Sedimentology and ichnology of late Cambrian to early Ordovician Skolithos sandstone in the Deadwood Formation, Northern Black Hills, South Dakota, and Southeastern Bear Lodge Mountains, Wyoming

William Peter Sokoloski
The University of Toledo

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SEDIMENTOLOGY AND ICHNOLOGY OF LATE CAMBRIAN TO EARLY ORDOVICIAN SKOLITHOS SANDSTONE IN THE DEADWOOD FORMATION, NORTHERN BLACK HILLS, SOUTH DAKOTA, AND SOUTHEASTERN BEAR LODGE MOUNTAINS, WYOMING

by

William P. Sokoloski

Submitted as partial fulfillment of the requirements for

the Master of Science Degree in

Geology

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Graduate School

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May 2005
An Abstract of

SEDIMENTOLOGY AND ICHNOLOGY OF LATE CAMBRIAN TO EARLY ORDOVICIAN SKOLITHOS SANDSTONE IN THE DEADWOOD FORMATION, NORTHERN BLACK HILLS, SOUTH DAKOTA, AND SOUTHEASTERN BEAR LODGE MOUNTAINS, WYOMING

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The upper part of the Cambrian-Ordovician Deadwood Formation contains a Late Cambrian Skolithos-bearing sandstone unit (LCSS) and an Early Ordovician Skolithos-bearing sandstone unit (EOSS). These rock units were originally referred to as the Aladdin sandstone. Sections of these rock units (5 in the LCSS and 8 in the EOSS) in the northern Black Hills of South Dakota and southeastern Bear Lodge Mountains of Wyoming were measured, described and sampled. A literature search was conducted for other Skolithos sandstone units to determine the stratigraphic range and physical characteristics of the Skolithos ichnospecies. In addition, 13 petrographic thin sections of samples were examined to obtain detailed information on the sandstones and Skolithos trace fossils.

Overall, environmental interpretations based on outcrop and petrographic thin section descriptions agree well with the findings of previous investigators. Rock intervals containing abundant Skolithos tubes are formed by succeeding periods of burrowing, erosion and deposition as the suspension-feeding polychaetes and/or phoronids burrowed vertically into the substrate to form Skolithos tubes in order to feed
at the sediment surface. Cross-bedding features and *Skolithos* tubes that terminate at bedding planes indicate the susceptibility of these substrates to wave-generated bottom currents. This condition is characteristic of the *Skolithos* ichnofacies. Beds containing only *Skolithos* trace fossils in the EOSS were deposited during storm events with finer-grained, lower energy deposits, bioturbated by deposit-feeding animals, following these beds. The presence of variously shaped fodinichnia (feeding) or pascichnia (grazing) trace fossils mark an environmental change at the end of EOSS time, which correlates with the timing of other events that apparently reduced the abundance and diversity of the *Skolithos*-making animals into two long ranging (Precambrian to Recent) representative ichnospecies, *S. linearis* and *S. verticalis*.

The modal *Skolithos* density is 0.4 *Skolithos* tubes per cm in the LCSS and 0.5 *Skolithos* tubes per cm in the EOSS, although the LCSS contains thicker portions that do not contain any *Skolithos* tubes. *S. linearis* (tubes larger than 4 mm in diameter) and *S. verticalis* (tubes 1 to 2.5 mm in diameter) occur in both rock units, but *S. verticalis* is predominant in both sandstones. These trace fossils do not necessarily represent different organisms as both ichnospecies can be the same size (3 to 4 mm in diameter).

Petrographic thin section analysis reveals these sediments must have been rapidly eroded and quickly buried in order for low-survivability grains like feldspar to be preserved rather than weathered away in the humid climate as this part of the North American craton was located near the equator. Quartz-mica schist fragments also indicate Precambrian basement rocks were exposed in the Black Hills during EOSS time. Thin section analysis of 183 *Skolithos* tubes did not provide any definitive results regarding how the *Skolithos*-making animal constructed its burrow.
ACKNOWLEDGEMENTS

I sincerely thank my thesis committee members Dr. James A. Harrell, Dr. Vernon M. Brown and Dr. Mark J. Camp of the University of Toledo, Department of Earth, Ecology and Environmental Science. Dr. Harrell deserves credit for the thesis topic, objectives, methodology and main overview. Dr. Brown supervised the fieldwork and was particularly helpful at the initial site in Spearfish Canyon, which the knowledge he shared with me carried over to the other sites. Dr. Camp provided helpful comments as well, which I greatly appreciate. Thank you all for your commitment, expertise and guidance. I thank the University of Toledo for the financial support I received as a graduate teaching assistant. And, most of all, I thank my parents William S. and Janet L. Sokoloski, grandmother Evelyn R. (Greiger) Finke, and sister Jennifer J. Sokoloski for their love, support and inspiration.
DEDICATION

This work is dedicated in loving memory of my grandparents William Rinehart Finke, Stephen Paul and Verdine (Hug) Sokoloski.
# TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................................................ii

ACKNOWLEDGEMENTS ....................................................................................................................................................... iv

DEDICATION ........................................................................................................................................................................ v

LIST OF FIGURES .......................................................................................................................................................... viii

LIST OF TABLES ............................................................................................................................................................. xi

CHAPTER ONE INTRODUCTION ................................................................................................................................. 1

  Statement of the Problem ............................................................................................................................................... 1
  Objectives of the Study ................................................................................................................................................... 2

CHAPTER TWO LITERATURE REVIEW ......................................................................................................................... 3

  Geology of the Black Hills ........................................................................................................................................... 3

    Introduction ................................................................................................................................................................. 3
    Precambrian Rocks .................................................................................................................................................... 3
    Early Paleozoic Rocks .............................................................................................................................................. 6
    Structure and Physiography ..................................................................................................................................... 7

  Aladdin Sandstone ....................................................................................................................................................... 11

  *Skolithos* Trace Fossil ............................................................................................................................................. 23

    Introduction ................................................................................................................................................................. 23
    Previous Work on the *Skolithos* Ichnofacies ................................................................................................................ 24

      Depositional Environment ......................................................................................................................................... 24
      Type of Animal .......................................................................................................................................................... 34
      Stratigraphic Range .................................................................................................................................................. 42

CHAPTER THREE METHODOLOGY ............................................................................................................................... 60

  Fieldwork ........................................................................................................................................................................ 60
  Laboratory Work ............................................................................................................................................................ 63

CHAPTER FOUR RESULTS ............................................................................................................................................... 67

  Fieldwork ........................................................................................................................................................................ 67

    Introduction ................................................................................................................................................................. 67
    Composition and Color ............................................................................................................................................... 68
    Grain Size .................................................................................................................................................................... 68
    Bedding Characteristics ............................................................................................................................................. 71
    Bedding Contacts ....................................................................................................................................................... 72

    *Skolithos* Characteristics ........................................................................................................................................ 75

      Orientation and Shape ........................................................................................................................................... 75
      Length and Diameter ................................................................................................................................................. 76
LIST OF FIGURES

Figure 1. Location of the Black Hills in parts of Wyoming and South Dakota. ............ 4

