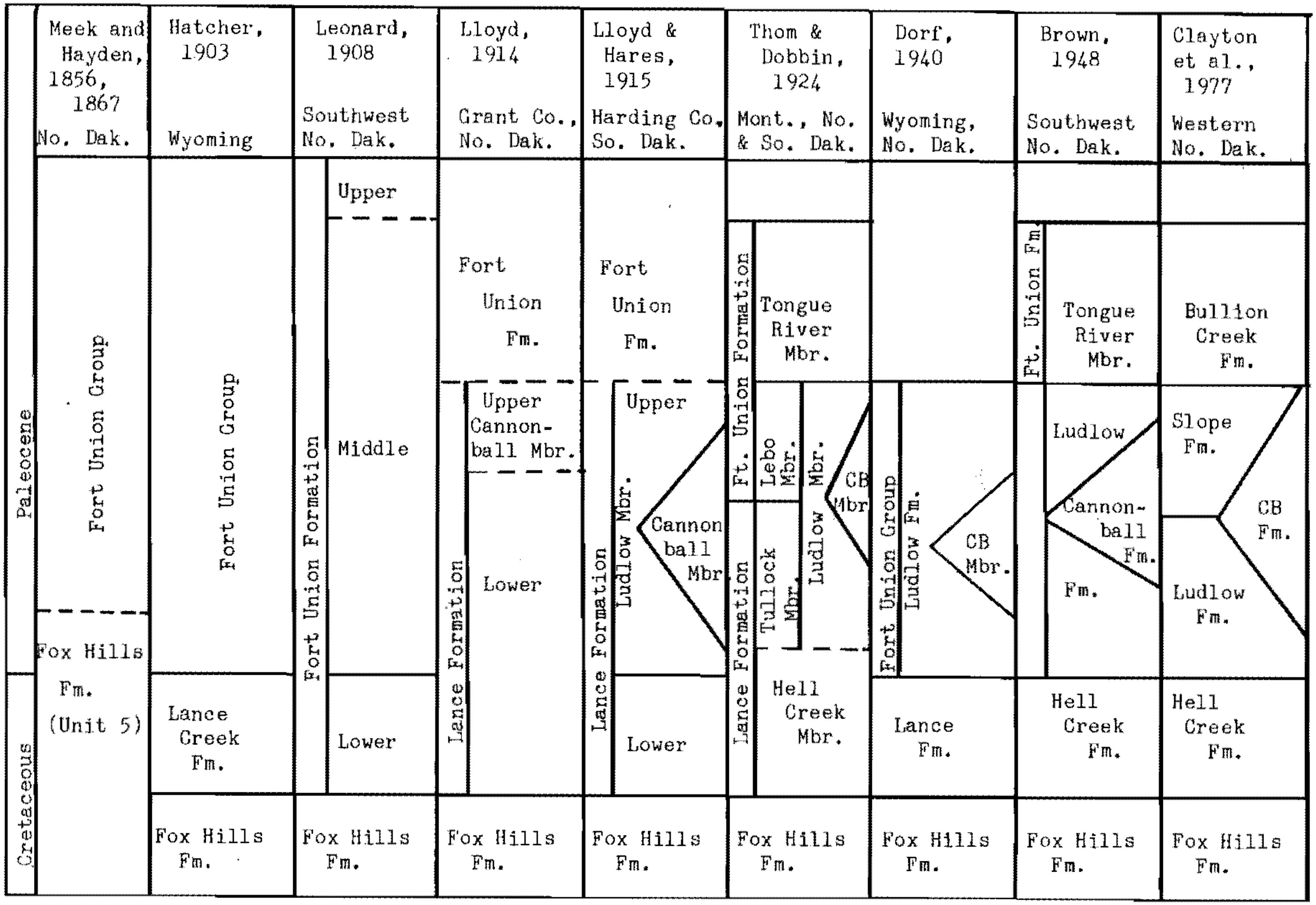
Previous Work

Stratigraphy

The history of the stratigraphic nomenclature for the rocks that are today designated as the Cannonball Formation (summarized in Table 1) is complex and goes back to the time of the earliest geologic expeditions in North Dakota. The first known record of Cannonball rocks was that of Meek and Hayden (1856a), who incorporated the Cannonball strata with the Upper Cretaceous Fox Hills strata (then defined as "Formation No. 5").

In later years, confusion resulted because of the association of the Cannonball with the Fort Union and Lance Formations. The term "Fort Union" was initially used to designate coal-bearing strata in the country around Fort Union at the mouth of the Yellowstone River.

Table 1. Abbreviated historical summary of the Upper Cretaceous and lower Tertiary stratigraphic section nomenclature used in Wyoming, Montana, South Dakota, and North Dakota.


Paleocene
Cretaceous
Meek and Hayden, 1856, 1867
No. Dak.
Fort Union Group
Fox Hills Fm. (Unit 5)
Hatcher, 1903
Wyoming
Fort Union Group
Lance Creek Fm.
Fox Hills Fm.
Leonard, 1908
Southwest No. Dak.
Fort Union Formation
Upper
Middle
Lower
Fox Hills Fm.
Lloyd, 1914
Grant Co., No. Dak.
Fort Union Fm.
Lance Formation
Upper Cannon-ball Mbr.
Lower
Fox Hills Fm.
Lloyd & Hares, 1915
Harding Co., So. Dak.
Fort Union Fm.
Lance Formation
Ludlow Mbr.
Upper
Cannon ball Mbr
Lower
Fox Hills Fm.
Thom & Dobbin, 1924
Mont., No. & So. Dak.
Ft. Union Formation
Tongue River Mbr.
Ft. Union
Lebo Mbr.
Lance Formation
Tullock Mbr.
Ludlow Mbr.
CB Mbr
Hell Creek Mbr.
Fox Hills Fm.
Dorf, 1940
Wyoming, No. Dak.
Fort Union Group
Ludlow Fm.
CB Mbr.
Lance Fm.
Fox Hills Fm.
Brown, 1948
Southwest No. Dak.
Ft. Union Fm
Tongue River Mbr.
Ludlow
Cannon-ball Fm.
Fm.
Hell Creek Fm.
Fox Hills Fm.
Clayton et al., 1977
Western No. Dak.
Bullion Creek Fm.
Slope Fm.
CB Fm.
Ludlow Fm.
Hell Creek Fm.
Fox Hills Fm.

The "Fort Union" was later extended to cover areas in North Dakota, eastern Montana, Wyoming, and South Dakota.

The term "Lance beds" was introduced by Hatcher (1903) to include the beds above the Cretaceous Fox Hills Formation and below the Fort Union in Converse County, Wyoming. This nomenclature was later extended into Montana, Colorado, South Dakota, and North Dakota.

In 1914, Lloyd (p. 249) formally defined the "Cannonball marine member" as the upper 250 to 300 feet (76 to 91 m) of the Lance Formation and designated as the Cannonball type area the bluffs of the Cannonball River in Tps. 132 and 133 N., R. 88 W. (Lloyd and Hares, 1915, p. 533, added R. 87 W. to the type area). This designation was a result of Lloyd's study along the Cannonball River and its tributaries in southwest-central North Dakota and was in some contradiction to Leonard (1908) who assigned all the strata in southwestern North Dakota above the Fox Hills Formation and below the White River Formation to the Fort Union. Leonard (1908, p. 49) also included in the Fort Union strata containing beds of fossil oyster shells that he discovered 5 miles (8 km) southwest of the Yule Post Office (no longer in existence), or, approximately 15 miles (24 km) north-northeast of Marmarth, Slope County, North Dakota.

In 1915, Lloyd and Hares (p. 528) named and defined the "Ludlow lignitic member" of the Lance Formation. In the same paper, they discussed (p. 540) the oyster beds near Yule as representing a western extension of the Cannonball.

A contrary view was expressed by Thom and Dobbin in 1924. They said (p. 497) that the upper part of the "Cannonball marine member of the Lance" was equivalent to the "Lebo shale member of the Fort Union formation" in Montana. In addition, the upper Ludlow was said to be equivalent to the "Lebo shale" and the lower Ludlow to the "Tullock member of the Lance formation." Further, they suggested that the lower member of the Lance Formation in North Dakota was equivalent to the "Hell Creek beds" of Brown (1907) in Montana.

Dorf (1940) utilized Tertiary plants in the Ludlow Formation as evidence that the Ludlow, and therefore the Cannonball, were similar to the Fort Union and were of Paleocene age. However, he stated that the lower member of the Lance (Hell Creek) was of Cretaceous age. Thus, the Lance Formation included only Hell Creek strata, and the Ludlow beds were elevated to formational status of which the Cannonball beds constituted a member. Both were placed in the Fort Union Group. The Cannonball was raised to formational status by Fox and Ross (1942) who supported a Paleocene age based on foraminiferal evidence.

Brown (1948, p. 1271) reported a second brackish-water tongue of the Cannonball containing the bivalve Corbula. He first discovered the tongue in 1931 but did not publish this find until 1948. He stated later (1962, p. 10) that the Corbula tongue occurs approximately 150 feet (46 m) below the oyster tongue of Leonard (1908).

The stratigraphy of the Cannonball has been discussed to varying degrees by many workers. Many have reported their discovery of new Cannonball outcrops thereby extending the limits of the formation. Some of the more notable authors include Hall (1958), Lemke (1960), Cvancara (1965, 1976), Pipiringos et al. (1965), and Monnens (1980). A detailed discussion on the stratigraphic history of the Cannonball Formation is given by Cvancara (1965).

Paleontology and Age

Early workers such as Meek and Hayden (1856a, 1857) confused the marine strata of the Cannonball Formation, and thus its age, with those of the Cretaceous Fox Hills Formation. The confusion was settled when the Cannonball was defined and named by Lloyd (1914) and placed as a member of the Lance Formation. The Lance Formation, at that time, was considered to be an equivalent of the Fort Union. Based primarily on floral evidence presented by Knowlton (1911), both the Lance and the Fort Union were assigned an Eocene age. This probably influenced Lloyd (1914, p. 248) who, with some hesitation, assigned the "marine member of the Lance Formation" a Tertiary age.

A prominent early study of the Cannonball fauna was published by Stanton (1920). He listed and described 2 species of foraminiferids, 63 molluscs (31 bivalves, 31 gastropods, 1 scaphopod), and 2 species of sharks. Using these molluscs, Stanton concluded that the "Cannonball member of the Lance formation" was of Cretaceous age even though the Cannonball lacked ammonites and other distinctively Mesozoic groups. Because 30 percent of the Cannonball molluscs were also known from the Fox Hills Formation, in addition to the apparent lack of marine Tertiary rocks in the Western Interior, he was convinced that a Late Cretaceous age was more accurate for the entire Lance Formation.

A Cretaceous age was generally accepted until Dorf (1940) re-examined the Lance and Fort Union floras and concluded that the Ludlow, the continental equivalent of the Cannonball, contains a Paleocene flora. Thus, the Cannonball must also be considered of Paleocene age.

At approximately the same time, Fox and Ross (1940) examined in detail the Cannonball foraminiferids and identified 64 species.

Of these species, 38 were also reported to occur in the Midway (Paleocene) of the Texas Gulf Coast further supporting a Paleocene age for the Cannonball. Swain (1949, p. 174) concurred with Fox and Ross when he reported ostracode species in the Cannonball common to the Midway of Texas.

Brown (1948) reported his discovery of a Cannonball brackish-water tongue exposed in the Little Missouri Valley containing the bivalve *Corbula*. He stated (1962, p. 10) that the *Corbula* tongue occurs 150 feet (46 m) below the Cannonball tongue described by Leonard (1908, p. 48) containing beds of the oyster *Ostrea subtrigonalis* Evans and Shumard.

Cvancara (1965, 1966) described and illustrated 30 species of Cannonball bivalves. In his comprehensive stratigraphic study, Cvancara (1965, p. 104) concluded that more similarity exists between Cannonball bivalve species and the Paleocene species from the London and Paris Basins than with those from the Midway Group of Texas. Based on this, he proposed a Thanetian (middle Paleocene) age for the Cannonball.

Cvancara (1966, 1970a) also reported teredinid bivalves from the Cannonball. He described (1970a) teredinid pallets that established the Paleocene existence of the extant genus *Nototeredo*.

In 1969, Fox and Olsson reported 7 species of planktic foraminiferids. Though planktic foraminiferids are rare in the Cannonball, their assemblage belongs to a zone indicative of the Danian Stage of the Paleocene. The more common benthic foraminiferids were analyzed by Fenner (1974) who identified 26 species. In 1976, Fenner further identified 50 species of benthic foraminiferids and 4 species of planktic foraminiferids from 60 water test wells in western North Dakota.

Van Alstine (1974) examined the fauna from the Cannonball brackish-water tongues in Slope and Golden Valley Counties, southwestern North Dakota. The biota of the nonmarine Ludlow (now the Slope Formation), which interfingers with the Cannonball in this area, was also analyzed. Dr. Edward S. Belt, Professor of Geology, Amherst College, Amherst, Massachusetts, reported (1983, personal communication) the easternmost occurrence of the bivalve Corbula (Bicorbula) subtrigonalis in the lower Cannonball tongue in the SW 1/4 Sec. 36, T. 135 N., R. 105 W.

Additional invertebrate and vertebrate forms reported from the Cannonball include corals (Vaughan, 1920; Wilson, 1957), crabs (Holland and Cvancara, 1958), the nautiloid cephalopod Hercoglossa ulrichi (Feldmann, 1972), lobsters (Feldmann and Holland, 1971), the fossil burrow Ophiomorpha (=Halymenites) (Cvancara, 1965; Van Alstine, 1974; Monnens, 1980; Goodrum, 1982), sharks (Stanton, 1920; Leriche, 1942; Pipiringos et al., 1965), and skates, rays, turtles, and crocodiles or alligators (Cvancara, 1965; Pipiringos et al., 1965).

Sloan (1970) concluded that the Cannonball was in the Puercan and Torrejonian (early to middle Paleocene) stages based on mammalian remains in the overlying Tongue River Formation. This was contradicted by Holtzman (1978) who also examined fossil mammals from the base of the Tongue River Formation that indicated, to him, a middle-late Paleocene (middle Tiffanian) age for this unit. By association, he concluded that the uppermost part of the Cannonball is also late Paleocene in age.

Studies of the Cannonball flora have provided additional evidence to support a Paleocene age. The macroflora has been studied by Brown

(1962) and Stanley (1965). The microflora consists of spores, pollen, dinoflagellates, and hystrichosphaerids and has been described by Stanley (1965) and Robertson (1975). Cvancara (1970b) reported 2 species of Cannonball driftwood, commonly bored by teredinid bivalves.

Structural Setting

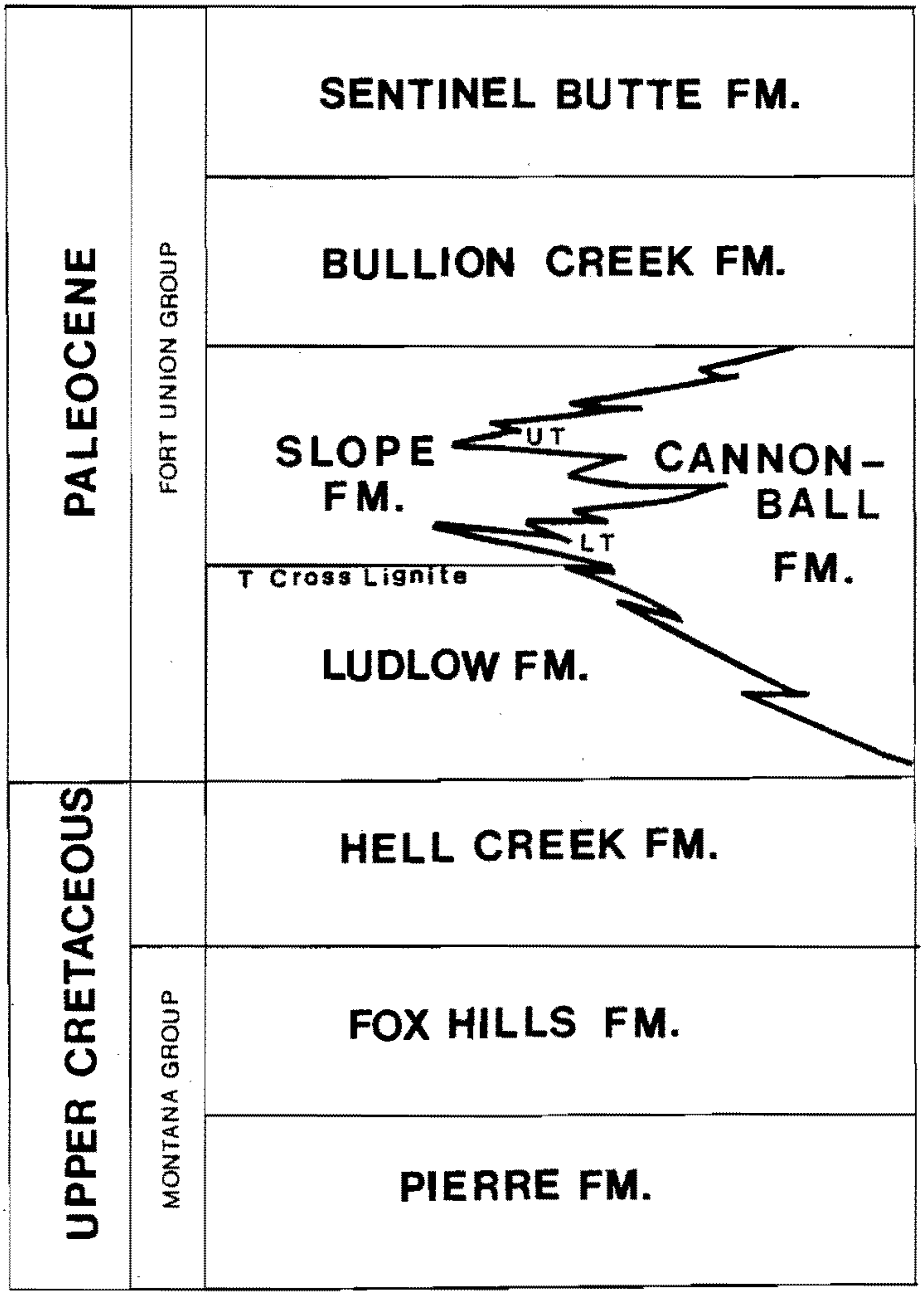
The Cretaceous and Tertiary rocks in North Dakota are structurally influenced by the Williston Basin. This intracratonic basin covers 51,600 square miles (133,644 sq km) of North Dakota as well as parts of South Dakota, Montana, Manitoba, and Saskatchewan and has a thickness of up to 15,000 feet (4,570 m) of Phanerozoic sedimentary rocks (Carlson and Anderson, 1965). Other structures superimposed upon the basin consist of anticlines, lineaments, and highs (Gerhard et al., 1982).

The Cretaceous and Tertiary rocks in North Dakota generally dip toward the center of the basin, located about 40 miles (64 km) southeast of Williston (Carlson, 1982, p. 4). Dips are most commonly gentle, less than 1 degree; however, minor structures may locally change the amount and direction of dip. A more detailed discussion of local structure is given by Cvancara (1976, p. 12-13).

Regional Stratigraphy

The stratigraphy of the early Tertiary in North Dakota is complex and nomenclature has been revised in recent years. Controversy has revolved around the Ludlow, Cannonball, and Tongue River Formations, and problems with correlation of the Ludlow and Tongue River between North Dakota, South Dakota, and Montana has resulted in the introduction (Clayton et al., 1977) of two new formation names in North Dakota, the Slope Formation and the Bullion Creek Formation (Fig. 1).

Fig. 1. Generalized stratigraphic column for Upper Cretaceous and Paleocene strata in North Dakota. (UT = upper Cannonball tongue, LT = lower Cannonball tongue)


PALEOCENE
UPPER CRETACEOUS
FORT UNION GROUP
MONTANA GROUP
SENTINEL BUTTE FM.
BULLION CREEK FM.
SLOPE FM.
CANNONBALL FM.
UT
LT
T Cross Lignite
LUDLOW FM.
HELL CREEK FM.
FOX HILLS FM.
PIERRE FM.

The lignitic Ludlow Formation formerly included strata between the Cannonball and Hell Creek Formations in northwestern South Dakota and southwestern North Dakota. However, with the introduction of the Slope Formation, the Ludlow is restricted to this interval of strata only in central North Dakota, and to strata between the Hell Creek and the T Cross lignite in western North Dakota, where Clayton et al. (1977) considered the Cannonball to be absent. Thus, the nonmarine Slope Formation, consisting of alternating beds of poorly-consolidated claystone, siltstone, sandstone, and lignite, includes strata that were previously considered the upper part of the Ludlow Formation in western North Dakota, in addition to part of the Tongue River Formation in central North Dakota. By definition, the top of the Slope Formation is marked by a widespread, white siliceous zone (Rhame Bed) interpreted as a paleosol (Moore, 1976; Wehrfritz, 1978; Monnens, 1980).

The Slope Formation is unconformably overlain by the Bullion Creek Formation. This unit also consists of alternating beds of poorly-consolidated claystone, siltstone, sandstone, and lignite, and includes sedimentary rocks beneath the Sentinel Butte Formation but above the Rhame Bed. It is equivalent to those strata previously considered to belong to either part or all of the Tongue River Formation in central and western North Dakota.

The Slope Formation, with its type section along the Little Missouri River in Slope County, overlies the Cannonball Formation in central North Dakota and the Ludlow in western North Dakota, where the top of the T Cross lignite is considered to be the contact between the Ludlow and Slope Formations. Because both tongues of the Cannonball occur above this bed, they are, by definition (Clayton et al., 1977), brackish-water lithofacies of the Slope Formation. It is the author's opinion that the brackish origin of these deposits is the result of a connection with more normal marine Cannonball sediments in central North Dakota and, therefore, the two tongues containing brackish faunas in western North Dakota are stratigraphic equivalents of part of the Cannonball in northwest-central North Dakota. Thus, for the purpose of this study, the Cannonball Formation is considered to interfinger with both the Ludlow and Slope Formations, the Cannonball continental equivalents.

The Cannonball, along with the Ludlow, Slope, Bullion Creek, and Sentinel Butte Formations comprise the Fort Union Group. This stratigraphic classification is used by the North Dakota Geological Survey; however, the United States Geological Survey uses the Fort Union as a formation rather than a group.

The Fort Union Group is underlain by the Hell Creek Formation, consisting of, in many places, poorly-consolidated sandstone, siltstone, bentonitic shale, and minor lignite deposited in a fluvial-deltaic environment. Below the Hell Creek are the sandstones and shales of the Fox Hills Formation, representing nearshore marine conditions; that overlies the Pierre Shale, consisting of shales and mudstones with minor sandstone, deposited in a more offshore marine environment. The Pierre-Hell Creek sequence is mostly of Late Cretaceous age although the top of the Hell Creek may be Paleocene in age (Archibald, 1982).

Overlying the Fort Union Group are the shales and sandstones of the continental Golden Valley Formation of Paleocene and Eocene age (Hickey, 1972, 1977).

These Upper Cretaceous and lower Tertiary rocks generally crop out in southwestern and southern North Dakota. The rocks of the Cannonball Formation are found primarily in southwest-central North Dakota, most commonly in the drainage of the Missouri River and especially its western tributaries, the Heart River, the Cannonball River, and Cedar Creek.

METHODS OF STUDY

Fossil Localities

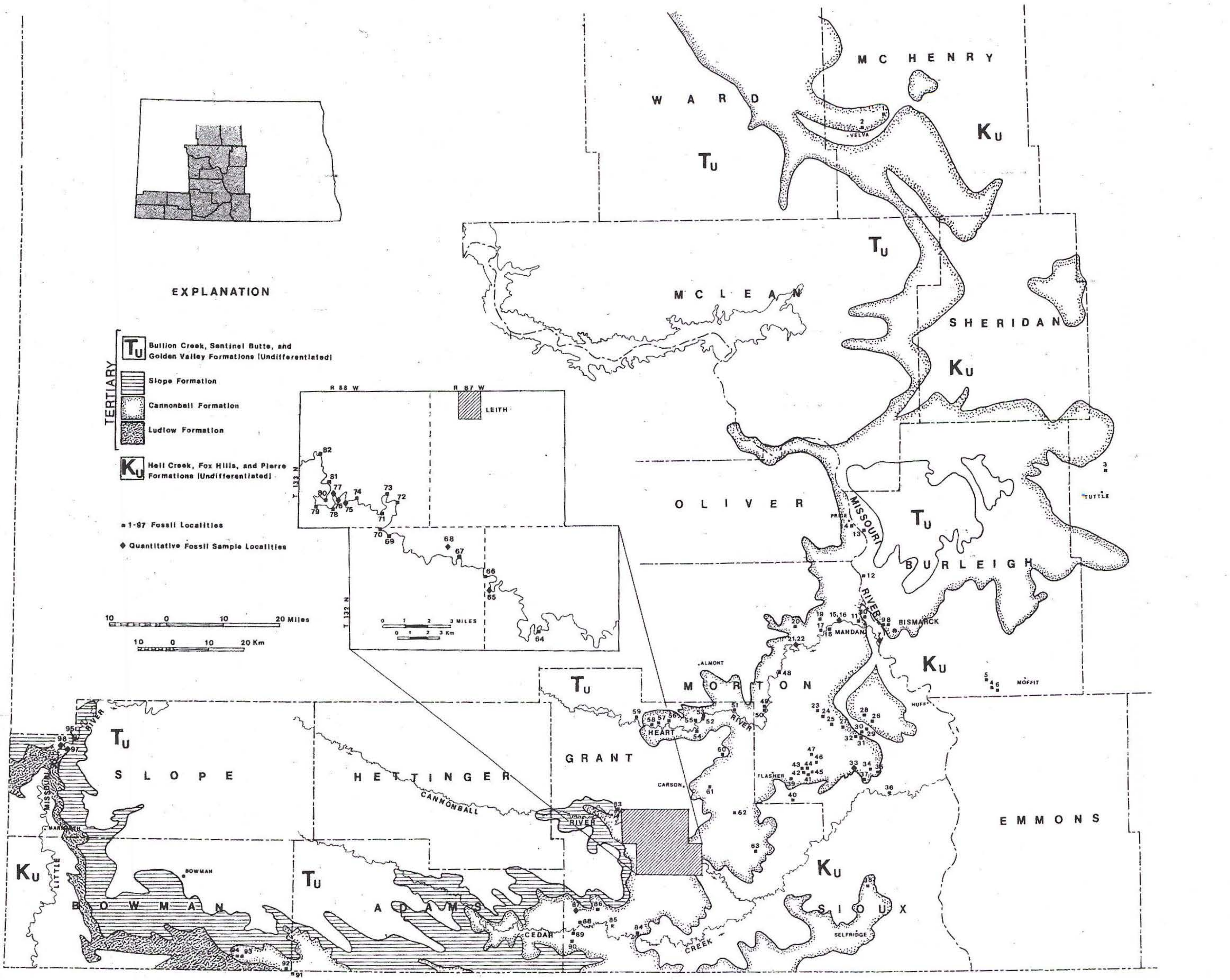
Cannonball fossils occur primarily at scattered outcrops in southwest-central North Dakota and in southwestern (Slope County) North Dakota. These fossils have been collected and described over the past years by many workers. Cvancara (1965, Appendix C) compiled a list of recorded species occurrences, 97 of which are used in this study. The localities of these 97 reported occurrences have been numbered in a roughly geographic succession from northeast to southwest as shown in Fig. 2. Generally, one number represents one locality; however, in two cases, two different numbers were used to represent the same geographic locality (15, 16 and 21, 22). The reason for assigning two successive numbers to one outcrop is that different fossils were reported to occur in two distinct units; for example, a fossiliferous mudstone and a fossiliferous sandstone are both present. Thus, each lithology was considered a discrete occurrence and assigned a number.

Fieldwork

The fieldwork for this investigation was accomplished during July and August, 1982. The purpose of the fieldwork was twofold. First, in order to determine any fossil species dominance, quantitative collecting of fossils was necessary, and second, in order to determine any correlation between fossil occurrence and lithology, samples of the matrix enclosing the fossils were collected. Rock colors were recorded in accordance with Goddard et al. (1948).

Fig. 2. Geologic map of southwestern North Dakota showing Cannonball and adjacent formations (after Bluemle, 1983), and showing the fossil localities used in this study. The localities marked by the diamond symbol are those sampled by the author. Locality and sample descriptions are given in Appendix I and II. Although all fossil collecting localities are known Cannonball outcrops, Bluemle (1983) did not extend the Cannonball bedrock limits to include all of them.

Pg 18


EXPLANATION
TERTIARY
Tu Bullion Creek, Sentinel Butte, and Golden Valley Formations (Undifferentiated)
Slope Formation
Cannonball Formation
Ludlow Formation
Ku Hell Creek, Fox Hills, and Pierre Formations (Undifferentiated)
■ 1-97 Fossil Localities
◆ Quantitative Fossil Sample Localities
10 0 10 20 Miles
10 0 10 20 Km
R 88 W
R 87 W
LEITH
T 133 N
T 132 N
0 1 2 3 MILES
0 1 2 3 Km
WARD
MC HENRY
VELVA
MCLEAN
SHERIDAN
OLIVER
BURLEIGH
MORTON
GRANT
SLOPE
HETTINGER
BOWMAN
ADAMS
SIOUX
EMMONS
MISSOURI RIVER
HEART RIVER
CANNONBALL RIVER
CEDAR CREEK
LITTLE MISSOURI RIVER
BISMARCK
MANDAN
PRICE
TUTTLE
MOFFIT
HUFF
ALMONT
CARSON
FLASHER
SELFRIDGE
BOWMAN
MARMARTH
Tu
Ku

Field Area

Of the 97 reported fossil occurrences, 13 localities (shown on Fig. 2 by the diamond symbol) were examined by the author. These localities were chosen based on their reported relatively diverse and dense fossils and are found primarily in Grant and Morton Counties, southwest-central North Dakota. In addition, two localities in Slope County, southwestern North Dakota, were investigated where the Cannonball tongues are exposed.

Both fossils and their enclosing matrix were collected at these 13 localities and brought back to the University of North Dakota for study. Fossil samples were assigned University of North Dakota accession numbers. In addition to the fossils collected by the author, some of the same localities had been resampled by Dr. Alan Cvancara several years earlier. His collected fossils were also used in this study and are distinguished from the author's samples by having different accession numbers (Appendix II).

Rock samples were not assigned accession numbers and are thus referred to by their corresponding locality number.

Fossil Sampling

An attempt was made to collect fossil samples in a quantitative manner. However, because the Cannonball outcrops vary considerably in fossil concentration, degree of lithification, and quality of fossil preservation, several methods were employed. These included:

1) Extracting specimens from a given volume of rock. The poorly-consolidated rocks were disaggregated by soaking in water and fossils recovered by sieving through a screen. This method was tried

and abandoned primarily because at most outcrops the fossil concentration, even in large volumes of sediment, was too low to make this method feasible.

2) Line intercept transect method. This method involved counting all specimens along a given line of exposure. Once again, the low concentration of fossils made this method impractical at many outcrops. However, it was found applicable at locality 65 where the bivalve Isognomon occurs. Because of shell deterioration, extraction was not possible and this method was employed to determine the abundance of this taxon.

3) Quadrat method. Fossils present in a one square meter area were counted and identified. The application of this method was required at the upper Cannonball tongue outcrop, locality 96, where pods and discontinuous beds of poorly preserved oyster shells occur.

4) Because of the relatively low concentration of fossils at the majority of Cannonball outcrops, the method most commonly used involved collecting visible fossils from the surface of a measured area of outcrop. The areal dimensions varied for each outcrop and were dependent upon fossil distribution and concentration along with outcrop geometry. The collected area (given for each locality in Appendix II) did not necessarily correspond to the total outcrop area.

Grain Size Analysis

Textural parameters were determined for all collected rock samples. This was accomplished by first dispersing the rock and then sieving. Dispersal proved to be a problem for some samples; however, a method using hydrogen peroxide (Carver,1971, p. 58) that destroys organic matter was generally effective.

After dispersal and drying, the samples were wet-sieved with a 4-phi (62 μm) screen to separate the silt and clay from the sand fraction. The silt and clay were then pipetted according to the method of Carver (1971, p. 79-87). The dried sand was sieved using a Ro-Tap at intervals of 1 phi.

Organic Carbon Analysis

All rock samples were analyzed for organic carbon. A variety of analytical techniques can be used to determine total organic matter and each method presents unique sources of error. The Cannonball rock samples were analyzed for organic carbon content using the hydrogen peroxide technique of Jackson (1958, p. 222-225). Basically, this technique destroys the organic matter in a sample by oxidation. An estimate of the original abundance is obtained by comparing the initial and final weight of the sample. Organic matter analysis via oxidation with H_2O_2 is simple, fast, and requires minimal equipment. However, only the most readily oxidized compounds are destroyed and the oxidation of the organic matter is rarely complete. In addition, uncertainties of diagenesis make absolute values of organic "fossil" carbon difficult to interpret. However, the relative differences in organic carbon between samples are probably real.

Cluster Analysis

Cluster analysis is an efficient way of displaying complex relationships among many objects. The purpose of cluster analysis is to define the degree of similarity between units defined by, in this case, binary (presence-absence) data.

Two modes of data analyses were used, R-mode and Q-mode. R-mode analysis is used to express the similarity relations between pairs of characters (in this case, pairs of taxa). Q-mode expresses similarity relations between examples (in this case, fossil localities).

There are 30 known species of bivalves from the Cannonball (Cvancara, 1965; Van Alstine, 1974). Of these, less than 10 are found in abundance over a wide geographical area. Others are found in abundance locally, and still others are found only rarely. A record of species occurrence has been documented by Cvancara (1965, Appendix C) for 115 localities and by Van Alstine (1974, Appendix III) for four localities.

Because some bivalves are found rarely, certain species were not included. If a species was present at less than four localities, and occurred in small numbers, it was excluded. As a result of such exclusion, the following species (reported by Cvancara, 1965, 1966) were eliminated: *Nucula* sp., *Nuculana thomi*, *Crenella cedrensis*, *Crenella stantoni*, *Arcuatula schallerensis*, *Adula* sp., *Phenacomya haresi*, *Corbicula cytheriformis*, and *Laternula*? *subgracilis*.

