GEOLOGY OF THE CANNONBALL FORMATION (PALEOCENE) IN THE WILLISTON BASIN, WITH REFERENCE TO URANIUM POTENTIAL

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A. M. CVANCARA

REPORT OF INVESTIGATION NO. 57

NORTH DAKOTA GEOLOGICAL SURVEY

E. A. Noble, State Geologist

1976

PREPARED FOR THE U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
GRAND JUNCTION OFFICE
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COVER: Reconstruction of a shoreline of the Cannonball sea with the crab *Camarocarcinus arnesoni* Holland and Cvancara, shipworm-bored driftwood, and a small bivalve. Drawing by A. Cvancara.

CONTENTS

ILLUSTRATIONS

ABSTRACT

The Paleocene Cannonball Formation is a marine, non-lignitic-bearing clastic sequence in the lower part of the Fort Union Group. It is overlain by the lignite-bearing Tongue River Formation in places and both overlain and underlain by the lignite-bearing Ludlow Formation in places. The Cannonball crops out primarily in southwest-central North Dakota and probably occurs throughout the western one-half of the state. It occurs also in northwestern South Dakota and may extend into parts of Saskatchewan and Manitoba. Poorly consolidated, very fine- to fine-grained, light to medium brownish yellow-weathering sandstone and light gray-weathering, sandy mudstone are the principal types of lithology. Mudstone generally predominates in North Dakota whereas sandstone seems to predominate in South Dakota. The thickest recognized sequence is 385 feet in the subsurface in southeastern Hettinger County, North Dakota; thinning generally seems to occur away from this area except for another thickening to the north in Dunn County and possibly Ward County. The Cannonball is known to thin to 25 feet or less in western Slope County. Rocks of the Late Cretaceous and Early Tertiary, including the Cannonball, generally dip about 10-20 feet per mile toward the center of the Williston basin, except locally, where dips may be less or considerably greater. Principal macrofossils are bivalve and gastropod mollusks and principal larger microfossils are foraminiferids. Specific age assignments for the Cannonball vary from early to late Paleocene. The Cannonball sediments are interpreted to have been deposited adjacent to a lowland in a complex of environments, including tidal flat, lagoon, beach, shoreface, and shelf. Certain sandstones, underlain with gradational contact by sandy mudstones, are considered to be barrier island or regressive shoreline deposits. The occurrence of these sandstones at two or more stratigraphic levels in places implies repetitive progradation seaward with intervening transgressive pulses. The presence of the crustacean burrow Ophiomorpha *in well-sorted sandstones, the sandy content and small size of foraminiferids of the mudstones, and the relative thickness of mudstones associated with certain sandstones, suggests relatively shallow water depths, perhaps about 100 feet and less.*

Although uranium in the Williston basin has been found almost entirely in lignite and nonmarine carbonaceous rocks, its occurrence in the marine Cannonball Formation is possible. If the Cannonball, Ludlow, Tongue River, and Sentinel Butte Formations are at least partly penecontemporaneous, a variety of depositional environments were in areal juxtaposition during the Paleocene. Streams originating or passing through coastal plain bogs could have carried uranium ions (derived from volcanic materials) to the Cannonball sea where they were deposited syngenetically. Epigenetic uranium may occur in Cannonball mudstones or sandstones that directly underlie the Ludlow Formation, which is known to contain volcanic materials.

INTRODUCTION

The Early Tertiary marine Cannonball Formation, of less than 400 feet of medium and fine clastic sediments, is restricted to the center of the North American continent. Recognized only in western North Dakota and northwestern South Dakota, the Cannonball Formation by definition lacks lignite but is overlain and underlain by lignite-bearing strata. This report summarizes the geology of the Cannonball Formation, the stratigraphy of which is based on previous surface information and recent subsurface data, and evaluates its potential for uranium.

ACKNOWLEDGMENTS

This study was supported by part of

grant AT(05-1)-1633 from the U.S. Atomic Energy Commission. The North Dakota State Water Commission provided unpublished subsurface stratigraphic data for Dunn, Grant, Morton, and Sioux Counties. W. E. Fenner, graduate student at the University of North Dakota, kindly allowed me the use of his Cannonball foraminiferid occurrences in many of the wells, which aided greatly in the stratigraphic correlations. C. G. Carlson, North Dakota Geological Survey, provided useful aid and advice during the course of this study.

MATERIALS AND METHODS

The cross sections prepared for this report (pls. 1-3) are, with one exception, based exclusively on recent unpublished and published subsurface data of the North Dakota State Water Commission because complete outcrop sections of the Cannonball Formation are rare. These subsurface data, although based on samples, are, in certain cases, difficult to use because of inconsistent or incomplete descriptions. The datum for the cross sections is the top of the Pierre Shale. The Cannonball interval in many of the wells was identified with the aid of foraminiferid occurrences compiled by W. E. Fenner of the Department of Geology, University of North Dakota. Contacts of the Cannonball were changed in many instances from those placed by previous workers. The isopach and sandstone percentage map (pl. 4) is based primarily on the same type of Water Commission data; about 70 control points were used (table 1). Mechanical logs were not utilized because I am presently unable to consistently identify the Cannonball interval from them. The system of designating the legal description of well or outcrop localities is that used by the Water Commission.

STRATIGRAPHY

Definition and Relationship to Other Rock Units

Lloyd (1914) named the Cannonball Formation after the Cannonball River for exposures along the bluffs of this river in Tps 132 and 133N, R88W, southern Grant County, North Dakota. In 1915, he and Hares added R87W to the type area (pl. 4). General stratigraphic summaries of the formation have been provided by Cvancara (1965, 1972), Hall (1958), and Lloyd and Hares (1915), and discussions of the unit in specific areas have been given by many workers (e.g., Carlson, 1973; Kume and Hansen, 1965; Laird and Mitchell, 1942; and Lemke, 1960).

The Cannonball Formation and its continental equivalent, the Ludlow Formation, constitute the lower part of the Paleocene Fort Union Group. Overlying formations of this group are the Tongue River and Sentinel Butte. Underlying the Cannonball-Ludlow strata is the Hell Creek Formation of Late Cretaceous age.

Distribution

In North Dakota, the Cannonball Formation probably occurs throughout most of the western one-half of the state (fig. 1). It has been positively identified as far east as northwestern Kidder County, as far west as western Slope County, and as far north as northeastern Bottineau County (pl. 4). It crops out primarily in the south-central part of the state in the drainage of the Missouri River, mainly along its western tributaries—the Heart and Cannonball Rivers and Cedar Creek. Outcrops are sparse in the southwestern part of the state; in the Little Missouri Valley, the unit is exposed as two, thin brackish tongues (pl. 2, sec. 8; fig. 2H, I). Small, scattered outcrops also occur in the Souris River area. Elsewhere, the Cannonball is largely concealed by younger bedrock, or glacial drift, or both.

In South Dakota, the Cannonball is restricted to the northwestern part of the state in northeastern Harding (Bolin, 1956; Denson, Bachman, and Zeller, 1959, p. 21 and pl. 1; Stevenson, 1956b, 1957), northern Perkins (Bolin, 1955, 1956; Curtiss, 1955; Denson, Bachman, and Zeller, 1959, p. 21 and pls. 1, 10; Stevenson, 1954c-d, 1956a-b), and northwestern Corson (Stevenson, 1954a-b) Counties. It is likely that a 100-foot

Table 1. Stratigraphic data of the Cannonball Formation.

Location	County	Well or outcrop	Surface elevation[a]	Depth to top of Fm.	Thickness[a]				Source
					Total	Sandst.	Mudst.	Carb.	
21-14-2,3,10;11; 22-14,14,15,22, 23,26,27,34,35	Perkins(S.D.)	Outcrop	--	--	155	117	37	1	Hall(1958, p. 49-50)
22-12-4	Perkins(S.D.)	Outcrop	--	--	108	61?	39?	0?	Hall(1958, p. 50)
129-98-32 (& 23-9-23,24)	Adams and Perkins(S.D.)	Outcrop	--	--	72	56?	10?	0	Hall(1958, p. 51)
129-100-21cc	Bowman	Outcrop	--	--	58[b]	56?	2?	0	Hall(1958, p. 52)
130-90-28-32,33	Sioux	Outcrop	--	--	212[b]	134?	52?	1?	Hall(1958, p. 55-56)
131-82-13c	Sioux	Outcrop	2376	6 (top eroded)	227[b]	100?	102?	0?	Cvancara(1965, p. 318-324)
131-94-20cbc	Adams	NDSWC 4312[c]	2500	40	380	60	320	0	Croft(1974, p. 200)
131-99-34daa	Bowman	H&H Service	2760	213	227	29	198	0	Croft(1974, p. 218)
132-91-28ddd	Hettinger	NDSWC 3627	2469	243	360	64	296	0	Trapp(1971, p. 108-109)
132-93-22bcb	Hettinger	NDSWC 3525	2514	88	368	92	276	0	Trapp(1971, p. 114-115)
132-97-7cab	Adams	NDSWC 4313	2665	270	240	70	170	0	Croft(1974, p. 253)
133-88-32b-a	Grant	Outcrop	2303	--	197[b]	29?	169?	0?	Cvancara(1965, p. 285-288)
133-89-4dad	Grant	NDSWC 4484	2120?	31	329	155	174	0	NDSWC, unpub. data
133-97-34bbb	Hettinger	NDSWC 3556	2733	310	210	57	153	0	Trapp(1971, p. 152-153)
134-81-6,7; 134-82-1,12; 135-82-36	Morton	Outcrop	--	--	270[b]	139?	108?	1?	Hall(1958, p. 57-58)
134-85-21bab	Grant	NDSWC 4516	2200	53 (top eroded)	213	82	131	0	NDSWC, unpub. data
134-91-31ccc	Hettinger	NDSWC 3527	2378	196	385	142	243	0	Trapp(1971, p. 157)
134-94-8dcc	Hettinger	NDSWC 3629	2465	435	288	51	237	0	Trapp(1971, p. 172)
134-97-15ccc	Hettinger	NDSWC 3555	2677	413	154	23	131	0	Trapp(1971, p. 191)
135-86-15ddd	Grant	NDSWC 4515	2231	82	321	83	238	0	NDSWC, unpub. data
135-93-12ccc	Hettinger	NDSWC 3553	2438	357	253	63	190	0	Trapp(1971, p. 205)
135-97-4dca	Hettinger	NDSWC 3628	2567	551	174	43	131	0	Trapp(1971, p. 219)
135-104-14ca, 135-105-10cc	Slope	Outcrop	2760 (top Cannonball)	--	25	0	25	0	Cvancara(1965, p. 251-255), Van Alstine(1974, p. 86-89)
136-78-28	Emmons	Outcrop	--	--	115[b]	90?	1?	?	Hall(1958, p. 62-63)
136-79-8c	Morton	Outcrop	2008	2 (top eroded)	126[b]	52?	74?	0	Cvancara(1965, p. 327-330)
136-83-13d	Morton	Outcrop	--	--	275	49?	200?	0	Mod. fr. Laird and Mitchell (1942, p. 36-37); Hall(1958, p. 38-39)

Table 1. Stratigraphic data of the Cannonball Formation (cont.).