Figure 2. Geologic map of the Black Hills................................................................. 5

Figure 3. Generalized Paleozoic stratigraphic column of the Black Hills............... 8

Figure 4. Physiography of the Black Hills............................................................... 10

Figure 5. Cross-bedding terminology used by Seeland (1961) in his study of the LCSS and EOSS. ................................................................. 15

Figure 6. Sketch of trough cross-bedding occurring in the LCSS at Little Elk Creek Canyon................................................................. 16

Figure 7. Tabular cross-bedding in the EOSS at Deadwood................................. 18

Figure 8. Rose diagram of 251 cross-bed orientation measurements indicating LCSS paleocurrent directions. .............................................. 19

Figure 9. Rose diagram of 204 cross-bed orientation measurements indicating EOSS paleocurrent directions.............................................. 20

Figure 10. Typical bathymetry of some common trace fossil assemblages. ............ 25

Figure 11. The distribution of Skolithos linearis in the lower Cambrian Bradore Formation of southern Labrador (Canada). .............................................. 26

Figure 12. Archetypical ichnofacies and their characteristic environments. ........ 27

Figure 13. A general model of oxygen-dependant trace fossil associations. ........ 28

Figure 14. A non-quantitative plot of trace fossil diversity in subaqueous environments relative to various salinity conditions. .................. 29

Figure 15. Bioturbation and fabric resulting from different depositional settings. .... 30

Figure 16. Trace fossils characteristic of the Skolithos ichnofacies....................... 32

Figure 17. Morphology of possible Skolithos-making animals.............................. 37

Figure 18. Modern Phoronopsis virdis dwelling tubes.............................................. 40
Figure 19. Reconstructions of a hypothetical phoronid organism making sedimentary structures associated with the *Skolithos linearis* tubes of the Carrara Formation (Cambrian) in southeast California.... 43

Figure 20. Schematic cross section of the sedimentary structures associated with *Skolithos linearis* collected from the Cambrian Carrara Formation in southeast California. ................................................................................. 44

Figure 21. Comparator for judging ichnofabric indices. ............................................. 46

Figure 22. The number of *Skolithos* piperock occurrences through the Paleozoic. ... 47

Figure 23. Four phase history of tiering among suspension feeders in the benthic marine ecosystem............................................................... 49

Figure 24. Apparent stratigraphic range of the characteristic *Skolithos* ichnospecies. ................................................................................................ 52

Figure 25. Marine trace-maker diversity from Precambrian through Tertiary....... 56

Figure 26. Epifaunal and infaunal suspension feeder tiering complexity through the Phanerozoic with changes in the number of *Skolithos* ichnospecies. .... 59

Figure 27. Locations of the LCSS and EOSS sites in the Black Hills. ................. 61

Figure 28. Modal and maximum grain sizes of the LCSS and EOSS (estimated using a visual comparator). ..................................................... 69

Figure 29. Apparent trends in the stratigraphic distribution of modal grain size in the LCSS at Dalton Lake and EOSS at Whitewood Peak and Deadwood. .................................................................................. 70

Figure 30. Well-cemented zones and *Skolithos* in the lower part of the LCSS at Boxelder Creek. ................................................................................. 73

Figure 31-A. *Skolithos* in EOSS interval C-8 at Deadwood.................................. 77

Figure 31-B. Same image as Figure 31-A, but with bold lines added to mark *Skolithos* tubes in EOSS interval C-8 at Deadwood................................................. 78

Figure 32. The LCSS at the Dalton Lake site containing hematite-filled *Skolithos* tubes. .................................................................................... 79

Figure 33. *Skolithos* tubes in positive relief in LCSS interval H-8 at the Dalton Lake site. ....................................................................................... 80
Figure 34. *Skolithos* tubes in positive relief from the friable sandstone at the Dalton Lake site. .......................................................................................................................... 81

Figure 35. *Skolithos* tubes in EOSS interval D-4 at Whitewood Peak.................. 82

Figure 36. Box-and-whisker plots of *Skolithos* diameters measured in the LCSS and EOSS. .................................................................................................................. 84

Figure 37. Box-and-whisker plots of *Skolithos* diameters measured at each site. ..... 85

Figure 38. Box-and-whisker plots of *Skolithos* densities measured in the LCSS and EOSS. .................................................................................................................. 87

Figure 39. Box-and-whisker plots of *Skolithos* densities measured at each site. ..... 88

Figure 40. Terminology for the preservation of trace fossils................................. 91
LIST OF TABLES

Table 1. Different nomenclature used by authors referring to the two prominent Skolithos-bearing rock units of the Deadwood Formation .................................. 12

Table 2. The most common trace-making taxa characterizing various salinity facies ................................................................................................. 29

Table 3. Recognizing trace fossils and non-biogenic structures ......................... 31

Table 4. Characteristic Skolithos ichnospecies ................................................. 35

Table 5. Relative stratigraphic positions of the thin-sectioned samples .............. 93
CHAPTER ONE

INTRODUCTION

Statement of the Problem

There are two prominent Skolithos-bearing sandstones among the sedimentary rocks in the Black Hills. These sandstones were originally considered to be parts of the same rock unit named the ‘Aladdin sandstone’. Later workers found that these sandstones are stratigraphically distinct and have referred to them in various conflicting terms in the geologic literature. Although the petrography, ichnology and sedimentology of these sandstones have been discussed, they have never been used together to explain in detail the precise nature and origin of both rock units.

Skolithos (also spelled Skolithus, Scolithus and Scolithos) is a trace fossil (i.e., ichnofossil) commonly appearing as long, straight, vertical tubes representing the burrows of a marine worm or worm-like organism. The Skolithos trace fossil is found mainly in sandstone from a variety of high energy, sandy-bottomed marine environments. It occurs throughout the Phanerozoic, but the abundance of dense assemblages of Skolithos tubes (i.e., Skolithos ‘piperock’) decreases through the Paleozoic and occurs
rarely afterward. Why this happened is not clear. There is also much remaining to be learned about the animal responsible for *Skolithos*.

**Objectives of the Study**

The purpose of this study is to describe the precise nature of the *Skolithos*-bearing Aladdin sandstone and the underlying *Skolithos*-bearing sandstone unit of the upper part of the Deadwood Formation, and to seek new information about the *Skolithos* ichnofacies. More specifically, the objectives are:

1. to describe and sample in detail the two prominent *Skolithos*-bearing sandstone units in the northern Black Hills, South Dakota, and southeastern Bear Lodge Mountains, Wyoming;

2. to do detailed petrographic descriptions of the sandstone samples;

3. to synthesize all literature related to the *Skolithos* trace fossil and present new information regarding its stratigraphic range; and

4. to use the details of the stratigraphy, petrography, and ichnology of these sandstones to deduce how they were deposited and, possibly, to develop new information on the animal responsible for the *Skolithos* tubes.
CHAPTER TWO

LITERATURE REVIEW

Geology of the Black Hills

Introduction

The Black Hills are located in southwestern South Dakota and northeastern Wyoming. Their northwest extension in Wyoming is termed the Bear Lodge Mountains (Fig. 1). The Black Hills form an asymmetric dome that was uplifted during the Laramide Orogeny, a mountain-building phase occurring in the western United States and Canada from about Late Cretaceous to Early Paleogene (Fig. 2). The Rocky Mountains are the prominent feature formed during this time (Harris 1975). Although the Black Hills are much smaller in size in comparison to the Rocky Mountains, they are significant, because they represent the easternmost major uplift of Precambrian basement blocks in the western United States during Laramide time (Lowell 1974, p. 275).