Bivalves such as *Crassostrea glabra* and *Isognomon lloydi* were used even though they were found at less than four localities because, where present, they occur in high concentration and are considered environmentally significant. Further, any locality with less than two bivalve species or fossil types was considered insignificant and was eliminated from the analyses.

In the final tally, 20 species of bivalves from 97 localities constituted the data. Gastropods, crabs, shark teeth, *Ophiomorpha*, driftwood, and corals were also included to determine any relationships these macrofossils may have with the associations and distribution of the bivalves.

The first step in cluster analysis is to calculate a matrix of all combinations of similarities between objects. In Q-mode analysis, the similarity in the type of bivalves and macrofossils between collecting localities is compared, and a similarity coefficient is calculated for each possible pair of localities. The similarity coefficient used for this study is called the Dice Similarity Coefficient (Cheatham and Hazel, 1969) and is:

$$\frac{2C}{N_1 + N_2} \text{ X } 100$$

where C is the total number of fossil types common to both localities, N_1 the number of fossil types found at locality one, and N_2 the number found at locality two. Two different Q-mode analyses were performed for this study. One used 97 localities, and the other, 50 localities. The second analysis was done because only 50 of the selected 97 localities have known lithology, and correlation of rock type with fossil associations is of interest.

In R-mode analysis, the same similarity coefficient is used. However, the variables have different meaning. In this case, C represents the number of samples common to two bivalves or macrofossils, N_1 the number of samples in which fossil one occurs, and N_2 the number of samples in which fossil two occurs. As before, a similarity coefficient is calculated for all possibly pairs of taxa.

After the matrix is complete, the next step in clustering involves searching the matrix and combining into one group the two objects with the highest mutual similarity. Then, the similarity measure between the group and the other objects are calculated as the average between each member of the group and each remaining object. This process is repeated until all objects belong to one large group. This procedure, called the unweighted pair group method, is one of several commonly used clustering techniques. The results of clustering are graphically displayed by a dendrogram which shows the relationships between the object and the similarity measure. In these analyses, the similarities become greater as the measure approaches 100.

Bivalve Counts

The fossils collected from the 13 outcrops chosen for this study were cleaned, identified, and counted. The number of bivalve individuals was estimated by counting hinges. Fragments were noted, especially when large numbers were present, but not included in the counts. Gastropods were also counted but only if the last whorl was present. All other fragments were merely noted.

Bivalve Measurements and Morphological Characters

In order to determine the niche and life habits of Cannonball bivalves, a series of measurements was made on all obtainable specimens. These consisted of specimens collected primarily for this study along with those already present in the University of North Dakota collection. In addition, Cannonball fossils belonging to the University of Michigan were obtained on loan. Measurements were made in accordance with the method outlined by Stanley (1970, p. 19). These included shell height, shell length, and shell width. For each bivalve species, the values of these measures from each specimen were averaged and used to calculate bivalve obesity and bivalve elongation. The ratio of shell height/width determines the degree of obesity and the shell length/height ratio the degree of elongation. Other morphological characters were also examined, including the presence of pedal and siphonal gapes, pallial sinus, and marginal denticulation in addition to ligament and valve type (equivalved or inequivalved).

Because most of the Cannonball bivalve genera are extant, research on the life habits of these modern-day representatives was a valuable interpretative aid. This information, along with the above measurements and morphological characters, was used to interpret feeding type (deposit-feeding or suspension-feeding) and mode of life (epifaunal or infaunal).

RESULTS

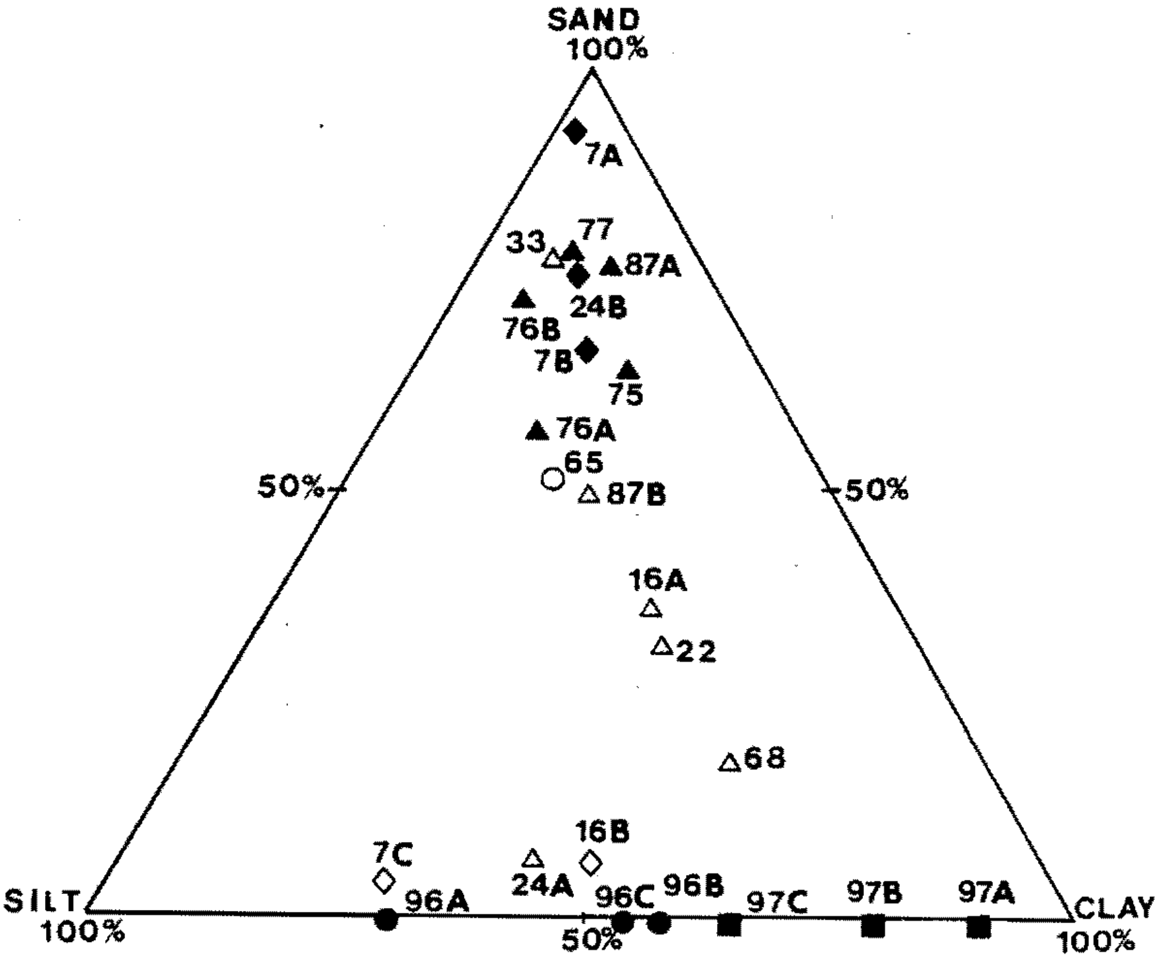
Lithology

General

At the thickest exposure of the Cannonball Formation, along the Heart River in northeastern Morton County (locality 21), the Cannonball is approximately 300 feet (91 m) thick (Cvancara, 1965, p. 34). In the subsurface, a maximum thickness of 395 feet (120 m) was reported by Fox and Olsson (1969) from a well core at Garrison Dam, and a thickness of 385 feet (117 m) by Cvancara (1976) in North Dakota State Water Commission Well 3527 in southeastern Hettinger County. The Cannonball thins westward to two tongues that have a combined thickness of approximately 50 feet (15 m) in Slope and Golden Valley Counties, North Dakota. Thinning of the formation also occurs to the south (Cvancara, 1976, Pl. 4).

The lithology of the Cannonball is variable. The textural diversity of rocks collected for this study is shown in Fig. 3; however, there are two major lithotypes, mudstone and sandstone (Fig. 4). The term "stone", usually used to designate an indurated sediment, may be somewhat misleading. Cannonball rocks, like most of the Tertiary section in North Dakota, are predominantly poorly-consolidated, although well-lithified beds also occur. The nearly unconsolidated character of these rocks makes them almost tantamount to sediments, and to refer to them as such is tempting, and probably not totally incorrect.

Fig. 3. Sand-silt-clay ratios for Cannonball samples with interpreted bivalve association found in each. Numbers correspond to localities shown in Fig. 2. A complete locality and sampling description is given in Appendix II.



BIVALVE ASSOCIATIONS

◆ GLYCYMERIS-ARCTICA

■ OSTREA-CORBULA-CORBICULA

▲ CRASSATELLA-NUCULA

● CRASSOSTREA-CORBICULA-CORBULA

△ MODIFIED CRASSATELLA-NUCULA

◇ NO MACROFOSSILS FOUND

Fig. 4. Photograph of Cannonball outcrop in the type area (North side of Cannonball River, T132N-R88W-11b, southern Grant County, North Dakota) showing the major Cannonball lithotypes: sandstone (A) and mudstone (B). A sandstone concretion (C) and what appear to be sandstone dikes and sills (D) are also present. (Photograph taken by Dr. A. M. Cvancara)


D
B
A
C

However, because the Cannonball deposits have undergone some lithification (desiccation, compaction, and cementation), and for the sake of consistency, the term "stone" will be utilized throughout.

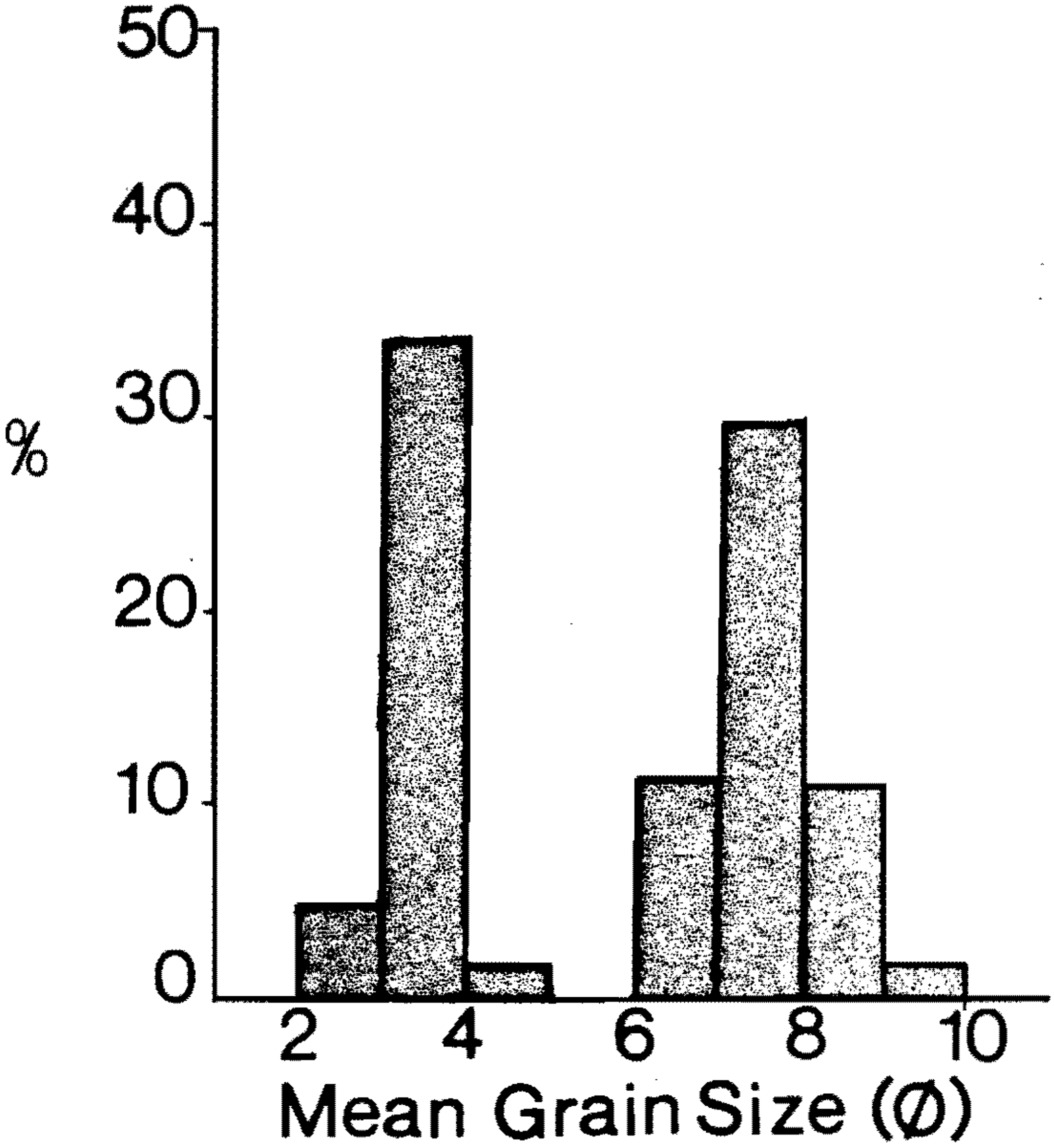
The mean grain size distribution of the Cannonball is bimodal as reflected in Fig. 5. Based on 44 samples randomly chosen by Fenner (1974), the mean grain size ranges from fine sand to clay (2 phi to 10 phi). Of the total distribution, 34 percent is between 3 and 4 phi (reflecting the fine-grained sandstone) and 53 percent of the total distribution is between 6 and 9 phi (reflecting the silt and clay of mudstone). This distribution reflects the observable dominance of mudstone over sandstone in North Dakota.

At many places, the Cannonball alternates vertically from sandstone to mudstone (Fig. 4) and the contact between the two is most commonly gradational. Fenner (1974, p. 16) reported that the thickness of the sandstone averages about 23 feet (7 m) and the mudstone, 40 feet (12 m). Although mudstone is generally more abundant throughout North Dakota, the Cannonball in South Dakota is primarily sandstone, and has a reported (Goodrum, 1982, p. 38) maximum thickness of 135 feet (41 m). Cvancara (1976, Pl. 4) also indicated a higher percentage of the sandstone lithology (75 percent sandstone, 25 percent mudstone) in extreme southern North Dakota (Bowman and Adams Counties). Hence, it appears that as the total thickness of the Cannonball in North Dakota decreases to the south, the sandstone percentage increases.

Mudstone

The term "mudstone" is used here rather loosely to encompass all Cannonball rocks with a content of greater than 50 percent silt and

Fig. 5. Distribution of mean grain size of Cannonball rocks in North Dakota, based on 44 randomly selected samples from Morton, Grant, and Oliver Counties, North Dakota, reported by Fenner (1974).


50
40
30
20
10
0
%
2
4
6
8
10
Mean Grain Size (Ø)

clay. A closer examination of the textural parameters reveals that, when classified according to Folk (1974, p. 26), there is a great deal of variation and Cannonball "mudstone" includes claystone, siltstone, mudstone, sandy mudstone, and sandy claystone.

Cannonball mudstone appears light olive gray (5 Y 5/2) on weathered surfaces and brownish gray (5 YR 4/1) to olive gray (5 Y 4/1) on fresh, moist surfaces. It commonly has a blocky appearance. According to Fenner (1974, p. 17-18), clay minerals are primarily montmorillonite and illite with lesser amounts of kaolinite and possibly chlorite. Cannonball mudstone contains varying amounts of sand. In addition, thin, intercalated sandstone and mudstone beds are common, especially near the contact between the thicker mudstone-sandstone units.

Two types of concretions occur in Cannonball mudstone. Most abundant are calcite-cemented mudstone concretions that often contain plant fragments but few other fossils. Less common are the densely crystalline micrite concretions. In contrast, these commonly contain molluscs and other fossils. The mudstone enclosing both types of concretions, like most Cannonball mudstone in southwest-central North Dakota, is not particularly fossiliferous. The mudstone of the Cannonball tongues in southwestern North Dakota, however, has abundant fossil bivalves.

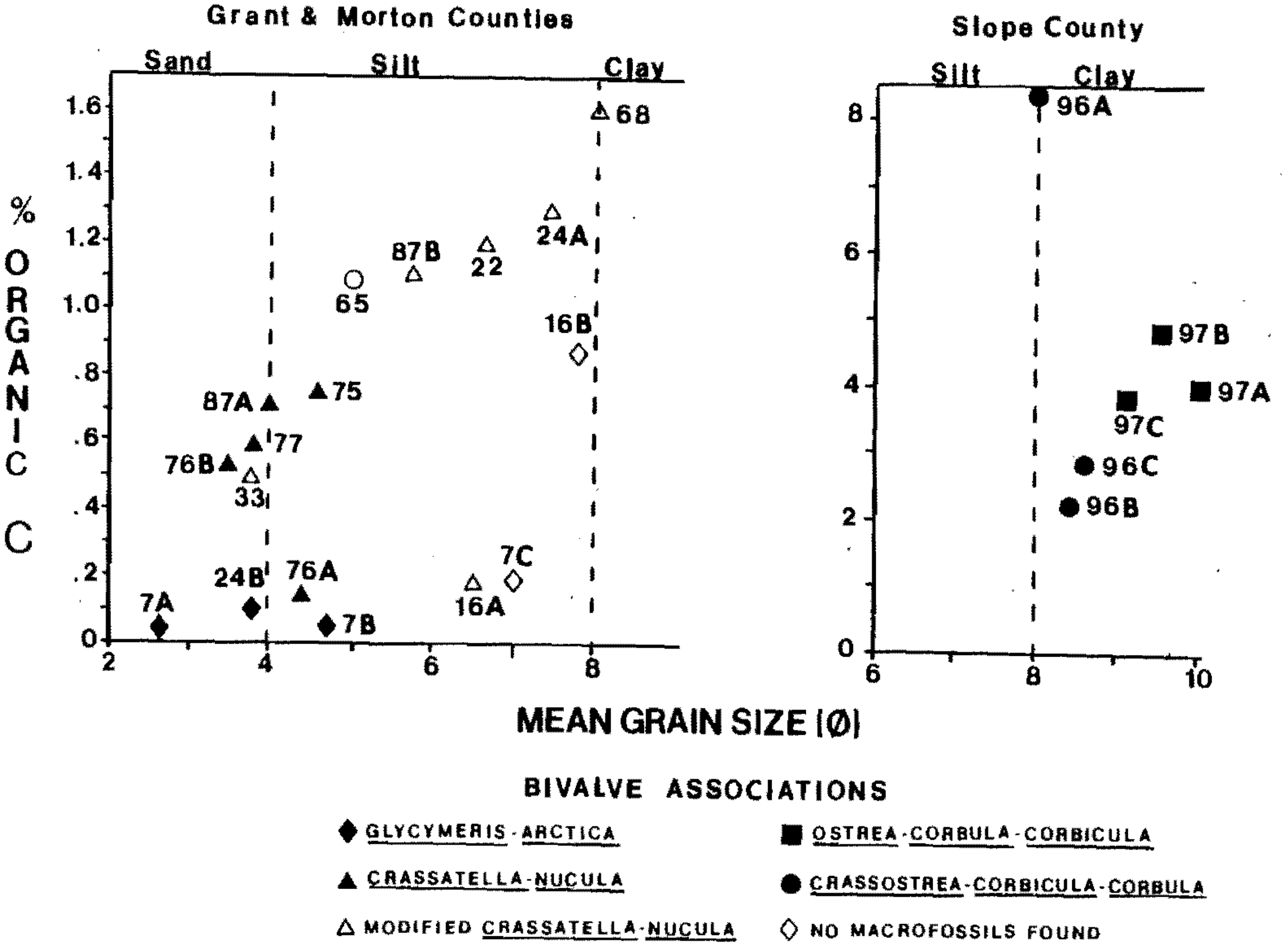
The organic carbon content of Cannonball mudstone is variable but averages about 4 percent in the Cannonball tongues and about 1 percent in southwest-central North Dakota. In both cases, there appears to be a general increase of organic carbon content with decrease in mean grain size (Fig. 6); however, exceptions occur. For example, sample 96A, from the upper tongue, has a mean grain size of about 8 phi and contains 69 percent silt and 31 percent clay, a siltstone by Folk's (1974, p. 26) classification, and it contains 8.6 percent organic carbon. This is anomalous when compared to sample 96B, collected approximately 1 foot (0.3 m) above 96A, that has a mean grain size of 8.6 phi, 43 percent silt, 57 percent clay (classified as a mudstone), but only 2.6 organic carbon.

Sandstone

Sandstone in the Cannonball exhibits considerable variation. Color varies with sandstone lithology and ranges from pale yellowish orange (10 YR 8/6) on weathered surfaces to moderate yellowish brown (10 YR 5/4) on fresh surfaces for sandstone with low clay content, yellowish gray (5 Y 7/2) and olive gray (5 Y 4/1) on weathered and fresh surfaces for sandstone with moderate clay content, and light olive gray (5 Y 5/2) and olive black (5 Y 2/1) on weathered and fresh surfaces for sandstone with high clay content. Texturally, these sediments range from a fine- to very fine-grained, well-sorted quartz sandstone to a muddy sandstone. Mean grain size ranges from 2.7 to 5 phi. In addition to quartz, mica is generally also present. Glauconite content ranges from 0 to 2 percent (Cvancara, 1976, p. 8) and contributes to the sediment's green tint that sometimes becomes so apparent the sandstone can be termed a "greensand."

Planar and tabular cross-bedding is found in Cannonball sandstone and apparently is restricted to this lithology, but good exposures showing cross-bedding are not abundant. The thickness of cross-bed

Fig. 6. Mean grain size versus percent organic carbon for Cannonball samples with interpreted bivalve associations found in each. Numbers correspond to collecting localities shown in Fig. 2. A complete locality and sampling description is given in Appendix II.



Grant & Morton Counties
Sand
Silt
Clay
% ORGANIC C
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
2
4
6
8
68
24A
87B
22
65
16B
87A
75
77
76B
33
7C
24B
76A
7A
16A
7B
Slope County
Silt
Clay
8
6
4
2
0
6
8
10
96A
97B
97A
97C
96C
96B
MEAN GRAIN SIZE (Ø)
BIVALVE ASSOCIATIONS
◆ GLYCYMERIS-ARCTICA
▲ CRASSATELLA-NUCULA
△ MODIFIED CRASSATELLA-NUCULA
■ OSTREA-CORBULA-CORBICULA
● CRASSOSTREA-CORBICULA-CORBULA
◇ NO MACROFOSSILS FOUND

sets is reported (Cvancara, 1965, p. 39) to vary from a few inches to 10 inches (to 25 cm).

Although most Cannonball sandstone is poorly consolidated, it commonly contains well-indurated sandstone bodies. Some of these are subspherical concretions ranging in size from small, fist-sized forms to larger (up to 2.5 feet, 0.8 m, in shortest dimension) concretions (Cvancara, 1976, p. 8). The larger concretions are generally calcite-cemented and do not commonly contain fossils. The smaller forms have common phosphatic cement and contain crabs and other fossils. In addition to these concretions, well-lithified, laterally persistent, lenticular beds occur in Cannonball sandstone. These beds thicken and thin over a distance, and average 2 to 6 feet (0.6 to 1.8 m) thick. In southern Morton County, there are at least two topographic benches, each at a different stratigraphic level, capped with a persistent, lithified sandstone. Cvancara (1980, p. 34) has traced two of these benches for distances of 40 and 70 miles (64 and 113 km).

The organic carbon content of the sandstone is slightly lower than that of the mudstone in the Cannonball. There is, however, some variation in amount of organic carbon within the sandstone with values ranging from near zero (0.04 percent) to about 1 percent (Fig. 6). As in the mudstone, there appears to be a relationship between decreasing grain size and increasing organic carbon content within the sandstone. Although there is a scatter of points, such a relationship is generally apparent.

Cannonball Bivalve Species

Overall, bivalve species diversity is low in the Cannonball. Superfamilies with highest diversity include Nuculacea (3 species), Arcacea (2 species), Pteriacea (2 species), Ostreacea (2 species), and Myacea (3 species).

In terms of abundance, the following bivalves are most common in southwest-central North Dakota (in approximately this order): *Arctica ovata*, *Dosiniopsis deweyi*, *Nucula planomarginata*, *Crassatella evansi*, *Glycymeris subimbricata*, *Caestocorbula sinistrirostella*. In addition, teredinid borings are common in Cannonball driftwood. In southwestern North Dakota, the following bivalves have been reported from the tongues: *Crassostrea glabra*, *Ostrea* sp., *Corbicula berthoudi*, and *Corbula* (*Bicorbula*) *subtrigonalis*.

The following bivalve species were used in this study. Some of their names have been updated following more recent literature (discussed in Appendix V) since these bivalves were reported and described by Cvancara (1966).

- Superfamily Nuculacea
    - Family Nuculidae
        - *Nucula planomarginata* Meek and Hayden
    - Family Nuculanidae
        - *Nuculana evansi* (Meek and Hayden)?
        - *Nuculana mansfieldi* (Stanton)

- Superfamily Solemyacea
    - Family Solemyidae
        - *Solemya bilix* White

- Superfamily Arcacea
    - Family Cucullaeidae
        - *Cucullaea solenensis* Stanton

- Family Glycymerididae
    - _Glycymeris_ _subimbricata_
- Superfamily Pteriacea
    - Family Pteriidae
        - _Pteria_ _linguaeformis_ (Evans and Shumard)
    - Family Isognomonidae
        - _Isognomon_ _lloydi_ (Stanton)
- Superfamily Ostreacea
    - Family Ostreidae
        - _Crassostrea_ _glabra_ (Meek and Hayden)
        - _Ostrea_ sp.
- Superfamily Lucinacea
    - Family Lucinidae
        - _Codakia_? (_Claibornites_) _cedrensis_ (Stanton)
- Superfamily Crassatellacea
    - Family Crassatellidae
        - _Crassatella_ _evansi_ Hall and Meek
- Superfamily Arcticacea
    - Family Arcticidae
        - _Arctica_ _ovata_ (Meek and Hayden)
- Superfamily Corbiculacea
    - Family Corbiculidae
        - _Corbicula_ _berthoudi_ White
- Superfamily Veneracea
    - Family Veneridae
        - _Dosiniopsis_ _deweyi_ (Meek and Hayden)
- Superfamily Myacea
    - Family Corbulidae
        - _Corbula_ (_Bicorbula_) _subtrigonalis_ (Meek and Hayden)
        - _Corbula_ _mactriformis_ (Meek and Hayden)
        - _Caestocorbula_ _sinistrirostella_ Cvancara

Superfamily Hiatellacea
    Family Hiatellidae
        Panopea? cf. _P_. _simulatrix_ Whiteaves

Superfamily Pandoracea
    Family Periplomatidae
        Periploma sp.

Bivalve Associations

General

Five bivalve associations (and a sub-association) are defined based on both field observations and the apparent associations of the bivalve species reported from 97 localities (Fig. 2), displayed graphically by the R-mode and Q-mode cluster dendrograms (Figs. 7, 8, and 9). The associations are quantified from the fossils collected at the 13 outcrops selected for this study. The bivalve associations, listed below, have been interpreted as occurring at the indicated localities visited by the author for this study. University of North Dakota accession numbers refer to fossil samples from each locality.

Bivalve Association	Locality Number	Univ. of N. D. Accession No.
Ostrea-*Corbula*-*Corbicula*	97	A2564
Crassostrea-*Corbicula*-*Corbula*	96	A2565
Isognomon	65	A2559
Glycymeris-*Arctica*	7	A2543
	24	A2545
Crassatella-*Nucula*	75	A2553, A2554
	76	A2555, A2556
	77	A2558
	87?	A2547, A2548
Modified *Crassatella*-*Nucula*	16	A2549, A2550
	22	A2563
	24	A2552
	33	A2546
	68	A2562
	87	A2560, A2561

The most distinguishing bivalves were used to name the associations. The first bivalve in the name appears primarily in that association and rarely or not at all in any other association. The other bivalves in the name may commonly occur in another association but are more characteristically found with the first bivalve.

Fig. 7. R-mode dendrogram based on 20 bivalve species, gastropods, crabs, driftwood, shark teeth, and Ophiomorpha from 97 localities shown in Fig. 2.

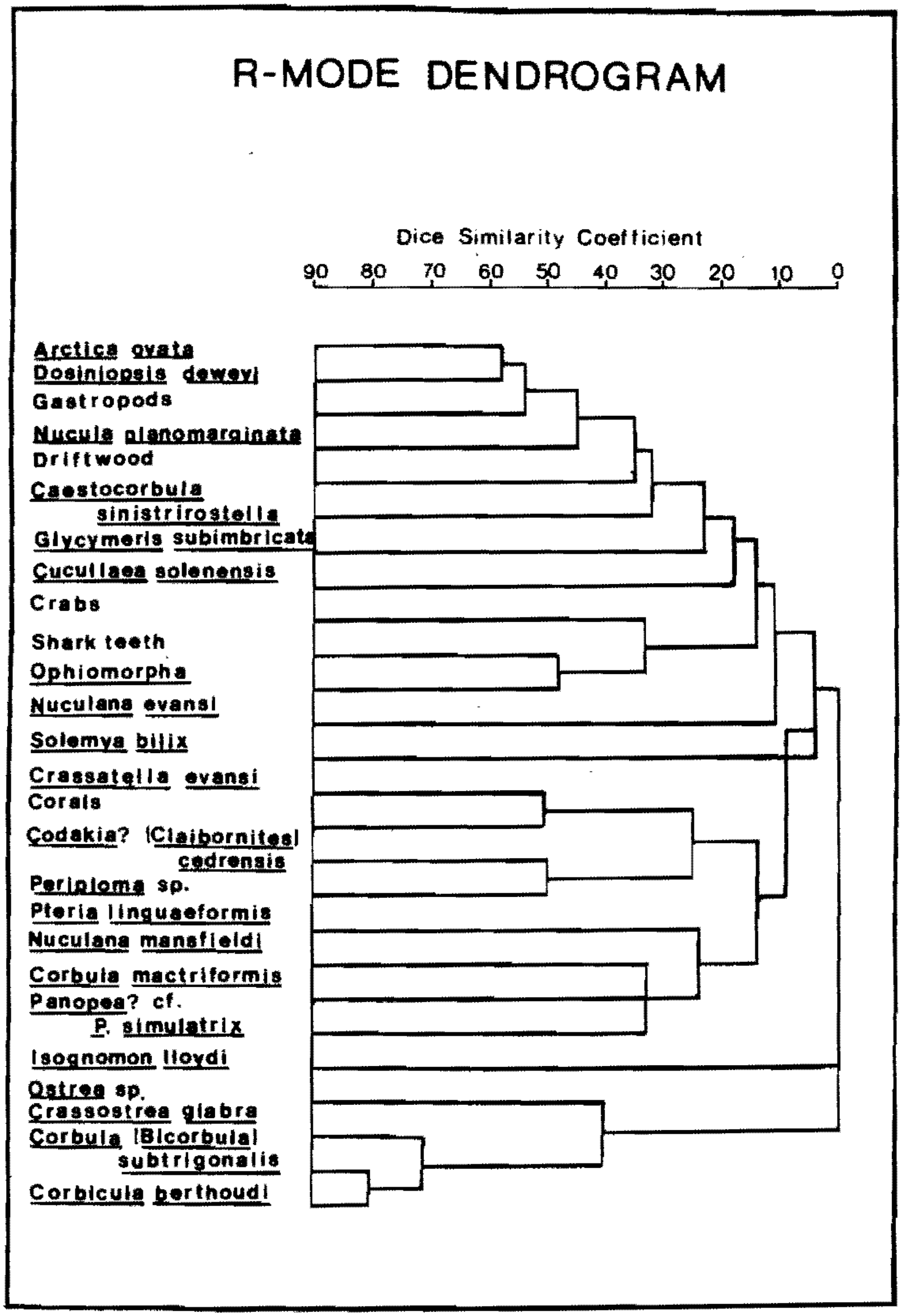

R-MODE DENDROGRAM
Dice Similarity Coefficient
90
80
70
60
50
40
30
20
10
0
Arctica ovata
Dosiniopsis deweyi
Gastropods
Nucula planomarginata
Driftwood
Caestocorbula sinistrirostella
Glycymeris subimbricata
Cucullaea solenensis
Crabs
Shark teeth
Ophiomorpha
Nuculana evansi
Solemya bilix
Crassatella evansi
Corals
Codakia? (Claibornites) cedrensis
Periploma sp.
Pteria linguaeformis
Nuculana mansfieldi
Corbula mactriformis
Panopea? cf. P. simulatrix
Isognomon lloydi
Ostrea sp.
Crassostrea glabra
Corbula (Bicorbula) subtrigonalis
Corbicula berthoudi

Fig. 8. Q-mode dendrogram based on 20 bivalve species, gastropods, crabs, driftwood, shark teeth, and <u>Ophiomorpha</u> reported from 97 localities shown in Fig. 2.

Q-MODE DENDROGRAM

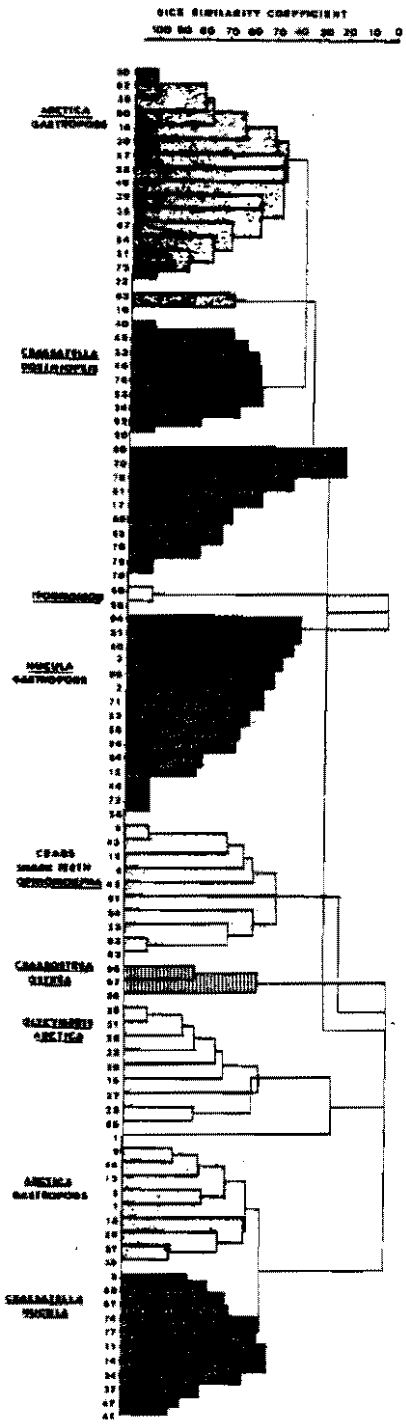


Fig. 9. Q-mode dendrogram based on 20 bivalve species, gastropods, crabs, teredinid-bored driftwood, shark teeth, and *Ophiomorpha* reported from 50 localities with known lithology. Clusters are numbered 1 to 7.