Location	County	Well or outcrop	Surface elevation[a]	Depth to top of Fm.	Thickness[a] Total	Sandst.	Mudst.	Carb.	Source
136-87-36abd	Grant	NDSWC 4486	1900	40 (top eroded)	185[b]	37?	148?	0	NDSWC, unpub. data
136-88-13aaa	Grant	NDSWC 4513	2191	160	303	58	245	0	NDSWC, unpub. data
137-86-3aad	Morton	NDSWC 4752	1970	128	237	48	189	0	NDSWC, unpub. data
137-88-21ddc	Grant	NDSWC 4485	2110	220	272	0	272	0	NDSWC, unpub. data
137-89-9aba	Grant	NDSWC 4511	2305	535	286	110	176	0	NDSWC, unpub. data
137-94-4cbc	Stark	NDSWC 3542	2545	667	133	111	22	0	Trapp(1971, p. 266)
137-96-22ccc	Stark	NDSWC 3534	2640	572	146	99	47	0	Trapp(1971, p. 277)
137-98-12bbb	Stark	NDSWC 3693	2744	657	117	105	12	0	Trapp(1971, p. 280)
138-83-10d	Morton	Outcrop	1977	--	213[b]	73?	140?	0?	Cvancara(1965, p. 335-342)
138-92-32ddd	Stark	NDSWC 3547	2352	681	208	59	149	0	Trapp(1971, p. 288-289)
138-99-24ccc	Stark	NDSWC 3690	2620	625	150	68	82	0	Trapp(1971, p. 303)
139-83-12dba	Morton	NDSWC 4751	1960	114	270	69	198	3	NDSWC, unpub. data
139-85-30aab	Morton	NDSWC 4651	2065	280	245	50	195	0	NDSWC, unpub. data
139-88-34bcc	Morton	NDSWC 4753	2070	300	230	0	230	0	NDSWC, unpub. data
139-91-11dcd	Stark	N.D. Hwy. Department	2432	863	105	0	105	0	Trapp(1971, p. 305-306)
139-95-1dda	Stark	N.D. Hwy. Department	2312	780	123	4	119	0	Trapp(1971, p. 328)
139-98-13ddd	Stark	NDSWC 3540	2517	651	199	71	128	0	Trapp(1971, p. 358)
140-76-18bbc	Burleigh	USGS 1935[d] (& outcrop)	--	–	275	--	--	--	Kume & Hansen(1965, p. 46)
140-88-16adb	Morton	NDSWC 4754	2280	570	202	70	132	0	NDSWC, unpub. data
141-81-12d	Burleigh	Outcrop	1728	22 (top eroded)	47[b]	29?	18?	0	Cvancara(1965, p. 347-349)
141-90-19ccd	Mercer	NDSWC 3433	2080	667	211	45	166	0	Trapp(1971, p. 407-408)
141-92-27ccc	Stark	NDSWC 3545	2163	663	147	72	75	0	Trapp(1971, p. 413)
141-96-29ccc	Dunn	NDSWC 4529	2483	962	258	154	104	0	NDSWC, unpub. data
142-81-4adc	Burleigh	USGS 1984 (& outcrop)	–	--	340?	--	–	--	Kume & Hansen(1965, p. 46)
142-82-5daa	Oliver	NDSWC 3647	1955	204	316[b]	40?	276?	0	Croft(1970, p. 78)
142-84-24bba	Oliver	NDSWC 4312	2006	484	212	28	184	0	Croft(1970, p. 84)
142-86-20bba	Oliver	NDSWC 3559	2062	658	167	0	167	0	Croft(1970, p. 89)
142-92-9dab	Dunn	NDSWC 4467	1990	780	255	20	235	0	NDSWC, unpub. data
143-73-18ab	Kidder	Outcrop	–	--	?	?	?	?	Rau et al (1962, p. 8), Cvancara(1965, p. 55)
143-85-3dad	Oliver	NDSWC 3557	1988	440	200	41	159	0	Croft(1970, p. 106)

Table 1. Stratigraphic data of the Cannonball Formation (cont.).

Location	County	Well or outcrop	Surface elevation[a]	Depth to top of Fm.	Thickness[a] Total	Sandst.	Mudst.	Carb.	Source
144-82-14	McLean	Outcrop	--	--	55[b]	34?	21?	0?	Hall(1958, p. 60)
145-95-22dad	Dunn	NDSWC 4468	2235	904	256	122	134	0	NDSWC, unpub. data
146-84-5?	McLean?	US Army Engrs.	--	200+	395?	?	?	0	Fox & Olsson(1969, p. 1397, 1399)
146-85-10cbb	Mercer	NDSWC 3560	2041	556	228	0	228	0	Croft(1970, p. 229)
146-90-20ccc	Mercer	NDSWC 3575	2120	960	160	0	160	0	Croft(1970, p. 238)
147-78-34	Sheridan	Outcrop	--	--	40?[b]	38?	2?	0?	Sherrod(1963, p. 47)
148-97-33a	Dunn	NDSWC 4478	1920	762	144	45	95	4	NDSWC, unpub. data
152-77-5b	McHenry	Outcrop	--	--	5[b]	?	?	?	Lemke(1960, p. 29, 62)
153-80-16c	McLean	Outcrop	1535	1 (top eroded)	43[b]	3?	40?	?	Lemke(1960, p. 31), Cvancara(1965, p. 349-352)
154-96-12ccb	Williams	NDSWC test	1885	325	60?[b]	44?	16?	0?	Armstrong(1967, p. 64)
155-85-4c	Ward	Blum 1	1985	598	322?	60?	262?	0	Mod. fr. Lemke(1960, p. 20)
157-85-16d	Ward	J.H. Kline 1	1679	350	330?	106?	224?	0	Mod. fr. Lemke(1960, p. 11)
158-73-29ccc	Pierce	USBR[e]	1484	76 (top eroded)	10?[b]	0?	10?	0?	Randich(1971, p. 347)
158-74-21aab	Pierce	USBR	1478	38 (top eroded)	12?[b]	12?	0?	0?	Randich(1971, p. 348)
163-76-17d	Bottineau	Outcrop	--	--	?	?	?	?	Lemke(1960, p. 28, 31)
163-101-35cbb	Divide	USGS 3075	2265	500?	165?[b]	?	?	?	Armstrong(1965, p. 98)