Precambrian Rocks

The oldest rocks exposed in the Black Hills are granite and minor gneiss. These are over 2.5 billion years old, and comprise less than one percent of the region’s Precambrian outcrop. These Archean-age rocks are found in only three places: Little Elk
Figure 1. Location of the Black Hills in parts of Wyoming and South Dakota (white rectangle in lower map). The Black Hills National Forest (shown in dark gray) and the USGS 7.5 minute quadrangle maps covering the Black Hills appear in the upper part of this figure.
Figure 2. Geologic map of the Black Hills (from Feldmann and Heimlich 1980, Fig. 2.1).
Creek northeast of Nemo, Bear Mountain northwest of Custer in South Dakota, and Warren Peaks north of Sundance in Wyoming. Those at Bear Mountain and Warren Peaks intrude older schist. The other Precambrian rocks are mainly Early Proterozoic metamorphosed sandstone and shale with subordinate amounts of interbedded metabasalt and metagabbro (Dewitt et al. 1986, p. 12). The Harney Peak Granite crystallized approximately 1.7 billion years ago and is found exclusively in the south-central Black Hills. This granite intrudes both the Archean and Early Proterozoic rocks in this area (Dewitt et al. 1986, p. 32).

**Early Paleozoic Rocks**

The Cambrian-Ordovician Deadwood Formation is the earliest Paleozoic unit to be deposited on the Precambrian basement. This formation varies in thickness as a result of greater pre-Mississippian erosion toward the south and the progressive north-northwest depositional offlap of the formation through time (Kulik 1965, p. 13). It is 6 to 100 feet (1.8 to 30.5 m) thick in the southern Black Hills and thickens to about 410 feet (125 m) at the type section at Deadwood in South Dakota (Kulik 1965, p. 12). The formation can be divided into lower, middle and upper members measuring 90 feet (27.4 m), 156 feet (47.5 m) and 164 feet (50 m) in thickness, respectively, at its type section (Kulik 1965, p. 239-240). The lower member is sandstone, limestone and shale; the middle member consists mainly of shale with some interbedded limestone pebble conglomerate; and the upper member is mainly sandstone. The Aladdin sandstone occurs at the top of the upper member.

The Aladdin sandstone is 6 to 15 feet (1.8 to 4.6 m) thick and is suggested to be as much as 35 feet (10.7 m) when ‘worm-burrowed’ beds are included within its type
locality at Sheep Mountain in Wyoming (Kulik 1965, p. 131, 132). The distinct cross-
bedding and frequent *Skolithos* trace fossils make it a useful stratigraphic marker bed in
the northern Black Hills. The transition from Late Cambrian to Early Ordovician time
apparently occurred without a major interruption in sedimentation in this region (Carlson
1960, p. 41-42), and it was during this time that the Aladdin sandstone was deposited

The Ordovician Winnipeg Formation directly overlies the Aladdin sandstone in
the northern Black Hills. This contact is unconformable in South Dakota and most of the
surrounding region (Carlson 1960, p. 65). The Winnipeg has two members in the Black
Hills, the lower Icebox and the upper Roughlock (Carlson 1960, p. 49). The Icebox is a
fissile, non-calcareous green shale containing phosphatic and pyrite nodules, and is up to
40 feet (12.2 m) thick. The Roughlock is a tan, calcareous siltstone averaging about 20
feet (6.1 m) in thickness (Gries and Martin 1985, p. 265). Steamboat Rock, just south of
Nemo in South Dakota, is this formation’s most southern outcrop (Gries and Steece 1985,
p. 176, 178). The Paleozoic stratigraphy of the Black Hills is summarized in Figure 3.

**Structure and Physiography**

The Black Hills form an elliptical dome 125 miles (201.6 km) long and 60 miles
(96.7 km) wide (Feldman and Heimlich 1980, p. 11). The Williston Basin in North
Dakota and Montana flanks the hills to the north, while the Powder River Basin in
Wyoming and Montana lie to the west. The Black Hills uplift began 60 to 65 million
years ago and is divided into western and eastern blocks. The western block plunges
northward and is bordered to the west by the Black Hills monocline. The Bear Lodge
Mountains are a major feature of this block that are separated from the eastern block by
Figure 3. Generalized Paleozoic stratigraphic column of the Black Hills (from Feldmann and Heimlich 1980, Fig. 2.9). Unconformable bedding contacts are indicated by ‘u’.
the Fanny Peak monocline, which trends approximately north-south along the Wyoming-South Dakota border. The eastern block encompasses the bulk of the Black Hills and is characterized by anticline-syncline pairs that trend northward (Dewitt et al. 1986, p. 50). The eastern block exhibits greater structural relief (up to 10,000 ft or 3,048 m) and scattered domes created by Tertiary intrusions. The mechanics of the Black Hills uplift are uncertain, but thrust faults from the west or east have been suggested as a probable catalyst (Berg 1962; 1981). No such faults reach the surface in the Black Hills, but they are present westward in the Bighorn and Beartooth Mountain ranges in Wyoming and Montana, respectively (Dewitt et al. 1986, p. 50).

The bedrock lithology and geologic structure of the Black Hills control the formation of major physiographic features in this region. Darton and O’Harra (1905, p. 1) described these prominent landscapes as the ‘central crystalline area’, ‘limestone plateau’, ‘red valley’, and ‘hogback rim’ (Fig. 4). The central crystalline area contains Precambrian metamorphosed igneous and sedimentary rocks that are exposed in the central Black Hills. The limestone plateau, underlain by Mississippian limestones, forms the area’s main physiographic divide, but the red valley is arguably the region’s most conspicuous landform. The latter is carved from the relatively incompetent lithologies of the Permian-Triassic Spearfish Formation (Feldman and Heimlich 1980, p. 17). The Mesozoic Sundance, Lakota, and Fall River formations combine to create a prominent escarpment or ‘Dakota hogback’ along the outer edge of the red valley (Feldman and Heimlich 1980, p. 18). A Cenozoic igneous province forms yet another physiographic region (Karner 1985, p. 126). These Tertiary intrusions are more competent than the surrounding sedimentary strata and form several peaks across the northern Black Hills.
Figure 4. Physiography of the Black Hills (from Feldman and Heimlich 1980, Fig. 2.4).
while exposing younger sedimentary strata.