Glycymeris-*Arctica* Association - cluster 1

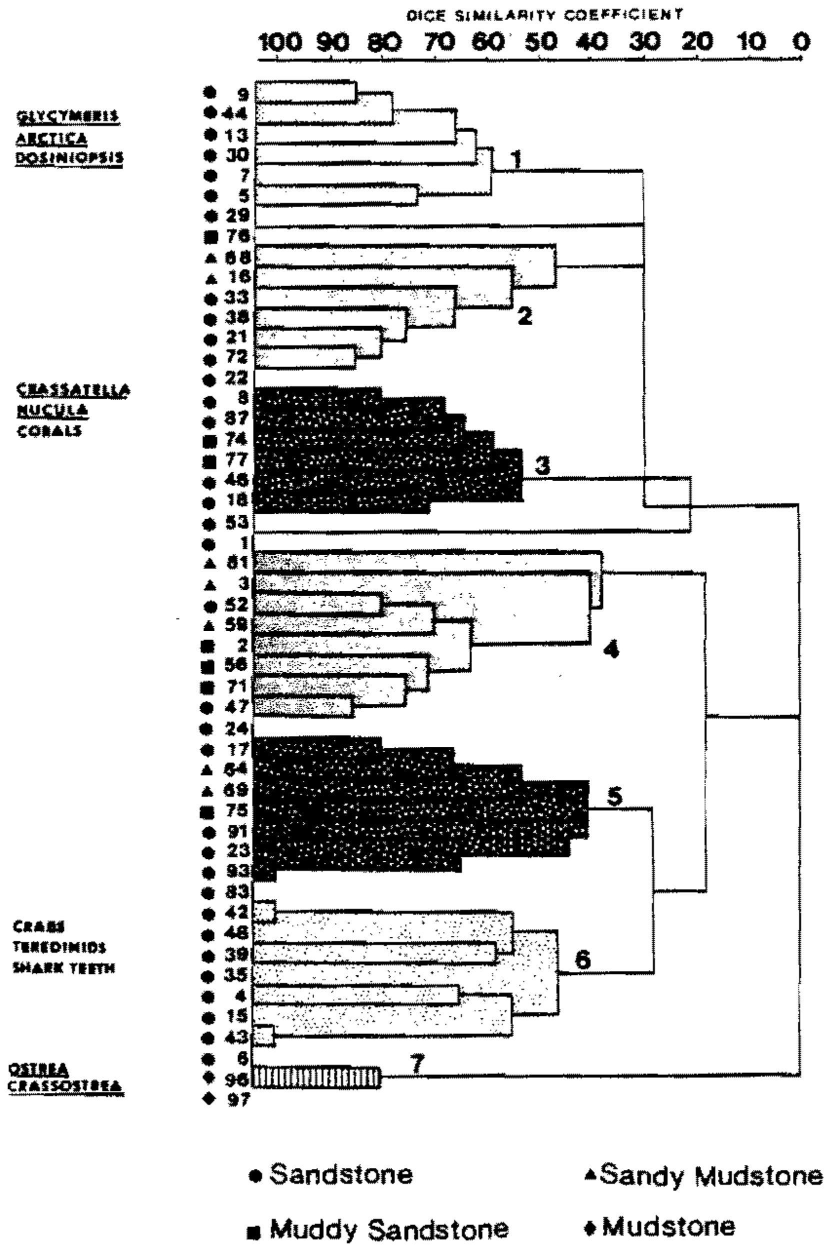
Crassatella-*Nucula* Association - cluster 3

Ophiomorpha-Crab-Driftwood-Shark Teeth Association - cluster 6

Modified *Crassatella*-*Nucula* Association - clusters 2, 4, 5

(*Crassostrea*-*Corbicula*-*Corbula* Association
Ostrea-*Corbula*-*Corbicula* Association - cluster 7

Q-MODE DENDROGRAM



Ostrea-Corbula-Corbicula Association

The Ostrea-Corbula-Corbicula association is found only in mudstone in the lower Cannonball tongue best exposed on the east side of the Little Missouri River, Slope County, North Dakota (locality 97). The tongue is approximately 7.5 feet (2.3 m) thick and overlies the T Cross lignite bed so that it occurs in the Slope Formation.

Diversity is low and the three bivalves that name this association are, as far as is known, the only ones present. Neither are any other macrofossils found; however, Van Alstine (1974, p. 89) reported two species of foraminiferids from this unit, common Trochammina sp. and rare ?Haplophragmoides sp., both collected near the top of the tongue. Bivalves were collected from a 3.5-foot-thick (1.1 m) section of the unit that is 2.5 feet (0.8 m) above the T Cross bed. The bivalves appear to be concentrated in thin (less than 4 inches, or 10 cm) zones with uncertain lateral extent. Three of these zones are readily apparent.

Three rock samples were examined from this unit. There is an apparent increase in grain size up-section (samples 97A, 97B, and 97C, respectively, Fig. 6). Organic carbon content for all three samples is about 4 percent. The bivalves in this association are apparently restricted to the upper portion of the unit where the sediments are coarser grained.

Of the three bivalves found, Ostrea sp. is most abundant, comprising about 65 percent of the total number of bivalve specimens collected. Corbula (Bicorbula) subtrigonalis comprises about 23 percent and Corbicula berthoudi about 12 percent. All bivalves, especially Corbula and Corbicula, are weathered, heavily encrusted with selenite, and commonly distorted.

Crassostrea-Corbicula-Corbula Association

The upper tongue of the Cannonball is characterized by three bivalves, Crassostrea glabra, Corbicula berthoudi, and Corbula (Bicorbula) subtrigonalis. Strata of the upper tongue are exposed in the Little Missouri Valley and occur about 100 feet (30 m) above the lower tongue (Van Alstine, 1974). Locality 96 contains this association. Strata belonging to what is now called the Slope Formation (Clayton et al., 1977) occur both above and below the approximately 33-foot-thick (10 m) tongue.

This tongue is distinguished by large numbers of oysters, found in the lower part of the unit, that form both pods (Fig. 10) and discontinuous beds (Fig. 11) that vary in thickness from less than 4 inches to 1.3 feet (0.1 to 0.4 m). Some of the oyster pods occur directly above a coal bed that marks the contact with the underlying Slope strata. These pods are commonly overlain by oyster beds and are separated from them by a varying thickness of mudstone. The oysters appear to be of one species, Crassostrea glabra. The shells in these pods and beds are poorly preserved (in addition to being naturally distorted) and are hard to extract without fragmenting them. The concentration of the shells is high. For example, in a one square meter area, 196 single shells were counted. (Appendix II gives additional counts.)

Found in association with Crassostrea glabra are the bivalves Corbicula berthoudi and Corbula (Bicorbula) subtrigonalis. However, these latter species occur about 1.5 to 3.0 feet (0.5 to 0.9 m) above the oyster pods and beds. Corbicula and Corbula do not form pods and beds, but instead, are found scattered, with much lower concentration, on the surface of the mudstone. This mudstone is somewhat lithologically

Fig. 10. An oyster pod in the upper Cannonball tongue in southwestern North Dakota (locality 96). All oysters belong to a single species, *Crassostrea glabra*.

Fig. 11. Discontinuous oyster beds in the upper Cannonball tongue in southwestern North Dakota (locality 96). All oysters belong to a single species, *Crassostrea glabra*.

different than that enclosing Crassostrea. The most striking difference is the organic carbon content. Whereas the Crassostrea beds (sample 96A) have an extremely high organic carbon content (8.6 percent), the mudstone containing Corbicula and Corbula (sample 96C) has only 2 to 3 percent.

Corbicula appears to be more abundant than Corbula, comprising 72 percent of the specimens compared with 28 percent for Corbula. Many of these bivalves are distorted and covered with selenite.

These two bivalves, in addition to Crassostrea, exclusively comprise this association. Microfossils appear to be lacking from these strata. Van Alstine (1974) reported the lack of microfossils in the upper tongue but did cite (p. 21) the occurrence of Ophiomorpha. This trace fossil occurs at locality 95 in Cannonball sandstone about 3 feet (1 m) above a Crassostrea bed.

Isognomon Association

Although a single bivalve species does not constitute an association, a separate association is erected for Isognomon lloydi for several reasons. First, where Isognomon is present, no other macrofossils have been found, and secondly, it is found in relatively high concentration. Furthermore, it appears to be geographically restricted, for it is found at only two localities in southern Grant County along the Cannonball River. It is, therefore, plausible that the occurrence of this bivalve is environmentally specific.

At locality 65, Isognomon occurs in a muddy sandstone (sample 65, Fig. 3) with a moderately high organic carbon content (Fig. 6) of about 1 percent. The shells are concentrated in two zones (Fig. 12), each less than 4 inches (10 cm) thick, with uncertain lateral extent.

Fig. 12. Poorly-preserved specimens of _Isognomon lloydi_ concentrated primarily in two zones in muddy sandstone, and showing the underlying thinly-bedded sandstone and mudstone (locality 65).

Fig. 13. Pieces of the hinge belonging to _Isognomon lloydi_.

Concentration is moderately high (3.4 specimens per linear meter average; Appendix II). The *Isognomon* shells were deteriorated, and any attempt to extract them from the sediment only resulted in crumbling. The best that could be collected were several hinges. The characteristic hinge of *Isognomon* (Fig. 13) is straight and traversed by a series of parallel, vertical grooves.

Glycymeris-Arctica Association

The bivalves included in the *Glycymeris-Arctica* association were found primarily at sandstone exposures in northeastern Morton County and bivalves found at locality 7 exemplify this association. The species that distinguishes this association is *Glycymeris subimbricata*. As reflected in Fig. 9 (cluster 1), this bivalve occurs at localities with sandstone lithology, and from field observations, this species appears to be restricted to fine-grained sandstone that is moderately-sorted to well-sorted and has low organic carbon content (for example, samples 7A and 7B, Figs. 3 and 6).

Although bivalve diversity is moderately low (generally less than five bivalve species), a variety of other bivalves and macrofossils may occur with *Glycymeris*. The most common is *Arctica ovata*. This bivalve may, in fact, dominate the association in some places. However, the prevalence of *Arctica* in the Cannonball Formation rules it out as a diagnostic member of this association. Other bivalves that commonly occur within this association include *Dosiniopsis deweyi* and *Nucula planomarginata*, and less commonly, *Caestocorbula sinistrirostella* and *Cucullaea solenensis*. Other macrofossils include gastropods, shark teeth, driftwood (commonly bored by teredinid bivalves), and *Ophiomorpha*.

From the fossils collected at each of the sampled outcrops, Glycymeris averages 23 percent, Arctica 19 percent, Dosiniopsis 17 percent, and Nucula 4 percent. Gastropods average 24 percent. The condition of these fossils varies from well-preserved, complete specimens to fragments.

Crassatella-Nucula Association

The Crassatella-Nucula association is found primarily at exposures in the Cannonball type area (Fig. 2) along the Cannonball River, Grant County, North Dakota, and is exemplified at localities 75, 76 and 77. Although typically found in sandstone, both the mud and organic carbon content of the enclosing rock (samples 75, 76A, 76B, and 77, Figs. 3 and 6) are generally higher than they are in the rock containing the Glycymeris-Arctica association.

The presence of Crassatella evansi distinguishes this association from the Glycymeris-Arctica association. In fact, in outcrops where Crassatella is present, Glycymeris is rarely found. However, some of the associated bivalves and macrofossils commonly occur in both associations. For example, Arctica ovata and Dosiniopsis deweyi are quite common in both associations. Other bivalves and macrofossils, although in both associations, appear to display greater affinity for one of the associations. Nucula planomarginata, for example, may be found in the Glycymeris-Arctica association but occurs more commonly in the Crassatella-Nucula association.

Bivalve diversity in this association is high (generally seven to ten bivalve species). Some of the other bivalves found with Crassatella and Nucula include Caestocorbula sinistrirostella, Codakia? (Claibornites) cedrensis, Periploma sp., and Nuculana mansfieldi. From the bivalves collected at each of the sampled outcrops containing this association, *Crassatella* averages 22 percent, *Nucula* 13 percent, *Arctica* 13 percent, *Dosiniopsis* 21 percent, *Caestocorbula* 6 percent, and other bivalve genera 25 percent.

The *Crassatella*-*Nucula* association also has high diversity of other macrofossils. Both gastropods and corals are prevalent; in fact, gastropods, especially those of the family Aporrhaidae, dominate this association. Of the total fossils collected at each of the sampled outcrops containing this association, these gastropods average 78 percent. Gastropods from other families average 9 percent, bivalves 10 percent, and other macrofossils 3 percent. Trace fossils were noted at these outcrops and they appear to be primarily burrows. These fossils generally have an oblique to horizontal orientation to the bedding planes.

Modified Crassatella-Nucula Association

The modified *Crassatella*-*Nucula* association is erected to serve as a sub-association of the *Crassatella*-*Nucula* association for the following reasons:

Many Cannonball localities contain bivalves commonly found in the *Crassatella*-*Nucula* association such as *Arctica*, *Crassatella*, *Dosiniopsis*, *Nucula*, *Nuculana*, and gastropods. However, at these localities the faunas lack the high diversity of the veritable *Crassatella*-*Nucula* association as found in the muddy sandstone along the Cannonball River. The bivalve *Glycymeris*, however, is lacking and neither do the fossils found at these localities occur in well-sorted sandstone as do the fossils of the *Glycymeris*-*Arctica* association. Therefore, these fossils appear to have more relationship to the *Crassatella*-*Nucula* association than the *Glycymeris*-*Arctica* association.

The modified Crassatella-Nucula association, in summary, differs from the veritable association in having lower diversity of its contained fauna (commonly less than five bivalve species), considerably fewer aporrhaid gastropods, and more variable lithology (ranging from poorly-sorted sandstone to mudstone). Localities where either the veritable Crassatella-Nucula or its modified sub-association occur appear to include many of those comprising clusters 2, 3, 4, and 5 (Fig. 9).

It was noted in the field (and apparent in Fig. 9), that the localities where this modified form of the Crassatella-Nucula association seems to occur, have both variable lithology and variable contained faunas. For example, at locality 16, common corals along with gastropods and the bivalve Arctica ovata are found in a sandy mudstone. In contrast, in some places such as locality 81, deposit-feeding bivalves such as Nuculana and gastropods (primarily aporrhaids) occur in mudstone. This type of occurrence is common in the mudstone overlying the sandstone containing the highly diverse veritable Crassatella-Nucula association.

Ophiomorpha-Crab-Driftwood-Shark Teeth Association

The association of Ophiomorpha, crabs, driftwood, and shark teeth was noted in the field and it also forms a distinct cluster (Fig. 9, cluster 6) on the Q-mode dendrogram. Therefore, it warrants a separate designation. However, as it does not contain abundant bivalves, it was not sampled quantitatively in the field.

Ophiomorpha, crabs, driftwood, and shark teeth commonly, but not exclusively, occur together. They are usually associated in well-sorted sandstone. Generally, where the trace fossil Ophiomorpha is present, there are few, if any, molluscs in association.

Crabs are found well preserved in phosphatic sandstone concretions. Holland and Cvancara (1958) described two genera collected in Morton and Burleigh Counties. They reported (p. 498) abundant driftwood and shark teeth along with a few small molluscs in association with the crabs.

Driftwood, commonly bored by teredinid bivalves, and shark teeth are common in the Cannonball and occur in both mudstone and sandstone. However, they occur more frequently in sandstone.

At some localities there are several species of bivalves present; however, even at these places, overall diversity remains low. Of the bivalves, Arctica ovata is found most commonly, although other forms such as Dosiniopsis deweyi, Nucula planomarginata, and Crassatella evansi may occur.

PALEOECOLOGY

General

Trophic analysis of marine deposit-feeding and suspension-feeding macroinvertebrates is commonly used as an aid to interpret depositional environments. This practice is based on the premise that the distribution of these invertebrates is largely dependent upon food resources and turbidity. Because these factors are controlled primarily by substratum character and water movement, macroinvertebrate distribution can reflect sedimentary environments. Turpaeva (1953) first proposed the idea of feeding or trophic groupings on the basis of Holocene benthic macroinvertebrates. A trophic group is defined by listing species present in an environment and determining their trophic niches. Groups generally have a nucleus composed of only a few species that numerically dominate (greater than 80 percent) the group. In fossil benthic shelly faunas, this dominance enhances the potential of specimens of the nucleus species to be preserved.

The marine benthos is dominated by deposit-feeding and suspension-feeding trophic types, and a trophic group nucleus may be composed of either one or both of these types. Because suspension feeders filter the overlying water column, and because high turbidity will clog filtering mechanisms, they generally feed most effectively in relatively clear water. Conversely, deposit feeders obtain their food from the sediment. This form of feeding commonly contributes to sediment reworking and increased turbidity. Deposit feeders are physiologically equipped with special adaptations to avoid clogging of feeding and respiratory structures. They can, therefore, exist and often thrive in environments of high turbidity commonly associated with fine-grained sediments.

A trophic group nucleus with a paucity of deposit feeders generally indicates an inadequate food source in the sediment, whereas a dominance of deposit feeders suggests an environment not conducive to suspension feeders, probably due to sediment instability and high turbidity (Rhoads and Young, 1970). Many trophic groups have a dominance of mixed trophic types (both deposit feeders and suspension feeders), indicative of a physically stable bottom. A reworked mud surface is effective in limiting suspension feeders only when the surface becomes mobile (Rhoads and Young, 1970).

The trophic group model has been applied to paleoecology by many workers (for example, Rhoads, Speden, and Waage, 1972; Walker, 1972; Thayer, 1974; and Stanton and Dodd, 1976). The usefulness of this technique cannot be argued; however, its limitations in paleoecology must be considered. For example, inferring feeding habits for ancient organisms is commonly prone to error. Modern analogs are not always accurate and feeding habits may not have been constant through time. In addition, functional morphology may not be reliable (Scott, 1978). To further compound the problem of paleoecological interpretation, Lawrence (1968) determined that up to 75 percent of the organisms present in an environment are unlikely to be fossilized. Selective preservation and the resulting relative rank abundance, affected by shell durability, predation, rates of reproduction and growth, the amount and duration of transport, and sedimentation rates, can lead to erroneous conclusions.

When applying the trophic group model to the Cannonball bivalve associations, these problems must be considered; however, their severity is lessened for the following reasons: 1) Functional morphology is fairly reliable for bivalves (Scott, 1978); 2) most of the Cannonball genera are extant, and the use of modern analogs to determine feeding habits is probably fairly accurate; and 3) although selective preservation has certainly been a factor in fauna preservation, transportation appears to have been minimal as judged from evidence at most Cannonball outcrops; and where it has been an influencing factor, it can usually be recognized.

Functional Morphology and Paleoecology of Dominant Cannonball Bivalves

General

The following discussion examines in detail the functional morphology and paleoecology of the 11 most common Cannonball bivalve species. The modern-day niches of extant genera are also presented. The terms used in this discussion to describe the morphological features of the bivalves are in accordance with the usage of Stanley (1970, p. 116) and are summarized in Table 2.

The value of the characters defined in Table 2, in addition to the presence or absence of other morphological features, is presented in Table 3 for the 20 Cannonball bivalves used in this study. The autecology for each species is presented in Table 4.

TABLE 2

DESCRIPTIVE TERMS USED TO DESCRIBE MEASURED BIVALVE MORPHOLOGICAL CHARACTERS (from Stanley, 1970, p. 116).

Character Value	Descriptive Term
Maximum Length cm (inches)	
< 1.5 (0.6)	Very small
1.6 - 3.5 (0.7 - 1.3)	Small
3.6 - 5.0 (1.4 - 1.9)	Moderately small
5.1 - 7.0 (2.0 - 2.7)	Moderately large
7.1 -10.0 (2.8 - 4.0)	Large
> 10.0 (4.0)	Very large
$\frac{\text{Length}}{\text{Height}}$ (Elongation)	
≤ 1.19	Equant
1.20 - 1.39	Moderately elongate
1.40 - 1.59	Elongate
> 1.60	Very elongate
$\frac{\text{Height}}{\text{Width}}$ (Obesity)	
≤ 1.29	Strongly inflated
1.30 - 1.49	Inflated
1.50 - 1.69	Moderately inflated
1.70 - 1.99	Compressed
> 2.00	Very compressed

TABLE 3

MORPHOLOGICAL CHARACTERISTICS OF CANNONBALL BIVALVES

Species	Max. Length (inch/cm)	L/H	H/W	Pallial Sinus	Equivalved	Marginal Denticulation	Pedal Gape	Siphonal Gape	Ligament E or I
Nucula planomarginata	1.0/2.5	1.2	1.6		X				I
Nuculana evansi	0.4/1.0	1.7	1.4	X	X			X	E
Nuculana mansfieldi	0.6/1.6	1.9	1.7	X	X			X	E
Solemya bilix	0.8/2.6	2.6	1.5	X	X		X	X	I
Cucullaea solenensis	1.7/4.3	1.2	1.1		X	X			E
Glycymeris subimbricata	2.1/5.3	1.1	1.3		X	X			E
Pteria linguaeformis	0.8/1.9	1.5	1.8						E
Isognomon lloydi	-	-	-		X?				I
Crassostrea glabra	5.5/14.0	-	-						I
Ostrea sp.	0.5/1.2	-	-						I
Codakia? (*Claibornites*) *cedrensis*	1.5/3.7	1.0	2.7		X				E
Crassatella evansi	1.8/4.6	1.1	1.4		X	X			I
Arctica ovata	3.3/8.3	1.2	1.8		X				E
Corbicula berthoudi	3.0/7.7	-	-		X				E
Dosiniopsis deweyi	1.5/3.9	1.1	1.7	X	X				E
Corbula (*Bicorbula*) *subtrigonalis*	1.4/3.6	-	-	X					I
Corbula mactriformis	0.6/1.5	1.3	1.8	X					I
Caestocorbula sinistrirostella	0.4/1.0	1.5	1.4	X					I
Panopea cf. *P. simulatrix*	1.4/3.5	1.9	2.4		X				E?
Periploma sp.	1.3/3.4	1.4	2.3	X					I

TABLE 4

AUTECOLOGY OF CANNONBALL BIVALVES

Species	Survival of Cenera	Cannonball Distribution	Life Position Infaunal	Life Position Epifaunal	Mode of Feeding	Salinity	Preferred Substratum
Nucula planomarginata	L	C	Shallow		D	NM	S - MS
Nuculana evansi	L	U	Shallow		D	NM	MS - SM
Nuculana mansfieldi	L	U	Shallow		D	NM	S - MS
Solemya bilix	L	R	Deep		?	NM	?
Cucullaea solenensis	L	U	Shallow		SP	NM	S
Glycymeris subimbricata	L	C	Shallow or on surface		SP	NM	S
Pteria linguaeformis	L	R		Byssally-att.	SP	NM	?
Isognomon lloydi	L	R		Byssally-att.	SP	H	MS
Crassostrea glabra	L	G		Cemented	SP	H	M
Ostrea sp.	L	G		Cemented	SP	H	M
Codakia? (*Claibornites*) *cedrensis*	L	U	Deep		SP	NM	MS
Crassatella evansi	E	C	Shallow		SP	NM	S - MS
Arctica ovata	L	C	Shallow		SP	NM	S - MS
Corbicula berthoudi	L	G	Shallow		SP	H	M
Dosiniopsis deweyi	E	C	Deep		SP	NM	S - MS
Corbula (*Bicorbula*) *subtrigonalis*	L	G	Shallow		SP	H	M
Corbula mactriformis	L	R	Shallow		SP	?	?
Caestocorbula sinistrirostella	E	C	Shallow		SP	NM	S - MS
Panopea cf. *P. simulatrix*	L	R	Deep		SP	NM	?
Periploma sp.	L	R	Deep		SP	NM	MS

Key:
L = genus living
E = genus extinct
S = sand
MS = muddy sand
SM = sandy mud
M = mud
? = not observed

C = common to the Cannonball (10 or more localities)
U = uncommon to the Cannonball (5 - 10 localities)
R = rare to the Cannonball (less than 5 localities)
G = geographically restricted to southwestern North Dakota

NM = normal marine
H = hyposaline

Shallow = less than 2 - 3 cm
Deep = greater than 2 - 3 cm

D = deposit feeder
SP = suspension feeder

Deposit Feeders

The protobranchs, the oldest group of bivalves, have paired flexible extensions of the palps that project from the shell and collect food particles directly from the sediment. Most deposit-feeding bivalves migrate while feeding by means of the foot projecting from the antero-ventral part of the shell. Most are rapid burrowers with thin, streamlined shells.

Nucula planomarginata

Nucula planomarginata is found in a variety of sediment types but is most common in sand with a relatively high percentage of silt and clay. It is a small (maximum length of approximately 1.0 inch or 2.5 cm), and thin-shelled, deposit feeder. The shell is typical of the genus *Nucula* in that it is moderately elongated and moderately inflated. The pronounced anterior expansion of the shell is indicative of a large foot that enables *Nucula* to be a reasonably rapid burrower regardless of the inflated shell (Stanley, 1970, p. 85).

Species belonging to the genus *Nucula* are found today at many depths and in many environments; however, most are restricted to substrata that are relatively rich in organic matter, few live in shifting sands, and the majority are found in cool water.

Suspension Feeders

By far the majority of bivalve species are suspension feeders. Suspension feeders may or may not have siphons, but all forms feed directly from the water although the level (distance above the sediment-water interface) varies. Suspension feeders can be broadly classified as either epifaunal suspension feeders, infaunal nonsiphonate suspension feeders, infaunal siphonate feeders, or infaunal mucous tube feeders (Stanley, 1968, p. 214-229).

Glycymeris subimbricata

Glycymeris subimbricata is found in well-sorted, fine-grained sandstone. This taxodont is characterized by a thick, subcircular shell with radial ribs and a crenulate margin. It is moderately large (maximum length of 2.1 inches or 5.3 cm), and is strongly inflated.

Living glycymerids occur almost exclusively in high-energy environments. Some are shallow, infaunal burrowers and others appear to live freely, lying horizontally on the surface while being moved around by currents. They are not deep water forms but neither do they tolerate intertidal conditions well (Keen, 1958, p. 41). Most live in shallow to intermediate depths (6 to 650 feet or 2 to 200 m), and no glycymerids are known to inhabit either brackish water or deep oceans (Thomas, 1975, p. 221-223).

Glycymerids are opportunistic (in the sense of Levinton, 1970). They invade high stress environments that are generally inhospitable to many macroinvertebrates and, as a result, their occurrence is common in communities with low species diversity.

Glycymerids first appeared near the beginning of the Cretaceous, and have since retained the simple shell form (Thomas, 1975, p. 220). Based on associated lithology and faunas, Thomas (1975, p. 223) concluded that glycymerids throughout the Cenozoic have prospered in current-swept marine environments. Found in well-sorted, fine-grained sandstone and in association with only a few other macroinvertebrates, Glycymeris subimbricata appears to have been no exception.

Arctica ovata

Arctica ovata, the most common bivalve in the Cannonball Formation, is found in lithologies ranging from well-sorted sandstone to sandstone with a high percentage of silt and clay. It is large (maximum length of 3.3 inches or 8.3 cm), thick-shelled, moderately elongate, and slightly compressed. The lack of a pallial sinus indicates that Arctica ovata was a shallow burrower.

Arctica islandica is the only living arcticid. This species has a large foot and the mantle lobes fuse to form two stout siphons. It is a shallow burrower and lives a fairly sessile life. A. islandica is generally found in sandy to sandy-muddy bottoms in shallow subtidal environments. Abbott (1974, p. 518) reported A. islandica from depths of 30 to 480 feet (9 to 146 m). Today this species is restricted to cold seas and is considered a North American Boreal Faunal Province form.

Isognomon lloydi

Isognomon lloydi occurs in sandstone with a high percentage of silt and clay. Shell measurements were not obtainable because of poor preservation. However, the presence of an auricle and byssal notch indicates that I. lloydi was an epifaunal, byssally-attached form. Two other morphological characters are discernible: The shell is thick, and from the collected fragments, it also appears that the species was quite large.

Most modern species of Isognomon are gregarious and all are apparently restricted to the shallow-water subtidal or to the intertidal environments. These forms are either byssate, free-swinging bivalves, or byssate fissure dwellers. The free-swinging species attach to raised surfaces and are thus often subject to strong waves and currents. For example, *Isognomon alatus* is a large form with a thick, costate shell that attaches to the prop roots of mangroves (Kauffman, 1969, p. N145). The byssally-attached inhabitants of fissures are afforded protection from strong wave and current action. *Isognomon radiata* is a thin-shelled, smooth form that commonly lives in protected environments such as beneath rocks or within branching corals (Stanley, 1970, p. 136).

Kauffman (1969, p. N151-152) listed morphological criteria to recognize *Isognomon* species inhabiting the fissure dweller niche versus free-swinging forms on the basis of shell outline, auricle, and byssal notch. The poor preservation of *I. lloydi* makes it difficult to determine shell shape, or with any accuracy, the size and shape of the auricle and byssal notch. The thickness of the shell and its large size could possibly be an adaptation to stressful conditions such as waves and currents, fluctuating salinity, or both.

Modern forms differ from ancient forms in several respects. For example, whereas modern species of *Isognomon* are generally found in water of normal marine salinity, ancient forms have been associated with brackish waters. *Isognomon maxillata*, in thick accumulations in the Miocene Choptank Formation of Maryland, has been interpreted (Gernant, 1970, p. 50), based on faunal associations, to have thrived in brackish water.

In addition, for unknown reasons, most modern *Isognomon* species are thin-shelled, whereas fossil forms commonly have thick shells. Further, Davies (1975, p. 82) reported that modern species are restricted to warm waters whereas their predecessors were apparently widely distributed without climatic restriction.

Crassostrea glabra and *Ostrea* sp.

The life habits of the oysters have been studied extensively and are well documented (Stenzel, 1971, p. N1016-N1028 gave an excellent synopsis) and will, therefore, not be examined in detail here. Oysters are sedentary bivalves that lack a foot and have thus adapted to a life permanently cemented to the substratum. As a result, most fossil forms have been preserved *in situ*, simplifying ecological interpretation.

Crassostrea glabra occurs in lenses and pods. The shells are commonly cemented together indicating that the oysters formed banks or reefs, using the shells of other oysters, dead or alive, as a place of attachment. The shell, forced to grow in a restricted space, has an irregular, often contorted shape. *Crassostrea glabra*, as in many species of *Crassostrea*, has a very large (maximum length of 5.5 inches or 14.0 cm), thick and heavy shell.

In contrast, *Ostrea* sp. is very small (maximum length of 0.5 inch or 1.2 cm), and relatively thin-shelled. The shell outline is orbicular or teardrop-shaped and not often contorted. This suggests that the oyster developed primarily in an unconfined space. This is further supported by its scattered, isolated distribution within the rock. The substratum this species used for attachment is unclear. There is no evidence of attachment on the shell. Also perplexing is the small size of this species. Van Alstine (1974, p. 53) suggested that either *Ostrea* sp. was a small, unattached adult form, or was a juvenile oyster that never reached maturity perhaps due to introduction into a hostile environment. If the latter were true, there should be some evidence of the mature form somewhere within the Cannonball. The relatively large number of individuals preserved suggests that this form was common and probably thrived in its environment. Furthermore, although the shell is small for *Ostrea*, the size indicates maturity beyond the larval stage of fixation. Before fixation, the larval shell is only 0.25 to 0.425 mm long (Stenzel, 1971, p. N1007). This presents a perplexing problem because if a larval shell does not become attached, it generally perishes. Stenzel (1971, p. N1012) listed four extinct oyster species that apparently survived and matured lying loose on the sea bottom. However, this occurrence is rare and unheard of in modern forms. Further, none of the four oysters was of the genus *Ostrea*. It therefore appears that *Ostrea* sp. was either one of these rare exceptions, or more likely, the form did attach to some type of substratum (though not to other shells) and the attachment area was obscured during preservation. Stenzel (1971, p. N995) stated that unless preservation is extremely good, the attachment area is commonly undeterminable. It is possible this oyster attached to unpreserved objects such as an alga or some other type of aquatic vegetation or some soft-bodied animal.

Crassatella - *Dosiniopsis* - *Caestocorbula*

These three bivalves are relatively common in the Cannonball; however, niche reconstruction is hindered because all three genera are extinct. Each of these bivalves is found in sandstone with variable amounts of silt and clay.

Crassatella evansi is moderately small (maximum length of 1.8 inches or 4.6 cm), and has a relatively thick, heavy shell that is truncated posteriorly. Its lack of a pallial sinus suggests that it was either nonsiphonate or possessed short siphons. In either case, this morphological characteristic, along with the equant, inflated form, requires that, if *C. evansi* was an infaunal form, it was a very shallow burrower. Stanley (1970, p. 75) showed that bivalves possessing truncated posterior margins commonly lie just below the substratum surface so that the posterior truncation parallels the sediment surface. This niche is suggested for *Crassatella evansi*.

In contrast, *Dosiniopsis deweyi* is moderately small (maximum length of 1.5 inches or 3.9 cm), and has a thin, smooth shell that is subcircular and slightly compressed. It possesses a relatively deep pallial sinus indicating that it had siphons.

The shell thickness, exterior ornamentation, and degree of elongation of *Dosiniopsis deweyi* is similar to the modern bivalve *Dosinia elegans* (also of the Veneridae) although this form is more compressed. *D. elegans* is reported (Stanley, 1970, p. 165-166) to occur in sand flats washed by strong tidal currents but not exposed to severe wave action, and recorded burrowing depths range from 1 to 4 inches (3 to 10 cm).

A direct comparison of these two forms may not be totally accurate due to the more compressed shape of *Dosinia*. However, based on all other morphological characters, *Dosiniopsis* was most likely a deep burrower.