[a]In feet

[b]Section incomplete

[c]N. Dak. State Water Commission

[d]U.S. Geol. Survey

[e]U.S. Bur. Reclamation

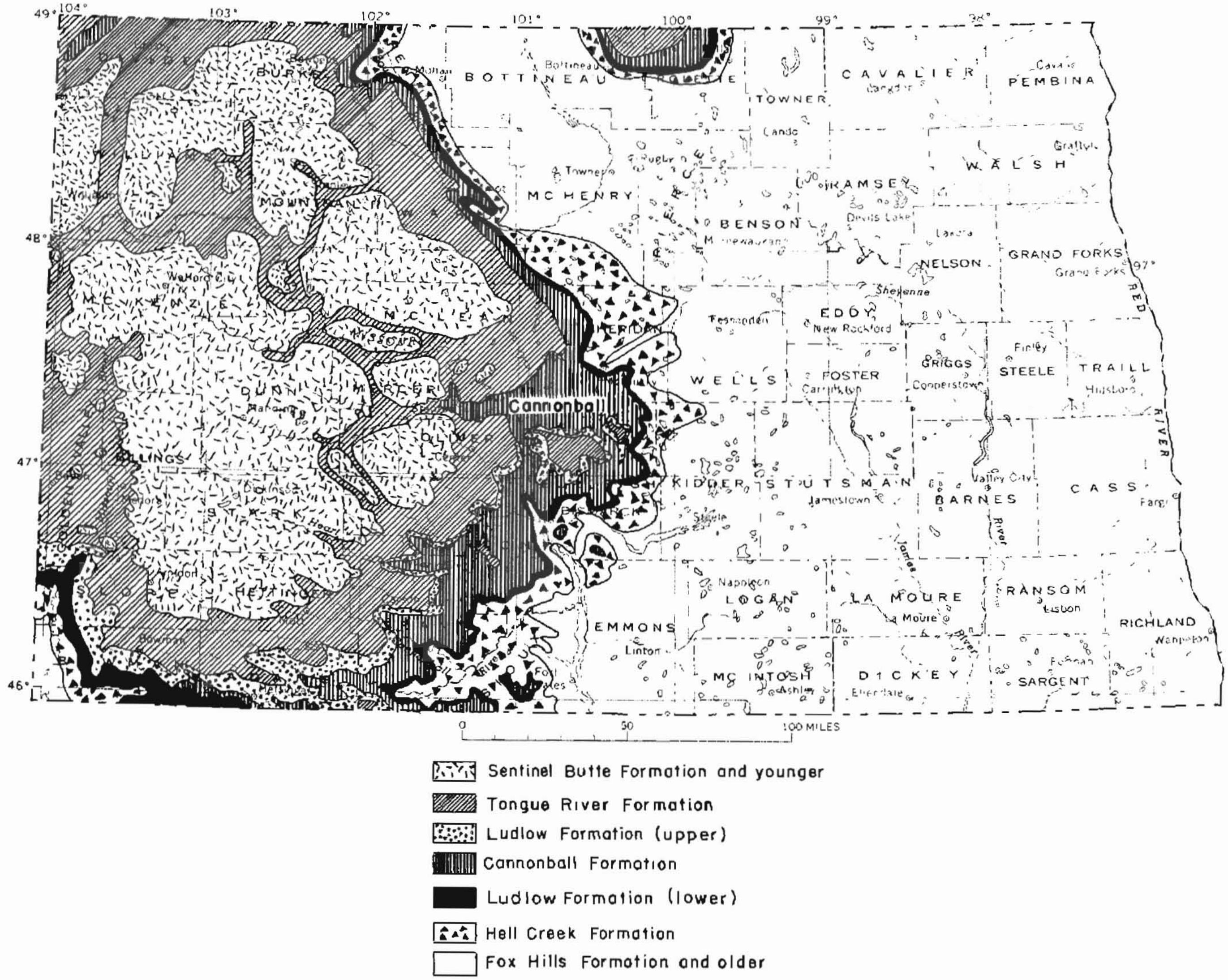

Figure 1. Geologic map of Cannonball Formation and adjacent rock units in North Dakota (modified from Carlson, 1973 by Carlson, October, 1975).

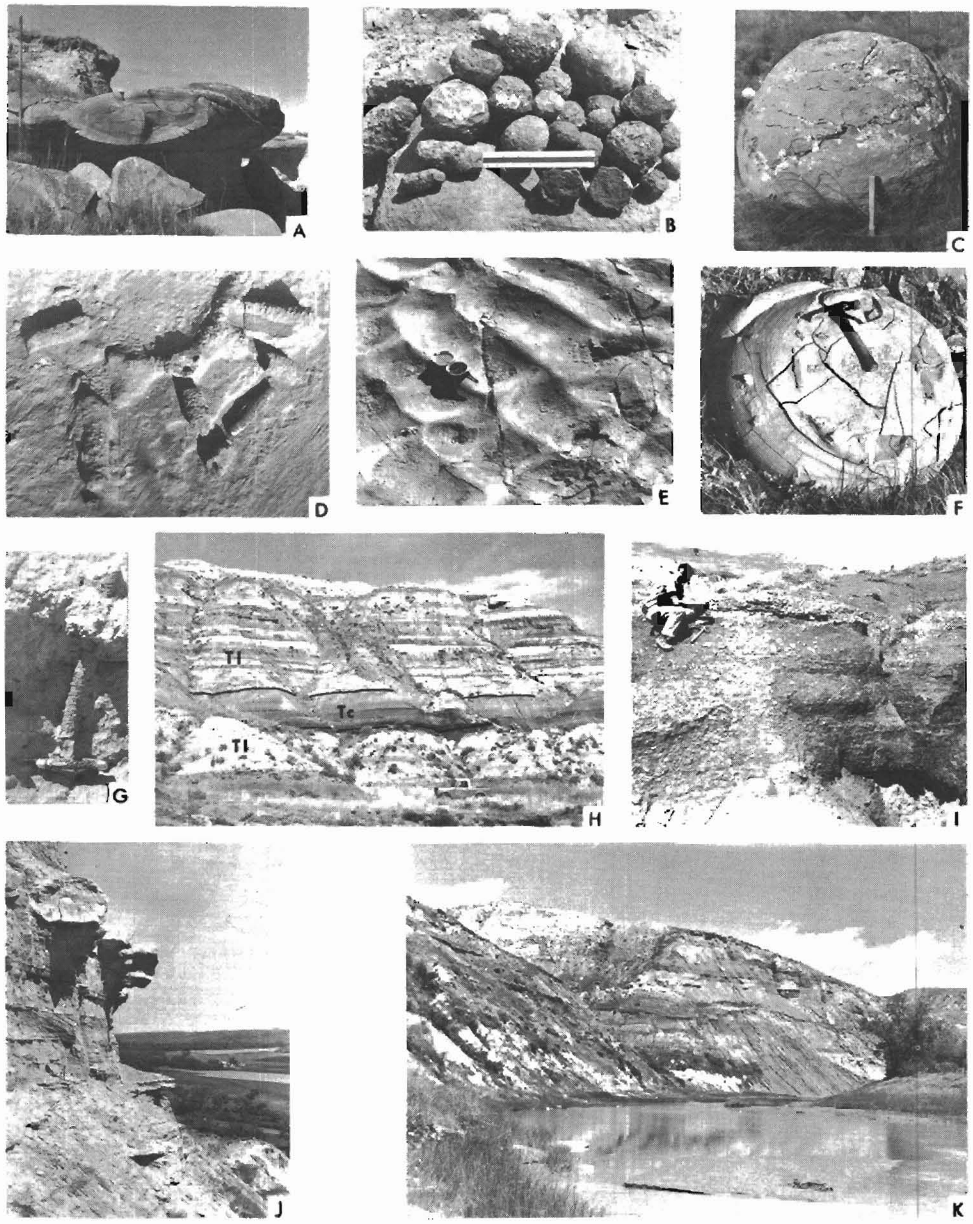

Figure 2. Sedimentary and organic structures, and exposures of Cannonball Formation in North Dakota. A, lenticular, well indurated sandstone, 6.6 air miles south-southeast of Leith (132-87-9bd); June 29, 1962. B, well indurated, phosphatic, sandstone concretions, 6 air miles east-northeast of Flasher (135-83-21db); July 17, 1962. C, "cannonball," sandstone concretion, 3 miles west-southwest of Raleigh (133-85-9ac); June 27, 1962. D, *Ophiomorpha* sp. parallel to bedding, northeast road cut exposure, 2.6 air miles south-southeast of Elgin (133-89-2b); specimen is in lowest *Ophiomorpha* occurrence of section 1 (fig. 3); pocket knife handle is 3.25 inches long; August 26, 1962. E, interference current ripple marks in lenticular, well indurated sandstone, 6.3 air miles south-southeast of Leith (132-87-9b); most pronounced set of ripples trends N. 2° E.; June 29, 1962. F, "cannonball," sandstone concretion with *Ophiomorpha* sp., 6.6 air miles southeast of Leith (132-87-3db); hammer handle is 10 inches long; July 4, 1962. G, *Ophiomorpha* sp. normal to bedding, east bank of Timber Creek, 11.2 air miles north of Thunderhawk (130-90-9bb); pocket knife handle is 3.25 inches long; August 11, 1961. H, upper tongue of Cannonball Formation (Tc) within Ludlow Formation (Tl) (pl. 2, sec. 8), southwest-facing exposure about 0.5 mile west of Little Missouri River, 15.4 air miles north-northeast of Marmarth (135-105-10cc); light streak just below "Tc" is 6-inch-thick oyster bed; August 7, 1962. I, close-up of bed of oyster *Crassostrea glabra* (Meek and Hayden) at same site as for fig. 2H; darkest lithology below oyster bed is 2-foot-thick lignite bed directly overlying light gray claystone; August 7, 1962. J, lenticular, well indurated sandstone overlying poorly consolidated, crossbedded sandstone, 12 air miles west-southwest of Mandan (138-83-11cc); July 13, 1962. K, thickest, well-exposed section of Cannonball Formation (fig. 3, sec. 4), 12.2 air miles west-southwest of center of Mandan (138-83-10dd); exposure is 0.25 mile west of site shown in fig. 2J, and resistant sandstone at top of south-facing cutbank is same as that in fig. 2J; July 11, 1962.

sandstone placed in the lower Tongue River Formation (Pipiringos, Chisholm, and Kepferle, 1965, p. A8-A11, A22) in the Cave Hills of north-central Harding County represents the Cannonball Formation farther southwest than known previously.

Elsewhere, the Cannonball Formation has not been recognized. Its presence, however, has been suggested in extreme southeastern Saskatchewan and southwestern Manitoba (Taylor, Mathews, and Kupsch, 1966, p. 191-192).

Lithology and Sedimentary Structures

Two principal types of lithology occur—sandstone and mudstone, both poorly consolidated. In North Dakota, the mudstone generally predominates; the sandstone beds are also relatively thin, usually about 45 feet thick and less. In South Dakota, however, sandstone appears to predominate (e.g., Hall, 1958, p. 49-51; Stevenson, 1956a) (pl. 4). The zero sandstone percentage value is deceiving at section 8 (pl. 2) in western Slope County. About 2.8 miles to the northeast, at least 6.5 feet of Cannonball sandstone occurs (Van Alstine, 1974, p. 82).

The sandstone is generally grayish green where moist and fresh and weathers light to medium brownish yellow where dry. It contains neglible to appreciable silt and clay and forms steeper slopes where the silt and clay content is higher. The sandstone is usually very fine- to fine-grained, largely of quartz, micaceous, and generally with about 1-2% glauconite. Planar, tabular crossbedding (fig. 2J) is relatively common, in sets of a few inches to generally a maximum of about 10 inches. Gypsum fills fractures, which are parallel, oblique, or normal to the bedding, or occurs as common, individual selenite crystals. Small marcasite nodules are common.