**Aladdin Sandstone**

Newton and Jenney (1880 as reported by Kulik 1962, p. 5) originated the term ‘*Scolithos* sandstone’ to describe the rock unit in the Black Hills that is ‘often riddled with small holes perpendicular to bedding’. McCoy (1952, p. 13) named this lithology the ‘Aladdin sandstone’ after a town in Wyoming, apparently because of its close proximity to the unit’s type section, which he declared to be the south side of Sheep Mountain in the Bear Lodge Mountains (Crook County, Wyoming, T57N / R62N / Section 3). McCoy (1952, p. 17) included the underlying massive red sandstone, which occurs farther south and was thought to have no *Skolithos* tubes, in the Aladdin sandstone. Subsequent authors noted lithologic and paleontologic differences between these sandstone units and referred to them by different names (Table 1). The name ‘Early Ordovician *Skolithos* Sandstone’ (EOSS) will herein be used for McCoy’s type Aladdin. Similarly, the name ‘Late Cambrian *Skolithos* Sandstone’ (LCSS) will refer to the southern massive red sandstone unit. The LCSS is poorly exposed near its northernmost outcrop in Deadman Gulch, just south of Sturgis. Its southernmost exposure is located about 28 miles (45.2 km) south of Deadwood (Kulik 1965, p. 90). The EOSS outcrops from Sheep Mountain to Deadwood and has been identified in the subsurface of the Williston Basin in North Dakota, at Moorcroft in eastern Wyoming, and as far east as Pierre in South Dakota (Kulik 1962, p. 36; 1965, p. 131).

These sandstone units exhibit different textures, colors, mineralogies, thicknesses, bedding characteristics, and underlying rock units. The LCSS is a typically massively
Table 1. Different nomenclature used by authors referring to the two prominent *Skolithos*-bearing rock units of the Deadwood Formation. *

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* The present study refers to these rock units as the Late Cambrian *Skolithos* Sandstone (LCSS) and Early Ordovician *Skolithos* Sandstone (EOSS). McCoy (1952, p. 3, 19-20) considered these sandstones to be the same rock unit, but interpreted them differently. Seeland (1961, p. 21) suggested the two units were facies of the same rock unit. Kulik (1962, p. 43, 48) used different names, but did not give a definite interpretation for the LCSS. Kulik (1965, p. 93, 131) gave a more definite interpretation for the LCSS and EOSS. Ladle (1972, p. 136) studied the petrography and sedimentation of the LCSS and underlying Deadwood deposits. Stanley (1984, p. 182) studied the ichnology of the Deadwood Formation.
bedded, fine- to coarse-grained, reddish, siliceous and ferruginous quartz arenite sandstone containing fine- to medium-sand sized grains of glauconite (Kulik 1965, p. 90). It becomes a subarkose sandstone about 12 miles (19.3 km) southeast of Little Elk Creek at Dark Canyon (Ladle 1972, p. 136). The rock unit is thickest (70 ft or 21.3 m) in Little Elk Creek Canyon. The EOSS is a typically massively bedded, very fine- to fine-grained, tan to white, essentially non-glaucnitic, siliceous or calcareous quartz arenite sandstone that is interbedded with bioturbated argillaceous sandstone in the lower part (Kulik 1965, p. 131). The EOSS is thickest at Sheep Mountain where McCoy (1952) measured 12 feet (3.7 m) and Kulik (1962, p. 40; 1965, p. 131) measured 35 feet (10.7 m). Kulik suggests McCoy may have chosen the first massive bed at Sheep Mountain as the type section in order to conform to the descriptions and thickness of the EOSS outcrops in the northern Black Hills. Ladle (1972, p. 137) found that within the sand fraction of four LCSS petrographic thin sections, quartz sand-sized grains decrease in abundance from 86 to 54 percent, glauconite increases in abundance from 4 to 13 percent, and feldspar increases in abundance from 1 to 3 percent from north to south. In addition, from north to south, sparry calcite cement increases from zero to 12 percent and the amount of dolomite cement increases from zero to 3 percent. Metamorphic rock fragments decrease in abundance from one percent to trace amounts from north to south; muscovite and epidote are less common and occur in trace amounts in both samples from the north and south (Ladle 1972, p. 137). Cores of EOSS extracted near the town of Savoy in the central northern Black Hills consist of 59 to 85 percent quartz grains, 2 to 25 percent dolomite and 13 percent calcite with trace amounts of plagioclase, microcline, glauconite, and pyrite (Owen 1975, p. 63-64).
Seeland (1961, p. 52) reported that only ‘planar’ type cross-beds of McKee and Weir (1953) occur in the LCSS and EOSS. According to McKee and Weir (1953), there are three main types of cross-bedding. Identification is based on the character of their lower bounding surface (Fig. 5). The three types are (1) ‘simple’ if the lower bounding surface is depositional rather than erosional; (2) ‘planar’ if the lower bounding surface is erosional, implying the surface was beveled and subsequently deposited upon; and (3) ‘trough’ if the lower bounding surface is curved with concave-up laminations, implying the surface was erosionally scoured and subsequently filled (McKee and Weir 1953, p. 385; McKee 1964, p. 284). McKee and Weir (1953) further describe these types by the shape of the cross-bed ‘set’. A set is a group of essentially conformable strata or cross-beds, which are separated from other sedimentary units by surfaces of erosion, nondeposition, or an abrupt change in rock characteristics (McKee and Weir 1953, p. 382-383). “A ‘lenticular set’ is bounded by converging surfaces, at least one of which is curved. A ‘wedge-shaped set’ is bounded by planar, converging surfaces, and a ‘tabular set’ is bounded by planar, essentially parallel surfaces. Nearly all simple cross-bed sets are lenticular or wedge-shaped, while most planar cross-beds sets are either tabular or wedge-shaped. All trough cross-bed sets are lenticular’ in shape (McKee and Weir 1953, p. 388). In other geologic literature, the terms ‘tabular cross-bedding’ (Boggs 1987, p. 157) and ‘tabular-planar cross-bedding’ (Selley 1988, p. 129) have both been used to describe foresets (i.e., the inclined laminations of cross-bedding) that are bounded by planar surfaces.

Kulik (1965, p. 92) found that ‘lenticular’ trough cross-bed sets are common and ‘tabular’ cross-beds are rare in the LCSS (Fig. 6). Kulik (1965, p. 132) found that cross
Figure 5. Cross-bedding terminology used by Seeland (1961) in his study of the LCSS and EOSS (from McKee and Weir 1953, Fig. 2).
Figure 6. Sketch of trough cross-bedding occurring in the LCSS at Little Elk Creek Canyon (from Kulik 1965, Fig. 44).
bedding is “consistently tabular and the laminations dip consistently in one direction contrasted to the [trough-type cross-beds] in the [LCSS].” He also states, “occasionally the laminations near the top [of the cross-bed] are inclined, but at the base they curve slightly to become nearly tangential” in the EOSS (Kulik 1965, p. 132; Fig. 7). Large-scale ‘tabular’ and ‘festoon’ (trough) cross-beds were observed at one site in the EOSS by Stanley (1984, p. 207). Boggs (1987, p. 157) states, with respect to cross-bedding in general, “the laminae of tabular cross-beds are commonly planar, but curved laminae that have a tangential relationship to the basal surface also occur.” Cross-bed foresets form tangential bottomsets if the suspended load is large, or if the height of the lee slope of the foreset is small compared to flow depth. In this way, the suspended sediment will pile up at the base of the lee slope rapidly enough to keep pace with the growth of the ‘avalanche’ deposits causing the lower part of the foreset laminae to curve outward and approach the bottomset laminae asymptotically (Boggs 1987, p. 156). In nature, tangential bottomsets are rare and tangential topsets are virtually non-existent in cross-bedding (Selley 1988, p. 128).