Caestocorbula sinistrirostella is very small (maximum length of approximately 0.4 inch or 1.0 cm), and has a thin, inequivalved shell that is elongate but inflated. The elongation is due to a prominent rostral or siphonal snout on the posterior extremity. A broad pallial sinus further suggests the animal was siphonate. However, the shallowness of the pallial sinus suggests that the bivalve probably did not burrow deeply.

Corbula - *Corbicula*

Corbula (*Bicorbula*) *subtrigonalis* and *Corbicula berthoudi* are common in the lower and upper Cannonball tongues. Their preservation, however, is so poor that no reliable morphological niche reconstruction can be attempted. Today, both genera exist in fresh, brackish, and marine water (Cox et al., 1969), and thus they are poor paleoecological indicators. Both forms may attach via byssal threads when young and may or may not become infaunal with maturity.

Sinclair (1971, p. 14) reported burrowing depths of up to 3 feet (1 m) for the genus *Corbicula*. This genus is a hearty and adaptable bivalve. The exotic, freshwater form, *Corbicula fluminea*, was apparently introduced to North America in the early 1900's and has since spread to most river basins in Mid-America to the point where it is causing damage to hydroinstallations (Sinclair, 1971, and McMahon, 1982, give synopses).

Corbula is also an adaptable form. It possesses very short siphons and burrows shallowly. Stanley (1970, p. 189) noted that the species *Corbula caribaea* secretes byssal threads and attaches to the substratum even after burrowing.

Corbula mactriformis also occurs in the Cannonball, although it is not common nor found in association with *Corbula* (*Bicorbula*) *subtrigonalis*. This species is more commonly associated with Tertiary freshwater sediments in North Dakota, e.g., the Bullion Creek Formation (Bickel, 1973).

PALEOENVIRONMENTS OF THE CANNONBALL FORMATION BASED ON BIVALVE ASSOCIATIONS

Ostrea-Corbula-Corbicula Association

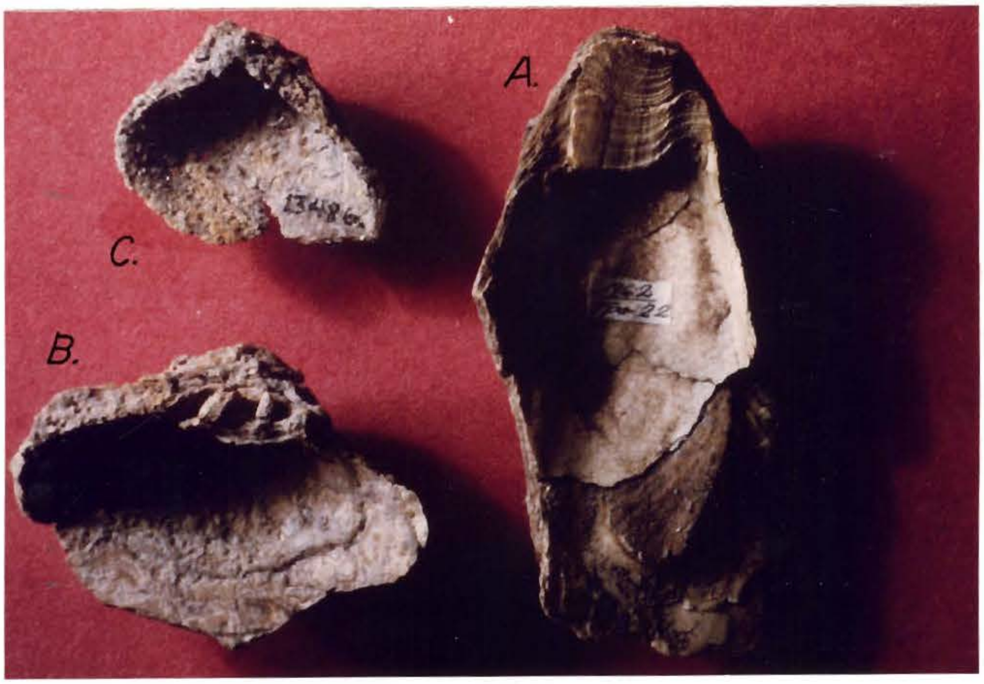
The _Ostrea-Corbula-Corbicula_ association (Fig. 14) occurs in the lower Cannonball tongue. The enclosing sedimentary rocks represent, as far as is known, the initial influx of the Cannonball Sea into the extreme western part of North Dakota. Where exposed, the tongue overlies the T Cross lignite, a laterally extensive lignite that supposedly corresponds to the Giannonatti bed of northwestern South Dakota (Hares, 1928, p. 47). Flores (1981, p. 187) proposed that thick, laterally extensive coal beds form in poorly drained backswamps associated with abandoned meander beds of channels. This type of swampy environment became influenced by marine conditions when the Cannonball Sea transgressed westward.

The exceedingly fine grain size and high organic carbon content of the rocks enclosing the _Ostrea-Corbula-Corbicula_ association indicate that deposition took place in a low-energy environment. The reported (Van Alstine, 1974) occurrence of the agglutinated foraminiferids _Trochammina_ and ?_Haplophragmoides_ indicates a low-salinity environment, for Greiner (1970, p. 83) reported that agglutinated foraminiferids predominate in such environments. Moreover, Phleger (1960, p. 280) reported _Trochammina_ as an important element of the marine marsh fauna in the northern Gulf of Mexico. _Ostrea_ sp. also indicates a low-salinity environment. _Ostrea_ is considered polyhaline to euhaline (Stenzel, 1971, p. N1039); however, most oysters succeed

Fig. 14. Exterior view of bivalves comprising the Ostrea-Corbula-Corbicula association including Ostrea sp. (A), Corbula (Bicorbula) subtrigonalis (B), and Corbicula berthoudi (C).

Fig. 15. Interior view of bivalves comprising the Crassostrea-Corbicula-Corbula association including Crassostrea glabra (A), Corbicula berthoudi (B), and Corbula (Bicorbula) subtrigonalis (C).


A.
B.
C.


A.
C.
13418 6.
B.

in lower salinity environments where predators cannot survive. The associated bivalves, Corbula and Corbicula, are not useful paleoenvironmental indicators because of their occurrence in many environments.

Low-salinity, low-energy environments are found primarily in estuaries and lagoons. Variations in the influx of freshwater from rivers commonly result in salinity fluctuations, and faunal mass mortalities are not uncommon. Perhaps these conditions account for the fossiliferous zones within the lower tongue. Each zone is separated by nonfossiliferous rocks that may represent a period when water conditions were not conducive to life because of a drastic salinity change, an overwhelming increase in sediment supply, or perhaps a severe seasonal temperature change.

This association, and associated strata, is overlain by mudstone that contains a freshwater fauna (Van Alstine, 1974). After the regression of the brackish Cannonball water, nonmarine deposition apparently resumed.

Crassostrea-Corbicula-Corbula Association

The Crassostrea-Corbicula-Corbula association (Fig. 15) is found in the upper Cannonball tongue. The sedimentary rocks containing this association and the Ostrea-Corbula-Corbicula association are separated by a nonmarine sedimentary section approximately 100 feet (30 m) thick. However, it is apparent from the fauna that, when the Cannonball Sea again transgressed this area, the resulting environment was similar to that represented by the Ostrea-Corbula-Corbicula association in the lower tongue. The upper tongue also commonly overlies a lignite bed and the mudstone lithology and high organic-carbon content resemble that of the lower tongue. The low-diversity fauna, again, suggests brackish conditions.

The upper tongue is characterized by discontinuous lateral beds and pods of the oyster Crassostrea glabra (Figs. 10 and 11) representing the existence of oyster reefs and patches during deposition. According to Stenzel (1971, p. N1039), nearly all oyster reefs develop in brackish water associated with lagoons. He further reported (p. N1038) that Crassostrea appears to include the most euryhaline oysters and they will generally tolerate lower salinities than those belonging to the genus Ostrea. Herein may be the reason for the abundance of Crassostrea in the upper tongue and its absence in the lower tongue. Parker (1960, p. 315) reported that in the subhumid zone of the Gulf of Mexico, Ostrea may completely replace Crassostrea during droughts when salinity increases. Van Alstine (1974, p. 31) suggested that the upper tongue possibly represents an environment of lower salinity than that of the lower tongue. He further suggested that deposition of the upper tongue took place closer to the paleostrandline than did the deposition of the lower tongue.

The pods and beds represent an in situ oyster community. No other macrofossils were found in the pods and beds except Crassostrea. There is not even any evidence of oyster-boring organisms that commonly plague oyster environments. This is unusual, especially when the Cannonball oysters are compared to oyster assemblages in the Fox Hills Formation in North Dakota. There, numerous organisms, including boring sponges and bryozoans, worms, gastropods, chordates, and other bivalves have been reported (Palubniak, 1972, p. 67-68; Feldmann and

Palubniak, 1975, p. 226) in association with Crassostrea. Van Alstine (1974) also reported a lack of microfossils in the upper tongue.

An environment capable of supporting such prolific oyster reef development but inhospitable to other brackish forms is hard to imagine. Two possibilities may account for this unusually low diversity. One, perhaps only Crassostrea was preserved. At best, even Crassostrea is poorly preserved and commonly crumbles to powder upon extraction. Two, perhaps the environment was not conducive to other forms, i.e., the salinity was too low or too variable, or possibly the water temperature was too cool.

The oyster beds are commonly overlain by an unfossiliferous mudstone. The oysters may have been suffocated by this sediment or perhaps a change in water salinity contributed to their death.

Approximately 1.5 to 3.0 feet (0.5 to 0.9 m) above the oyster beds, a mudstone, slightly different texturally than that containing Crassostrea, contains the bivalves Corbicula and Corbula. Based on these two bivalves alone and the apparent lack of other forms, it is hard to determine what environment their presence indicates. It does suggest, however, that conditions changed to the extent that Crassostrea no longer flourished. Their presence in the lower tongue in the Ostrea-Corbula-Corbicula association and their apparent lack in the freshwater rocks intervening between the two tongues indicates a brackish-water preference.

Isognomon Association

The occurrence of Isognomon in the Cannonball is unique in that it is geographically restricted and no other macrofossils have been found in association with it. Fenner (1983, personal communication) further reported a lack of foraminiferids in sample 65 containing Isognomon. The reasons for this are not clear and can only be speculated upon. Perhaps it is a result of selective preservation, or perhaps Isognomon lived in a stressful environment not conducive to other forms. Whatever the reason, there are other characteristics that make its occurrence unusual.

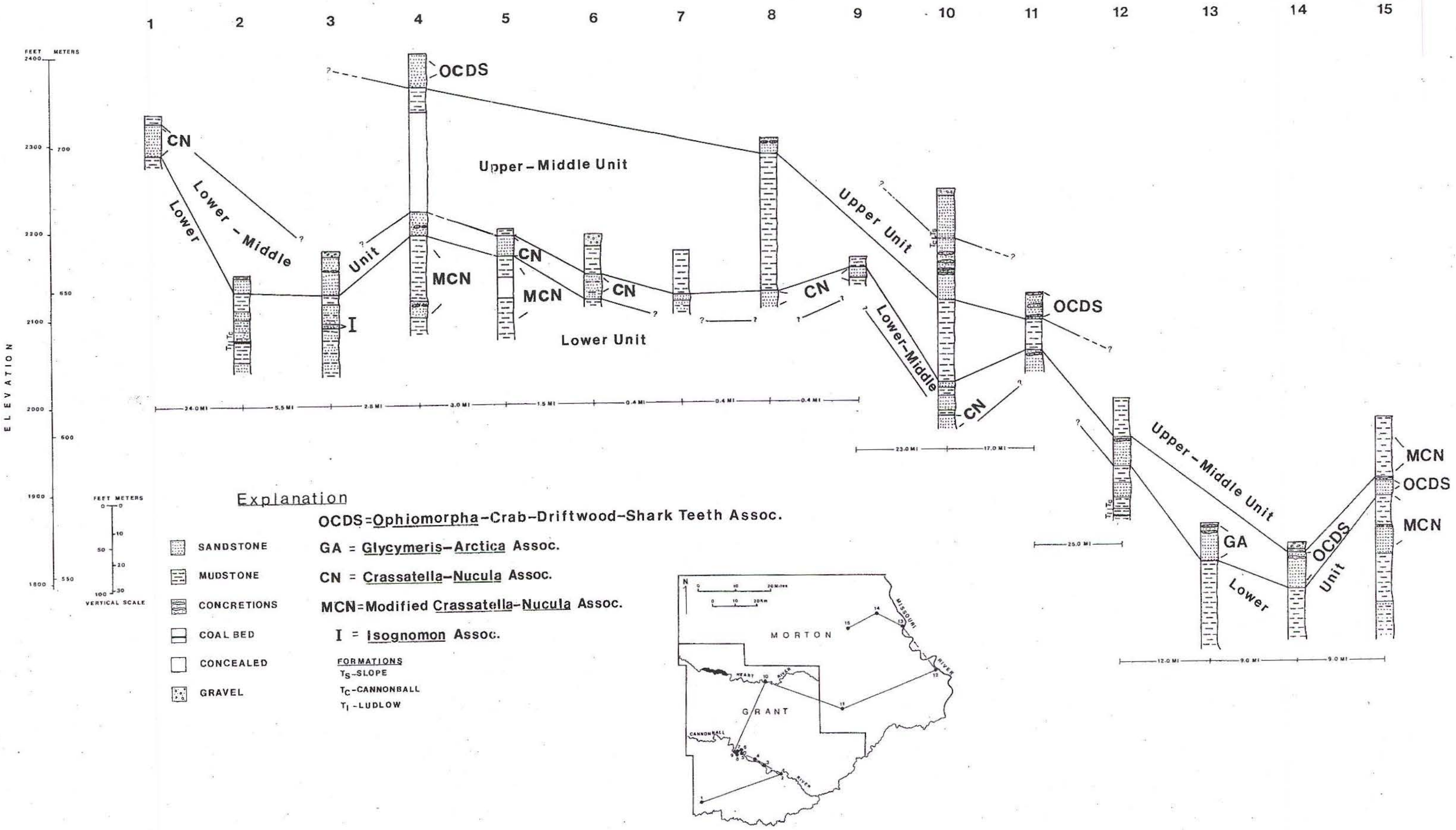
When the measured section in which Isognomon occurs is correlated with other nearby measured sections, it appears to be stratigraphically fairly low in the Cannonball, near the Cannonball-Ludlow contact (Fig. 16). This seems unusual because fossils are said (Cvancara, 1976, p. 14) to be relatively rare near the base or the top of the Cannonball.

The gregarious nature of individuals of Isognomon increases the likelihood that large numbers of specimens would be preserved together. Such is the case with the Cannonball form. The shells of I. lloydi are concentrated in two thin zones (Fig. 12). However, the deteriorated condition of the specimens makes it difficult to determine with absolute certainty if the shells were preserved in living position or were transported by waves and currents and eventually deposited together forming the fossiliferous zones.

The Isognomon shells occur in sandstone with a high organic carbon content and a high percentage of silt and clay. The rocks, both above the upper Isognomon zone and below the lower Isognomon zone, are thinly bedded sandstone and mudstone. An environment with alternating mud and sand deposition could occur in several places. For example, low-energy, lower shoreface sedimentation such as this results from the influence of both nearshore and offshore processes. However, Cvancara (1965, p. 269) noted that

Fig. 16. Cross-section of the Cannonball Formation across Grant and Morton Counties, southwest-central North Dakota showing correlation and distribution of the lithologic units and the bivalve associations. Sections are arranged according to elevation. The section numbers refer to detailed locality descriptions given in Appendix IV.

Pg 83


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
FEET
METERS
2400
2300
700
2200
650
2100
2000
600
1900
1800
550
ELEVATION
OCDS
CN
Upper-Middle Unit
Lower-Middle
Lower
Unit
I
MCN
CN
MCN
CN
Lower Unit
CN
Upper Unit
Lower-Middle
CN
OCDS
Upper-Middle Unit
GA
Lower
OCDS
Unit
MCN
OCDS
MCN
T_l T_c
24.0 MI
5.5 MI
2.8 MI
3.0 MI
1.5 MI
0.4 MI
0.4 MI
0.4 MI
23.0 MI
17.0 MI
25.0 MI
12.0 MI
9.0 MI
9.0 MI
FEET METERS
0
10
50
20
100
30
VERTICAL SCALE
Explanation
SANDSTONE
MUDSTONE
CONCRETIONS
COAL BED
CONCEALED
GRAVEL
OCDS = Ophiomorpha-Crab-Driftwood-Shark Teeth Assoc.
GA = Glycymeris-Arctica Assoc.
CN = Crassatella-Nucula Assoc.
MCN = Modified Crassatella-Nucula Assoc.
I = Isognomon Assoc.
FORMATIONS
T_s-SLOPE
T_c-CANNONBALL
T_l-LUDLOW
N
0 10 20 Miles
0 10 20 Km
MORTON
MISSOURI
RIVER
HEART RIVER
GRANT
CANNONBALL
RIVER

the thickness of the beds in this section is extremely variable and irregular. This variability of bedding thickness would be more suggestive of tidally-influenced deposits. Such deposits commonly include interbedded sand and mud related to the alternation of periods of current activity and slack water conditions.

Tidal flats are commonly associated with estuaries and lagoons and can occur behind barrier islands. They have a predominance of either mud or sand depending on the sediment source. Sediments on a tidal flat also vary because of energy distribution. Tidal flats can be divided into intertidal and subtidal subenvironments. In the intertidal zone, sediments near the low-water line are generally sand due to strong wave activity. The sand becomes progressively muddier landward until mud deposition predominates on the intertidal flat near the high-water line because of low current and wave activity. The subtidal subenvironment is characterized by channels, sand bars and shoals. Tidal flats do not support high-diversity faunas. Weimer et al. (1981, p. 192) concluded the following:

> Tidal flats are biologically rigorous environments because of subjection to extremes in currents, water depth, salinity, temperature, desiccation, erosion, and rapid deposition. Indigenous organisms are generally well adapted forms capable of dealing with the stresses of the environment. The number of species is therefore generally small, but the number of individuals is large.

It is proposed that the Isognomon lloydi localities represent a shallow-water environment associated with a tidal flat. This proposal is supported by the following facts:

1) Isognomon is a shallow-water form and is not found today in low-energy, lower shoreface environments associated with deeper water.

2) The lack of other faunal forms (extremely low diversity) and the apparent abundance of Isognomon suggests a high-stress environment.

3) The irregular bedding, variable thickness, and intercalation of sandstone and mudstone suggest these rocks were deposited in a rapidly-changing, dynamic environment.

4) Glauconite appears to be lacking in the muddy sandstone enclosing Isognomon. This mineral is common in Cannonball sandstone, especially where the sandstone has a high mud content. Glauconite is believed to form most commonly in water depths ranging from 100 to 2,300 feet (30 to 700 m) and is rare in water less than 33 feet (10 m) (Porrenga, 1967). The apparent scarcity of glauconite here further supports the idea of shallow-water deposition.

Glycymeris-Arctica Association

The low diversity and predominance of suspension-feeding bivalves, along with the good sorting and low content of organic carbon in the enclosing rock, indicate that the Glycymeris-Arctica association existed in an environment influenced by waves and currents. The presence of Glycymeris, a form well adapted to life in high-energy conditions, indicates that the water was agitated. An upper shoreface or foreshore environment of a mainland beach or beach associated with a barrier island is proposed.

Many of the fossils found in this association are broken, but the fragments are primarily angular, not rounded, and the fragmenting appears to be primarily the result of outcrop weathering. Postmortem transport would be expected in a high-energy environment such as this, and perhaps some has occurred. It appears somewhat paradoxical, however, that there is so little evidence of transportation, i.e., no well-rounded shells are present.

Regardless of any postmortem transportation, Glycymeris is closely associated with this environment, and it can be assumed with reasonable assurance to have been an inhabitant. The common occurrence of Arctica in association with Glycymeris suggests that it also probably survived in these higher energy conditions. Dosiniopsis has been found in this association with its fragile shell fairly well preserved and articulated (locality 7). This bivalve, a moderately deep burrower and therefore sheltered from stressful conditions, was also a likely inhabitant.

Over 90 percent of the bivalves found in this association are suspension feeders and the trophic nucleus is composed of the above three genera. A schematic interpretation of the autecology of the preserved dominant invertebrates of this association along with photographs of Glycymeris, Arctica, and Dosiniopsis, is shown in Fig. 17.

Crassatella-Nucula Association

Rocks bearing the Crassatella-Nucula association are well exposed in the Cannonball type area along the Cannonball River in southern Grant County (for example, localities 75, 76, and 77, Fig. 2). The fossils are found primarily in a glauconitic, muddy sandstone unit approximately 3 to 6 feet (1 to 2 m) thick. Cannonball outcrops where this association was found are somewhat unusual because the sandstone-mudstone couplets (Fig. 4), so common at many Cannonball outcrops, are lacking. Instead, the fossiliferous zone is underlain by either mudstone or thinly bedded sandstone and mudstone, and overlain by a thick section of mudstone. Correlation (Fig. 16) of the measured sections in this area shows that the sandstone containing

Fig. 17. *Glycymeris-Arctica* Association

a. Schematic interpretation of autecology of dominant macroinvertebrates including the shallow-burrowers *Glycymeris subimbricata* (G) and *Arctica ovata* (A), the deep-burrower *Dosiniopsis deweyi* (D), along with crabs (B), shark teeth (T), aporrhaid gastropods (P), and other gastropods (Q).

b. *Glycymeris subimbricata*, dorsal of double-valved specimen showing inflated shell shape.

c. *Glycymeris subimbricata*, exterior of right valve showing radial rib ornamentation.

d. *Glycymeris subimbricata*, interior of right valve showing marginal denticulation.

e. *Dosiniopsis deweyi*, dorsal exterior of incomplete double-valved specimen.

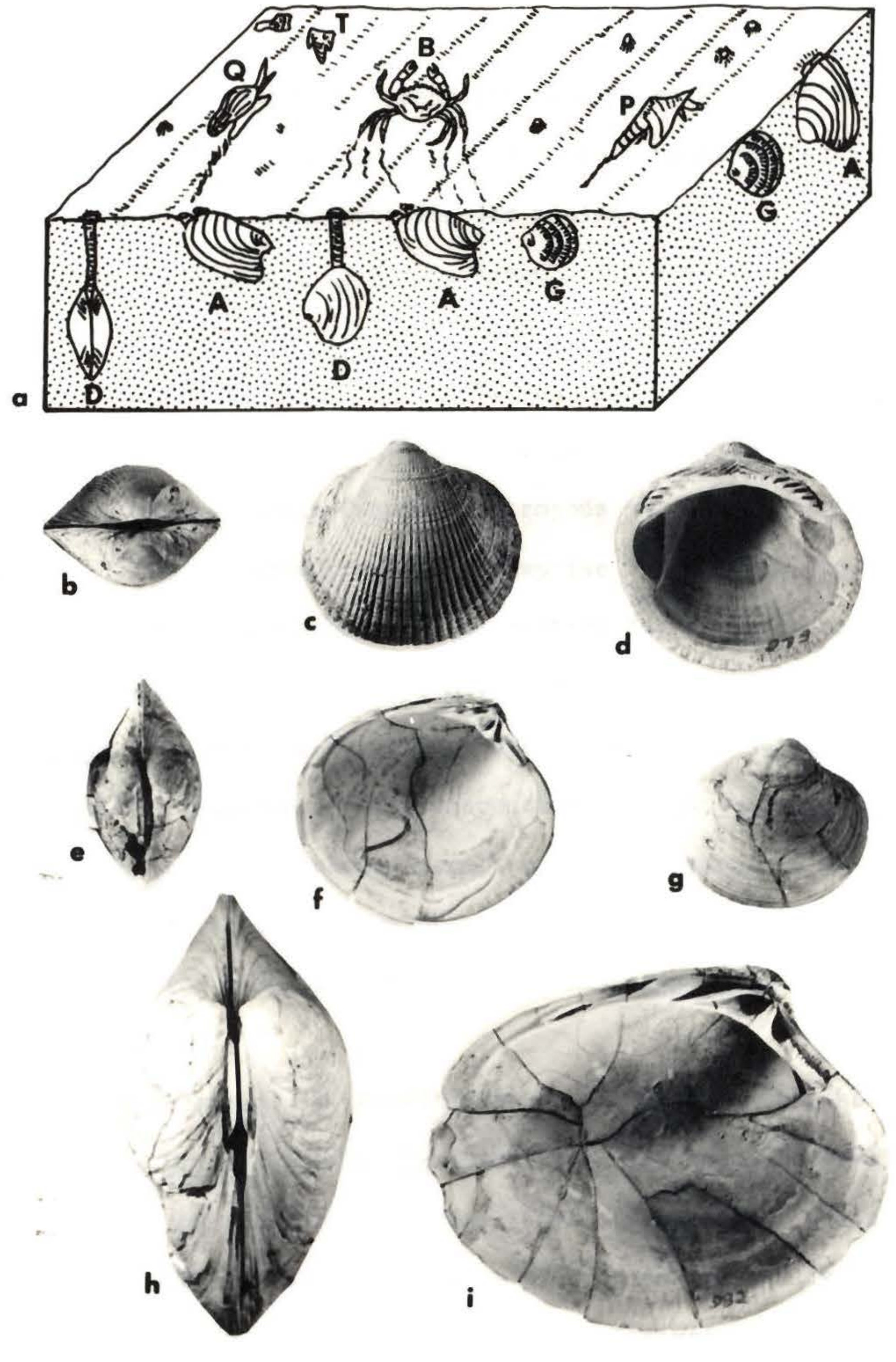
f. *Dosiniopsis deweyi*, interior of left valve valve showing subcircular shape and pallial sinus.

g. *Dosiniopsis deweyi*, exterior of right valve showing fine growth lines.

h. *Arctica ovata*, dorsal exterior of double-valved specimen.

i. *Arctica ovata*, interior of left valve.

(Photographs of bivalves courtesy of Dr. A. M. Cvancara.)


T
Q
B
P
A
G
A
A
G
D
D
a
b
c
d
e
f
g
h
i

the Crassatella-Nucula association occurs in the lower middle part of the Cannonball section.

Fossil preservation at these outcrops is very good. Many bivalves are articulated and fossil specimens are rarely broken (even the delicate wings of the aporrhaid gastropods are commonly intact) suggesting postmortem transportation was minimal.

Although the Crassatella-Nucula association characteristically has high bivalve species diversity (relative to other Cannonball bivalve associations), it is the faunal dominance of gastropods, especially those of the Aporrhaidae (Fig. 18) that makes this association unique. These deposit-feeding gastropods may account for over 75 percent of the preserved fauna and comprise the trophic group nucleus. Although not nearly as abundant as the gastropods, bivalves are well represented in this association and commonly include the deposit feeder Nucula, the shallow-burrowing suspension feeders Crassatella and Arctica, and the deeper-burrowing suspension feeders Dosiniopsis and Periploma. Solitary, cup-shaped corals are also common. A schematic interpretation of the autecology of the preserved dominant invertebrates in this association along with photographs of Crassatella and Nucula, is shown in Fig. 19.

The high percentage of deposit feeders, along with suspension feeders, in the Crassatella-Nucula association indicates several sedimentary and environmental aspects. First, a community dominated by deposit feeders implies an abundance of food in the sediment. Secondly, turbidity would be expected to be relatively high as a result of the ploughing action of these gastropods and protobranch bivalves. However, turbidity was not so high as to exclude

Fig. 18. *In situ* aporrhaid gastropods and a naticid gastropod in muddy sandstone containing the *Crassatella-Nucula* association (locality 76).
(Photograph taken by Dr. A. M. Cvancara)

Fig. 19. Crassatella-Nucula Association

a. Autecology of dominant invertebrates including the shallow-burrowing suspension feeders Crassatella evansi (C) and Arctica ovata (A), the deep-burrowing suspension feeder Dosiniopsis deweyi (D), the shallow-burrowing deposit feeder Nucula planomarginata (N), along with aporrhaid gastropods (P), other gastropods (Q), scaphopods (S), and corals (R).

b. Nucula planomarginata, left exterior showing subovate shell and fine growth lines.

c. Nucula planomarginata, dorsal exterior of incomplete left valve.

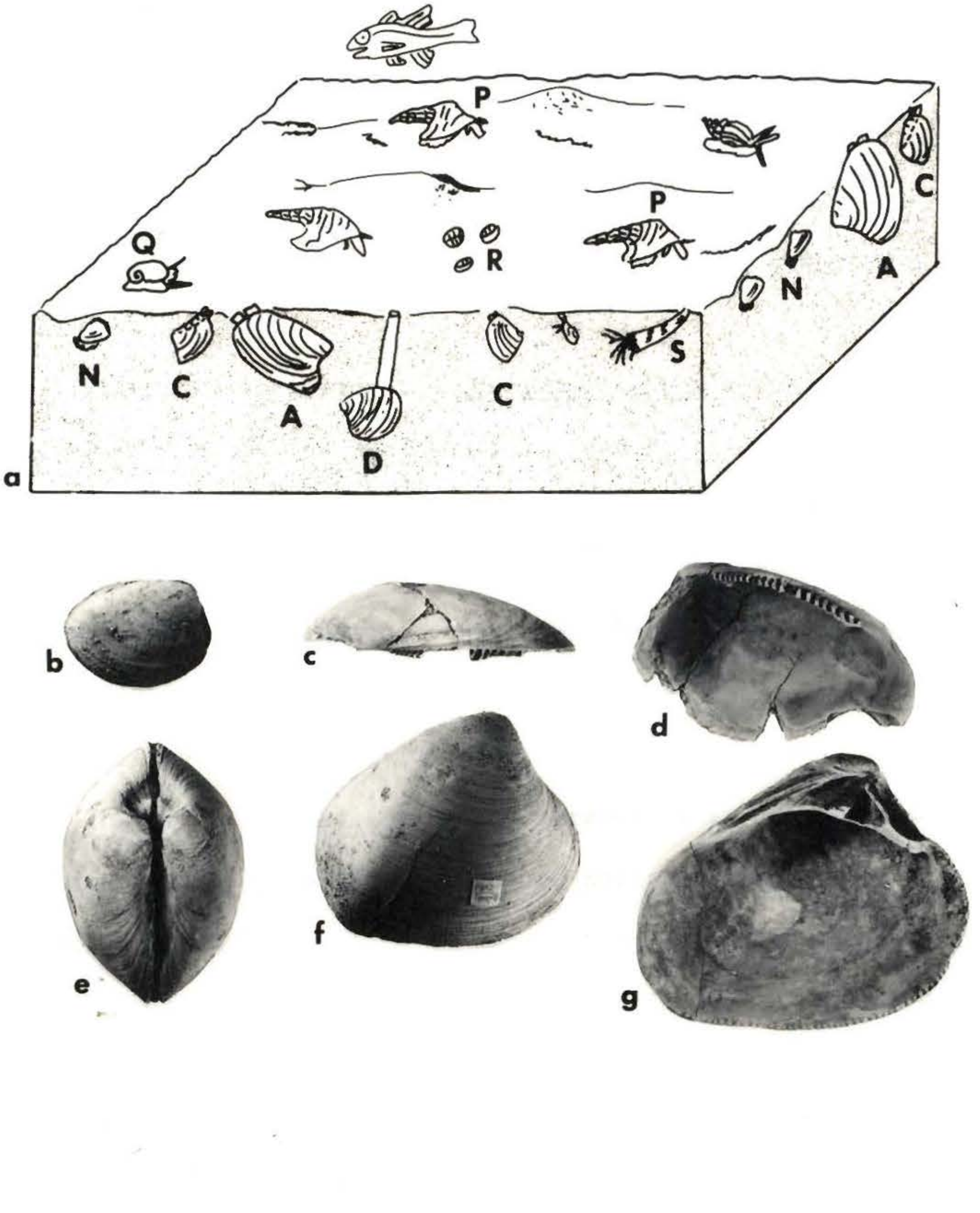
d. Nucula planomarginata, interior of incomplete left valve showing dentition and muscle scars.

e. Crassatella evansi, dorsal exterior of double-valved specimen.

f. Crassatella evansi, exterior of right valve showing truncated posterior margin and fine growth lines.

g. Crassatella evansi, interior of left valve showing marginal denticulation.

(Photographs of bivalves courtesy of Dr. A. M. Cvancara.)


P
C
Q
R
P
A
N
N
N
C
A
C
S
D
a
b
c
d
e
f
g

suspension-feeding bivalves and corals. Finally, the number of shallow-burrowing suspension feeders and corals occurring along with deep-burrowing bivalves, indicates that the bottom must have been soft but not extremely mobile and energy conditions fairly low. The fauna also suggests that the salinity was normal marine.

Successful, highly diverse marine communities generally occur in environments where the water is of "normal" salinity (35 ppm), well-oxygenated, and rich in nutrients, and where sedimentation rate and turbidity do not fluctuate. Conditions such as these are most likely present in shallow subtidal environments, possibly the lower shoreface to offshore. Proposal of this setting is supported by the following:

1) The rocks enclosing the Crassatella-Nucula association have a high percentage of both sand and mud. Sedimentation in the lower shoreface is influenced by both nearshore and offshore processes. As a result, both sand and mud accumulate, and, if the sediment does not undergo extensive bioturbation, they are commonly intercalated. Extensive bioturbation has apparently destroyed or precluded the existence of any laminations in these rocks.

2) The trace fossils (primarily burrows) that are found with this association generally have an oblique to horizontal orientation to the bedding planes. This type of orientation is indicative of a prevalence of deposit feeders and is usually associated with low-energy environments such as the lower shoreface to offshore (Seilacher, 1967).

3) The high diversity of the Crassatella-Nucula association suggests a stable, subtidal environment. In general, benthic-shell diversity is highest within the subtidal, normally saline environment

and decreases in the intertidal and estuarine environments of less stable and brackish conditions (Boucot, 1981, p. 257).

4) The relatively high percentage of glauconite further indicates a subtidal environment.

5) There is a lack of high-energy forms such as the bivalve *Glycymeris*. Although burrows are common, *Ophiomorpha* is notably missing. *Ophiomorpha* is reported (DeWindt, 1974, p. 1138) to occur in "clean" sand and is abundant below mean tide level in the lower foreshore and upper shoreface. The occurrence of *Ophiomorpha* in the "cleaner" Cannonball sandstone but its lack in rocks containing the *Crassatella*-*Nucula* association suggests that these latter rocks were deposited in an environment that existed some distance seaward of the foreshore and upper shoreface.