Within the poorly consolidated sandstone in outcrop are common lenticular and concretionary beds and concretions that are the carbonate-cemented equivalent of this rock type. These structures, however, have not been commonly reported in the subsurface data. The indurated sandstone is usually light to medium bluish green to greenish gray where fresh and weathers light to medium brownish yellow. Small, brown and black, lignitic plant fragments are generally present. The lenticular (fig. 2A, J) and concretionary beds are usually 2-2.5 feet thick but may be up to 6 feet thick. I have observed oscillation and interference ripples (fig. 2E) in these beds at three localities in Grant County (Cvancara, 1965, p. 39-40) and one in Morton County (Heart River, on line common to secs 19 and 24, T139, Rs 81 and 82). Larger (up to 2.5 feet in the shortest dimension) sandstone concretions are generally flattened-subspherical (nearly spherical types are rare; fig. 2C, F) and of a composition similar to that of the lenticular beds; fossils are uncommon to rare. Cone-in-cone structure rarely forms a peripheral layer surrounding these concretions. Smaller (mean diameter about 2.5 inches) sandstone concretions, subspherical to fusiform (fig. 2B), are phosphatic (Holland and Cvancara, 1958, p. 498), and medium grayish brown on fresh surfaces and weather light yellowish gray to light grayish yellow. Crabs are most conspicuous in these concretions, but mollusks, shark teeth, and other vertebrate and wood fragments also occur. Indurated claystone also occurs in the poorly consolidated sandstone, as small (few inches in the smallest dimension) nodules and lenticular beds up to 0.5 foot thick. As the claystone beds weather they form a characteristic rubble of yellowish to dark orange yellow "chips" on the surface of exposures.

Mudstone is the other major lithology; it has been called shale by most workers, but I prefer "mudstone" because the rock is nearly always blocky and lacks fissility. This mudstone is usually medium to very dark gray on moist and fresh surfaces and light gray on dry, weathered surfaces. It is generally sandy and micaceous; the main clay minerals are montmorillonite and illite with smaller amounts of kaolinite and possibly chlorite (Fenner, 1974, p. 17, 18, 33; based on 5 samples from 3 outcrop sections in Morton and Grant Counties). The mudstone is commonly thinly interbedded with lenticular beds of silt or very fine- to fine-grained, commonly crossbedded sandstone. The contact of this rock type with the poorly consolidated sandstone is usually gradational, and interbedding occurs in places. Selenite crystals and marcasite nodules are common. Mudstone concretions, the carbonate-cemented equivalent of this rock type, are common. They are usually flattened and of a size similar to that of the sandstone concretions; light to medium gray to medium bluish gray on fresh surfaces, they weather light gray to medium brownish-yellow. Small, black and brown lignitic plant fragments are common to abundant but other fossils occur sparingly. Limestone concretions, up to 2 feet "thick," also occur in the mudstone; they are dark bluish gray to nearly black on fresh surfaces and weather light whitish gray. Fossils, mainly mollusks, occur more commonly in these limestone concretions than in any other type. A lesser carbonate content results in a mudstone rather than a limestone concretion. Presumed clastic dikes and sills occur in the upper part of a mudstone at a south-facing bluff exposure in southern Grant County (132-88-11b). These structures are about 1 foot thick (or wide), occur parallel and oblique to the bedding, and are of fine-grained sandstone similar to that of the overlying unit.

Considerable variation occurs within the basic lithologic types. The sandstone may be very clayey, or strikingly green so as to be termed a "greensand"; the "greensand," however, is usually relatively thin and less persistent than the characteristically grayish-green sandstone. The mudstone may be mottled, a combination of light to medium grayish tan or grayish green and medium gray where fresh and moist, and light gray or light grayish to brownish yellow where weathered and dry. Mottling seems to be accompanied by more silt than sand in the non-clay fraction. Sandstone and mudstone may be combined in varying proportions; this results in a gradual change from one rock type to another or interbedding, whereby each bed may be less than 1 inch or more than several feet thick.

Lindberg (1944) studied the heavy minerals from 23 samples from 4 sections in the lower Cannonball from both sandstone and mudstone. Of 17 minerals identified, green amphibole was dominant. For comparison with other units, the Fox Hills Formation was also characterized by green amphibole, whereas the Hell Creek and Ludlow Formations were characterized by high percentages of epidote, garnet, and sphene. Denson and Gill (1965, p. 24-26) found the Hell Creek (2 samples) characterized by a preponderance of opaque minerals and epidote, the Ludlow (8 samples) with abundant garnet and a low percentage of opaque minerals, and the Tongue River (lower, 33 samples) with abundant opaque minerals and abundant garnet, zircon, and tourmaline. From one sandstone sample in the Cannonball in McHenry County, Lindberg (in Lemke, 1960, p. 32) identified 13 heavy minerals, of which garnet, epidote, and zircon occurred in the highest percentages.

Persistence of Lithologic Units

Although much of the bedding is lenticular, certain of the thicker units are relatively persistent in places. In southern Morton County, at least three laterally traceable sandstones, separated by mudstones and forming topographic benches, have been recognized: the lowest is 75-89 feet above the base of the formation, the middle one is about 104 feet above the lowest, and the highest is about 65 feet above the middle one (Laird and Mitchell, 1942, p. 19). I have traced what appears to be the middle sandstone unit for about 60 miles from east-central Sioux to northwestern Burleigh County (Cvancara, 1965, fig. 7). Also, this unit seems to be traceable farther westward into Grant County (Cvancara, 1965, fig. 6). I have also traced what appears to be the upper sandstone unit for more than 40 miles from east-central Sioux County to northeastern Morton County (Cvancara, 1965, fig. 7). Hall (1958, p. 18-21) subdivided the Cannonball into three unnamed members encompassing 20 units of alternating sandstone and siltstone; each of the members contains one of the bench-forming sandstones of Laird and Mitchell (1942). Hall said his 10 units are generally recognizable within the outcrop area of the Cannonball in Morton, Grant, and Sioux Counties, and only the upper four units are relatively persistent to the west. I question, however, the validity and stratigraphic usefulness of subdividing the formation into so many units (see Hall's pls. 3-5).

In the subsurface, away from the main area of exposure in Morton, Grant, and Sioux Counties, there seems to be a decreasing persistence of recognizable lithologic units (pls. 1-3). The middle sandstone unit of Laird and Mitchell (1942), however, may extend as far to the southwest as north-central Adams County (pl. 3, well 15).

Contacts

Defining and recognizing contacts of the Cannonball Formation is troublesome as with many rock units. Being a marine unit, it has been recognized so as to exclude lignites, but its specific boundaries cannot always be consistently drawn.

As for the lower contact, which seems to be consistently conformable, Lloyd and Hares (1915, p. 536) said: "No definite line could be drawn in the field between the Cannonball marine member and the lower part of the Lance [= Ludlow and Hell Creek Formations]. The contact of the two groups of strata is exposed at only a few places, and in all cases it seems to be impossible to tell where the beds of non-marine origin stop and those of marine origin begin." However, in three representative sections (p. 532-534), lignite or brownish shale were considered as directly underlying the basal beds of the Cannonball. Following this practice, most workers (e.g., Laird and Mitchell, 1942; Hall, 1958; Cvancara, 1965) have generally placed the lower contact above the highest lignite or lignitic or carbonaceous shale (fig. 3, sec. 7). I have attempted to follow this approach in this report, but in certain wells (e.g., pl. 3, wells 18 and 19) lignite or lignitic shale was absent so the lower contact was chosen arbitrarily.

Both disconformable and conformable relationships occur at the upper contact. A contact relationship of thinly interbedded mudstone and sandstone of the Cannonball presumably disconformably overlain by a "basal," massive Tongue River sandstone has been recognized in several places, as in Burleigh (Kume and Hansen, 1965, p. 47), Mercer and Oliver (Carlson, 1973, p. 22-23), and McLean (Bluemle, 1971, p. 12) Counties. A different disconformable relationship exists also, as exemplified on Heart Butte Creek just above its mouth (fig. 3, sec. 2) in northern Grant County. Here, a "basal," poorly consolidated sandstone with a poorly consolidated sandy conglomerate of the Tongue River Formation overlies a poorly consolidated, Cannonball sandy mudstone with a sharp and irregular contact. Lloyd and Hares (1915, p. 538) have observed similar "channel sandstones" overlying Cannonball strata at other localities. Presumed conformable contacts also occur, as at two localities (fig. 3, secs. 1 and 3) in Grant County; at both localities Cannonball sandstone passes gradually into overlying Tongue River sandstone. Little superficial difference is apparent between the two sandstones, except that of the Tongue River, which weathers to a lighter color (light grayish yellow versus light to medium brownish yellow for the Cannonball sandstone), appears less well sorted, and is slightly coarser. Whatever the contact relationships, it has been common practice to recognize a lower or "basal" Tongue River sandstone overlying the Cannonball beds as was done initially (Lloyd and Hares, 1915, p. 538). I have generally followed this practice in this report (e.g., pl. 2, well 12), although a "basal" sandstone may contain beds of finer clastics as well (e.g., pl. 3, well 19). Where Ludlow strata overlie those of the Cannonball, the upper Cannonball contact is difficult to place with consistency, especially because of uncertainty as to how far the upper Ludlow can be recognized eastward (pls. 2 and 3; fig. 1).