The orientation of cross-bed dip directions, which reflect current directions, is not consistent in the LCSS (Fig. 8) but it is in the EOSS (Fig. 9). Cross-bedding in the LCSS may have formed in shallower water as a result of north–south oscillating tidal currents, wind-generated bottom currents, a fairly strong southwest-flowing wave-generated longshore current, as well as density currents produced by the mixing of seawater with land-derived freshwater (Seeland 1961, p. 84; Kulik 1965, p. 94). These currents produced cross-bedding that does not necessarily dip in the same direction as the seafloor paleoslope. According to Kulik (1965, p. 94), the LCSS seafloor sloped north-northwest.
Figure 7. Tabular cross-bedding in the EOSS at Deadwood. Kulik (1965, p. 132) states the bottom cross-bed sets ‘occasionally’ become nearly tangential with the lower bounding surface like those seen in the upper half in this picture. Parts of *Skolithos* (S) trace fossils can be seen in the lower part of the figure. The arrows point to portions of longer *Skolithos* tubes. Tubes are stained dark brown by limonite.
Figure 8. Rose diagram of 251 cross-bed orientation measurements indicating LCSS paleocurrent directions (from Seeland 1961, Fig. 17).
Figure 9. Rose diagram of 204 cross-bed orientation measurements indicating EOSS paleocurrent directions (from Seeland 1961, Fig. 16).
The cross-bed dip directions suggest that the average current direction in the LCSS was south 25 degrees west and due west in the EOSS (Seeland 1961, p. 56, 84). The differences in cross-bed dip directions between the LCSS and EOSS may be related to differences in rates of deposition, amount of relief in source areas, strength and direction of bottom currents, and water depth. The EOSS was probably deposited in deeper waters that were influenced by stronger bottom currents operating on a seafloor sloping westward in the same direction as the current (Kulik 1965, p. 133).

The lower contact of the LCSS is placed directly above bioturbated and occasionally thinly laminated sandstone, which erodes more easily than the overlying LCSS (Kulik 1965, p. 92). The lower contact of the EOSS occurs directly above glauconitic, argillaceous or silty, brown sandstone that is often flaggy in appearance (Kulik 1962, p. 50). A contact between the LCSS and the EOSS has not been found and other deposits of the Deadwood Formation apparently separate these rock units. Seeland (1961, p. 75) did not find definite ‘marker horizons’ in either the LCSS or EOSS, and thus it seems impossible, or at least very difficult, to correlate the same bedding interval in different parts of the northern Black Hills if other characteristics like Skolithos tubes cannot be used.

Body fossils are scarce in both the LCSS and EOSS. The few recovered remains from the EOSS include a trilobite (Bellefontia) found 4 feet (nearly 1.2 m) below McCoy’s (1952) type Aladdin, which was collected by coring into the Bull Creek Anticline in the extreme northeast corner of Wyoming (Lochman-Balk and Duncan 1950, p. 350). A trilobite (Hysticurus) and a cephalopod (Ectenoceros) were collected 0.5 feet (0.2 m) above the base of the EOSS at Deadwood (Seeland 1961, p. 46). These fossils
have been considered indicative of the lower Ordovician. The body fossils from the LCSS include Trempealean age (Saukia zone) trilobites, collected from the top of the southern red sandstone in the Little Elk Creek and Boxelder Creek areas near the town of Nemo (Kulik 1965, p. 98). W. A. Furnish observed, however, “oolitic beds occurring on top of this sandstone facies at Little Elk Creek and probably Dark Canyon are Middle Ordovician in age based on recovered conodonts” (personal communication to Kulik 1965, p. 97).

The *Skolithos* trace fossil is the most common fossil in both sandstones. Unlike McCoy (1952, p. 17), Seeland (1961, p. 20) and later authors saw *Skolithos* tubes in the LCSS to the south. *Skolithos* is common in the upper 15 feet (4.6 m) and the lower 10 feet (3 m) of this rock unit at Little Elk Creek and Boxelder Creek, respectively, and is not confined to any particular horizon (Kulik 1962, p. 30; Kulik 1965, p. 92). Stanley (1984, p. 182-184) referred to *Skolithos* tubes at Deadwood, Bridal Veil Falls, and Little Elk Creek variously as *Skolithos verticalis* and *Skolithos linearis*.

The source rocks for the sand grains in these *Skolithos*-bearing sandstones may include the Sioux Quartzite from eastern South Dakota and the underlying sandstone of the Deadwood Formation (Kulik 1962, p. 19), the northeast-southwest trending Transcontinental Arch located east of the Black Hills (Peterson 1988, p. 83, 87), and basement rocks exposed in the Black Hills. The sand was deposited in a warm, wet tropical climate, as the region was located approximately five degrees north of the equator (Dott and Prothero 1994, p. 233). Seeland (1961, p. 74-75) considered the LCSS a shallow marine sheet deposit rather than a deltaic deposit as proposed by McCoy (1952, p. 20), but Kulik (1965, p. 93-94) interpreted it as either a deltaic or nearshore marine
deposit and Ladle (1972, p. 168) suggested it originated as offshore barrier islands and tidal-channel fill. The EOSS also surely was deposited in a shallow, nearshore marine environment, perhaps as part of a barrier island complex, as indicated by the textural maturity of the sand, cross-bedding, and the Skolithos trace fossil (McCoy 1952, p. 20; Kulik 1962, p. 43; Kulik 1965, p. 13; Stanley 1984, p. 189). The lack of other trace fossils in the EOSS has been attributed to very high current or wave energies, which other organisms found intolerable (Stanley 1984, p. 189). It has been suggested that a regressing sea deposited both the LCSS and EOSS (Kulik 1965, p. 133).

**Skolithos Trace Fossil**

**Introduction**

The term ‘ichnology’ is derived from the Greek words ‘iknos’ meaning ‘trace or track’, and ‘logos’ meaning ‘word or study’. Ichnology is thus the study of trace fossils (i.e., ichnofossils), and these may be modern traces (neoichnofossils) or geologically ancient traces (paleoichnofossils) of plants and animals. Ichnofossils include individual footprints of animals (tracks); sets of multiple tracks indicating movement (track ways); continuous locomotion traces (trails); dwelling structures, including Skolithos, made in un lithified sediment (burrows) or in hard substrates such as shell, rock or wood (borings); and other miscellaneous bioerosion traces (Ekdale et al. 1984, p. 5).