Modified *Crassatella*-*Nucula* Association

The variability of the fossil assemblages and the enclosing lithology at various localities suggests that the modified *Crassatella*-*Nucula* association represents more than one environment. The following environments are possibly represented by this association:

1) The muddy sandstone and sandy mudstone that commonly contain a low-diversity fauna may represent a subtidal environment somewhat similar to that of the *Crassatella*-*Nucula* association but which, for unknown reasons, lacked the high diversity fauna. Perhaps the environment was slightly different from that of the veritable *Crassatella*-*Nucula* association and lacked the stability to support a high-diversity community. Or perhaps the community had higher diversity but this diversity has been obscured in preservation.

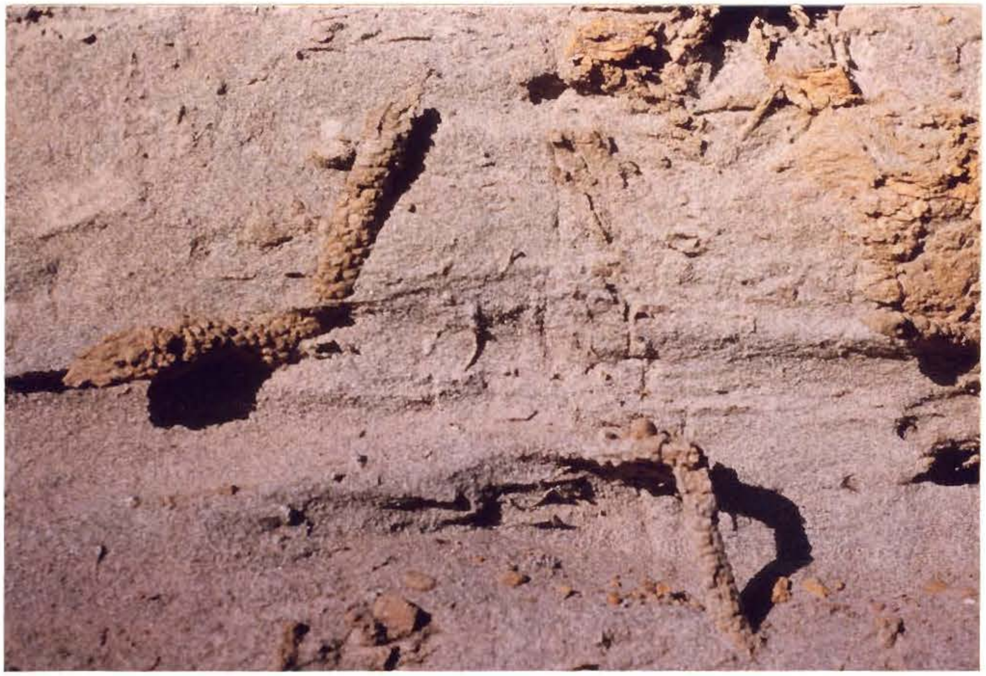
2) The mudstone containing the low-diversity fauna composed primarily of deposit feeders probably represents a subtidal environment not conducive to the existence of suspension feeders. The mudstone lithology, along with the dominance of deposit feeders, indicates a quiet, low-energy environment where the substratum was probably too mobile and thus the turbidity too high for suspension feeders. It may also have been a somewhat restricted or stagnant environment, possibly oxygen-poor, sulphide-rich, or both. Deposit feeders are capable of persevering in these inhospitable environments whereas suspension feeders, more dependent upon well-circulated water in order to obtain food, do not generally fare well. Sulfide (generally in the form of marcasite) is common at many Cannonball outcrops, although it has not been determined if it is primary.

Ophiomorpha-Crab-Driftwood-Shark Teeth Association

The association of *Ophiomorpha* and crabs suggests a nearshore environment. *Ophiomorpha* (Fig. 20), the supposed trace fossil of the ghost shrimp *Callianassa*, is commonly reported (Weimer and Hoyt, 1964; Howard, 1972; DeWindt, 1974) to occur in well-sorted sandstone deposited in higher-energy environments (upper shoreface to foreshore) associated with beaches. Likewise, crabs are nearshore inhabitants. Holland and Cvancara (1958) described and illustrated the crab *Camarocarcinus* (Fig. 21) and they further suggested (p. 499), based on the excellent preservation, that the fossil crabs were buried by shifting sands while in their burrows. Thus, the crabs apparently lived in an environment where waves and currents affected the substratum

Fig. 20. Ophiomorpha in well-sorted sandstone (roadcut exposure, T154N-R78W-30cd, 0.5 mile or 0.8 km northwest of Verendrye, North Dakota). (Photograph taken by Dr. A. M. Cvancara)

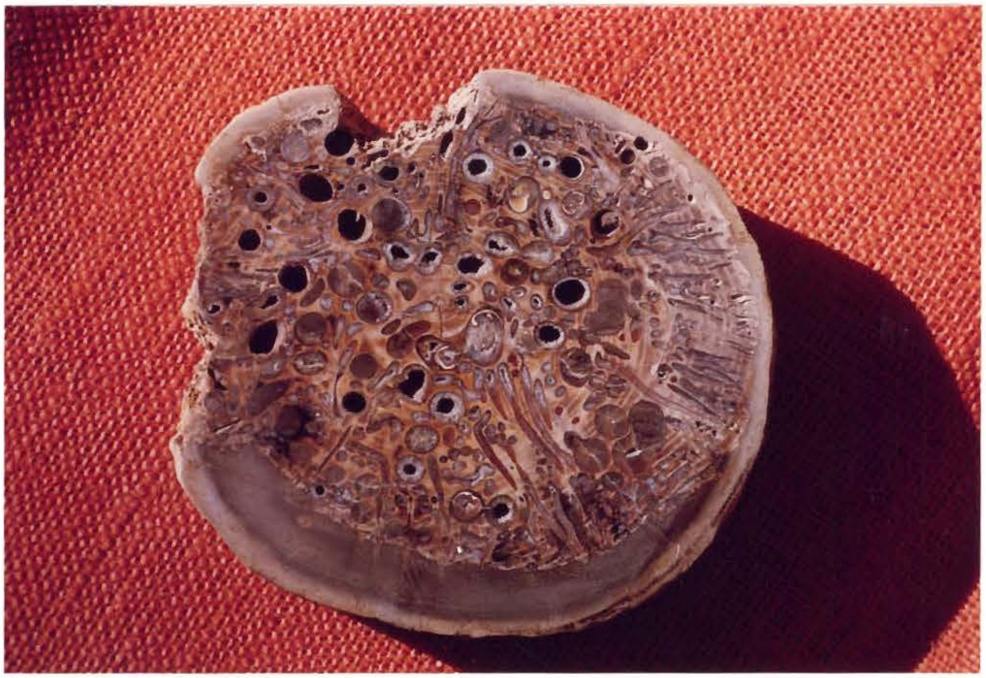
Fig. 21. Crabs (Camarocarsinus arnesoni Holland and Cvancara) from the Cannonball Formation collected 5 miles (8 km) west and 1.1 miles (1.8 km) south of Moffit, southern Burleigh County, North Dakota. (Photograph taken by Dr. A. M. Cvancara)



and these conditions occasionally (such as during a storm) redistributed large volumes of nearshore sand.

It is proposed, based on the association of Ophiomorpha and crabs, that sandstone in which the Ophiomorpha-Crab-Driftwood-Shark Teeth association is found represent a nearshore environment in the vicinity of the strandline. This proposal is supported by the common occurrence of both shark teeth and driftwood (Fig. 22) in association with Ophiomorpha and crabs. These forms would be expected to accumulate, as they do today, along the strandline of the beach environment.

Fig. 22. Teredinid-bored driftwood from the Cannonball Formation (locality unknown). (Photograph taken by Dr. A. M. Cvancara)



DISCUSSION

Stratigraphic Relationships of Lithologic Units and Bivalve Associations

On a local scale, the interrelationships between Cannonball lithofacies are complex. For this reason, the Cannonball Formation cannot easily be subdivided into well-defined lithologic units. On a larger scale, however, major lithologic trends are apparent. The most striking example of this in southwest-central North Dakota is the lateral persistence of sandstone units as reflected by the Cannonball topographic benches.

The topographic benches are helpful in correlation, making possible subdivision of the Cannonball Formation in southwest-central North Dakota into four major lithologic units (lower, lower-middle, upper-middle, and upper). It is not proposed that the Cannonball formally be subdivided into lithologic units, but their establishment is to aid in the interpretation of Cannonball stratigraphy. Subdividing the Cannonball into these units helps to explain the distribution, both vertically and laterally, of the bivalve associations. Conversely, knowledge of the distribution of these associations helps interpretation of Cannonball history.

Lower Unit

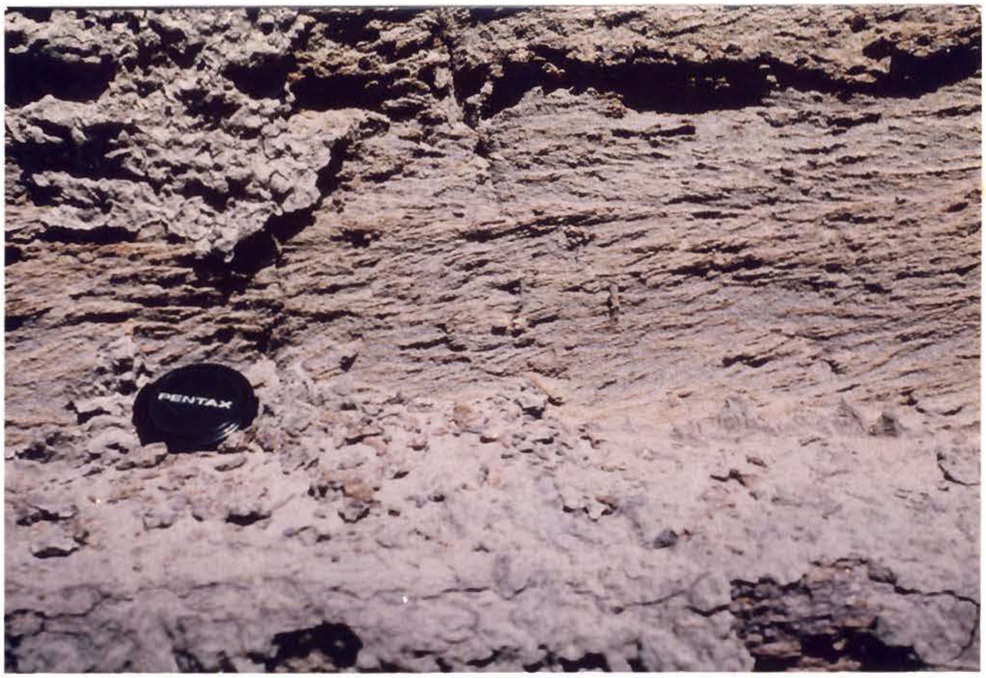
The lower unit consists of those rocks above the Cannonball-Ludlow contact but below the middle, bench-forming sandstone. The thickness of this unit is extremely variable, ranging from approximately 50 to 150 feet (15 to 46 m).

The Cannonball-Ludlow contact is placed, when possible, above the highest lignite or carbonaceous shale (Cvancara, 1976, p. 10). The rocks above this contact are variable but commonly consist of thinly-bedded, fine-grained sandstone intercalated with highly carbonaceous mudstone. The thickness of these thin units of sandstone and mudstone varies from less than an inch to several feet but they can generally be traced across the entire outcrop. The sandstone units may exhibit small-scale cross-bedding (Fig. 23) and they commonly contain plant material in the form of lignitized wood chips.

Lithologic variability increases upsection from the Cannonball-Ludlow contact. In some areas, the lithology becomes predominantly mudstone. In other areas, sand bodies of substantial thickness occur. Sandstone in these bodies may be 20 to 30 feet (6 to 9 m) thick and may contain a well-indurated lenticular bed that forms a topographic bench. This lower bench was first noted by Laird and Mitchell (1942) in southern Morton County; however, it is commonly indistinct and untraceable (Cvancara, 1980, p. 34).

Although lower Cannonball deposits appear to be relatively barren of fossils, several exceptions occur. First, Isognomon occurs in the lower part of the section at localities 65 and 66 along the Cannonball River. Second, a few molluscs can be found in the thicker sandstone and sandy mudstone. This is the case at locality 16 where corals, gastropods, and the bivalve Arctica ovata occur. These forms are interpreted to belong to the modified Crassatella-Nucula

Fig. 23. Small-scale cross-bedding in muddy sandstone in the lower Cannonball unit (locality 22).



PENTAX

association. In addition, bioturbation is sometimes apparent indicating some type(s) of organism(s), probably soft-bodied forms such as annelids, were present.

The lower unit of the Cannonball is well exposed near the base of the outcrop at localities 7, 16, 22, and 65. The variability of the textural and organic parameters of these rocks are shown in Figs. 3 and 6 (samples 7C, 16A, 16B, and 65).

Lower-Middle Unit

The lower-middle unit includes the moderately-sorted to well-sorted sandstone unit represented by the middle Cannonball bench. The bench is held up by lenticular bodies of well-indurated sandstone approximately 2 to 2.5 feet (0.6 to 0.8 m) thick that occurs within poorly-consolidated sandstone 20 to 45 feet (6 to 14 m) thick (Cvancara, 1980, p. 34).

Cvancara (1980, p. 34) has traced this bench for approximately 70 miles (113 km) from northeastern Morton and southwestern Burleigh Counties to southwestern Grant County. In the Cannonball type area, Tps. 132 and 133 N., R 88 W., the bench becomes largely indistinct and appears to thin to a poorly-sorted sandstone several feet (approximately 1 m) thick (for example, at localities 75, 76, 77, and 81).

Overall, fossils, especially molluscs, are more abundant in this unit than any other subdivision and three different associations are found. The occurrence of the *Ophiomorpha*-Crab-Driftwood-Shark Teeth association, such as at locality 15, or the *Glycymeris*-*Arctica* association, such as at locality 7, occur in the thicker, well-sorted sandstone exposures. The *Glycymeris*-*Arctica* association, however, appears to occur primarily in northeastern Morton County, although it has also been found to occur as far north as southern McHenry County (locality 1). In addition, the *Crassatella*-*Nucula* association occurs in the thin, poorly-sorted, glauconitic sandstone at exposures in the type area (localities 75, 76, 77, and 81) where the middle bench becomes indistinct.

The textural parameters and the organic carbon content for samples from this unit include 7A, 7B, 75, 76A, 76B, 77, and 87A and are shown in Figs. 3 and 6.

Upper-Middle Unit

The upper-middle unit contains those rocks between the middle and upper bench-forming sandstones and is primarily composed of mudstone. The thickness of the mudstone varies from less than 50 to over 150 feet (15 to 46 m) but appears to be laterally persistent throughout most of central North Dakota. Not surprisingly, this unit is thickest where the middle sandstone bench thins and becomes indistinct, i.e., those mudstone sections overlying the poorly-sorted sandstone (lower-middle unit) containing the *Crassatella*-*Nucula* association in the Cannonball type area. The mudstone contains a variable amount of sand and may in some areas, particularly near the upper or lower sandstone contact, be a muddy sandstone.

Fossils in this unit are not particularly abundant. In the Cannonball type area (localities 68, 69, and 81), scattered deposit-feeding bivalves, gastropods, and occasional scaphopods occur. Fossils from this unit are interpreted as belonging to the modified *Crassatella*-*Nucula* association.

Upper Unit

The upper unit is defined as the thick sandstone body that commonly occurs near or at the top of the Cannonball Formation in central North Dakota. This sandstone also commonly forms a topographic bench due to the presence of concretionary sand bodies in the unit. The thickness of this unit ranges from 20 to 40 feet (6 to 12 m). Cvancara (1980, p. 34) traced the upper bench approximately 40 miles (64 km) from east-central Morton County to southern Grant County, and about 40 miles (64 km) from northeastern Grant County to east-central Sioux County. The bench, so presumably the entire unit, does not appear to extend into northeastern Morton County. This unit is well exposed north of locality 65 (NW¼ Sec. 9, T. 132 N., R. 87 W., 6.5 miles south-southeast of Leith, southern Grant County).

The well-sorted, upper bench-forming sandstone commonly contains the Ophiomorpha-Crab-Driftwood-Shark Teeth association and, in some places, a few molluscs. However, molluscs are not nearly as abundant in this unit as in the sandstone coinciding with the middle bench.

Environments of Deposition

The complexity of the interrelationships between Cannonball lithofacies makes interpretation of depositional environments difficult. Part of the problem is due to poor or inadequate stratigraphic control. Exposures are excellent in some areas and nonexistent in others. For example, very few exposures are found west of Grant and Morton Counties or north of Oliver County. This leaves a large gap along with uncertain facies relationships between the exposures in southwest-central North Dakota and southwestern North Dakota where the Cannonball tongues are exposed in the Little Missouri Valley. Subsurface data in the form of electric logs have proven to be of little value in differentiating Tertiary formations.

A depositional model for the Cannonball Formation must account for the following sedimentary characteristics:

1) The presence of two brackish-water mudstone tongues in southwestern North Dakota.

2) The repeated occurrence of sandstone-mudstone couplets common in the Cannonball section in southwest-central North Dakota.

3) The lateral complexity of lithofacies on a local scale as well as the persistence of two, possibly three, topographic benches in central North Dakota.

4) The distribution of the bivalve associations and other fossil forms.

5) The abundance of plant material throughout the Cannonball.

6) The presence and distribution of glauconite.

Before a depositional history of the Cannonball Sea can be interpreted, a few pertinent and influencing factors should be considered.

Source of the Cannonball Sea

The source of the Cannonball Sea has long been an intriguing mystery as well as a point of controversy to many geologists. Because the Cannonball Formation appears to thin naturally to the west and south, and because it is uncertain whether the formation thickens or thins to the north and east, the earliest workers (Lloyd and Hares, 1915, p. 541) proposed that the Cannonball Sea entered North Dakota from the east or northeast. Since then, several proposals have been made and generally include a connection with either the Gulf of Mexico, the Arctic Ocean, or both.

Cvancara (1965, p. 99-101) presented reasons against a northern source of the sea based primarily on the lack of correlative Paleocene marine units in Canada. However, the nearest marine correlative in any direction appears to be in southern Illinois and southeastern Missouri approximately 900 miles (1,448 km) to the southeast (the Clayton and Porters Creek Formations).

Determining the source of the Cannonball Sea based strictly on stratigraphic trends is not conclusive and other workers have attempted to use faunal affinities. For example, based on Cannonball foraminiferids collected from the Souris River area that resemble Arctic forms, Lemke (1960, p. 31) proposed an Arctic connection. Conversely, Fox and Ross (1942) used foraminiferids from southwest-central North Dakota that resemble those of the Midway Group to support a Gulf Coast connection. Such a duality of provincial affinity not only exists for the foraminiferids but also for other forms, including the bivalves.

Arctica ovata, the most common Cannonball bivalve, closely resembles the only extant species, *Arctica islandica*. This species is today restricted to cold temperate (Boreal Province) waters of the North Atlantic (Nicol, 1951, p. 104). Using the provincial affinities of modern-day descendants to interpret marine connections and climatic conditions is very tempting and, in many cases, is probably accurate. However, caution must be used. Davies (1975, p. 82) made the following statement regarding genera of families common in the Mesozoic and Cenozoic record:

> In Mesozoic time some were apparently widely distributed without climatic restriction, but are now restricted to either warm seas (_Cucullaea_, _Isognomon_) or to cold seas (Astartidae, Arcticidae, Aporrhaidae). These raise the question of how far back in geological history they can safely be taken as climatic indices.

Although the Cannonball contains forms that are today restricted to either cold or warm seas, many bivalves such as _Nuculana_, _Arctica_, _Crenella_, _Panopea_, along with aporrhaid gastropods (Davies, 1975, p. 39), are considered Boreal or Arctic forms. Based on these provincial affinities, it could be proposed that the climate was cold temperate. However, floral studies (Brown, 1962; Sloan, 1970) indicate a warm temperate climate for the northern Great Plains region during the Paleocene.

The presence of cold water forms, therefore, does not appear to be the result of climatic species zoning alone. Reasonably, if the marine Cannonball water came only from the southeast, i.e., the Gulf of Mexico, the waters in a warm temperate climate would be too warm to support cold temperate molluscs. However, a marine connection from northern water could result in the introduction of boreal forms to southern warm temperate climates.

Although Paleocene rocks in Alberta, Canada have generally been considered nonmarine, the Paskapoo Formation, an equivalent of the Fort Union, was interpreted (Russell, 1940) to be at least estuarine and an extension of the Cannonball Sea. This conclusion was based on the occurrence of _Micrichnus_, trails made by a horseshoe crab in these strata.

Erickson (1978, p. 81) reported the occurrence of _Arctica_ cf. _A_. _ovata_ in the Timber Lake Member of the Fox Hills Formation of Cretaceous age. Based on its presence along with several other North

American Boreal Faunal Province bivalves, he proposed that linkage of the sea in the Western Interior with the Gulf Coast ceased in late Fox Hills time and that the regressing sea was divided into northern and southern basins. He further suggested that after the northward regression of the Fox Hills Sea, marine connections through the Canadian Arctic and Hudson Bay were terminated. He then suggested that the connection was re-established through Hudson Bay in Paleocene time and that this resulted in the entry of the Cannonball Sea, thus providing the Cannonball with a temperate fauna.

A recent study (Marincovich et al., 1983) tentatively correlates the Cannonball Formation with Paleogene deposits at Ocean Point, northern Alaska, on the basis of molluscs and ostracodes. The low species diversity in both deposits compared to the highly diverse fauna in coeval deposits in the Gulf of Mexico embayment, West Greenland, and northwestern Europe, is used to support their proposal that the Arctic Ocean was geographically restricted during this portion of Paleogene time.

Although these recent studies do not provide any firm evidence of a source for the Cannonball, a northern connection probably should not be totally disregarded. Unfortunately, without additional stratigraphic or biologic evidence, the question of source may well remain unresolvable.

Paleostrandlines

The interfingering of the Cannonball with nonmarine sedimentary rocks in southwestern North Dakota and northern South Dakota, along with thinning to the west and south, indicates that strandlines were present in these areas. The brackish-water mudstone tongues exposed in the Little Missouri Valley have a combined thickness of only 50 feet (15 m).

In contrast, recent studies (Monnens, 1980; Goodrum, 1982) in the vicinity of the North Cave Hills, northwestern South Dakota, reported up to 135 feet (41 m) of Cannonball represented by two bench-forming, fine-grained, coarsening-upward sandstone units. A high-energy mainland beach model has been proposed by Goodrum (1982, p. 107) based on apparently well-preserved sedimentary structures and the absence of evidence for a lagoonal or back-barrier environment of deposition.

How the North Cave Hills section correlates with the Cannonball tongues, only 40 miles (64 km) to the north, is uncertain. Although different from the rocks of the tongues in both thickness and lithology, the North Cave Hills Cannonball rocks also differ markedly from the Cannonball in central North Dakota in the following respects:

1) In South Dakota, the primary lithology is sandstone, whereas in North Dakota, both mudstone and sandstone are common, although mudstone predominates.

2) Generally, the rocks in South Dakota are well-lithified (although some are friable) and sedimentary structures are well-preserved. In contrast, the majority of North Dakota rocks are poorly lithified (most workers are, in fact, tempted to call them sediments) and as a result, sedimentary structures are not readily apparent.

3) Although fossils are only marginally abundant in North Dakota, they are severely lacking in South Dakota. No molluscs have been

reported. The only reported forms that have marine affinities are shark teeth and Ophiomorpha-like burrows.

It thus appears that the Cannonball in North Dakota represents somewhat different environments of deposition than the North Cave Hills Cannonball rocks. Goodrum (1982, p. 118), using paleocurrent data in the North Cave Hills, determined a north-northeast to south-southwest direction for the paleostrandline strike. This agrees with the proposal of Pipiringos et al. (1965) of a north-south strandline in the North Cave Hills. Where strandlines existed to the north and east of the principal Cannonball outcrops in North Dakota remains unknown.

Water Depths

Klein (1974) demonstrated that, if no abnormal thickening, thinning, or deformation occurred, nearshore water depths could be estimated from the thickness of barrier island and deltaic sedimentary sequences. Cvancara (1976, p. 16) used this approach to estimate a wave base of at least 40 feet (12 m) for nearshore environments. Goodrum (1982, p. 120) estimated depths of 45 to 65 feet (14 to 20 m) in the North Cave Hills area.

For the following reasons, the mudstone of the Cannonball Formation in central North Dakota also appears to represent relatively shallow-water deposition:

1) Planktic foraminiferids are rare and those found are smaller than those common in deeper water sediments (Fox and Olsson, 1969, p. 1400). However, benthic foraminiferids are relatively common and are found primarily in the mudstone (Fenner, 1974, p. 55, 1976, p. 73).

2) Both Cannonball mudstone and sandstone contain abundant plant material, commonly lignatized. Its abundance in the mudstone

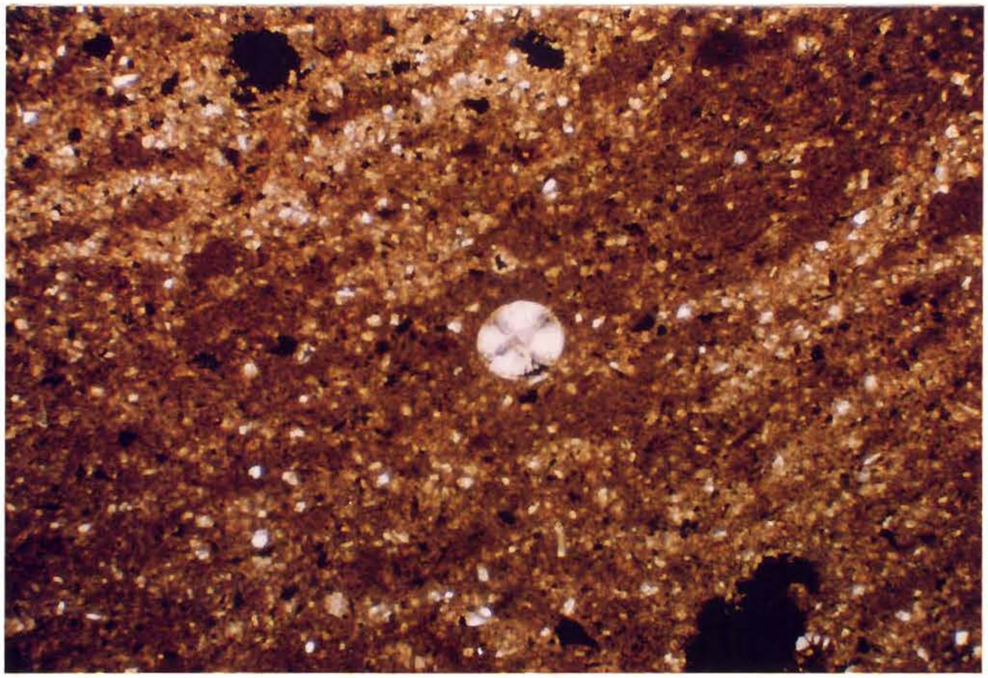
provides further support to shallow-water deposition.

3) A thin-section examination of the micrite concretions found within the mudstone reveals well-preserved evidence of bioturbation and possible algal mats. In addition, round calcite bodies resembling calcispheres occur (Fig. 24). Calcispheres are believed (Bathurst, 1971, p. 70) to represent the reproductive bodies of algae. Today, calcispheres are found only in environments in shallow protected water where circulation is restricted or semirestricted (Marszalek, 1975, p. 271). The presence of algae in an environment indicates deposition occurred in the photic zone, and also in relatively shallow water.

4) Glauconite, common in many Cannonball rocks, is often used as a broad depth indicator. Cloud (1955, p. 484) reported its formation in normal marine environments with slightly reducing conditions and in depths ranging from 30 to 6,000 feet (9 to 1,800 m). However, Porrenga (1967) said its formation is most common at depths ranging from 100 to 2,300 feet (30 to 700 m).

5) Bivalves are generally not good bathymetric indicators and can be used only in a broad sense. Infaunal bivalves are found at all depths. However, deposit feeders prefer fine-grained sediments rich in organic matter, and, because these sediments are most abundant in deeper, quieter waters, the proportion of deposit feeders commonly increases with depth (McAlester and Rhoads, 1967).

Fig. 24. Photomicrograph of micrite concretion from Cannonball mudstone (locality 68) showing bioturbation and a calcisphere (displaying uniaxial cross). Diameter of calcisphere is 0.2 mm.



The preceding reasons and the lack of obvious deep-water, open-marine sediments strongly suggest that the mudstone in the Cannonball represents shallow, restricted or semirestricted, water conditions, although deeper than the nearshore environments. Cvancara (1976, p. 16) suggested, and it appears reasonable, that water depths for the mudstone were up to 100 feet (30 m).

Depositional Models for the Cannonball Formation

The Cannonball Formation remains somewhat of an enigma in the Paleocene sequence in that it is a marine unit found only in the Williston Basin wedged in a thick accumulation of nonmarine sedimentary rocks. These nonmarine deposits accumulated east of the Rocky Mountain region as a result of uplift of ranges associated with the Laramide Orogeny from Late Cretaceous to Eocene time.

Based on floral evidence (Brown, 1962; Sloan, 1970), the climate in the northern Great Plains region was probably warm temperate. The dominantly fine-grained sediments of the Cannonball suggest that deposition was distant from the source. Although the sand is fine- to very fine-grained, it is commonly angular to subangular and appears quite fresh. The sand is predominantly quartz; however, feldspars (primarily plagioclase varieties) are also common along with volcanic rock fragments. These volcanic fragments, rich in plagioclase content, are also surprisingly fresh and unaltered. What the Cannonball mineralogy indicates about its source is uncertain without further studies. Although some of the sediments were probably reworked Fox Hills sandstone, it is quite probable the Cannonball had more than one source. The fine grain size, along with the floral evidence, further suggests a lowland terrain adjacent to the Cannonball Sea.

Previous workers (primarily Cvancara, 1965, 1976) have suggested that the Cannonball was deposited in a complex of depositional environments that included tidal flat, lagoon, beach, shoreface, and shelf. The Frisian Islands in the North Sea on the northern coast of the Netherlands and northern Germany have been proposed (Cvancara, 1965, 1976) as a modern analog. In this area, the coast has well-developed tidal flats and is protected by a series of barrier islands, separated from the mainland by a lagoon of variable width. For the most part, the model appears quite feasible for the Cannonball. However, such a model does provoke a few additional thoughts.

The bivalve associations and the Cannonball lithologies suggest that the environments of deposition in western North Dakota were different than those in central North Dakota. But, how they related to each other should also be considered.

In western North Dakota, the Cannonball is represented by two brackish-water tongues. In marine environments, brackish water generally occurs near the strandline where rivers empty. At some distance seaward, the freshwater influx ceases to have an effect and the water becomes of normal marine salinity. In between these two areas, a salinity gradient exists. The tongues, separated by approximately 100 feet (30 m) of nonmarine rocks, are evidence that the Cannonball Sea transgressed this area at least twice. Based on foraminiferid faunas, Fenner (1976, p. 77-78) reported that in the subsurface, the fauna changed from one of normal saline affinities to one of brackish-water affinities west of Adams County. Thus, brackish-water conditions existed as far west as western Slope County and as far east as Adams County and these occurrences are probably the result of the salinity gradient migrating with the transgression and regression.

In central North Dakota, the Cannonball is represented by thicker sections of mudstone and sandstone containing a more normal marine fauna. However, the major lithologic trends and persistence of the Cannonball benches strongly suggests at least two transgressive and regressive events also occurred in this area during Cannonball time.

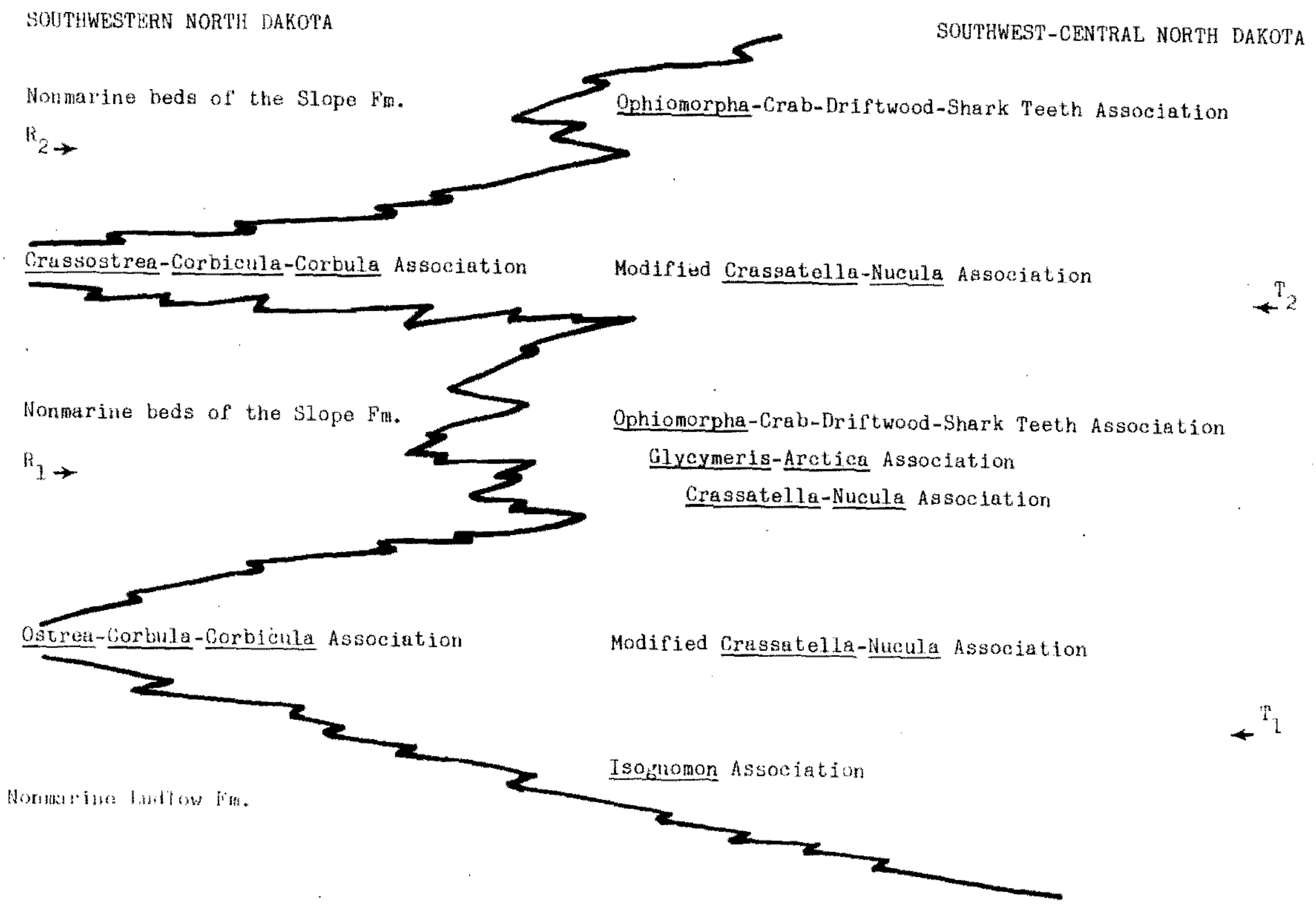
It cannot be stated with certainty that the Cannonball tongues correlate in time with the major transgressive events in central North Dakota because the possibility exists that additional Cannonball tongues were deposited but were not preserved, or are present in the subsurface. However, it seems reasonable, that the deposition of the lower and upper tongues can be correlated with transgressive events in central North Dakota (Fig. 25).