Thickness

As presently known, the thickest area of Cannonball seems to occur in northeastern Adams, southeastern Hettinger, and western Grant Counties just

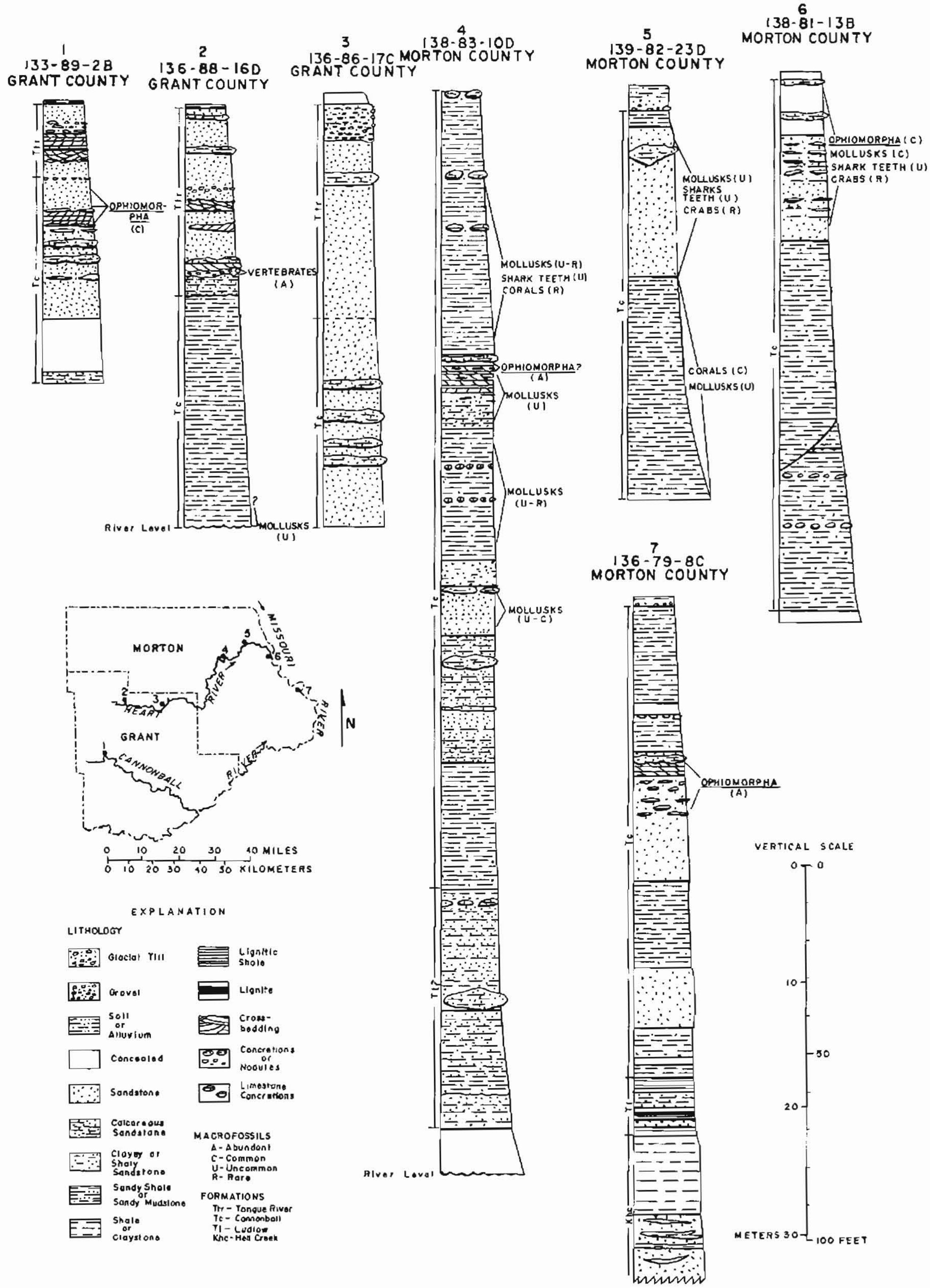

Figure 3. Selected outcrop sections of Cannonball Formation and adjacent rock units in Grant and Morton Counties, North Dakota (modified from Cvancara, 1965, figs. 3-5).

west of the type area of the formation; the thickest sequence recognized is 385 feet in NDSWC well 3527 (134-91-32ccc) in southeastern Hettinger County (pl. 4). A thicker value of 395 feet was reported by Fox and Olsson (1969) at Garrison Dam, but I question this value. The Cannonball thins to the south, west, and generally to the north from the thick area just described but thickens in Dunn County. The few questioned thickness values in Burleigh and Ward Counties (pl. 4) imply a thickening to the east and north of the Missouri River. In western Slope County (pl. 2, sec. 8; fig. 2H) the formation is represented by two tongues with an aggregate thickness of only 25 feet. The thickest outcrop section is in southern Morton County (136-83-13d) and reported (Laird and Mitchell, 1942, p. 36-37) as about 307 feet thick. I have considered the lowest 25 feet to be in the Ludlow. This section, however, is very poorly exposed. The thickest, well-exposed, noncomposite outcrop section, although incomplete, is on the Heart River in northern Morton County (fig. 3, sec. 4 and fig. 2K) where at least 213 feet of the formation are present (the lower 76.2 feet of the exposed section may be in the Ludlow Formation).

STRUCTURE

Little structural information is available for Cannonball strata, but considerable data exist for Late Cretaceous and Tertiary rocks in general. The single main structural feature affecting surficial bedrock in western North Dakota is the north-northwest trending Williston basin; primary anticlines within the basin are the northwest-trending Cedar Creek (southwesternmost part of state) and the north-trending Nesson (northwestern part of state) anticlines. Superimposed on the basin are numerous other anticlines, synclines, joints, and faults (Osterwald and Dean, 1957). Ballard (1942, p. 1568), using the top of the "Dakota Sandstone" as datum, showed the center of the basin about 50 miles southeast of the city of Williston. Benson (1952, p. 228), however, believed that structure contours on the top of Tertiary strata would show the basin's center farther east.

Dips toward the center of the Williston basin are generally less than 1°; on the asymmetrical Cedar Creek anticline, however, they are considerably greater. Hares (1928, p. 44), measuring dips on the Fox Hills Sandstone, reported 5°-20° on the southwest limb and 3° or less on the northeast limb. Dips on the flanks of the Nesson anticline are on the order of 71 feet per mile (Anderson, 1969). In much of the basin the regional dip is 10-20 feet per mile with considerable variation above and below this range depending on specific place (Anderson, 1969) and stratigraphic position.

In southwestern North Dakota, some distance from the axis of the Cedar Creek anticline, the average dip is 26 feet per mile to the northeast (Hares, 1928, p. 45, using lignite beds in the Ludlow and Tongue River Formations). Kepferle and Culbertson (1955, p. 137), working in the same general area, calculated a regional dip of 25-50 feet per mile to the northeast and north.

In northwestern South Dakota, within the area of Cannonball outcrops, the dip direction varies from northeast to northwest toward the center of the Williston basin (Petsch, 1953; structure contours on top of Upper Cretaceous Greenhorn Formation). The regional dip is generally 7-30 feet per mile, although values of 40-50 feet per mile (up to 65 feet per mile according to Winchester and others, 1916, p. 36) are known. Minor folds and faults, generally with amplitudes and displacements of less than 20 feet, are superimposed on the regional structure (Bolin, 1955, 1956; Curtiss, 1955; Stevenson, 1954a-d, 1956a-b).

In south-central North Dakota, the regional dip is generally to the northwest. In southern Morton County, using the base of the Ludlow as a datum, Laird and Mitchell (1942, p. 38, pl. 2) found an average regional dip to the north and northwest of 15 feet per mile. Small domes and noses, nearly at right angles to the regional strike, are also present. The structure is similar in north-central Morton County where the regional dip is 5-10 feet per mile to the northwest but with numerous, superimposed local irregularities (Hancock, 1921, p. 11). In Burleigh County, the regional dip, based on elevations of the Tongue River-Cannonball contact, is to the west and northwest at an estimated 12-14 feet per mile (Kume and Hansen, 1965, p. 46). To the south in Emmons County, the regional dip is 10-20 feet per mile (although dips up to 50 feet per mile are common) to the northwest as based on elevations on a datum in the uppermost Fox Hills Sandstone (Fisher, 1952, p. 29).

In the Knife River area of west-central North Dakota (most of Mercer and parts of McLean, Dunn, and Stark Counties), the structure has been determined from elevations on a Tongue River lignite bed (Benson, 1952, p. 228-236). In the southern part of the area the regional dip is to the north to northwest at an average of 15 feet per mile. In the northern part, the beds are nearly flat with a slight dip to the west. Several local structures are superimposed on the regional structure, the larger being east-trending synclines and anticlines. Near the axis of the Williston basin in the Fort Berthold Indian Reservation, the regional dip is generally to the northeast at an average of less than 8 feet per mile, as based on elevations on Tongue River lignite beds (Bauer and Herald, 1921, p. 117-118).

In the Souris River area of north-central North Dakota, structure at depth may differ considerably from that at or near the surface. The regional dip in western Bottineau and Renville Counties is about 16 feet per mile to the southwest, as gained from structure contours at the top of the Pierre Formation (Anderson, 1969). However, younger Late Cretaceous and Tertiary rocks may lie within a broad, shallow, northwest-trending shallow syncline lying between the Coteau du Missouri and the Turtle Mountains; its axis is nearly coincident with the east loop of the Souris River. On this syncline are superimposed minor folds and undulations. Steepest dips occur near the escarpment of the Coteau, and within 10 miles away the beds are nearly horizontal (Lemke, 1960, p. 104-108).

In northwesternmost North Dakota the regional dip is about 21 feet per mile to the south-southeast (Anderson, 1969).