Ichnofossils are useful tools for making geologic interpretations of paleoenvironmental conditions, because they are less likely to be transported (and, hence, recycled) and are more likely to have a modern analogue than body fossils (Seilacher 1967, p. 422). The recurrent nature of trace fossil assemblages or ‘ichnofacies’ in
subaqueous settings makes them very useful in making environmental interpretations (Seilacher 1964, p. 253; Seilacher 1967, p. 413; Ekdale et al. 1984; Ekdale 1988; Ekdale and Mason 1988). An ichnofacies is formed by different groups of animals with similar behavioral patterns producing traces with similar basic characters (Seilacher 1953, p. 432-434). The conditions determining the predominant ichnofacies in these settings include water depth (Fig. 10), food supply (Fig. 11), substrate consistency (Fig. 12), oxygenation (Fig. 13), salinity (Fig. 14, Table 2), and depositional rates (Fig. 15).

There are some pitfalls to using trace fossils for geologic interpretations. For example, the same species may at times produce different structures corresponding to different behavioral patterns, or produce different structures corresponding to an identical behavior but in different substrates. Also, identical structures may be produced by the activity of different trace-making organisms, if their behavior is similar; and a particular biogenic structure may be produced by two or more different organisms living together, or in succession, in the same structure (Ekdale et al. 1984, p. 18). Equally important, specific non-biogenic sedimentary structures may appear similar to a particular ichnofossil, which may lead to erroneous geologic interpretations. Some useful criteria in distinguishing trace fossils from non-biogenic structures are given in Table 3. It is, therefore, necessary to use all available geologic information when using trace fossils as an aid in making geologic interpretations.

**Previous Work on the Skolithos Ichnofacies**

**Depositional Environment**

*Skolithos* is an ‘ichnogenus’ usually found in the *Skolithos* ichnofacies (Fig. 16). It should be noted that the occurrence of a particular ichnogenus does not necessarily
Figure 10. Typical bathymetry of some common trace fossil assemblages and their characteristic ichnofossils (after Crimes 1975; modified from Ekdale et al. 1984, Fig. 15-2). Ichnofossils are listed below.

1. borings of *Polydora*  
2. *Entobia*  
3. echinoid borings  
4. *Trypanites*  
5. pholadid burrow  
6. pholadid burrow  
7. *Diplocraterion*  
8. unlined crab burrow  
9. *Skolithos*  
10. *Diplocraterion*  
11. *Thalassinoides*  
12. *Arenicola*  
13. *Ophiomorpha*  
14. *Phycodes*  
15. *Rhizocorallium*  
16. *Teichichnus*  
17. *Crossopodia*  
18. *Asteriacites*  
19. *Zoophycos*  
20. *Lorenzinia*  
21. *Zoophycos*  
22. *Paleodictyon*  
23. *Taphrhelminthopsis*  
24. *Helminthoida*  
25. *Spirorhaphe*  
26. *Cosmorhaphe*
Figure 11. The distribution of *Skolithos linearis* in the Lower Cambrian Bradore Formation of southern Labrador (Canada). This is interpreted as resulting from suspension-feeding animals regularly portioning limited space. The tubes are randomly dispersed when density is low to average, and uniformly spaced at high densities. The diagram represents a 400 square centimeter area with the distance between burrows shown in millimeters (from Pemberton and Frey 1984, Fig. 3).
Figure 12. Archetypical ichnofacies and their characteristic environments (from Buatois et al. 1998, Fig. 7, as adapted from Pemberton et al. 1992).
Figure 13. A general model of oxygen-dependent trace fossil associations. Domicnia-dominated associations (dwelling structures), A, occur where bottom water and interstitial water are aerobic (fully oxygenated). Pascichnia-dominated associations (grazing traces), B, are found where the bottom water is aerobic or dysaerobic, and the interstitial water is dysaerobic (poorly oxygenated). Fodinichnia-dominated associations (feeding traces), C, occur where the bottom water is aerobic or dysaerobic and the interstitial water is anaerobic (anoxic). An abiotic situation, D, occurs where bottom water and interstitial water are anaerobic and sediment is primarily laminated. Sk = Skolithos, Sc = Scalarituba, Sp = Spirophyton, Ph = Phycosiphon, Ch = Chondrites, Zo = Zoophycos (from Ekdale and Mason 1988, Fig. 1).
Figure 14. A non-quantitative plot of trace fossil diversity in subaqueous environments relative to various salinity conditions. The salinity-based trend of trace diversity reflects a similar salinity-based trend of species diversity of organisms (modified from Ekdale 1988, Fig. 2).

Table 2. The most common trace-making taxa characterizing various salinity facies (Ekdale 1988, Table 1).
Figure 15. Bioturbation and fabric resulting from different depositional settings. (A) Slow, continuous deposition where the rate of bioturbation equals or exceeds that of deposition. (B) Rapid deposition [or deposition under anoxic conditions], where animal activity is precluded, bioturbation resumes at the depositional break at the top of the unit. (C) Alternating rapid and slow deposition with erosion; note truncation of burrows at the erosion surfaces. (D) Slow, continuous deposition without erosion; the faint stratification is emphasized by a suite of trace fossils produced by animals during phases of non-deposition; depositional phases favor a different animal community and different behavior patterns. (E) Rhythmic deposition interspersed with erosion; note truncated burrows (modified after Howard 1978 as in Ekdale et al. 1984, Fig. 8-1).
Table 3. Recognizing trace fossils and non-biogenic structures (modified from Ekdale et al. 1984, Tables III-1 and III-2, p. 30, 34).