In western North Dakota, the depositional setting included a low-lying, swampy nearshore environment with rivers emptying into lagoons of variable width, supplying sediment for a series of north-trending barrier islands.

In central North Dakota, the interrelationships of laterally adjacent environments were apparently more complicated and probably included the subenvironments associated with tidal flats, lagoons and bays, beaches (associated with both barrier islands and the mainland), and shelf-like environments. This would account for the complexity of lithofacies seen on a local scale (even at one outcrop).

Fenner (1976) further refined Cvancara's (1976) model by suggesting the presence of a northward-trending barrier-island chain through

Fig. 25. Generalized distribution and correlation of Cannonball faunal associations with major transgressions (T) and regressions (R) during Cannonball time.


SOUTHWESTERN NORTH DAKOTA
SOUTHWEST-CENTRAL NORTH DAKOTA
Nonmarine beds of the Slope Fm.
Ophiomorpha-Crab-Driftwood-Shark Teeth Association
R_2 →
Crassostrea-Corbicula-Corbula Association
Modified Crassatella-Nucula Association
T_2 ←
Nonmarine beds of the Slope Fm.
Ophiomorpha-Crab-Driftwood-Shark Teeth Association
Glycymeris-Arctica Association
R_1 →
Crassatella-Nucula Association
Ostrea-Corbula-Corbicula Association
Modified Crassatella-Nucula Association
T_1 ←
Isognomon Association
Nonmarine Ludlow Fm.

central North Dakota, just west of the present Missouri River. The deeper water, more open-sea environments, he suggested, were to the east and southeast of the barrier-island chain. With this model, the entire area between the strandline in western North Dakota and the barrier-island chain was one "big" lagoon (well over 100 miles or 161 km wide). In the west, where rivers empty, the water was hyposaline but it became a normal marine, shelf-like environment, albeit shallow water, towards the east.

If the term "lagoon" is used in the broad sense, that is, any body of water with limited connection with the sea (not the geomorphological sense that lagoons are narrow, shallow, elongate bodies of water separating the shoreline and a barrier island, it is probably more correct to refer to the Cannonball body of water as a lagoon rather than a sea. However, one barrier-island chain migrating across a huge lagoon does not appear to account for the complexity of the lithofacies, or, more importantly, does not answer the question why open-marine sediments were not deposited over the barrier island sand deposits as the chain migrated westward.

The possibility is proposed here that in North Dakota the Cannonball Sea was present in only part of the state and that deeper water, open-marine conditions did not exist in North Dakota. A north-trending strandline was also probably present somewhere near the present Missouri River. The source of the sea would have been from either the north-northeast or south-southeast, and in either case, the Cannonball water in North Dakota was unrestricted only in the direction of the source. With this model, barrier islands could have been present concurrently in both western and central North Dakota, or in any vicinity where there was a supply of sediment. Differences in freshwater influx and energy conditions resulted in varying environments of deposition and faunas. In addition to more adequately explaining the lack of deeper water sediments, this model also helps resolve why many of the sandstone units appear to be mainland beach deposits and why others appear to be beaches associated with barrier islands.

Depositional History of the Cannonball Formation

The following is a brief synopsis of a suggested depositional history that took place in North Dakota during Cannonball time. The intent of proposing this history is to account for major lithologic trends. It should be kept in mind that the following events do not occur at one particular time in the early Paleocene, but that environments continually migrated throughout Cannonball time.

1) The first transgression of the Cannonball Sea resulted in the deposition of both the lower and lower-middle units. In addition, it seems likely that the lower tongue was deposited when the sea reached its maximum westward transgression.

The lower unit was deposited in an environment that developed on the edge of the approaching sea. The resulting tidal flat sediments display a high degree of lithologic variability. The complex mosaic of lithofacies relationships resulted from the interfingering of the tidal flat subenvironments, that is, the intertidal and upper subtidal. Sediments in these subenvironments would include alternating beds of mud and sand deposited in the intertidal and the sand and mud deposited in the subtidal associated with channel fill, tidal point bars, and sand shoals.

Overall, the tidal flat environment was probably too stressful for most organisms with the exception of burrowing, soft-bodied forms. The bivalve Isognomon was also apparently able to thrive in the shallow water.

As the transgression continued over the area and the water depth increased, new environments such as restricted bays or small lagoons, and scattered barrier islands replaced the tidal flat environment. In other areas, tidal flat deposition apparently continued. Faunas flourished in some of the nearshore environments associated with the small barrier islands and mainland beaches in central North Dakota. These sand bodies may have been more extensive than is apparent but were possibly partially or totally reworked as the transgression continued. These sediments are represented today by the sometimes distinct, but generally untraceable, lower bench-forming sandstone that occurs in southern Morton County.

At the time of maximum transgression, barrier-island and mainland beaches were present. Crabs and the organism that made Ophiomorpha, along with suspension-feeding bivalves, inhabited the nearshore, higher energy environments (represented by the Glycymeris-Arctica association in some exposures). A diverse faunal community (represented by Crassatella-Nucula association) probably thrived in the more stable subtidal environment where water was deeper (shelf-like). Also during this time of maximum transgression, brackish water in western North Dakota (Slope County) resulted in deposition of the lower tongue (Fig. 25) containing the fauna belonging to the Ostrea-Corbula-Corbicula association.

2) Regression resulted in the withdrawal of brackish water in Slope County and a resumption of nonmarine deposition there. This regression also resulted in migration of the barrier islands and mainland beaches along with their contained biotic communities. These barrier islands and mainland beaches are represented today by the middle bench-forming sandstone.

3) A transgression and the resultant deposition of a thick section of mudstone in central North Dakota followed the first regression. Fine-grained sediments were present in the deeper subtidal areas that supported communities composed primarily of deposit-feeding organisms. During this time, the westernmost extent of the sea is probably represented by the upper Cannonball tongue. However, based on the fauna (_Crassostrea_-_Corbicula_-_Corbula_ association and the lack of microfossils), the water probably had lower salinity than during deposition of the lower Cannonball tongue. The presence of a sandstone unit containing the trace fossil _Ophiomorpha_ near the top of the upper Cannonball tongue indicates that transgression continued to the point where a barrier island migrated over the brackish sediments. It is likely, therefore, that the upper Cannonball tongue extends even farther to the west.

4) What appears to be the final regression of the Cannonball is represented by the laterally persistent upper Cannonball bench that also most likely represents prograding barrier island and mainland beaches. The upper bench-forming sandstone was probably a relatively high-energy, nearshore to shoreface environment. Fossils, with the exception of _Ophiomorpha_, crabs, driftwood, and shark teeth, are few.

PROBLEMS DESERVING FURTHER STUDY

This study has concentrated on only one fossil form. Because bivalve morphological features commonly reflect environmental stresses, bivalves are among the most useful paleoecological indicators. However, more could now be gained by a detailed study of fossil forms other than bivalves to determine paleoecological relation of the forms to the bivalve associations defined in this study and to aid interpretation where bivalves are missing. Among the other forms, those most useful would include gastropods, corals, and trace fossils. Trace fossils, in particular, are often abundant where other fossils are not.

Cannonball sedimentary structures are not particularly abundant; however, there are probably enough to obtain useful data on a regional scale. Cross-bedding, found at sandstone exposures, could be measured to determine paleocurrent directions. This information could help determine the orientation of the sand bodies and their relationship to paleostrandlines.

Cannonball mineralogy is another subject deserving study. The large number of unaltered plagioclase feldspars and volcanic rock fragments suggests that a fair proportion of the grains are not reworked sediments. A detailed mineralogic study could provide information on the source of the sediments. In addition, a method might be developed to recognize the Cannonball in the subsurface. Mineralogy may be helpful in this respect as may some geochemical technique.

Finally, although a large proportion of Cannonball rocks are unconsolidated, some diagenesis has occurred (e.g., the formation of the concretionary bodies and benches) and deserves further study. The micrite concretions should also be examined, perhaps with the help of the SEM, to determine their origin.

SUMMARY AND CONCLUSIONS

Five bivalve associations and one sub-association, within the Cannonball Formation of North Dakota, are defined based on field observations and further supported by Q-mode and R-mode cluster analyses.

1) The *Ostrea*-*Corbula*-*Corbicula* association is geographically and stratigraphically restricted to the lower Cannonball tongue in southwestern North Dakota. The association occurs in a mudstone with a high organic carbon content and represents a low-energy, brackish-water environment located near the strandline. The low-diversity fauna, along with the presence of the oyster *Ostrea*, is characteristic of fluctuating low-salinity environments.

2) Geographically and stratigraphically restricted to the upper tongue of the Cannonball in southwestern North Dakota, the *Crassostrea*-*Corbicula*-*Corbula* association is characterized by discontinuous beds and pods of *Crassostrea* that represent *in situ*, low-diversity oyster banks and patches. The beds and pods are enclosed in a mudstone rich in organic carbon, that accumulated in a low-energy, brackish-water, lagoonal environment. The abundance of *Crassostrea* in the upper tongue and its lack in the lower tongue suggests that water conditions were more brackish (less marine) when the oyster banks and patches developed than during deposition of the sediments enclosing the *Ostrea*-*Corbula*-*Corbicula* association. Closer proximity to the paleostrandline may account for this. *Corbicula* and *Corbula* are not found in direct association with *Crassostrea* but occur

in lithologically different sediment above the Crassostrea beds. Their occurrence, and the disappearance of Crassostrea, suggests a change in environmental conditions, probably in salinity. The presence of Corbicula and Corbula and a sandstone unit containing Ophiomorpha near the top of the upper tongue suggests that a transgressive event continued after the demise of the oysters.

3) The Isognomon association is also geographically and stratigraphically restricted. It occurs in a muddy sandstone near the base (lower unit) of the Cannonball section in southern Grant County. The apparent lack of other macrofossils, along with the sedimentary characters, suggests a shallow-water, dynamic environment that was probably too rigorous for most faunal forms. It is suggested that Isognomon lived in the shallow water of the subtidal zone, or, in the intertidal subenvironment near the low-water line, associated with an extensive tidal flat environment that developed in North Dakota with the transgression of the Cannonball Sea.

4) Although the Glycymeris-Arctica association is found throughout a larger area than the preceding three associations, it occurs primarily in eastern Morton County. Further, it does not appear to occur in sediments above the middle bench-forming sandstone (lower-middle unit) of the Cannonball Formation. The Glycymeris-Arctica association is also confined to moderately-sorted to well-sorted sandstone. The trophic group nucleus is composed of suspension-feeding bivalves commonly found in association with Ophiomorpha. This fact, along with the overall low diversity and the environmental preference (high-energy, shallow water) of the distinguishing bivalve, Glycymeris subimbricata, suggests that the association represents a nearshore,

wave-agitated environment. This environment was probably associated with mainland and barrier island beaches.

5) The high-diversity Crassatella-Nucula association appears to occur only in southern Grant County, especially in the type area of the Cannonball Formation where the middle Cannonball bench-forming sandstone is indistinct. The glauconitic sandstone in which the association occurs is in the lower-middle unit of the section. Although both deposit-feeding and suspension-feeding bivalves are common, aporrhaid gastropods comprise the trophic group nucleus of this association. The dominance of these deposit-feeding gastropods, along with the deposit-feeding bivalves, suggests a relatively low-energy environment with an adequate supply of food in the sediment. The presence of suspension-feeding bivalves further suggests relatively low turbidity and a soft but not mobile substratum. The Crassatella-Nucula association represents a subtidal environment with normal marine salinity and stable sedimentologic and hydrologic conditions.

6) The modified Crassatella-Nucula association is not stratigraphically or geographically restricted. It occurs in lithologies ranging from muddy sandstone to mudstone and contains fossil forms commonly found in the Crassatella-Nucula association but lacks the high diversity and the dominance of aporrhaid gastropods of that association. Its occurrence may, in some places, be the result of more selective preservation of the veritable Crassatella-Nucula association. However, because it is found throughout much of the Cannonball, it is probably primarily representative of subtidal communities where living

conditions were less conducive to many forms and, thus, yielded lower diversity, possibly "immature" communities.

In addition to these bivalve associations, a biotic association, the *Ophiomorpha*-Crab-Driftwood-Shark Teeth association, also occurs in the Cannonball. This association is found only in well-sorted sandstone and probably represents an environment similar to that of the *Glycymeris*-*Arctica* association, i.e., a high-energy, nearshore environment associated with a mainland or barrier island beach. However, the accumulation of driftwood and shark teeth along with crabs and *Ophiomorpha* further suggests this association existed at or near the strandline. Unlike the *Glycymeris*-*Arctica* association, it is not geographically or stratigraphically restricted. However, it occurs most commonly in the upper bench-forming sandstone (upper unit).

The Cannonball biotic associations appear to be geographically and stratigraphically distributed as follows:

Ostrea-*Corbula*-*Corbicula*	:	Lower Cannonball tongue	Slope County, southwestern N. D.
Crassostrea-*Corbicula*-*Corbula*	:	Upper Cannonball tongue	Slope County, southwestern N. D.
Isognomon	:	Lower Cannonball unit	Southern Grant County, central N. D.
Glycymeris-*Arctica*	:	Lower-middle Cannonball unit	Primarily Eastern Morton County, central N. D.
Crassatella-*Nucula*	:	Lower-middle Cannonball unit	Southern Grant County, central N. D.
Modified *Crassatella*-*Nucula*	:	Not restricted in distribution	
Ophiomorpha-Crab-Driftwood-Shark Teeth	:	Not restricted in distribution	

The stratigraphic distribution does not appear to be the result of faunal community succession, but, rather due to environmentally controlling factors. These factors include salinity, water energy, substratum character, food availability, oxygen, and sedimentation rates.

During the time of deposition of the Cannonball Formation, there were at least two major transgressions and regressions. It seems likely, commensurate with the associations proposed, that deposition of the lower and upper tongues of the Cannonball Formation in southwestern North Dakota can be correlated with two major transgressive events in central North Dakota.

APPENDICES

APPENDIX I

CANNONBALL FOSSIL OCCURRENCE LOCALITIES

The locality descriptions in this appendix have documented fossil occurrence and were used in this study as data for cluster analyses. These localities are primarily from Cvancara (1965, Appendix C) who compiled a list of Cannonball fossil localities from both his collections and collecting localities reported by the United States Geological Survey. In addition, several fossil localities reported by Van Alstine (1974, Appendix I) were also used as data and are included in this appendix.

The following example will serve to explain the numbering of the localities in this appendix:

4. (7) *(27) T137N-R88W-28aaa;

4. The locality number used in this study. These localities are shown in Fig. 2 by their corresponding number.

(7) The Cannonball fossil locality number used by Cvancara (1965, Appendix C).

*(27) The locality corresponds to a described measured section by Cvancara (1965, Appendix A).

T137N-R88W-28aaa; the legal description of the locality. This numbering system is that used by the North Dakota State Water Commission and is based on the location in the public land classification of the United States Bureau of Land Management. T137N refers to the township north of the base line; R77W refers to the range west of the fifth principal meridian; 28 refers to the section number. The letters a, b, c, and d designate, respectively, the northeast, northwest, southwest, and southeast quarter sections, quarter-quarter sections, and quarter-quarter-quarter sections. In this example, 28aaa is in the NE¼NE¼NE¼ Sec. 28.

Those Cannonball fossil localities reported by the United States Geological Survey are indicated by the U.S.G.S. number in parentheses at the end of the locality description, for example, (U.S.G.S. 4892).

Those localities resampled by the author for this study are indicated in the description by including the University of North Dakota accession numbers of the fossil samples. Additional accession numbers of fossil samples from these localities (primarily those from the University of Michigan assigned by Cvancara, 1965) can be found by referring to Cvancara (1965, Appendix C).

The occurrence of specific macrofossils at each locality is given by Cvancara (1965, Appendix B).

1. (1) T153N-R79W-2abc; about 6.5 miles (10.5 km) northeast of Velva, southern McHenry Co., N. Dak. Small road-cut exposure on north side of gravel road. Fossils collected from well-indurated, very fine-grained sandstone bed (up to 2 feet or 0.6 m thick) at top of road cut.

2. (2) T153N-R79W-18cdb; 0.35 mile (0.6 km) northeast of southwest corner sec. 18, about 2.6 miles (4.2 km) east-northeast of Velva, southern McHenry Co., N. Dak. Road-cut exposure on southeast side of gravel road. Fossils collected from light green to tan gray clayey, poorly-consolidated sandstone, the top of which is about 2 feet (0.6 m) above the surface of gravel road.

3. (5) T143N-R73W-18dad; 0.35 mile (0.6 km) north of southeast corner sec. 18, about 4.5 miles (7.2 km) north-northeast of Tuttle, northern Kidder Co., N. Dak. Road-cut exposure on west side of N. Dak. Highway 3. Fossils collected from light grayish tan to sandy mudstone, about at level even with top of road and also about 5 feet (1.5 m) above road level.

4. (7) *(27) T137N-R77W-28aaa; 5 miles (8.0 km) west and 1.1 miles (1.8 km) south of Moffit, southern Burleigh Co., N. Dak. Road-cut exposure (sand blow-out) on west side of gravel road. Fossils collected from light greenish gray, poorly-consolidated, fine-grained sandstone in upper part of exposure.

5. (8) T137N-R77W-20dad; 0.7 mile (1.1 km) south of northeast corner sec. 20, 6 miles (9.7 km) west and 0.7 mile (1.1 km) south of Moffit, southern Burleigh Co., N. Dak. Road-cut exposures on both sides of gravel road, on sec. line common to secs. 20 and 21. Fossils collected from surface of light greenish gray, poorly-consolidated, fine-grained sandstone.

6. (9) T137N-R77W-28bbb; 6 miles (9.7 km) west and 1.1 miles (1.8 km) south of Moffit, southern Burleigh Co., N. Dak. Road-cut exposure on both sides of gravel road, on sec. line common to secs. 28 and 29. Fossils collected from surface of light greenish gray, poorly-consolidated, fine-grained sandstone.

7. (11) *(29) T138N-R81W-13bda; about 4.25 miles (6.8 km) south of Mancan, northeastern Morton Co., N. Dak. (about 0.5 mile or 0.8 km northwest of mouth of Heart River). East-facing, steep road-cut exposure, west side of Highway 1806. Fossils collected from light grayish green, poorly-consolidated, fine-grained sandstone at top of exposure. Univ. of N. Dak. accession number A2543.

8. (12) T139N-R80W-32bba; about 1.6 miles (2.6 km) northwest of junction U.S. highways 10 and 83 (0.4 mile or 0.6 km east of Bismarck Junior College), southern Burleigh Co., N. Dak. Road-cut exposure on south side of gravel road. Fossils collected from surface of light grayish green, poorly-consolidated, fine-grained sandstone.

9. (13) *(32) T139N-R80W-31aab; 2.1 miles (3.4 km) northwest of junction of U.S. highways 10 and 83 (about 0.25 mile or 0.4 km west-northwest of Bismarck Junior College), southern Burleigh Co., N. Dak. South-southwest facing man-made exposure, north side of small gully. Fossils collected from surface of light grayish green, poorly-consolidated, fine-grained sandstone.

10. (15) T139N-R81W-27bca; just west of courthouse, Mandan, northeastern Morton Co., N. Dak. Near top of a hill. (U.S.G.S. 9121)

11. (16) T139N-R81W-28b; 0.75 mile (1.2 km) west of Mandan, northeastern Morton Co., N. Dak. Bluff on north side of Heart River, 125 feet (38 m) above river level. (U.S.G.S. 9122; considered also about the same as U.S.G.S. 9120.)

12. (18) T140N-R81W-16a(?); about 1 mile (1.6 km) north of Harmon (about 10.5 miles or 16.9 km north of center of Mandan, northeastern Morton Co., N. Dak. East bank of Missouri River. (U.S.G.S. 16011 and also considered about the same as U.S.G.S. 16012.)

13. (19) *(33) T141N-R81W-12dda; about 9 miles (14.5 km) southwest of Wilton, northern Burleigh Co., N. Dak. West-facing cutbank exposure, east (left) bank of Missouri River (just south of east-west trending gully. Fossils collected from light grayish green, poorly-consolidated, fine-grained, 20.9 foot (6.4 m) sandstone in lower middle part of section.

14. (20) T142N-R81W-34d; about 1 mile (1.6 km) south of Price, Oliver Co., N. Dak. East-facing cutbank exposure, west (right) bank of Missouri River. (Same as U.S.G.S. 9126 and U.S.G.S. 15996.)

15. (22) *(31) T139N-R82W-23dda; 4.65 miles (7.5 km) west of railway station, center of Mandan, northeastern Morton Co., N. Dak. High road-cut exposure (slide area), north side of U.S. Highway 10. Fossils collected from poorly-consolidated, light greenish gray, fine-grained sandstone in upper part of section.

16. (22) *(31) Same as locality 15. Fossils collected from sandy mudstone in lower part of section. Univ. of N. Dak. accession numbers A2549 and A2550.

17. (23) T139N-R82W-34daa; about 5.75 miles (9.3 km) west-southwest of center of Mandan, northeastern Morton Co., N. Dak. Very small (about 7 by 10 yards or 6.4 by 9.1 m), south-facing blow-out exposure on north side of east-west trending gully. Fossils collected on surface of light grayish green, poorly-consolidated, fine-grained sandstone.

18. (24) T139N-R82W-34cac; about 6.5 miles (10.5 km) west-southwest of center of Mandan, northeastern Morton Co., N. Dak. West-facing cutbank exposure, east (right) bank of Heart River. Fossils collected from upper part of exposure from very fine to fine-grained, poorly-consolidated sandstone with well-indurated lenticular sandstone.

19. (25) T139N-R82W-20(?); probably about 8 miles (12.9 km) west of Mandan, northeastern Morton Co., N. Dak. (U.S.G.S. 9144)

20. (26) T139N-R83W-33aad; about 0.5 mile (0.8 km) south of Sweet Briar (about 11.5 miles or 18.5 km west of Mandan), northeastern Morton Co., N. Dak. East-facing cutbank exposure, west (right) bank of Sweet Briar Creek. Fossils collected from mottled dark gray and grayish tan poorly-consolidated, silty to sandy mudstone about 8.5 feet (2.6 m) below top of exposure.

21. (27) *(30) T138N-R83W-10dda; about 12 miles (19.3 km) west-southwest of Mandan, northeastern Morton Co., N. Dak. South-facing cutbank exposure, north (left) bank of Heart River. Fossils collected from light grayish green, fine-grained sandstone underlying 50 foot (15.2 m) mudstone at top of section. (About the same as U.S.G.S. 9143.)

22. (27) *(30) Same locality as 21. Fossils collected from light grayish to greenish tan, fine-grained sandstone in upper part of 54 foot (16.5 m), poorly-consolidated sandstone near middle part of section. Univ. of N. Dak. accession number A2563.

23. (28) T136N-R83W-13acc; about 7 miles (11.3 km) west-southwest of St. Anthony, southern Morton Co., N. Dak. Southwest-facing sand blowout exposure in pasture, east side of north-south trending gully. Fossils collected from surface of light grayish green, poorly-consolidated, fine-grained sandstone.

24. (29) T136N-R82W-18bbc; about 6.75 miles (10.9 km) west-southwest of St. Anthony, southern Morton Co., N. Dak. Road-cut exposure on east side of gravel road (0.25 mile or 0.4 km south of northwest corner sec. 18). Fossils collected from light grayish green, poorly-consolidated, very fine-grained sandstone. Univ. of N. Dak. accession numbers A2544, A2545 and A2551, A2552.

25. (30) T136N-R82W-20a; 3 miles (4.9 km) southeast of Old Strain (5.25 miles or 8.4 km west-southwest of St. Anthony), southern Morton Co., N. Dak. (U.S.G.S. 8454)

26. (31) T136N-R82W-21dac; 5 miles (8 km) southeast of Old Strain (about 4.5 miles or 7.2 km southwest of St. Anthony), southern Morton Co., N. Dak. (U.S.G.S. 8455 and 8456)

27. (32) T136N-R82W-27b; 5 miles (8 km) southeast of Old Strain (about 4.5 miles or 7.2 km southwest of St. Anthony), southern Morton Co., N. Dak. (U.S.G.S. 8456)

28. (33) T136N-R81W-17ccb; 1.8 mile (2.9 km) south of St. Anthony, southern Morton Co., N. Dak. Road-cut exposure on east edge of N. Dak. Highway 6.

29. (34) T136N-R81W-29cbb; 3.5 miles (5.6 km) south of St. Anthony, southern Morton Co., N. Dak. Road-cut exposures on both sides of N. Dak. Highway 6, on sec. line common to secs. 29 and 30 and on east-west half section line (secs. 29 and 30). Fossils collected from light grayish green, poorly-consolidated, fine-grained sandstone.

30. (35) T136N-R81W-31ccd; about 5 miles (8 km) south of St. Anthony, southern Morton Co., N. Dak. Small north-northwest-west-facing hillside exposure near top of flat upland in pasture. Fossils collected from light grayish green, poorly-consolidated, fine-grained sandstone.

31. (36) T135N-R81W-6daa; about 5.5 miles (8.9 km) south of St. Anthony, southern Morton Co., N. Dak. Road-cut exposure on east side of N. Dak. Highway 6.

32. (37) T132N-R82W-1aad; about 5.25 miles (8.4 km) south of St. Anthony, southern Morton Co., N. Dak. Small, isolated hill exposure on west side of road (0.25 mile or 0.4 km south of northeast corner sec. 1).

33. (38)*(23) T135N-R82W-36aab; 0.2 mile (0.3 km) west of junction N. Dak. Highways 6 and 21, about 6.25 miles (10.1 km) north of Breien, southern Morton Co., N. Dak. Northeast-facing hillside exposure in pasture, south side of N. Dak. Highway 21. Fossils collected from medium greenish gray, poorly-consolidated, fine-grained sandstone. Univ. of N. Dak. accession number A2546.

34. (39) T134N-R81W-5(?); about 6 miles (9.7 km) northwest of Solen, southern Morton Co., N. Dak. Top of flat-topped butte. (U.S.G.S. 9129)

35. (40) T134N-R81W-3dbc; about 5 miles (8 km) northwest of Solen, southern Morton Co., N. Dak. Near top of elongate, flat-topped hill trending north-northeast. Fossils collected from light greenish gray, poorly-consolidated, fine-grained sandstone in upper part of exposed section.

36. (41) T134N-R81W-36(?); about 8 miles (12.9 km) northwest of Solen, southern Morton Co., N. Dak. (U.S.G.S. 8448)

37. (42) T134N-R81W-17b; about 7 miles (11.3 km) northwest of Solen, southern Morton Co., N. Dak. Around border of high plateau. (U.S.G.S. 8446)

38. (43) *(25) T131N-R82W-13cca; about 8.5 miles (13.7 km) north-northeast of Selfridge, eastern Sioux Co., N. Dak. East-facing landslide exposure. Fossils collected from light grayish green, poorly-consolidated, fine-grained sandstone in upper part of section.

39. (44) *(21) T134N-R83W-7cda; about 3.25 miles (5.2 km) east-southeast of Flasher, southern Morton Co., N. Dak. Fossils collected from light greenish gray, poorly-consolidated, fine-grained sandstone in upper part of section, Mitchell Butte.

40. (44a) T134N-R83W-31aba; about 6 miles (9.7 km) southeast of Flasher, southern Morton Co., N. Dak. (U.S.G.S. 8387)

41. (45) T134N-R83W-3ddd; about 6 miles (9.7 km) east of Flasher, southern Morton Co., N. Dak. (U.S.G.S. 8445)

42. (47) T134N-R83W-4bbc; about 5 miles (8 km) east of Flasher, southern Morton Co., N. Dak. South-facing hillside exposure, north side of N. Dak. Highway 21. Fossils collected from small, light grayish brown, sandstone concretions mainly on upper part of hillside.

43. (48) T135N-R83W-32ddd; about 4.75 miles (7.6 km) east of Flasher, southern Morton Co., N. Dak. South and southwest-facing hillside exposure, north side of N. Dak. Highway 21. Fossils collected from small, light grayish brown, sandstone concretions mainly in upper part of hillside exposure.

44. (49) T135N-R83W-34cbd; about 6 miles (9.7 km) east of Flasher, southern Morton Co., N. Dak. Two road-cut exposures, south side of N. Dak. Highway 21. Fossils collected from surface of light grayish green, poorly-consolidated, fine-grained sandstone.

45. (50) T134N-R83W-3aaa; about 6 miles (9.7 km) east of Flasher, southern Morton Co., N. Dak. (U.S.G.S. 8444)

46. (51) *(22) T135N-R83W-26cb; about 2.5 miles (4.0 km) south of Fallon (about 7 miles or 11.3 km east-northeast of Flasher), southern Morton Co., N. Dak. Six road-cut exposures on both sides of gravel road along section common to secs. 26 and 27. Fossils collected from light greenish gray, poorly-consolidated, very fine-grained sandstone in upper part of section.

47. (52) T135N-R83W-22aad; 1.2 miles (1.9 km) south of Fallon (about 7.25 miles or 11.7 km east-northeast of Flasher), southern Morton Co., N. Dak. Road-cut exposure on west side of gravel road (0.2 mile or 0.3 km south of northeast corner sec. 22). Fossils collected from light greenish gray, poorly-consolidated, very fine-grained sandstone.

48. (58) T137N-R83W-6cc; about 17.5 miles (28.2 km) southwest of center of Mandan, northeastern Morton Co., N. Dak. (U.S.G.S. 9141)

49. (59) T136N-R84W-8bdd; about 11 miles (17.7 km) north of Flasher, southern Morton Co., N. Dak. West bluff of Heart River. (U.S.G.S. 8450)

50. (60) T136N-R84W-16c; about 10 miles (16.1 km) north of Flasher, southern Morton Co., N. Dak. (U.S.G.S. 8451)

51. (62) T136N-R85W-16bcb; about 10 miles (16.1 km) north of Lark, northern Grant Co., N. Dak. Road-cut exposures on both sides of road, on north one-half of section line common to secs. 16 and 17. (U.S.G.S. 15992)

52. (63) *(18) T136N-R86W-21aab; about 10 miles (16.1 km) south of Almont (northwestern Morton Co.) or about 12 miles (19.3 km) north-northeast of Carson, northern Grant Co., N. Dak. West-facing cutbank exposure, east (right) bank of Heart River. Fossils collected from dark gray to dark green, poorly-consolidated, clayey, very fine-grained sandstone near base of section.

53. (64) *(19) T136N-R86W-21dbc; about 10.5 miles (16.9 km) south of Almont (northwestern Morton Co.), or about 11.5 miles (18.5 km) north-northeast of Carson, northern Grant Co., N. Dak. West-facing cutbank exposure, east (right) bank of Heart River, near center of sec. 21. Fossils collected from dark gray to green, poorly-consolidated, clayey, very fine-grained sandstone near base of exposure.

54. (65) T136N-R86W-29ada; about 12 miles (19.3 km) south of Almont, northern Grant Co., N. Dak. East bluff of Heart River. (U.S.G.S. 8459)

55. (66) T136N-R86W-20ccd; about 12 miles (19.3 km) south of Almont, northern Grant Co., N. Dak. Northwest bluff of Heart River. (U.S.G.S. 8460)

56. (67) T136N-R87W-21cab; about 11.5 miles (18.5 km) north-northwest of Carson, northern Grant Co., N. Dak. South-facing cutbank exposure, north (left) bank of Heart River. Fossils collected mainly from dark gray, poorly-consolidated, sandy mudstone in lower part of exposure.

57. (68) T136N-R87W-19cdb; about 17 miles (27.4 km) southwest of Almont (northwestern Morton Co.), northern Grant Co., N. Dak. North bluff of Heart River. (U.S.G.S. 8463)

58. (69) T136N-R88W-24cca; about 19 miles (30.6 km) southwest of Almont (northwestern Morton Co.), northern Grant Co., N. Dak. Heart River. (U.S.G.S. 8464)

59. (70) *(16) T136N-R88W-16daa; about 14 miles (22.5 km) north-northeast of Elgin, northern Grant Co., N. Dak. West-southwest facing cutbank exposure, east (left) bank of Heart Butte Creek, just north of where it enters Heart River. Fossils collected from dark gray, poorly-consolidated, sandy mudstone in lower part of section.

60. (71) T135N-R85W-19ddd; about 2.5 miles (4.0 km) north of Lark, northern Grant Co., N. Dak. (U.S.G.S. 8447)

61. (72) T134N-R86W-15cac; about 4 miles (6.4 km) southwest of Lark, northern Grant Co., N. Dak. Railroad cut on Northern Pacific Railway. (U.S.G.S. 8388)

62. (73) T133N-R85W-9dba; about 3 miles (4.8 km) west-southwest of Raleigh, southern Grant Co., N. Dak. Railroad cut. (U.S.G.S. 8385 and probably about the same as U.S.G.S. 8386.)