PALEONTOLOGY

Fossil Groups

The Cannonball biota consists of foraminiferids (Fenner, 1974; Fox and Olsson, 1969; Fox and Ross, 1942; Van Alstine, 1974), corals (Vaughan, 1920; Wilson, 1957), bryozoans (Cvancara, 1965), mollusks (Cvancara, 1966, 1970a; Feldmann, 1972; Stanton, 1920; Van Alstine, 1974), ostracodes (Swain, 1949), crabs (Holland and Cvancara, 1958), lobsters (Feldmann and Holland, 1971), the crustacean burrow *Ophiomorpha* (Cvancara, 1965; Van Alstine, 1974; fig. 2D, G), rhizocorallid burrows (R. C. Holtzman, University of Minnesota; letter dated December 17, 1973), sharks (Leriche, 1942; Stanton, 1920), skates, rays, turtles, and crocodiles or alligators (Cvancara, 1965), dinoflagellates, hystrichosphaerids, spores, and pollen (Stanley, 1965; Robertson, 1975, p. 94-95) and driftwood (Cvancara, 1970b). Mollusks, mainly bivalves and gastropods in about equal numbers and relatively fewer other mollusks, are the most frequently occurring macrofossils; foraminiferids are the most frequently occurring of the larger microfossils.

Occurrence of Fossils

Fossils are not generally abundant within the Cannonball but may be so locally. Macrofossils occur throughout the formation but more frequently in sandstones than in mudstones. Concretions, especially those of limestone, contain macrofossils but do not represent such concentrations as do those of the Late Cretaceous Pierre and Fox Hills Formations. Macrofossils occur most abundantly in poorly consolidated, dark grayish green to greenish gray, clayey, glauconitic sandstone. Generally, macrofossils are fewer or absent in thinly interbedded (beds few inches or less thick) sandstone and mudstone.

A generalized macrofossil zonation

appears to exist, at least within the principal area of outcrop in southwest-central North Dakota (fig. 1). Most macrofossils occur in two units or zones, each of mainly poorly consolidated sandstone with well indurated, lenticular sandstone beds or concretions. Both zones occur near the middle of the formation (Cvancara, 1965, figs. 6 and 7). The lower zone is in the lower middle or lower part of the formation and contains most of the mollusks; crabs are rare. The upper zone occurs in the upper middle or upper part of the formation and contains fewer mollusks; crabs appear to occur more frequently here than in the lower zone. Other macrofossils appear to be about equally distributed in both zones.

Of the microfossil occurrences, that of the foraminiferids is best known. Foraminiferids occur primarily in mudstones and more commonly near the middle of the formation. Although foraminiferids occur through most of certain sections, they hardly ever have been found at or near the contacts of the formation (W. E. Fenner, oral communication, September, 1975; and pls. 2-4).

AGE AND CORRELATION

A Paleocene age for the Cannonball Formation has been arrived at from analysis of several fossil groups; however, specific age within the Paleocene is not yet established. Dorf (1940, p. 231) said the Ludlow Formation is Paleocene on the basis of plants; since the Cannonball interfingers with the Ludlow, it, too, is Paleocene. Brown (1962) corroborated a Paleocene age for the nonmarine strata of the Fort Union Group. Stanley (1965, p. 208), likewise, corroborated a Paleocene age for the Cannonball with dinoflagellates and hystrichosphaerids, and suggested (p. 206) an early Paleocene age with spores and pollen. Fox and Ross (1942) showed strong relationships of Cannonball foraminiferids with those of the Paleocene (Midway) species of the U.S. Gulf Coast. Jeletzky (1962, p. 1006-1007), citing the foraminiferal work of others, concluded the age of the Cannonball to be mainly Danian (early or early to middle Paleocene) but showed (his fig. 1) the upper part to be early Landenian (= Thanetian). (Usage of age names is after Berggren, 1972.) Fox and Olsson (1969), using planktonic foraminiferids, assigned an early Danian age to the Cannonball. Cvancara (1966, p. 281) indicated that the bivalves suggest a Thanetian (late or middle to late Paleocene) age. Sloan (1970, p. 441), on the basis of mammals in nonmarine strata overlying the Cannonball or its presumed equivalent, gave an age of about Puercan to Torrejonian (early or early to middle Paleocene). Recent study of fossil mammals from essentially the base of the Tongue River Formation in Grant and Morton Counties indicates a middle late Paleocene (middle Tiffanian) age (R. C. Holtzman, University of Minnesota; letter to C. G. Carlson, North Dakota Geological Survey, dated October 15, 1975) for this part of the formation and a similar age for at least the upper Cannonball.

In the U.S. Atlantic Province Paleocene (Midwayan) brackish or marine rock units that may be at least partially time equivalent to the Cannonball are the Brightseat, Hornerstown, and possibly Aquia and Vincentown Formations. In the Gulf province, selected possible equivalents are the Cedar Keys (Georgia, Florida); Clayton, Porters Creek, and Naheola (Alabama, Mississippi); Kincaid and Wills Point (Texas, Arkansas); and Velasco and lower Chicontepec (Mexico) Formations (summarized by Murray, 1961, p. 367-373). The nearest marine presumed equivalents of the Cannonball Formation are the Clayton and Porters Creek Formations in southeastern Missouri and southernmost Illinois, almost 900 miles to the southeast (Pryor and Glass, 1961; Stearns, 1957). Another possible correlative is the Waltman Shale Member of the Fort Union Formation, 250 miles to the southwest (from the Cannonball in northwestern South Dakota) in the Wind River Basin of central Wyoming. It has been considered marine (or brackish) because of marine-type shark remains in equivalent strata of the Shotgun Member, the presence of hystrichosphaerids, and the widespread presence of glauconite, some of which formed in place. It is considered middle to late Paleocene in age (Keefer, 1967, p. A1, A10, A23-A35).

DEPOSITIONAL ENVIRONMENTS

The climate during the Paleocene in the northern Great Plains was probably warm temperate; this is in contrast to a presumed equable subtropical climate in the Late Cretaceous and early Eocene (based on plant macrofossil and microfossil data summarized by Sloan, 1970, p. 428-429). A north-south climatic zoning is also evident (Brown, 1962, p. 96). Precipitation was moderate, as suggested by the mesophytic flora (Brown, 1962, p. 96), and probably exceeded evaporation (Stanley, 1965, p. 214).

During the Late Cretaceous to Eocene, the Rocky Mountain region was disturbed by the Laramide orogeny that resulted in the uplift of ranges from northern New Mexico into Canada. Sediments derived from these ranges accumulated in adjacent restricted basins and in the plains to the east. During the Paleocene, considerable sedimentation occurred, most of it nonmarine (Robinson, 1962, p. 233, 237). The notable marine exception is the sequence of the Cannonball Formation.

The terrain adjacent to the Cannonball sea was one of lowlands, as evidenced by the flora, extending hundreds of miles to the foothills and mountains (Brown, 1962, p. 95). The dominantly fine grain size of the Cannonball lithology—mostly very fine- to fine-grained sandstone and sandy mudstone—also suggests deposition of this formation adjacent to a lowland, similar to a low-sloping coastal plain. I envisage a setting similar to that of the coastal area of the Netherlands and part of northern Germany in the southern part of the North Sea. Here, a complex of sedimentary environments, including tidal flat, lagoon, beach, shoreface, and shelf is present (Klein, 1967; Reineck and Singh, 1973, p. 315-330, 355-370). The coast is directly exposed or protected by barrier islands (Frisian Islands) with a lagoon of variable width.

One type of sandstone of the Cannonball, on the order of 20 to 45 feet thick, is interpreted to be a barrier island (e.g., upper bench-forming sandstone in sec. 4, fig. 3; fig. 2J) or regressive shoreline sand deposit (e.g., sec. 1, fig. 3) (summary of characteristics of two kinds of deposits by Spearing, 1974). This sandstone type, overlying a mudstone with gradational contact or interbedded with it, generally becomes coarser grained upward. Sorting is good in the upper part, and rare to common mollusks, common to abundant *Ophiomorpha* (fig. 2D, G), and other fossils may be present. Planar, tabular, moderately high angle, tangential crossbedding (fig. 2J) is relatively common in the upper part of the section; other crossbedded sandstone (fig. 3, sec. 1) of the nonmarine Tongue River Formation may overlie the Cannonball sequence. Therefore, the shoreface, beach (foreshore and backshore), and dune environments may all be represented. More commonly, however, a mudstone directly overlies an *Ophiomorpha*-bearing, tabular crossbedded sandstone, and little evidence of the beach or dune environments has been observed in outcrop.

Mudstone underlying the presumed barrier island sandstone is in gradational contact with it and commonly contains sandstone interbeds. The mudstone is usually sandy as well and lenticular bedding (Reineck and Singh, 1973, p. 100) is common in places. Borings filled with sandstone may be present. This mudstone is interpreted to have been deposited primarily in the "transition zone" (= lower shoreface); the common sandstone interbeds were probably deposited during storms (Reineck and Singh, 1973, p. 285, 307-308).

As far as water depth for the sandstone-mudstone couplet, the crustacean burrow *Ophiomorpha* in well-sorted sandstone indicates intertidal or shallow subtidal depths, whereas the burrow in poorly sorted sandstone suggests somewhat greater depths (Weimer and Hoyt, 1964, p. 766). This is the principal trace fossil to have left a record in the shoreface environment of the Late Cretaceous of east-central Utah (Howard, 1971, p. 161), and such an environment is suggested for most of the well-sorted, *Ophiomorpha*-bearing sandstone of the Cannonball. Assuming minimal compaction and subsidence, the thickness of the sediments may be used to estimate water depth for the presumed barrier island sequences (Klein, 1974). From three outcrops in Morton County (fig. 3, secs. 4, 5, and 7), the presumed shoreface sand is 20-40 feet thick. Uncertain of whether the entire shoreface is represented at any of the outcrops, this still suggests a wave base of at least up to 40 feet in the area of the outcrops. Sandy mudstones underlying the sandstones are 23 to more than 59 feet at the three outcrops, suggesting deposition of the sandy mudstones in depths of up to about 100 feet, or perhaps more.