<table>
<thead>
<tr>
<th>Criteria for recognition of trace fossils</th>
<th>Criteria for recognition of non-biogenic structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Resemblance to a body form or body part of an organism.</td>
<td>➢ Resemblance to a primary inorganic sedimentary structure (e.g., ripple marks, sole marks, load structures, etc.).</td>
</tr>
<tr>
<td>➢ Uniform dimensions and/or continuity of structures.</td>
<td>➢ Resemblance to a secondary diagenetic structure, primarily caused by chemical events (e.g., concretions or nodules of chert, pyrite, etc. or dissolution features such as stylonites and collapse breccias).</td>
</tr>
<tr>
<td>➢ Uniform size of multiple structures.</td>
<td>➢ Variable or tapering dimensions (some trace fossils have different dimensions along their length).</td>
</tr>
<tr>
<td>➢ Lack of current alignment or orientation.</td>
<td>➢ Non-uniform size and/or shape of multiple structures.</td>
</tr>
<tr>
<td>➢ Regular and complex geometric pattern.</td>
<td>➢ Irregular geometric pattern.</td>
</tr>
<tr>
<td>➢ Burrow lining (e.g., clay) or wall structure (e.g., of agglutinated sand grains).</td>
<td>➢ Strict preferred orientation.</td>
</tr>
<tr>
<td>➢ Spreite (a biogenic structure composed of tightly joined remains of tunnel walls produced successively as a burrow was shifted broadside through the sediment by the burrower).</td>
<td>➢ Obvious mineral replacement.</td>
</tr>
<tr>
<td>➢ Meniscus-shaped fill (crescent-shaped structure in cross-section within the burrow filling).</td>
<td></td>
</tr>
<tr>
<td>➢ Pellets (e.g., feces, pseudofeces, construction elements, excavation wastes, and other pellets that are uniform in shape, size, and/or arranged in an orderly fashion).</td>
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</tr>
<tr>
<td>➢ Organic residue (usually black, soft flakey texture, and the presence of pyrite or other chemically reduced minerals)</td>
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<tr>
<td>➢ Very delicate morphologic features (e.g., small scratches in the sediment as the animal passed through).</td>
<td></td>
</tr>
<tr>
<td>➢ Preservation in full relief.</td>
<td></td>
</tr>
<tr>
<td>➢ Association with body fossils (mainly serves to emphasize a particular animal was present, done after identifying the ichnofossil, because the bioclasts are detrital and may not have been deposited synchronously with the making of the trace fossil).</td>
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</table>
Figure 16. Trace fossils characteristic of the *Skolithos* ichnofacies: 1, *Ophiomorpha*; 2, *Diplocraterion*; 3, *Skolithos*, and 4, *Monocraterion* (from Ekdale et al. 1984, Fig. 15-6, as modified after Frey and Pemberton 1984).
indicate the presence of the ichnofacies of the same name, and an ichnofacies may be identified without the presence of the namesake trace fossil (Ekdale 1988, p. 466). *Skolithos* trace fossils are found in sandstone representative of a variety of shallow marine, nearshore environments (Droser 1991, p. 317). Tidal sand flats, tidal channels, beach shorefaces and offshore sand bars are such environments that commonly contain *Skolithos* tubes (Ekdale et al. 1984, p. 170, 179, 192). The ichnofacies typically exemplifies intertidal or littoral settings having a ‘soft’ and shifting sandy substrate. The context of soft in this case refers to sand that can be squeezed through the fingers, but does not have a soupy consistency. The fluctuating water conditions in these nearshore environments favor the preservation of primary sedimentary structures such as cross-bedding and are characterized by abundant ‘domichnia’ (or ‘dwelling’) type trace fossils, which includes *Skolithos* and other burrows and tubes that are predominantly vertically oriented (Ekdale et al. 1984, p. 26). The length of such burrows is sometimes determined by sedimentological factors (Droser et al. 1994, p. 279). For example, the soft sandy substrate in these environments is susceptible to abrupt erosion that can shorten the burrow from its original length (Pienkowski 1985; Dott et al. 1986).

The occurrence of shallow water [*Skolithos*] traces in deeper water deposits of an Eocene deep sea fan in northern Spain suggests that bathymetry is not the main control on the distribution of the trace maker as once thought. Of greater importance may be substrate consistency, food availability, and the energy level of currents in the marine setting (Crimes 1977, p. 75). Bjerstedt and Erickson (1989, p. 203) suggested similar controls on the distribution of these trace fossils in shallow tidal and peritidal units of the Late Cambrian-Early Ordovician Theresa Formation in upstate New York.
Skolithos trace fossils are also particularly common in storm deposits (Travener-Smith 1980; Pemberton and Risk 1982; Pemberton and Frey 1984; Bjerstedt 1988; Landing et al. 1988; Vossler and Pemberton 1988; Romano 1991; Droser et al. 1994; Stanely and Pickerill 1998; Guocheng et al. 1996). Skolithos occurring in sands suddenly deposited, such as by a storm event, in an incongruous environment (e.g., further from shore in deeper marine settings where finer-grained material is typically deposited) is regarded as a separate Arenicolites ichnofacies. This setting lacks the high wave or current energy and repeated erosion exemplified by the Skolithos ichnofacies (Bromley and Asgaard 1991, p. 157). The opportunistic Skolithos-making organism soon succumbs to the normal muddy fair-weather deposition and the previous ichnofacies reoccurs producing trace fossils different than Skolithos.

Type of Animal

In the early 1800s many trace fossils, including Skolithos, were originally considered a type of sea flora and placed in the genus Fucoides (Howell 1943, p. 3). The earliest known reference to the Skolithos subgenus and the premier description of a Skolithos ichnospecies (Table 4) appears in Haldeman (1840, p. 3 [note that this author’s name has also been spelled Haldemann, Haddeman, and Haldimand; from Fenton and Fenton 1934, p. 343]) as ‘Fucoides? Linearis’, which implied doubt that the origin of the ichnofossil was due to plants. Hall (1847, p. 2-3) suggested that Haldeman’s ‘Skolithos’ be given the rank of a full ichnogenus and referred to the trace fossil as ‘Scolithus [or Skolithus] linearis’. These three spellings were a source of confusion until Howell (1943, p. 7) declared the original and correct ichnogenus name, Skolithos, be retained by the rules of zoological nomenclature.