63. (74) T132N-R85W-22bbb; about 1 mile (1.6 km) west of site of former Schaller Post Office, about 7.5 miles (12.1 km) south of Raleigh, southern Grant Co., N. Dak. (U.S.G.S. 8384)

64. (77) T132N-R87W-33bad; about 10 miles (16.1 km) south-southwest of Leith, southern Grant Co., N. Dak. West-facing cutbank exposure, east (right) bank of Cannonball River. Fossils collected as float.

65. (80) *(5) T132N-R87W-19bbd; about 7.75 miles (12.5 km) south of Leith, southern Grant Co., N. Dak. East-facing cutbank exposure, west (right) bank of former channel of Cannonball River. Fossils collected from 4 foot (1.2 m), medium grayish brown,

poorly consolidated, sandy mudstone, 85 feet (25.9 m) below top of section. Univ. of N. Dak. accession number A2559.

66. (81) T132N-R87W-18ccb; about 7.25 miles (11.7 km) south of Leith, southern Grant Co., N. Dak. North-facing cutbank exposure, south (right) bank of Cannonball River. (U.S.G.S. 7968 and U.S.G.S. 8378)

67. (82) T132N-R88W-11dda; about 6.5 miles (10.5 km) south of Leith, southern Grant Co., N. Dak. East of bridge across Cannonball River on road south of Leith. (U.S.G.S. 15998)

68. (83) *(6) T132N-R88W-11bbd; about 6 miles (9.7 km) south of Leith, southern Grant Co., N. Dak. South-facing bluff exposure, north side of Cannonball River (about a mile north of the river). Fossils collected from dark gray, poorly-consolidated, sandy mudstone and its contained dark gray limestone concretions in middle of section, and from poorly-consolidated, very fine to fine-grained sandstone and its contained concretions in lower part of section. Univ. of N. Dak. accession number A2562.

69. (84) *(7) T132N-R88W-5dca; about 6.5 miles (10.5 km) south-southwest of Leith, southern Grant Co., N. Dak. North-facing cutbank exposure, south (right) bank of Cannonball River. Fossils collected from dark gray, poorly-consolidated, sandy mudstone in lower part of exposure.

70. (85) T132N-R88W-5cab; about 9 miles (14.5 km) southwest of Leith, southern Grant Co., N. Dak. West bank of Cannonball River. (U.S.G.S. 7961)

71. (86) *(8) T133N-R88W-34abc; about 6 miles (9.7 km) southwest of Leith, southern Grant Co., N. Dak. Northwest-facing cutbank exposure, east (right) bank of Cannonball River. Fossils collected from lower part of light grayish green, poorly-consolidated, very fine to fine-grained, clayey sandstone in upper part of section, and from medium greenish gray concretions below in dark gray, poorly consolidated, sandy mudstone.

72. (87) T133N-R88W-26dcc; about 5.25 miles (8.4 km) southwest of Leith, southern Grant Co., N. Dak. West-facing cutbank exposure, east (left) bank of Cannonball River. Fossils collected from light grayish green, poorly-consolidated, fine-grained sandstone near top of exposure.

73. (88) T133N-R88W-26cbb; about 5.25 miles (8.4 km) southwest of Leith, southern Grant Co., N. Dak. West-facing cutbank exposure, east (left) bank of Cannonball River. Fossils collected mainly from light grayish green, poorly-consolidated, fine-grained sandstone and its contained indurated lenticular sandstone, in upper part of exposure; fossils also collected from dark gray, poorly-consolidated, sandy mudstone directly below.

74. (89) T133N-R88W-28dbd; about 6.5 miles (10.5 km) southwest of Leith, southern Grant Co., N. Dak. South and southwest-facing cutbank exposure, north (left) bank of Cannonball River. Fossils collected from medium to dark greenish gray, poorly-consolidated clayey sandstone in lower part of exposure.

75. (90) *(9) T133N-R88W-28ccd; about 6 miles (9.7 km) southwest of Leith, southern Grant Co., N. Dak. North-facing cutbank exposure, south (right) bank of Cannonball River. Fossils collected from almost throughout section, but occur mainly in dark grayish green, poorly-consolidated, clayey, fine-grained sandstone in lower middle part of section. Univ. of N. Dak. accession numbers A2553, A2554.

76. (91) *(10) T133N-R88W-29dad; about 6.25 miles (10.1 km) southwest of Leith, southern Grant Co., N. Dak. North-facing cutbank exposure, south (right) bank of Cannonball River. Fossils collected from dark grayish green, poorly-consolidated, clayey, fine-grained sandstone in lower part of exposure. Univ. of N. Dak. accession numbers A2555 and A2556.

77. (92) *(11) T133N-R88W-29dbb; about 6.25 miles (10.1 km) southwest of Leith, southern Grant Co., N. Dak. South-southeast-facing cutbank exposure, north (left) bank of Cannonball River. Fossils collected from dark grayish green, poorly-consolidated, clayey, fine-grained sandstone at about middle of section. Univ. of N. Dak. accession numbers A2557 and A2558.

78. (93) T133N-R88W-32ab; about 6 miles (9.7 km) south of former Kayser or probably about 7 miles (11.3 km) southwest of Leith, southern Grant Co., N. Dak. (U.S.G.S. 7965 and possibly U.S.G.S. 8377)

79. (94) T133N-R88W-31; about 6 miles (9.7 km) south of former Kayser or about 8 miles (12.9 km) southwest of Leith, southern Grant Co., N. Dak. (U.S.G.S. 7964)

80. (95) T133N-R88W-29c; about 6 miles (9.7 km) south of former Kayser or about 7.75 miles (12.5 km) southwest of Leith, southern Grant Co., N. Dak. (U.S.G.S. 8382)

81. (96) *(13) T133N-R88W-29baa; about 6 miles (9.7 km) southwest of Leith, southern Grant Co., N. Dak. West-facing cutbank exposure, east (left) bank of Cannonball River, about on sec. line common to secs. 20 and 29. Fossils collected from mottled, light grayish green and dark gray, silty mudstone or siltstone in upper part of section.

82. (97) T133N-R88W-17ccb; about 5 miles (8.0 km) southeast of former Kayser or about 7 miles (11.3 km) west-southwest of Leith, southern Grant Co., N. Dak. Bluff on Cannonball River. (U.S.G.S. 7962)

83. (98) *(15) T133N-R89W-2bca; about 2.5 miles (4.0 km) south of Elgin (and about 0.25 mile or 0.4 km north of Cannonball River), southern Grant Co., N. Dak. Road-cut exposure on northeast side of gravel road. Fossils collected from light grayish green, poorly-consolidated, very fine to fine-grained sandstone in upper middle part of section.

84. (99) T130N-R88W-30cdd; about 7 miles (11.3 km) north of Morristown (Corson Co., S. Dak.), southern Grant Co., N. Dak. Top of bluff. (U.S.G.S. 8468)

85. (101) T130N-R89W-21ccc; about 23 miles (37 km) south of Elgin (about 2 miles or 3.2 km north of Cedar Creek), southern Grant Co., N. Dak. Road-cut exposure on east side of road.

86. (103) T130N-R90W-12a; about 21 miles (33.8 km) south of Elgin (also about 4 miles or 6.4 km southwest of Pretty Rock Butte and about 2 miles or 3.2 km north of Cedar Creek). (U.S.G.S. 7970)

87. (104) *(2) T130N-R90W-9bbd; about 11.25 miles (18.1 km) north of Thunderhawk (Corson Co., S. Dak.), southern Grant Co., N. Dak. West-facing cutbank in pasture, east (left) bank of Timber Creek. Fossils collected from medium grayish green, poorly-consolidated, very fine to fine-grained sandstone at top of exposure and greenish gray sandy mudstone at base of exposure. (U.S.G.S. 7969) Univ. of N. Dak. accession numbers A2560, A2561 and A2547, A2548

88. (105) T130N-R90W-21bbb; about 9.25 miles (14.9 km) north of Thunderhawk (Corson Co., S. Dak.), southern Grant Co., N. Dak. Small road-cut exposure, east side of gravel road (0.25 mile or 0.4 km south of northwest corner of sec. 21). Fossils collected from both poorly-consolidated and well-indurated, gray, sandy mudstone and underlying medium grayish green, poorly-consolidated, fine-grained sandstone.

89. (106) T130N-R90W-32; about 7 miles (11.3 km) north of Thunderhawk (Corson Co., S. Dak.), western Sioux Co., N. Dak. Road-cut exposures on both sides of road, on section line common to secs. 32 and 33.

90. (107) T129N-R90W-5; about 6 miles (9.7 km) north of Thunderhawk (Corson Co., S. Dak.), western Sioux Co., N. Dak. Continuous road-cut exposure on west side of road.

91. (109) T23N-R9E-24dbb; about 11 miles (17.7 km) south of Reeder (Adams Co., N. Dak.), northern Harding Co., S. Dak. North-facing cutbank exposure, south (right) bank of North Fork Grand River, about on north-south half section line of sec. 24. Fossils collected from poorly-consolidated, very fine-grained sandstone (interbedded with dark gray mudstone), about 35 feet (10.7 m) above river level. (U.S.G.S. 7976)

92. (110) T129N-R99W-36ccc; about 5 miles (8 km) east-southeast of Haley, Bowman Co., N. Dak. North bank of North Fork Grand River. (U.S.G.S. 7974)

93. (111) T129N-R100W-22cbc; about 3 miles (4.8 km) west-northwest of Haley, Bowman Co., N. Dak. South-facing hillside exposure (south end of flat-topped hill). Fossils collected from light greenish tan (probably weathered), poorly-consolidated, very fine to fine-grained sandstone, about 6 feet (1.8 m) below top of hill.

94. (112) T129N-R100W-21cc; 12 miles (19.3 km) south and 3.5 miles (5.6 km) west of Scranton (or about 4 miles or 6.4 km west of Haley), Bowman Co., N. Dak. At quarter corner common to secs. 21 and 28. (U.S.G.S. 7975)

95. Van Alstine (1974, p. 13) fossil collecting locality 4, measured section 3, T135N-R105W-1ad; about 17.9 miles (28.8 km) north-northeast of Marmarth, Slope Co., N. Dak. East-facing cutbank exposure, east side of Little Missouri River.

96. (114) *(1) T135N-R105W-10ccd; about 15 miles (24.1 km) north-northeast of Marmarth, Slope Co., N. Dak. Southwest-facing hillside exposure, west side of Little Missouri River (about 0.5 mile or 0.8 km west of river) and east side of auto trail. Fossils collected from brownish black shale directly above 2 foot (0.6 m) thick lignite in lower part of section and also from brownish gray shale about 9.5 feet (2.9 m) above the same lignite. Univ. of N. Dak. accession number A2565.

97. Van Alstine (1974, p. 13) fossil collecting locality 5, measured section 4, T135N-R105W-14ca; about 14.4 miles (23.2 km) north-northeast of Marmarth, Slope Co., N. Dak. Northwest-facing cutbank exposure, east side of Little Missouri River. Univ. of N. Dak. accession number A2564.

APPENDIX II

SUMMARY OF CANNONBALL FOSSIL LOCALITIES EXAMINED FOR THIS STUDY

All localities in this appendix are shown in Fig. 2 by their corresponding number. An explanation of the locality legal description is given in Appendix I.

Locality 7

East-facing roadcut exposure, west side of Highway 1806, T138N-R81W-13bda; 0.5 mile (0.8 km) northwest of mouth of Heart River and about 4.25 miles (6.8 km) south of Mandan, northeastern Morton Co., N. Dak. Site of measured section 29 (Cvancara 1965, p. 332-335). Univ. of N. Dak. accession number A2543, R. Lindholm, July 23, 1982. Fossils collected from poorly-consolidated, fine-grained sandstone at top of exposure.

Area of Collection: Approximately 323 sq feet (30 sq m)

Rock samples:	7A, collected from sandstone 18.0 feet (5.5 m) below top of exposure
	7B, collected from sandstone 3.3 feet (1.0 m) below top of exposure
	7C, collected from nonfossiliferous mudstone at base of exposure

Rock color:

Weathered:	Pale yellowish orange (10 YR 8/6)
Fresh:	Dark yellowish orange (10 YR 6/6)

Collecting time: 3 hours

Locality 16

South-facing road-cut exposure, north side U.S. Highway 10 and north side of Heart River, T139N-R82W-23dda; 4.7 miles (7.5 km) west-northwest center Mandan, northeastern Morton Co., N. Dak. Site of measured section 31 (Cvancara 1965, p. 342-345). Univ. of N. Dak. accession number A2549, A. M. Cvancara, July 29, 1979, and A2550, R. Lindholm, August 1, 1982. Fossils collected from sandy mudstone near base of exposure.

Area of Collection: Height: 10.2 feet (3.1 m)
Length: 142.7 feet (43.5 m)

Area: 1,455.5 sq ft (135.0 sq m)

Rock samples: 16A, collected 2.6 feet (0.8 m) above base of unit
16B, collected 9.8 feet (3.0 m) above base of unit

Rock color:

Weathered: Light olive gray (5 Y 6/1)
Fresh: Brownish gray to olive gray (5 YR 4/1 to 5 Y 4/1)

Collecting time: A2549, 20 minutes
A2550, 3 hours

Locality 22

South-facing cutbank exposure, north bank of Heart River, T138N-R83W-10dda; approximately 3.5 miles (5.6 km) south-southeast of Sweet Briar or about 12 miles (19.3 km) west-southwest of Mandan, northeastern Morton County, N. Dak. Site of measured section 30 (Cvancara 1965, p. 335-342). Univ. of N. Dak. accession number A2563, R. Lindholm, September 5, 1982. Fossils collected from muddy green, fine-grained sandstone in upper part of poorly-consolidated sandstone near middle part of section.

Area of Collection: Height: 4.9 feet (1.5 m)
Length: 43.6 feet (13.3 m)

Area: 213.8 sq ft (20 sq m)

Rock sample: 22, collected 3.3 feet (1.0 m) above base of fossiliferous green sand unit

Rock color:

Weathered: Yellowish gray (5 Y 7/2)
Fresh: Olive gray (5 Y 3/2)

Collecting time: 1.5 hour

Locality 24

West-facing road-cut exposure on east side of gravel road, T136N-R82W-18bbc; 6.75 miles (10.9 km) west-southwest of St. Anthony, southern Morton County, N. Dak. Univ. of N. Dak. accession numbers A2544 and A2551, A. M. Cvancara, July 21, 1979 and A2545 and A2552, R. Lindholm, July 22, 1982. Fossils collected from muddy sandstone at base of exposure (A2551 and A2552) and from clean sandstone in upper part of exposure (A2544 and A2545).

Area of Collection: A2544 and A2545: 1,528 sq feet (142 sq m)
A2551 and A2552: 538 sq. feet (50 sq m)

Rock samples: 24A, collected from muddy sandstone 1.6 feet (0.5 m) above ground level
24B, collected from clean sandstone 3.3 feet (1.0 m) above contact with underlying muddy sandstone unit

Rock color:

A2544 and A2545: Weathered: Pale yellowish orange to dark yellowish orange (10 YR 8/6 to 10 YR 6/6)
Fresh: Moderate yellowish brown (10 YR 5/4)
A2551 and A2552: Weathered: Yellowish gray to light olive gray (5 Y 7/2 to 5 Y 5/2)
Fresh: Light olive gray to grayish brown (5 Y 5/2 to 5 YR 3/2)

Collecting time: A2544 and A2551, 30 minutes
A2545 and A2552, 3.5 hours

Locality 33

Northeast-facing exposure in pasture on south side of N. Dak. Highway 21, T135N-R82W-36aab; 0.2 mile (0.3 km) west of junction of N. Dak. Highways 21 and 6, approximately 6 miles (10 km) north of Breien, southern Morton Co., N. Dak. Site of measured section 23 (Cvancara, 1965, p. 315-317). Univ. of N. Dak. accession number A2546, R. Lindholm, August 2, 1982. Fossils collected from sandstone unit exposed in pasture.

Area of Collection: 1,303.5 sq feet (121.0 sq m)

Rock sample: 33, collected 7.5 feet (2.3 m) above base of unit

Rock color:

Weathered: Pale yellowish orange to grayish yellow (10 YR 8/6 to 5 Y 8/4)
Fresh: Moderate yellowish brown (10 YR 5/4)

Collecting time: 3 hours

Locality 65

East-facing cutbank exposure, west bank of former channel of Cannonball River, T132N-R87W-19bbd; approximately 7.75 miles (12.5 km) south of Leith, southern Grant Co., N. Dak. Site of measured section 5 (Cvancara, 1965, p. 267-270). Univ. of N. Dak accession number A2559, R. Lindholm and A. M. Cvancara, July 20, 1982. Fossils collected from muddy sandstone approximately 60 feet (18 m) above level of former channel of Cannonball River.

Note: Due to the deteriorated condition of the bivalve Isognomon (the only macrofossil observed), no quantitative collection was attempted. Instead, shells were counted using a line-intercept method.

Shell concentration: 34 / 16.4 foot (5 m) exposure, or approximately 2 shells / foot (7 shells / m) (upper zone)

17 / 16.4 foot (5 m) exposure, or approximately 1 shell / foot (3.4 shells / m) (lower zone)

Rock sample: 65, collected 0.8 feet (0.25 m) above base of contact between Isognomon sand and underlying sandstone.

Rock color:

Weathered: Light olive gray to yellowish gray (5 Y 5/2 to 5 Y 7/2)
Fresh: Brownish black to olive black (5 YR 2/1 to 5 Y 2/1)

Locality 68

South-facing bluff exposure, north side of Cannonball River (approximately 0.8 km north of river), T132N-R88W-11bbd; approximately 6 miles (9.7 km) south of Leith, southern Morton Co., N. Dak. Site of measured section 6 (Cvancara 1965, p. 270-273). Univ. of N. Dak. accession number A2562, R. Lindholm, September 5, 1982. Fossils occur in micrite concretions in upper part of mudstone unit in middle of section.

Note: No quantitative collection was made. Samples of the limestone concretions were collected 2 feet (0.6 m) below contact with overlying sandstone.

Rock sample: 68, collected 2.0 feet (0.6 m) below contact with overlying sandstone (rock enclosing limestone concretions)

Locality 75

North-facing cutbank exposure, south bank of Cannonball River, T133N-R88W-28ccd; approximately 6 miles (10 km) southwest of Leith, southern Grant Co., N. Dak. Site of measured section 9 (Cvancara, 1965, p. 277-280). Univ. of N. Dak. accession number A2553, A. M. Cvancara, July 24, 1979, and A2554, R. Lindholm, August 3, 1982. Fossils collected from muddy sandstone approximately 14.8 feet (4.5 m) above base level of Cannonball River.

Area of Collection:	Height:	4.3 feet	(1.3 m)
	Length:	11.5 feet	(3.5 m)
	Area	49.5 sq ft	(4.6 sq m)

Rock sample: 75, collected 16.4 feet (5.0 m) above base level of Cannonball River

Rock color:

Weathered: Light olive gray (5 Y 6/1)
Fresh: Olive gray (5 Y 4/1)

Collecting time: A2553, 1 hour
A2554, 1 hour

Locality 76

North-facing cutbank exposure, south bank of Cannonball River, T133N-R88W-29dad; approximately 6 miles (10 km) southwest of Leith, southern Grant Co., N. Dak. Site of measured section 10 (Cvancara, 1965, p. 280-283). Univ. of N. Dak. accession number A2555, A. M. Cvancara, July 24, 1979, and A2556, R. Lindholm and A. M. Cvancara, July 20, 1982. Fossils collected from muddy sandstone approximately 14.1 feet (4.3 m) above level of Cannonball River.

Area of Collection:

1) Height: 6.6 feet (2.0 m) (average of 3 measures)
   Length: 95.5 feet (29.1 m)
   Area: 630.3 sq ft (58.2 sq m)

2) Height: 5.9 feet (1.8 m) (average of 2 measures)
   Length: 34.4 feet (10.5 m)
   Area: 203.0 sq ft (18.9 sq m)
   TOTAL AREA: 833.3 sq ft (77.1 sq m)

Rock samples: 76A, collected 1.6 feet (0.5 m) below top of fossiliferous zone
76B, collected 1.6 feet (0.5 m) above bottom of fossiliferous zone

Rock color:

Weathered: Yellowish gray to light gray (5 Y 7/2 to 5 Y 6/1)
Fresh: Olive gray (5 Y 4/1)

Collecting time: A2555, 1 hour
A2556, 1.5 hours, 2 people

Locality 77

South-southeast-facing cutbank exposure, north bank of Cannonball River, T133N-R88W-29dbb; approximately 6 miles (10 km) southeast of center Leith, southern Grant Co., N. Dak. Site of measured section 11 (Cvancara, 1965, p. 283-285). Univ. of N. Dak. accession number A2557, A. M. Cvancara, July 24, 1979, and A2558, R. Lindholm, August 3, 1982. Fossils collected from a muddy sandstone approximately 9.8 feet (3.0 m) above base level of Cannonball River.

Area of Collection: Height: 3.3 feet (1.0 m)
Length: 375.0 feet (114.3 m)
Area: 1,237.5 sq ft (114.3 sq m)

Rock sample: 77, collected 2.1 feet (0.64 m) above base of fossiliferous unit

Rock color:

Weathered: Light olive gray (5 Y 6/1)
Fresh: Olive gray (5 Y 4/1)

Collecting time: A2557, 25 minutes
A2558, 2 hours

Locality 87

West-facing cutbank exposure, east bank of Timber Creek, T130N-R90W-9bbd; 0.2 mile (0.3 km) south of northwest corner sec. 9, approximately 11 miles (18 km) north of Thunderhawk (Corson Co., S. Dak.), southern Grant Co., N. Dak. Site of measured section 2 (Cvancara, 1965, p. 257-259). Univ. of N. Dak. accession numbers A2547 and A2560, A. M. Cvancara, July 25, 1979, and A2548 and A2561, R. Lindholm, August 4, 1982. Fossils collected from mudstone at base of exposure (A2560 and A2561) and from sandstone at top of exposure (A2547 and A2548).

Area of Collection:

1) Mudstone: Height: 4.3 feet (1.3 m)
Length: 95.1 feet (29.0 m)
Area: 408.9 sq ft (37.7 sq m)

2) Sandstone: Height: 4.9 feet (1.5 m)
Length: 83.7 feet (25.5 m)
Area: 410.1 sq ft (38.3 sq m)

Rock samples: 87A, collected from sandstone 12.5 feet (3.8 m) above contact with underlying mudstone unit
87B, collected from mudstone 4.3 feet (1.3 m) above base of exposure

Rock color: Mudstone:

Weathered: Olive gray (5 Y 4/1)
Fresh: Yellowish gray (5 Y 7/2)

Sandstone:

Weathered: Pale yellowish orange to dark yellowish orange (10 YR 8/6 to 10 YR 6/6)
Fresh: Dark yellowish orange to light brown (10 YR 6/6 to 5 YR 5/6)

Collecting time: A2547 and A2560, 55 minutes
A2548 and A2561, 1.5 hours

Locality 96

Southwest-facing hillside exposure, west side of Little Missouri River (0.5 mile or 0.8 km west of river), T135N-R105W-10ccd; approximately 15 miles (24 km) north-northeast of Marmarth, Slope Co., N. Dak. Site of measured section 1 (Cvancara, 1965, p. 250-257) and upper one-half of measured section 1 (Van Alstine, 1974, p. 71-77). Univ. of N. Dak. accession number A2565. Fossils collected from mudstone approximately 29.5 feet (9.0 m) from base of exposure and overlying first lignite (approximately 2.3 feet or 0.7 m thick) from base.

Note: Due to the extremely high concentration of the oyster Crassostrea in pods and discontinuous beds, and due to the deteriorated condition of the shells, the quadrat method was utilized to determine an average areal abundance.

Concentration of Shells: (Count taken from an oyster pod)

1 sq m: 153 single shells = 76 specimens

(Count taken from an oyster bed)

1 sq m: 196 single shells = 98 specimens

9.5 feet (2.9 m) above underlying lignite, the bivalves Corbula and Corbicula were collected.

Area of Collection:			
	Height:	11.5 feet	(3.5 m)
	Length:	57.4 feet	(17.5 m)
	Area:	660.1 sq ft	(61.3 sq m)

Rock samples: 96A, collected 0.5 feet (0.2 m) above lignite bed
96B, collected 1.3 feet (0.4 m) above lignite bed
96C, collected from surface where Corbula and Corbicula occur

Rock color:

Rocks enclosing the oyster pods and beds:

Weathered:	Dark gray (N 3)
Fresh:	Dark gray to black (N 3 to N 1)

Corbula-*Corbicula* rocks:

Weathered:	Yellowish gray to light olive gray (5 Y 8/1 to 5 Y 6/1)
Fresh:	Brownish black (5 YR 2/1)

Locality 97

Northwest-facing cutbank exposure, east side of Little Missouri River, T135N-R105W-14ca; approximately 14 miles (23 km) north-northeast of Marmarth, Slope Co., N. Dak. Site of measured section 4 (Van Alstine, 1974, p. 86-89). Univ. of N. Dak. accession number A2564, R. Lindholm and A. M. Cvancara, July 21, 1982. Fossils collected above T Cross lignite near base of exposure.

Area of Collection:	Height:	3.6 feet	(1.1 m)
	Length:	20.0 feet	(6.1 m)
	Area:	72.0 sq ft	(6.7 sq m)

Rock samples:
97A, collected 0.7 feet (0.2 m) above T Cross lignite
97B, collected 2.6 feet (0.8 m) above T Cross lignite
97C, collected 4.3 feet (1.3 m) above T Cross lignite

Rock color:

Weathered:	Light olive gray (5 Y 6/1)
Fresh:	Dark gray to black (N 3 to N 1)

Collecting time: 0.5 hour, 2 people

APPENDIX III

MACROFOSSIL COUNTS FROM FOSSIL LOCALITIES EXAMINED FOR THIS STUDY

Localities are described in detail in Appendix II and shown in Fig. 2 .

MACROFOSSIL COUNTS FROM SAMPLED LOCALITIES

Locality No.	7	16	16	22	24	24	24	24	33	65	68
Univ. of N. Dak. Accession No.	A2543	A2549	A2550	A2563	A2551	A2552	A2544	A2545	A2546	A2559	A2562
1. *Nucula planomarginata*	2						4+	2			No Quantitative Collection Made
2. *Cucullaea solenensis*	1										
3. *Glycymeris subimbricata*	6						4+	3+			
4. *Isognomon lloydi*										*	
5. *Crassostrea glabra*											
6. *Ostrea* sp.											
7. *Codakia*? (*Clairbornites*) *cedrensis*											
8. *Crassatella evansi*				+							
9. *Arctica ovata*	3+	2	2+	+	1+	3+	8+	5	4+		
10. *Corbicula berthoudi*											
11. *Dosiniopsis deweyi*	6	1		+	1+	2+		2	1		
12. *Corbula* (*Bicorbula*) *subtrigonalis*											
13. *Caestocorbula sinistrirostella*						1		1			
14. *Periploma* sp.											
15. Gastropods			+	+	4	7	2	9+	5+		
16. Shark teeth			4								
17. Corals		6	10								
18. *Ophiomorpha*	X										

	75	75	76	76	77	77	87	87	87	87	96	97
	A2553	A2554	A2555	A2556	A2557	A2558	A2547	A2548	A2560	A2561	A2565	A2564
1.			1			2+	1+			1+		
2.												
3.												
4.												
5.											*	
6.												33
7.				3								
8.	1+	1+	4	4+		2+	1	1				
9.						3+	+	+				
10.											53	6
11.						6						
12.											21	12
13.				1		2	1					
14.			7	1								
15.	**115+	**51+	**241+	**126+		**20+	17+	8+	***43+	***65+		
16.			1									
17.	2		3				4	4				
18.							X					

*	Present, areal counts are given in Appendix II
**	Primarily Aporrhaidae
***	Primarily Turritellidae
+	Fragments common
X	Present but not counted

APPENDIX IV

LOCALITIES OF MEASURED SECTIONS USED IN FIG. 16

The locality descriptions in this appendix correspond to the measured sections in Fig. 16. All sections are from Cvancara (1965). A detailed description of the measured sections is given by Cvancara (1965, Appendix A).

(1) West-facing cutbank exposure, east bank of Timber Creek, T130N-R90W-9bbd; 0.2 mile (0.3 km) south of northwest corner sec. 9, approximately 11 miles (18 km) north of Thunderhawk (Corson Co., S. Dak.), southern Grant Co., N. Dak. Site of measured section 2 (Cvancara, 1965, p. 257-259).

(2) West-facing cliff and cutbank exposure, east side of Cannonball River, T132N-R87W-36c; 11.5 miles (18.5 km) southeast of Leith, southern Grant Co., N. Dak. Site of measured section 3 (Cvancara, 1965, p. 259-264).

(3) East-facing cutbank exposure, west bank of former channel of Cannonball River, R132N-R87W-19bbd; approximately 7.75 miles (12.5 km) south of Leith, southern Grant Co., N. Dak. Site of measured section 5 (Cvancara, 1965, p. 267-270).

(4) Composite section; upper one half measured on south end of small hill, east side of north-south trending "mesa," T132N-R87W-9b; about 6.5 miles (10.5 km) south-southeast of Leith, southern Grant Co., N. Dak. Site of measured section 4 (Cvancara, 1965, p. 264-267); lower one-half of section measured on south-facing bluff exposure, north side of Cannonball River (about 0.5 mile or 0.8 km north of river), T132N-R88W-11bbd; approximately

6 miles (9.7 km) south of Leith, southern Morton Co., N. Dak. Site of measured section 6 (Cvancara, 1965, p. 270-273).

(5) Northwest-facing cutbank exposure, east (right) bank of Cannonball River, T133N-R88W-34abc; approximately 6 miles (9.7 km) southwest of Leith, southern Grant Co., N. Dak. Site of measured section 8 (Cvancara, 1965, p. 275-277).

(6) North-facing cutbank exposure, south bank of Cannonball River, T133N-R88W-28ccd; about 6 miles (9.7 km) southwest of Leith, southern Grant Co., N. Dak. Site of measured section 9 (Cvancara, 1965, p. 277-280).

(7) North-facing cutbank exposure, south bank of Cannonball River, T133N-R88W-29dad; about 6.25 miles (10.1 km) southwest of Leith, southern Grant Co., N. Dak. Site of measured section 10 (Cvancara, 1965, p. 280-283).

(8) Section (top) begins at top of north-facing bluff on south side of Cannonball River, continues downward to east and terminates at low cutbank exposure on east bank of Cannonball River, T133N-R88W-32; about 6.75 miles (10.9 km) southwest of Leith, southern Grant Co., N. Dak. Site of measured section 12 (Cvancara, 1965, p. 285-288).

(9) South-southeast-facing cutbank exposure, north bank of Cannonball River, T133N-R88W-29dbb; about 6.25 miles (10.1 km) southwest of Leith, southern Grant Co., N. Dak. Site of measured section 11 (Cvancara, 1965, p. 283-285

(10) Composite section; upper one-half measured on west-facing hill exposure, T136N-R86W-17c; about 9.75 miles (15.7 km) south of Almont (western Morton County) or 11.75 miles (18.9 km) north-northeast of Carson, northern Grant Co., N. Dak. Site of measured section 17 (Cvancara, 1965, p. 297-299); lower one-half measured on west-facing cutbank exposure, east bank of the Heart River, T136N-R86W-21aab; about 10 miles (16.1 km) south of Almont (northwestern Morton Co.) or about 12 miles (19.3 km) north-northeast of Carson, northern Grant Co., N. Dak. Site of measured section 18 (Cvancara, 1965, p. 299-304).

(11) South-southwest facing, partially grass-covered hill exposure in pasture, T135N-R83W-21d; about 2 miles (3.2 km) southwest of Fallon (or about 6 miles or 9.7 km east-northeast of Flasher), southern Morton Co., N. Dak. Site of measured section 20 (Cvancara, 1965, p. 307-310).

(12) Road-cut exposure (both sides of earth road) in upper part of section, bluff exposure in lower part of section, T136N-R79W-8c; about 1 mile (1.6 km) south of Huff, southern Morton Co., N. Dak. Site of measured section 28 (Cvancara, 1965, p. 327-332).

(13) East-facing, steep road-cut exposure, west side of Highway 1806, T138N-R81W-13bda; about 4.25 miles (6.8 km) south of Mandan, northeastern Morton Co., N. Dak. Site of measured section 29 (Cvancara, 1965, p. 332-335).

(14) High road-cut exposure (slide area), north side of U.S. Highway 10, T139N-R82W-23dda; 4.65 miles (7.5 km) west of railway station, center of Mandan, northeastern Morton Co., N. Dak. Site of measured section 31 (Cvancara, 1965, p. 342-345).

(15) South-facing cutbank exposure, north bank of Heart River, T138N-R83W-10dda; about 12 miles (19.3 km) west-southwest of Mandan, northeastern Morton Co., N. Dak. Site of measured section 30 (Cvancara, 1965, 335-342).

APPENDIX V

SYSTEMATIC PALEONTOLOGY: A REVIEW

The bivalve systematic paleontology of the Cannonball Formation has been well documented by Cvancara (1965, 1966), and my study did not include an extensive review of their classification. However, when applying paleoecology, it is important that the organisms used are properly identified and consistent with current nomenclature. The most inclusive and probably the most accepted compilation of bivalve taxonomy is the Treatise on Invertebrate Paleontology, Mollusca (Cox et al., 1969, Stenzel, 1971). Because these volumes were published after Cvancara (1966), all genera were updated following this source. When applicable, additional current literature was used.

This review presents any nomenclatorial changes and revisions I felt were necessary since Cvancara (1966). Many bivalves required no taxonomic change. This review does not deal in depth with synomony lists or bivalve descriptions because, for the most part, these have not changed and can be determined by referring to Cvancara (1966). In addition, Speden (1970) described the bivalves from the Late Cretaceous Fox Hills Formation, some of which also occur in the Cannonball Formation.

Phylum Mollusca

Class Bivalvia

Order Nuculoida

Superfamily Nuculacea

Family Nuculidae

Genus Nucula

Nucula planomarginata Meek and Hayden

This species was identified by Cvancara (1966, p. 293) as Nucula (Nucula) planimarginata. Although the Cannonball form exhibits morphological features characteristic of the genus, Cvancara expressed (p. 294) some reservation in placing the species in Nucula sensu stricto based on the lack of a crenulate inner margin and the ill-defined external radial ornamentation. His diagnosis was from Schenck (1934, p. 46), who included forms having both crenulate and non-crenulate inner margins in the subgenus Nucula.