The presumed barrier island sandstones occur at two or more stratigraphic levels and form topographic benches that may be traced for several tens of miles as mentioned under Stratigraphy, Persistence of lithologic units. This implies repetitive progradation seaward, followed perhaps by subsidence and intervening transgressive pulses. Fluctuation of the strandline of the Cannonball sea is also indicated by at least two Cannonball tongues separated stratigraphically by about 130 feet of nonmarine Ludlow sediments in western Slope County (pl. 2, sec. 8). With seaward progradation, one would expect finer lagoonal sediments overlying the barrier island sequence. However, this does not seem to be the case for the Cannonball, at least in the area of outcrop. Mudstones overlying presumed barrier island or nearshore sandstones contain no clear evidence of brackish conditions. These mudstones are interpreted as the result of marine transgression following progradation, although these mudstones generally do not exhibit clear erosional basal contacts. (There is also the possibility that broad, deep lagoons with free access to the open sea could have served as areas of deposition for these mudstones.)

Mudstones of the Cannonball are generally sandy and perhaps few, if any, were deposited as deep-water, offshore shelf muds. Planktonic foraminiferids from mudstones are relatively scarce and smaller than those expected from more open (deeper) water (Fox and Olsson, 1969, p. 1400). Common lignitic plant fragments and benthonic foraminiferids (Fenner, 1974) in the mudstones also suggest shallower waters, perhaps shallow subtidal depths. Mudstones of the two tongues in western Slope County (pl. 2, sec. 8) were deposited in brackish water, as indicated by oysters (fig. 21), other bivalves, and two foraminiferids. Here, tidal flats, lagoons, estuaries, and even barrier islands may have been local environments of deposition (Van Alstine, 1974). An unusual occurrence of fine clastics is a lenticular body of brownish gray to black carbonaceous shale within a sandy mudstone beneath a presumed barrier island sandstone (fig. 3, sec. 6). Although interpreted as an abandoned tidal channel (Cvancara, 1972, p. 73), a more likely explanation might be a filled turbidity current scour channel.

Besides the fair to well sorted barrier island or shoreline sandstones, other poorly sorted sandstones occur commonly in the Cannonball Formation. These sandstones generally contain the most fossils, both in terms of species and individuals, and may have been deposited within the lower shoreface (= "transition") zone (Reineck and Singh, 1973, p. 307-308).

URANIUM POTENTIAL

General

Denson and Gill (1965) summarized the uranium occurrences in the Williston basin except those in the Cave Hills of South Dakota, which have been described by Pipiringos, Chisholm, and Kepferle (1965). Noble (1973) discussed uranium production in North Dakota. Estimated reserves in the basin of rock containing 0.1 percent uranium are greater than 1 million tons (Denson and Gill, 1965, p. 64).

Uranium in the basin occurs primarily in impure lignite and lignitic shale (Vine, 1962) but has been found also in carbonaceous siltstone, phosphatic claystone, and sandstone. Generally, a thick sandstone directly overlies or underlies the uranium-bearing host rock.

The richer deposits are aligned about north-south along the axis of the Williston basin. The more significant deposits, containing 0.1 percent or more uranium, occur in the Cave Hills (northern Harding County, South Dakota; Ludlow and Tongue River Formations), Slim Buttes (southeastern Harding County, South Dakota; Ludlow Formation), and along the Little Missouri River escarpment in the vicinity of Saddle Butte and Rocky Ridge (eastern Billings and northwestern Stark Counties, North Dakota; Sentinel Butte Formation). All significant uranium deposits are less than 300 feet stratigraphically below the base of the pre-Oligocene unconformity or its projected base (Vine, 1962, p. 141-142). Overlying this unconformity are middle and late Tertiary rocks containing volcanic materials. A common belief (e.g., Denson and Gill, 1956) is that these volcanic materials were the source of the uranium. Groundwater leached the uranium from the volcanic materials and carried it downward and laterally. Lignite and carbonaceous rocks served as receptors that may have extracted uranium by ion exchange or by the formation of organometallic compounds. Uranium mineralization may have occurred since Oligocene (Pipiringos, Chisholm, and Kepferle, 1965, p. A50) or late Miocene (Denson and Gill, 1965, p. 67) time.

Cannonball Formation

Although uranium in the Williston basin has been found almost entirely in lignite and nonmarine carbonaceous rocks, a possibility for its occurrence in the marine Cannonball Formation does exist. Uranium is known from marine sandstone (e.g., Clinton and Carithers, 1956) and marine black shales (e.g., Swanson, 1956). A model for the syngenetic origin of possible uranium in the Cannonball is as follows.

If the Cannonball, Ludlow, Tongue River, and Sentinel Butte Formations are at least in part penecontemporaneous, they represent a variety of depositional environments that were areally in juxtaposition. Streams originiating or passing through coastal plain bogs (sites of later lignite formation) could have carried uranium ions, fixed by organic matter in solution (Vine, 1962, p. 161), that would be carried out to the Cannonball sea. (The source of the uranium ions might have been the volcanic materials known to occur primarily in the Sentinel Butte and Ludlow Formations.) The uranyl humates may have been concentrated as a flocculant precipitated by the action of sea water (Vine, 1962, p. 161), or plant debris and other organic matter may have extracted uranyl ions out of solution. Following this model, one might search for syngenetic uranium in the Cannonball mudstones. Although not as organic as certain Paleozoic black shales, they do contain considerable carbonaceous material, mainly in the form of small, lignitic plant fragments. Exploration might be concentrated where the content of carbonaceous material is highest, well below well-sorted sandstones.

Epigenetic uranium might be searched for in the Cannonball Formation where the Ludlow interfingers with and overlies that formation. This area, as presently known, generally covers Bowman, Slope, Billings, Dunn, Stark, and Hettinger Counties (pls. 1, 2, and 4). Groundwater could leach uranium from volcanic materials in the overlying Ludlow Formation and redeposit it in carbonaceous mudstones of the Cannonball. Or, the uranium might be deposited in permeable sandstones because of a reducing environment provided by localized carbonaceous material, or, perhaps, by hydrogen sulfide. Considerable stratigraphic study of the two formations is particularly warranted in the area of interfingering to provide a sound basis for future exploration. If sandstones should prove to be economically significant for uranium in the Williston basin, the search for these might be concentrated in the southern part of the area of occurrence of the Cannonball. Here, the sandstone percentage (pl. 4) is relatively high, and the overburden is generally less than in other areas of higher percentage farther north. Of some interest here is a 100-foot sandstone directly underlying the richest uranium-bearing bed (coal bed E) in the

Cave Hills of northern Harding County, South Dakota. It has been placed in the basal part of the Tongue River Formation (Pipiringos, Chisholm, and Kepferle, 1965, p. A8-A11, A22); however, it contains fossil shark and other fish remains, becomes coarser grained upward and contains low-angle, straight, cross strata (A. F. Jacob, personal communication, 1974), and may be Cannonball. This sandstone, directly under coal bed E, contains 0.001 percent uranium (Pipiringos, Chisholm, and Kepferle, 1965, Table 10).

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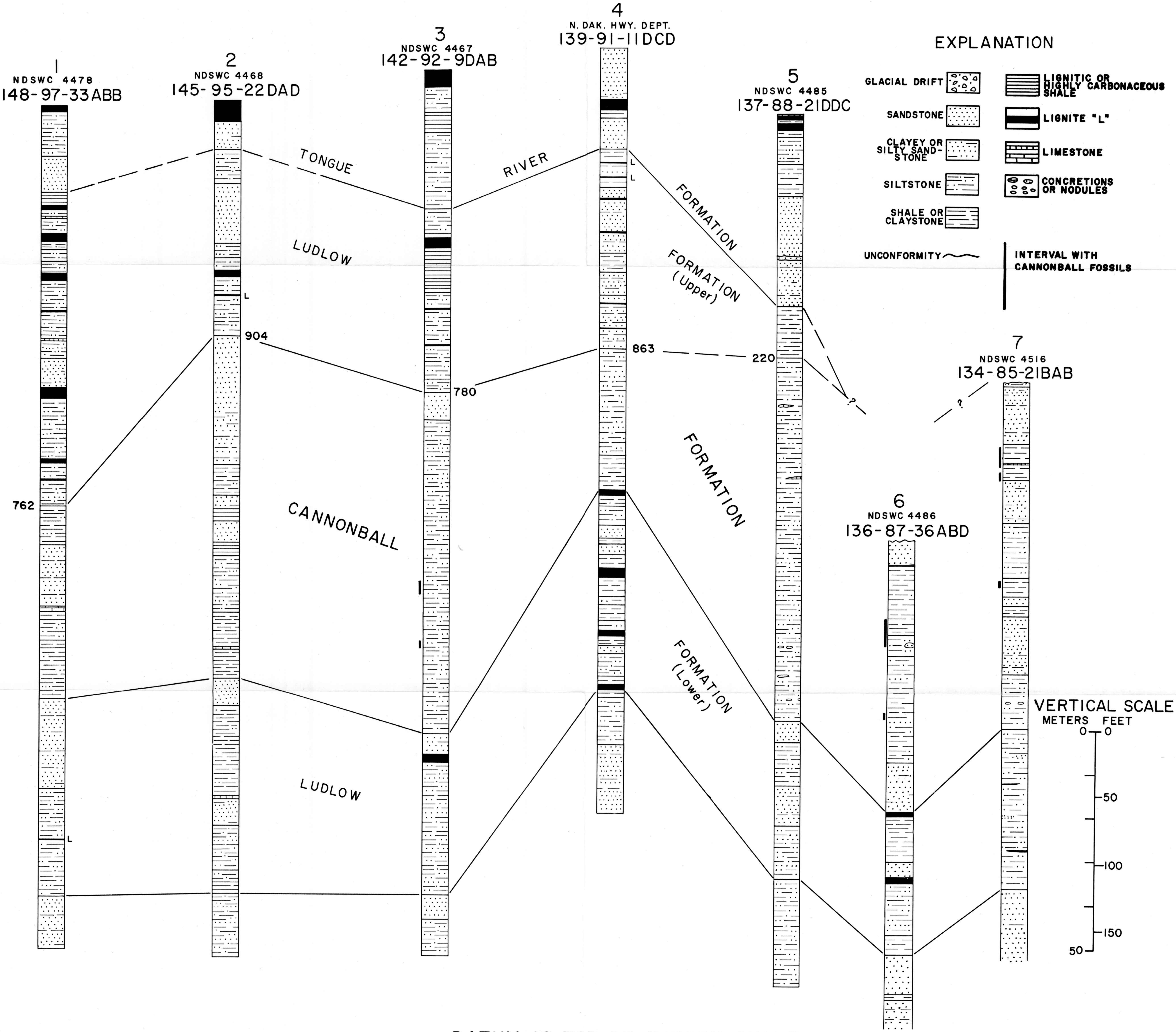
PLATE I NW-SE CROSS SECTION OF CANNONBALL AND ADJOINING FORMATIONS IN SOUTHWESTERN NORTH DAKOTA



DATUM IS TOP OF PIERRE SHALE

NUMBERS ALONG SECTIONS ARE DEPTHS TO TOP OF CANNONBALL FORMATION

PLATE 2 SW-NE CROSS SECTION OF CANNONBALL AND ADJOINING FORMATIONS IN SOUTHWESTERN NORTH DAKOTA

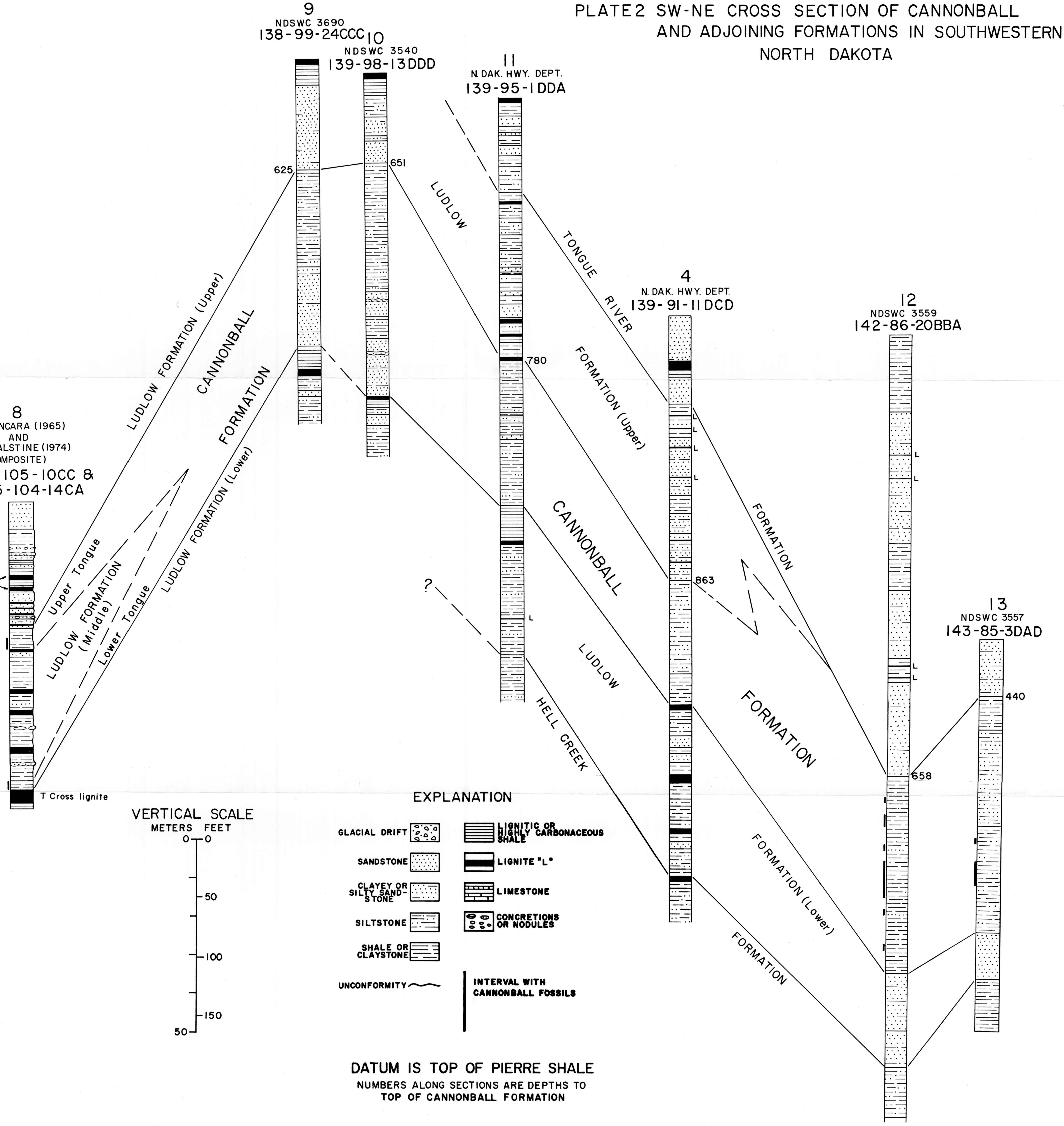


PLATE 3 SW-NE CROSS SECTION OF CANNONBALL AND ADJOINING FORMATIONS IN SOUTHWESTERN NORTH DAKOTA

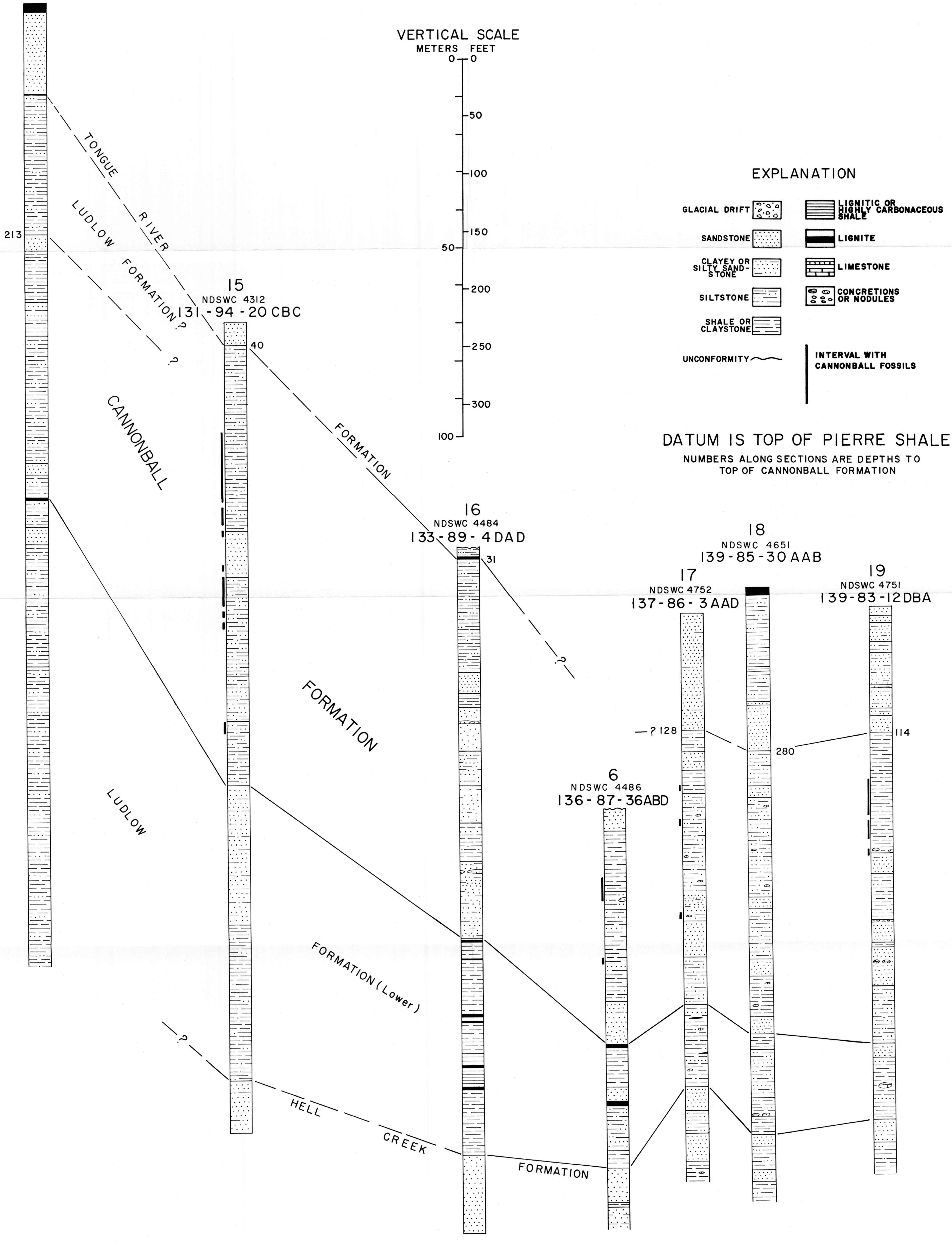


PLATE 4 ISOPACH AND SANDSTONE PERCENTAGE MAP OF CANNONBALL FORMATION IN NORTH DAKOTA