Cox et al. (1969, p. N231) did not list the presence or absence of a crenulate inner margin as diagnostic for the genus. However, those forms placed in the subgenus Nucula do possess both radial ribs and a crenulate inner margin. The Cannonball form should, therefore, be removed from this subgenus.

The inconsistency in spelling in the trivial name of this species has resulted in confusion. The original spelling by Meek and Hayden (1856b, p. 85) was planomarginata. Later, Meek (1876, p. 101) unfortunately listed N. planimarginata as the original spelling in the synonymies. However, because no explanation or statement of the intent of the name change is ever given, the change is considered the result of an unintentional spelling error. Thus, the original spelling will be used here.

These changes are in agreement with the work of Speden (1970, p. 31) who placed the Cannonball form as a synonym of Nucula planomarginata Meek and Hayden from the Fox Hills Formation.

Superfamily Nuculanacea

Family Nuculanidae

Genus Nuculana

Nuculana evansi (Meek and Hayden)

This species was assigned to Neilonella evansi (Meek and Hayden)? by Cvancara (1966, p. 297) on the basis of a groove under the beaks for the reception of an external ligament. Cvancara (1966) followed Yonge (1939), who placed Neilonella in the Nuculanidae. Cox et al. (1969, p. N235) effectively included Neilonella in the Malletiidae when they indicated that Neilonella is a synonym of the genus Saturnia. Using this classification, the Cannonball species must be removed from this latter genus because forms of the Malletiidae lack a resilifer and possess a predominantly external ligament. In addition, Saturnia is characterized by a thick shell and strong external sculpture, neither of which are present on the Cannonball species.

The Cannonball form is characteristic of genera in the Nuculanidae, and should be assigned to the genus Nuculana on the basis of a narrow ligament pit, concentric sculpture, and shell outline (Cox et al., 1969, p. N235).

Speden (1970, p. 36) considered the Cannonball form a synonym of Nuculana (Jupiteria) scitula (Meek and Hayden). The two forms appear similar in many external and internal characteristics although the Cannonball form has a much smaller resilifer. Because N. evansi is rare in the Cannonball and only several poorly preserved specimens are available for inspection, it is impossible to ascertain any other differences. At this point, it would be premature to concur with Speden (1970) on this assignment without additional study of both forms.

Nuculana mansfieldi (Stanton)

No change is necessary.

Order Solemyoida

Superfamily Solemyacea

Family Solemyidae

Genus Solemya

Solemya bilix White

This species is very rare in the Cannonball. Cvancara (1966, p. 303) placed it in Solemya, but with uncertainty, due to inadequate material and lack of knowledge of internal characters. Because no additional specimens were found or examined in this study, no refinement of this assignment can be made.

Order Arcoida

Superfamily Arcacea

Family Cucullaeidae

Genus Cucullaea

Cucullaea solenensis Stanton

No change is necessary.

Superfamily Limopsacea

Family Glycymerididae

Genus *Glycymeris*

Glycymeris subimbricata (Meek and Hayden)

No change is necessary.

Order Pterioida

Suborder Pteriina

Superfamily Pteriacea

Family Pteriidae

Genus *Pteria*

Pteria linguaeformis (Evans and Shumard)

No change is necessary.

Family Isognomonidae

Genus *Isognomon*

Isognomon lloydi (Stanton)

No change is necessary.

Suborder Ostreina

Superfamily Ostreacea

Family Ostreidae

Genus *Crassostrea*

Crassostrea glabra (Meek and Hayden)

Some confusion remains regarding the trivial name of this species. The oysters in the upper Cannonball tongue were initially all placed by T. W. Stanton in the species *Ostrea subtrigonalis* Evans and Shumard (Leonard, 1908, p. 49). The confusion started when Stanton (1910, p. 183) changed his mind and referred the Cannonball oysters to two species, Ostrea subtrigonalis and Ostrea glabra. Meek (1876, p. 509-510, Pl. 40, Figs. 1a-d, 2a-d) had described and illustrated both of these forms and Cvancara (1966, p. 322) pointed out that O. subtrigonalis is smaller, more arcuate, and possesses a less convex left valve than the Cannonball oysters. Cvancara suggested, therefore, that O. subtrigonalis is not represented in the Cannonball and thus assigned the Cannonball species to "Ostrea" glabra Meek and Hayden.

Cvancara (1966, p. 321) further placed this species in the genus Crassostrea because of the elongate shape, deep left valve, recess under the hinge, and position of the muscle scars.

After study of the Fox Hills oysters, Speden (1970, p. 94) considered Crassostrea glabra and Crassostrea subtrigonalis intergradational and placed Crassostrea glabra in synonomy with Crassostrea subtrigonalis. The Cannonball species, however, appears morphologically different from Crassostrea subtrigonalis. Of primary importance is the presence of up to 20 hollow denticles on either side of the ligament on the inner dorsal margin of the right valve of the Fox Hills species. These denticles, or chomata, are not present on Cannonball forms. According to Stenzel (1971, p. N1129), the genus Crassostrea diagnostically lacks chomata. Not only, therefore, do the Fox Hills and Cannonball forms belong to different species, but, they may also have different generic assignments. The assignment of this species to Crassostrea glabra will therefore be retained.

Genus Ostrea

Ostrea sp.

This form was first reported in the Cannonball by Van Alstine (1974) who questionably assigned it to Ostrea on the basis of its tear-drop shape, shallow umbonal cavity, and the presence of chomata. The lack of well-preserved material prohibited Van Alstine from determining the adductor-muscle scar shape and position, and, a more positive identification could not be made. Neither did specimens collected for my study provide the observation of these characters. However, on the basis of observable morphological features, especially the presence of chomata, the assignment of this form to Ostrea appears accurate and will not be questioned in this study.

Order Veneroida

Superfamily Lucinacea

Family Lucinidae

Genus Codakia

Codakia? (Claibornites) cedrensis (Stanton)

Following Chavan (1937), the Cannonball lucinoid was provisionally placed in Miltha (Plastomiltha) cedrensis by Cvancara (1966, p. 334-337), although he noted (p. 336) that the Cannonball form did not fit with certainty into any member of Chavan's classification. This assignment was provisional because, according to this classification, lateral teeth, present on the Cannonball species, are lacking in the subgenus Plastomiltha.

The Fox Hills Formation contains a species very similar to the Cannonball form. Morphological features and hinge characters appear almost identical. Speden (1970, p. 103) tentatively referred this species to Epilucina (following Chavan, 1937, who considered Epilucina a subgenus of Codakia and synonymized it with Claibornites). He also noted (p. 103) inconsistencies with this assignment, primarily weak posterior laterals posterodorsally above the end of the sunken ligament in contrast to the stronger posteroventral laterals diagnostic of *Epilucina*.

Following the most recent monographic study of the Lucinidae by Bretsky (1976), and Cox et al. (1969, p. N502), the Cannonball species should be removed from the genus *Miltha* because of its lack of a long anterior adductor scar and the presence of laterals.

Bretsky (1976, p. 238-239) discussed the Fox Hills-Cannonball form and noted that it differs from *Codakia sensu stricto* in lacking radial sculpture, having a more rounded shell, and a straighter anterior adductor muscle scar. However, these features are characteristic of *Claibornites*, which she tentatively assigned as a subgenus of *Codakia*. She further considered the subgenus *Claibornites* an early branch of the *Codakia* lineage and the Fox Hills-Cannonball species as possibly the earliest representative of *Claibornites*. This would account for the minor inconsistent characters that indicate this form may belong to a distinct group.

Comparison of the Cannonball species with *Codakia* (*Claibornites*) *symmetrica* (illustrated by Bretsky, 1976, p. 287-288, Pl. 32, Figs. 8-10), does reveal similar morphological (both external and internal) characters. The only notable difference is a longer, narrower anterior adductor scar in *C. symmetrica*.

Superfamily Crassatellacea

Family Crassatellidae

Genus *Crassatella*

Crassatella evansi Hall and Meek

No change is necessary.

Superfamily Arcticacea

Family Arcticidae

Genus *Arctica*

Arctica ovata (Meek and Hayden)

No change is necessary.

Superfamily Corbiculacea

Family Corbiculidae

Genus *Corbicula*

Corbicula berthoudi White

This species is common in the Cannonball tongues where specimens are numerous but poorly preserved. In addition, several rare specimens have also been reported from southwest-central North Dakota.

Cvancara (1966, p. 326-327) assigned the rare specimens collected in southwest-central North Dakota to *Corbicula berthoudi* based on an incomplete, but fairly well-preserved left and right valve. Although apparently similar in shape and overall proportions, Cvancara (1966, p. 328-329) designated specimens from the Cannonball tongues as *Corbicula* cf. *C. berthoudi* because not all morphological characters could be seen on his studied specimens. Van Alstine (1974, p. 46) collected and described specimens from the tongues that display internal and external morphological features not apparent on those

Cvancara studied. Van Alstine placed the specimens he collected in Corbicula berthoudi and placed Corbicula cf. C. berthoudi in synonomy with C. berthoudi.

Specimens collected for my study are from the Cannonball tongues and appear (although poorly preserved) similar to Van Alstine's designated hypotypes of this species; his assignment will therefore be followed here. No additional specimens of Corbicula berthoudi from non-tongue lithology have been found.

Superfamily Veneracea

Family Veneridae

Genus Dosiniopsis

Dosiniopsis deweyi (Meek and Hayden)

No change is necessary.

Superfamily Myacea

Family Corbulidae

Genus Corbula

Corbula (Bicorbula) subtrigonalis (Meek and Hayden)

Cvancara (1966, p. 343) chose to use Bicorbula as the generic name and assigned the species to Bicorbula subtrigonalis although he stated it could also have been treated as a subgenus of Corbula. Van Alstine (1974, p. 47) followed the diagnosis of Cox et al. (1969, p. N692), who did not recognize Bicorbula as a distinct genus, and placed the species in Corbula (Bicorbula) subtrigonalis. Following Cox et al. (1969), this designation is being retained.

Corbula mactriformis (Meek and Hayden)

Cvancara (1966, p. 345) placed this form in Bicorbula mactriformis following Vokes (1945). According to Vokes' revision of corbulids, the Cannonball species differs from true Corbula in possessing a chondrophore and lacking a posterior cardinal tooth on the left valve and a posterior lateral tooth on the right valve. As discussed in regard to Corbula (Bicorbula) subtrigonalis, Cox et al. (1969) did not recognize Bicorbula as a distinct genus but treated it as a subgenus of Corbula. Further, they diagnosed the subgenus as a large form. Moreover, they applied the restrictions used by Vokes (1945) to those forms belonging to the subgenus Corbula, but not at the generic level. Following Cox et al. (1969), this species should be placed in the genus Corbula, and because the Cannonball form is small, not diagnostic of the subgenus Bicorbula, this subgenus will not be used.

Genus Caestocorbula

Caestocorbula sinistrirostella Cvancara

No change is necessary.

Superfamily Hiatellacea

Family Hiatellidae

Genus Panopea

Panopea? cf. P. simulatrix Whiteaves

This form is very rare in the Cannonball Formation. Initially, Stanton (1920, p. 32) questionably referred the Cannonball specimen to Panope simulatrix Whiteaves. Because the hinge and internal characters are unknown, Cvancara (1966, p. 343) preferred only to indicate a comparison with the species. Additional specimens have not been found, and the hinge and internal characters remain unknown. Therefore, no taxonomic refinement can be made at this time.

Order Pholadomyoida

Superfamily Pandoracea

Family Periplomatidae

Genus *Periploma*

Periploma sp.

Periploma sp., a rare Cannonball form, was first reported by Cvancara (1966, p. 355). However, due to the paucity and imcompleteness of material, he withheld a trivial name. Speden (1970, p. 149) placed *Periploma* sp. in synonomy with the Fox Hills species *Periploma subgracile* (Whitfield). Unfortunately, this species is also rare in the Fox Hills Formation, and the comparison was evidently made on very little material. Although the forms appear similar, until additional Cannonball and Fox Hills specimens are collected and studied (especially hinge characters), it is premature to assign the Cannonball form to this species.

REFERENCES CITED

REFERENCES CITED

Abbott, R. T., 1974, American seashells, the marine Mollusca of the Atlantic and Pacific Coasts of North America: New York, Van Nostrand Reinhold Co., 663 p.

Archibald, J. D., 1982, A study of Mammalia and geology across the Cretaceous-Tertiary boundary in Garfield County, Montana: University of California Publications in Geological Sciences, v. 122, 286 p.

Bathurst, R. G. C., 1971, Carbonate sediments and their diagenesis (2nd ed.), Developments in sedimentology, v. 12: New York, Elsevier, 658 p.

Bickel, David, 1973, Non-marine mollusks and two new species of Pisidium from the Tongue River Formation (Paleocene), North Dakota: The Nautilus, v. 87, no. 1, p. 13-18.

Bluemle, J. B., 1983, Geologic and topographic bedrock map of North Dakota: North Dakota Geological Survey Miscellaneous Map 25.

Boucot, A. J., 1981, Principles of benthic marine paleoecology: New York, Academic Press, 407 p.

Bretsky, S. S., 1976, Evolution and classification of the Lucinidae (Mollusca; Bivalvia): Palaeontographica Americana, v. 8, no. 50, 337 p.

Brown, Barnum, 1907, The Hell Creek beds of the Upper Cretaceous of Montana; their relation to the contiguous deposits, with faunal and floral lists and a discussion of their correlation: American Museum Natural History Bulletin, v. 23, p. 823-845.

Brown, R. W., 1948, Correlation of Sentinel Butte shale in western North Dakota: American Association of Petroleum Geologists Bulletin, v. 32, no. 7, p. 1265-1274.

Brown, R. W., 1962, Paleocene flora of the Rocky Mountains and Great Plains: United States Geological Survey Professional Paper 375, 119 p.

Carlson, C. G., 1982, Geology of Grant and Sioux Counties, North Dakota: North Dakota Geological Survey Bulletin 67, 32 p.

Carlson, C. G., and Anderson, S. B., 1965, Sedimentary and tectonic history of North Dakota part of the Williston Basin: American Association of Petroleum Geologists Bulletin, v. 49, no. 11, p. 1833-1846.

Carver, R. E., 1971, Procedures in sedimentary petrology: New York, Wiley-Interscience, 635 p.

Chavan, André, 1937, Essai critique de classification des Lucines: Journal Conchyliologie, v. 81, p. 133-153.

Cheatham, A. H., and Hazel, J. E., 1969, Binary (presence-absence) similarity coefficients: Journal of Paleontology, v. 43, no. 5, p. 1130-1136.

Clayton, Lee, Carlson, C. G., Moore, W. L., Groenewold, Gerald, Holland, F. D., Jr., and Moran, S. R., 1977, The Slope (Paleocene) and Bullion Creek (Paleocene) Formations of North Dakota: North Dakota Geological Survey Report of Investigation 59, 14 p.

Cloud, P. E., Jr., 1955, Physical limits of glauconite formation: American Association of Petroleum Geologists Bulletin, v. 39, no. 4, p. 484-492.

Cox, L. R., Newell, N. D., Boyd, D. W., Branson, C. C., Casey, Raymond, Chavan, André, Coogan, A. H., Dechaseaux, Colette, Fleming, C. A., Haas, Fritz, Hertlein, L. G., Kauffman, E. G., Keen, A. M., LaRocque, Aurèle, McAlester, A. L., Moore, R. C., Nuttal, C. P., Perkins, B. F., Puri, H. S., Smith, L. A., Soot-Ryen, T., Stenzel, H. B., Trueman, E. R., Turner, R. D., and Weir, John, 1969, Part N Mollusca 6 Bivalvia, v. 1 and 2, in Moore, R. C., and Teichert, Curt, eds., Treatise on Invertebrate Paleontology: The Geological Society of America and the University of Kansas, 952 p.

Cvancara, A. M., 1965, Bivalves and biostratigraphy of the Cannonball Formation (Paleocene) in North Dakota: Doctoral Dissertation, University of Michigan, 469 p.

Cvancara, A. N., 1966, Revision of the fauna of the Cannonball Formation (Paleocene) of North and South Dakota: Contributions from the Museum of Paleontology, University of Michigan, v. 20, no. 10, 97 p.

Cvancara, A. M., 1970a, Teredinid (Bivalvia) pallets from the Paleocene of North America: Palaeontology, v. 13, no. 4, p. 619-622.

Cvancara, A. M., 1970b, North Dakota's state fossil: North Dakota Quarterly, v. 32, no. 3, p. 31-35.

Cvancara, A. M., 1976, Geology of the Cannonball Formation (Paleocene) in the Williston Basin, with reference to uranium potential: North Dakota Geological Survey Report of Investigation 57, 22 p.

Cvancara, A. M., 1980, Bench-forming sandstone as a correlation tool: Cannonball Formation (Paleocene), North Dakota: Preceedings of the North Dakota Academy of Science, v. 34, p. 34.

Davies, A. M., 1975, Tertiary faunas, Vol. II, the sequence of Tertiary faunas: New York, American Elsevier, 447 p.

DeWindt, J. T., 1974, Callianassid burrows as indicators of subsurface beach trend, Mississippi River delta plain: Journal of Sedimentary Petrology, v. 44, no. 4, p. 1136-1139.

Dorf, Erling, 1940, Relationship between floras of the type Lance and Fort Union Formations: Geological Society of America Bulletin, v. ~~4~~51, no. 12, p. 213-236.

Erickson, J. M., 1978, Bivalve mollusk range extensions in the Fox Hills Formation (Maestrichtian) of North and South Dakota and their implications for the Late Cretaceous geologic history of the Williston Basin: Proceedings of the North Dakota Academy of Science, v. 32, pt. 2, p. 79-89.

Feldmann, R. M., 1972, First report of *Hercoglossa ulrichi* (White, 1882) (Cephalopoda: Nautilida) from the Cannonball Formation (Paleocene) of North Dakota, U. S. A.: Malacologia, v. 11, no. 2, p. 407-413.

Feldmann, R. M., and Holland, F. D., Jr., 1971, A new species of lobster from the Cannonball Formation (Paleocene) of North Dakota: Journal of Paleontology, v. 45, no. 5, p. 838-843.

Feldmann, R. M., and Palubniak, D. S., 1975, Paleoecology of Maestrichtian oyster assemblages in the Fox Hills Formation, *in* Caldwell, W. G. E., ed., The Cretaceous System in the Western Interior of North America: The Geological Association of Canada Special Paper no. 13, p. 211-233.

Fenner, W. E., 1974, The foraminiferids of the Cannonball Formation (Paleocene, Danian) and their paleoenvironmental significance: Grant, Morton and Oliver Counties, North Dakota: M. S. Thesis, University of North Dakota, 135 p.

Fenner, W. E., 1976, Foraminiferids of the Cannonball Formation (Paleocene, Danian) in western North Dakota: Doctoral Dissertation, University of North Dakota, 206 p.

Flores, R. M., 1981, Coal deposition in fluvial paleoenvironments of the Paleocene Tongue River Member of the Fort Union Formation, Powder River area, Powder River Basin, Wyoming and Montana: Society of Economic Paleontologists and Mineralogists Special Publication 31, p. 169-190.

Folk, R. L., 1974, Petrology of sedimentary rocks: Austin, Texas, Hemphill Publishing Company, 182 p.

Fox, S. K., Jr., and Olsson, R. K., 1969, Danian planktonic Foraminifera from the Cannonball Formation in North Dakota: Journal of Paleontology, v. 43, no. 6, p. 1397-1404.

Fox, S. K., Jr., and Ross, R. J., 1940, Foraminiferal evidence for the Midway (Paleocene) age of the Cannonball marine beds in North Dakota [abs.]: Geological Society of America Bulletin, v. 51, p. 1940.

Fox, S. K., Jr., and Ross, R. J., 1942, Foraminiferal evidence for the Midway (Paleocene) age of the Cannonball Formation in North Dakota: Journal of Paleontology, v. 16, no. 5, p. 660-673.

Gerhard, L. C., Anderson, S. B., LeFever, J. A., and Carlson, C. G., 1982, Geological development, origin, and energy mineral resources of Williston Basin, North Dakota: American Association of Petroleum Geologists Bulletin, v. 66, no. 8, p. 989-1020.

Gernant, R. E., 1970, Paleoecology of the Choptank Formation (Miocene) of Maryland and Virginia: Maryland Geological Survey Report of Investigations 12, 90 p.

Goddard, E. H., Trask, P. D., DeFord, R. K., Rove, O. N., Singewald, J. T., Jr., and Overbeck, R. M., 1948, Rock-color chart: Washington, D. C., National Research Council (distributed by the Geological Society of America).

Goodrum, C. K., 1982, A paleoenvironmental and stratigraphic study of the Paleocene Fort Union Formation in the Cave Hills area of Harding County, South Dakota: M. S. Thesis, South Dakota School of Mines, 134 p.

Greiner, G. O. G., 1970, Distribution of major benthonic foraminiferal groups on the Gulf of Mexico continental shelf: Micropaleontology, v. 16, no. 1, p. 83-101.

Hall, G. A., 1958, The stratigraphy and geologic history of the Cannonball Formation (Paleocene): M. S. Thesis, University of North Dakota, 64 p.

Hares, C. J., 1928, Geology and lignite resources of the Marmarth field, southwestern North Dakota: United States Geological Survey Bulletin 775, 110 p.

Hatcher, J. B., 1903, Relative age of the Lance Creek (Ceratops) beds of Converse County, Wyoming, the Judith River beds of Montana and the Belly River beds of Canada: American Geologist, v. 31, p. 369-375.

Hickey, L. J., 1972, Stratigraphic summary of the Golden Valley Formation (Paleocene-Eocene) of western North Dakota, in Ting, F. T. C., ed., Depositional environments of the lignite-bearing strata in western North Dakota: North Dakota Geological Survey Miscellaneous Series 50, p. 105-122.

Hickey, L. J., 1977, Stratigraphy and paleobotany of the Golden Valley Formation (Early Tertiary) of western North Dakota: Geological Society of America Memoir 150, 183 p.

Holland, F. D., Jr., and Cvancara, A. M., 1958, Crabs from the Cannonball Formation (Paleocene) of North Dakota: Journal of Paleontology, v. 32, no. 3, p. 495-505.

Holtzman, R. C., 1978, Late Paleocene mammals of the Tongue River Formation, western North Dakota: North Dakota Geological Survey Report of Investigation 65, 88 p.

Howard, J. D., 1972, Trace fossils as criteria for recognizing shorelines in stratigraphic record, in Rigby, J. K., and Hamblin, W. K., eds., Recognition of ancient sedimentary environments: Society of Economic Paleontologists and Mineralogists Special Publication 16, p. 215-225.

Jackson, M. L., 1958, Soil chemical analysis: Englewood Cliffs, N. J., Prentice-Hall, 498 p.

Kauffman, E. G., 1969, Form, function, and evolution, in Moore, R. C., and Teichert, Curt, eds., Treatise on invertebrate paleontology, Part N Mollusca 6 Bivalvia, v. 1: The Geological Society of America and The University of Kansas, p. N129-N205.

Keen, A. M., 1958, Sea shells of tropical West America, marine mollusks from lower California to Columbia: Stanford, California, Stanford University Press, 624 p.

Klein, G. deV., 1974, Estimating water depths from analysis of barrier island and deltaic sedimentary sequences: Geology, v. 2, no. 7, p. 409-412.

Knowlton, F. H., 1911, Further data on the stratigraphic position of the Lance Formation ("Ceratop beds"): Journal of Geology, v. 19, p. 358.

Laird, W. M., and Mitchell, R. H., 1942, The geology of the southern part of Morton County, North Dakota: North Dakota Geological Survey Bulletin 14, 42 p.

Lawrence, D. R., 1968, Taphonomy and information losses in fossil communities: Geological Society of America Bulletin, v. 79, no. 10, p. 1315-1330.

Lemke, R. W., 1960, Geology of the Souris River area, North Dakota: United States Geological Survey Professional Paper 325, 138 p.

Leonard, A. G., 1908, The geology of southwestern North Dakota with special reference to coal: State Geological Survey of North Dakota, 5th Biennial Report, p. 27-114.

Leriche, Maurice, 1942, Contribution a l'étude faunes ichthyologiques marine des terrains Tertiares de la Plaine Cotière Atlantique et du centre des États-Unis: Societe geology France Mémoir 45, new ser., v. 20, pts. 2-4, 110 p.

Levinton, J. S., 1970, The paleoecological significance of opportunistic species: Lethaia, v. 3, p. 69-78.

Lloyd, E. R., 1914, The Cannonball River lignite field, Morton, Adams, and Hettinger Counties, North Dakota: United States Geological Survey Bulletin 541, p. 243-291.

Lloyd, E. R., and Hares, C. J., 1915, The Cannonball Marine Member of the Lance Formation of North and South Dakota and its bearing on the Lance-Laramie problem: Journal of Geology, v. 23, no. 6, p. 523-547.

Marincovich, L., Jr., Brouwers, E. M., and Hopkins, D. M., 1983, Paleogeographic affinities and endemism of Cretaceous and Paleocene marine faunas in the Arctic [abs.]: United States Geological Survey Polar Research Symposium, Abstracts with Programs, United States Geological Survey Circular 911, p. 45-46.

Marszalek, D. S., 1975, Calcisphere ultrastructure and skeletal aragonite from the alga Acetabularia antillana: Journal of Sedimentary Petrology, v. 45, no. 1, p. 266-271.

McAlester, A. L., and Rhoads, D. C., 1967, Bivalves as bathymetric indicators: Marine Geology, v. 5, p. 383-388.

McMahon, R. F., 1982, The occurrence and spread of the introduced Asiatic clam, Corbicula fluminea (Müller), in North America: 1924-1982: The Nautilus, v. 96, no. 4, p. 134.

Meek, F. B., 1876, A report on the invertebrate Cretaceous and Tertiary fossils of the upper Missouri country: Report of the United States Geological Survey of the Territories, v. 9, 629 p.

Meek F. B., and Hayden, F. V., 1856a, Descriptions of new species of Gasteropoda from the Cretaceous Formations of Nebraska Territory: Philadelphia Academy Natural Science Proceedings, v. 8, p. 63-69.

Meek, F. B., and Hayden, F. V., 1856b, Descriptions of twenty-eight new species of Acephala and one gasteropod, from the Cretaceous Formations of Nebraska Territory: Philadelphia Academy Natural Science Proceedings, v. 8, p. 81-87.

Meek F. B., and Hayden, F. V., 1857, Descriptions of new species and genera of fossils collected by Dr. F. V. Hayden in Nebraska Territory under the direction of Lieut. G. K. Warren, U. S. Topographical Engineer, with some remarks on the Tertiary and Cretaceous Formations of the north-west and the parallelism of the latter with those of other portions of the United States and territories: Philadelphia Academy Natural Science Proceedings, v. 9, p. 117-148.

Monnens, L. E., 1980, The stratigraphy of the Cenozoic deposits in the Cave Hills, northwestern Dakota: M. S. Thesis, Iowa State University, 102 p.

Moore, W. L., 1976, The stratigraphy and environments of deposition of the Cretaceous Hell Creek Formation (reconnaissance) and the Paleocene Ludlow Formation (detailed), southwestern North Dakota: North Dakota Geological Survey Report of Investigation 56, 40 p.

Nicol, David, 1951, Recent species of the veneroid pelecypod Arctica: Washington Academy of Science Journal, v. 41, no. 3, p. 102-106.

Palubniak, D. S., 1972, Paleoecology of Upper Cretaceous oysters in the Fox Hills Formation, North Dakota and comparisons with Recent oyster ecology: M. S. Thesis, Kent State University, 119 p.

Parker, R. H., 1960, Ecology and distribution patterns of marine macro-invertebrates, northern Gulf of Mexico, in Shepard, F. P., Phleger, F. B., and van Andel, T. H., eds., Recent sediments, northwest Gulf of Mexico, 1951-1958: The American Association of Petroleum Geologists, p. 302-337.

Phleger, F. B., 1960, Sedimentary patterns of microfaunas in northern Gulf of Mexico, in Shepard, R. P., Phleger, F. B., and van Andel, T. H., eds., Recent sediments, northwest Gulf of Mexico, 1951-1958: The American Association of Petroleum Geologists, p. 267-301.

Pipiringos, G. N., Chisholm, W. A., and Kepferle, R. C., 1965, Geology and uranium deposits in the Cave Hills area, Harding County, South Dakota: United States Geological Survey Professional Paper 476-A, 64 p.

Porrenga, D. H., 1967, Glauconite and chamosite as depth indicators in the marine environment: Marine Geology, v. 5, p. 495-501.

Rhoads, D. C., Speden, I. G., and Waage, K. M., 1972, Trophic group analysis of Upper Cretaceous (Maestrichtian) bivalve assemblages from South Dakota: American Association of Petroleum Geologists Bulletin, v. 56, no. 6, p. 1100-1113.

Rhoads, D. C., and Young, D. K., 1970, The influence of deposit-feeding organisms on bottom-sediment stability and community trophic structure: Journal of Marine Research, v. 28, p. 150-178.

Robertson, E. B., 1975, Pollen and spores as stratigraphic indices to the North Dakota Paleocene: Doctoral Dissertation, University of Minnesota, 192 p.

Russell, L. S., 1940, Micrichnus trails from the Paskapoo Formation of Alberta: Royal Canadian Institute Proceedings, v. 23, p. 67-74.

Schenck, H. G., 1934, Classification of nuculid pelecypods: Musée Royal d'Histoire Naturelle de Belgique Bulletin, v. 10, no. 20, p.1-78.

Scott, R. W., 1978, Approaches to trophic analysis of paleocommunities: Lethaia, v. 11, p. 1-14.

Seilacher, Adolph, 1967, Bathymetry of trace fossils: Marine Geology, v. 5, p. 413-428.

Sinclair, R. M., 1971, Annotated bibliography on the exotic bivalve Corbicula in North America, 1900-1971: Sterkiana, no. 43, p. 10-19.

Sloan, R. E., 1970, Cretaceous and Paleocene terrestrial communities of western North America: North American Paleontological Convention, Chicago, 1969, Proceedings E., p. 427-453.

Speden, I. G., 1970, The type Fox Hills Formation, Cretaceous (Maestrichtian), South Dakota, Part 2. Systematics of the Bivalvia: Peabody Museum of Natural History, Yale University, Bulletin 33, 222 p.

Stanley, E. A., 1965, Upper Cretaceous and Paleocene plant microfossils and Paleocene dinoflagellates and hystrichosphaerids from northwestern South Dakota: Bulletins American Paleontology, v. 49, no. 222, p. 179-384.

Stanley, S. M., 1968, Post-Paleozoic adaptive radiation of infaunal bivalve molluscs--a consequence of mantle fusion and siphon formation: Journal of Paleontology, v. 42, p. 214-229.

Stanley, S. M., 1970, Relation of shell form to life habits in the Bivalvia (Mollusca): Geological Society of America Memoir 125, 296 p.

Stanton, T. W., 1910, Fox Hills Sandstone and Lance Formation ("Ceratops Beds") in South Dakota, North Dakota and eastern Wyoming: American Journal of Science, 4th ser., v. 30, art. 16, p. 172-188.

Stanton, T. W., 1920, The fauna of the Cannonball Marine Member of the Lance Formation: United States Geological Survey Professional Paper 128-A, p. 1-60.

Stanton, R. J., Jr., and Dodd, J. R., 1976, The application of trophic structure of fossil communities in paleoenvironmental reconstruction: Lethaia, v. 9, p. 327-342.

Stenzel, H. B., 1971, Oysters, in Moore, R. C., and Teichert, Curt, eds., Treatise on invertebrate paleontology, Part N Mollusca 6 Bivalvia, v. 3: The Geological Society of America and The University of Kansas, p. N953-N1224.

Swain, F. M., 1949, Early Tertiary Ostracoda from the Western Interior United States: Journal of Paleontology, v. 23, no. 2, p. 172-181.

Thayer, C. W., 1974, Marine paleoecology in the Upper Devonian of New York: Lethaia, v. 7, p. 121-155.

Thom, W. T., Jr., and Dobbin, C. E., 1924, Stratigraphy of Cretaceous-Eocene transition beds in eastern Montana and the Dakotas: Geological Society of America Bulletin, v. 35, p. 481-506.

Thomas, R. D. K., 1975, Functional morphology, ecology, and evolutionary conservatism in the Glycymerididae (Bivalvia): Palaeontology, v. 18, pt. 2, p. 217-254.

Turpaeva, Y. P., 1953, Feeding and food groupings of marine benthic invertebrates: Trudy Institute Okeanologia, v. 6, p. 259-299.

Van Alstine, J. B., 1974, Paleontology of brackish-water faunas in two tongues of the Cannonball Formation (Paleocene, Danian), Slope and Golden Valley Counties, southwestern North Dakota: M. S. Thesis, University of North Dakota, 101 p.

Vaughan, T. W., 1920, Corals from the Cannonball Marine Member of the Lance Formation: United States Geological Survey Professional Paper 128-A, p. 61-66.

Vokes, H. E., 1945, Supraspecific groups of the pelecypod family Corbulidae: American Museum Natural History Bulletin, v. 86, art. 1, p. 1-32.

Walker, K. R., 1972, Trophic analysis: a method for studying the function of ancient communities: Journal of Paleontology, v. 46, no. 1, p. 82-93.

Wehrfritz, B. D., 1978, The Rhame Bed (Slope Formation, Paleocene): a silcrete and deep-weathering profile, in southwestern North Dakota: M. S. Thesis, University of North Dakota, 158 p.

Weimer, R. J., and Hoyt, J. H., 1964, Burrows of *Callianassa major* Say, geologic indicators of littoral and shallow neritic environments: Journal of Paleontology, v. 38, no. 4, p. 761-767.

Weimer, R. J., Howard, J. D., and Lindsay, D. R., 1982, Tidal flats, *in* Scholle, P. A., and Spearing, Darwin, eds., Sandstone depositional environments: American Association of Petroleum Geologists Memoir 31, p. 191-247.

Wilson, E. E., 1957, An investigation of the corals from the Cannonball Formation (Paleocene) of North Dakota [abs.]: Proceedings of the North Dakota Academy of Science, v. 11, p. 15-16.

Yonge, C. M., 1939, The protobranchiate Mollusca; a functional interpretation of their structure and evolution: Royal Society of London Transactions, ser. B, v. 230, p. 79-147.