<table>
<thead>
<tr>
<th><strong>S. linearis</strong> (Haldeman 1840)</th>
<th>Burrow shape and orientation is cylindrical to subcylindrical, straight and vertical to slightly curved or inclined. Diameter commonly ranges from 3 to 12 mm and lengths up to 1 m occur. Burrow wall is distinct to indistinct and may be annulated. Burrow forms include closely crowded, straight burrows to relatively isolated burrows, and slightly undulating burrows with the two extremes having been found intergraded.</th>
</tr>
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<tr>
<td><strong>S. verticalis</strong> (Hall 1843)</td>
<td>Burrow shape and orientation is cylindrical to prismatic (where in contact), straight to curved and vertical to inclined. Diameter commonly ranges from 1 to 4 mm and is 2 to 15 cm in length. Burrow wall is smooth and rarely corrugated. The sediment in the burrows tends to weather out readily, leaving the burrows as holes in the rock. Relative to <em>S. linearis</em>: the burrows are generally shorter and smaller, more commonly inclined and curved, and never are extremely crowded.</td>
</tr>
<tr>
<td><strong>S. magnus</strong> (Howell 1944)</td>
<td>Burrow shape and orientation is cylindrical to subcylindrical, vertical and may curve slightly. Diameter commonly ranges from 6 to 12 mm and lengths up to 20 cm occur. Burrow wall is indistinct, somewhat irregular and commonly spaced about 12 mm apart.</td>
</tr>
<tr>
<td><strong>S. ingens</strong> (Howell 1945)</td>
<td>Burrow shape and orientation is cylindrical and vertical. Diameter averages 7 to 9 mm. Howell’s specimens are 5.5 and 6.5 cm long. Burrows are distinct and characterized by slight bulges at irregular intervals; bulges are 3 to 4.5 mm long and increase diameter by 1.5 mm. The rock matrix within 6 to 12 mm from the burrow commonly weathers away more rapidly than the surrounding matrix or the burrow, and may be darker in color.</td>
</tr>
<tr>
<td><strong>S. annulatus</strong> (Howell 1957)</td>
<td>Burrow shape and orientation is cylindrical to subcylindrical, vertical and straight. Diameter averages 12 mm and length is up to 15 cm. Burrow wall is distinct, smooth with characteristic ring-like annulations that are 2 to 12 mm apart, individual rings range in length from 1 to 4 mm long. The burrows are commonly spaced about 25 mm apart.</td>
</tr>
<tr>
<td><strong>S. bulbus</strong> (Alpert 1975)</td>
<td>Burrow shape and orientation is cylindrical to subcylindrical, vertical to inclined (rarely up to 45 degrees), straight, curved, or undulated. Diameter ranges from 4 to 15 mm and is most commonly 7 to 11 mm. Burrow wall is distinct and smooth and characterized by widely spaced spherical to subspherical expansions and slight bulges along the length. The diameter of the bulbus expansions (maximum is 22 mm wide) are up to twice the diameter of the cylindrical portions of the burrow, but are not present on all burrows. Longest burrow segment void of prominent bulges is 26 cm. The bulbous expansions are more prominent and spherical than the slight expansions of <em>S. ingens</em> and <em>S. annulatus</em>.</td>
</tr>
</tbody>
</table>
Polychaetes (marine and fresh water segmented worms or annelids) and/or phoronids (an animal similar to bryozoa but belonging to a separate phylum, Phoronida) have been considered responsible for making *Skolithos* tubes (also referred to as burrows and pipes depending how they are viewed) in subaqueous environments (Fig. 17). Polychaetes are found in a wide range of environments such as brackish and shallow marine waters, including tidal pools, but rarely fresh water regimes and still more rarely in terrestrial habitats (the common type of polychaete found in terrestrial habitats are usually referred to as earthworms). They occur in the central Arctic from shoal waters to bathyal depths (200 to 4000 m), and littoral species at the poles occur even at abyssal depths (4000 to 5000 m) in the tropics (Tasch 1973, p. 451-452; Robinson 1987, p. 197). Modern polychaetes feed by trapping particulate organic matter of various origins with a small ball of secreted mucus or mucus net, or by utilizing a crown of tentacles equipped with cilia that, when moved, direct water over these extremities and toward the animal’s mouth (Jørgensen 1966, p. 16). The class Polychaeta in the phylum Annelida has been divided into at least three orders: Miskooida (Cambrian), Sedentaria (Cambrian to recent) and Errantida (Ordovician to recent). Of these, *Skolithos* tubes are most likely the preserved burrows of annelids belonging to the order Sedentaria. The order Miskooida is an extinct order whose members contain no chitinoid jaws, build no tubes, and are a well-preserved fossil fauna of the Middle Cambrian Burgess Shale of British Columbia in Canada. The order Sedentaria includes polychaetes that secrete a calcareous, or phosphatic substance that hardens to form a protective tube. This ability was first developed by polychaetes in Cambrian time. Sand grains, shell fragments and other materials from the seafloor are often cemented to these tubes as they harden. The order
Figure 17. Morphology of possible *Skolithos*-making animals: polychaete worm (A) and phoronid (B). The upper schematic is a representative tube-dwelling polychaete, *Amphitrite* (Robinson 1987, Fig. 12.1A), and the lower diagram is a cross section view of the phoronid, *Phoronis* (Shrock and Twenhofel 1953, Fig. 8-1H). Diagrams are not to scale.
Errantida includes jawed worms whose fossilized chitinous teeth-like parts are termed 'scolecodonts' (Tasch 1973, p. 456-460). Tasch (1973, p. 460) reports that numerous marine worms, probably polychaetes, and their trace fossils, including *Skolithos*, have uncertain affinities. For that reason, *Skolithos* in the past was placed in the Annelida class Sipunculoida. This class was reserved for 'worm-like' organisms lacking setae (coarse hair-like, chitinous bristles on the trunk or 'parapodia' of many annelids), parapodia (unjointed fleshy locomotory appendages on the later body walls of many marine annelids), and internal or external segmentation of the body (Twenhofel and Shrock 1935, p. 146).

The bryozoa-like phoronids are more primitive in body structure. These organisms are worm-like in shape, non-segmented (unlike polychaetes), suspension-feeding animals possessing no distinct head. They feed by extending their lophophore, a tentacle structure that surrounds the mouth of the animal (Tasch 1973, p. 213). Phoronids build two sorts of tubes: compact ‘subhemispherical’ masses (at least 5 cm in diameter), which are attached to hard objects on the seafloor like rocks; and tubes (extending above the substrate) made from material (e.g., chitin-like substances) excreted by the organism to which sediments adhere (Fenton and Fenton 1934, p. 345). The resemblance of polychaete and phoronid tubes to *Skolithos* is discussed later in this chapter.

The distribution of *Skolithos* burrows in the Lower Cambrian Bradore Formation in southern Labrador (Canada) has been interpreted as resulting from a suspension-feeding (i.e., filter-feeding) activity with the organisms partitioning limited space (see Fig. 11; Pemberton and Frey 1984). The suspension-feeding phoronid, *Phoronopsis*
*virdis* as well as some polychaetes may produce this type of distribution pattern (Johnson 1959, p. 1221).

Vossler and Pemberton (1988, p. 351) interpreted *Skolithos* tubes in upper Cretaceous storm deposits as representing the burrows of an opportunistic organism. They suggest the burrows’ small size (2 to 3 mm in diameter) and thin clay linings (0.1 mm thick) could be expected of an opportunistic species, which would be generally smaller in size than an equilibrium species living under normal environmental conditions (Vossler and Pemberton 1988, p. 353, 358). Vossler and Pemberton (1988, p. 356) suggest the opportunistic organism quickly constructed a primitive mucous-lined burrow after which sediment washed into the burrow and was subsequently preserved as a thin clay lining. The most common opportunistic faunas in modern open-marine settings are tube dwelling, or shallow-burrowing suspension-feeding polychaete worms (McCall and Tevesz 1983, p. 157). *Onuphis microcephala* is a modern polychaete known to construct chitinous tubes resembling *Skolithos*. These tubes measure 4 to 8 mm in diameter and extend as much as 45 cm into the sandy tidal creek banks along the coast of St. Catherines Island in Georgia (Pemberton and Frey 1985, p. 249, 254, 257). The dimensions of *O. microcephala* closely resemble that of *Skolithos linearis*.

Fenton and Fenton (1934, p. 342) noted that the ‘typical’ forms of the *Skolithos* ichnogenus are well represented by sand tubes made by phoronids in Morro Bay and Elkhorn Slough near Castroville in California. The modern phoronid *Phoronopsis virdis*, which apparently secretes substances to which sand grains adhere, constructs tubes that ‘closely’ approximate *Skolithos* in shape, size and spacing (Fig. 18), as do the tubes of another phoronid, *Phoronis architecta* (Fenton and Fenton 1934, p. 348). The Fentons
Figure 18. Modern *Phoronopsis virdis* dwelling tubes. These often resemble the size and straight shape of some *Skolithos* burrows. The *P. virdis* tubes above are from Bodega Bay in California (from Ekdale et al. 1984, Fig. 7-2b).
(1934) found the ‘flexuous’ tubes of Phoronopsis virdis extending to 15 mm above the sandy bottom and ending 1 to 2 mm below this substrate. If the Skolithos-making animal made tubes in a similar manner to P. virdis, it is probable that the tubes would have to be adequately buried by sediment, without breaking or collapsing the tube, in order to be preserved and closely resemble typical Skolithos ichnofossils. This seems highly unlikely. Skolithos tubes are usually not strongly inclined, and broken tubes have not been reported in previous works. Nevertheless, the dwelling structures produced by Phoronis architecta are built from a chitinoid membrane to which sand grains are cemented. The P. architecta tubes are 3 to 4 mm in diameter and 1 to 15 cm in length, or smaller and do match the size of Skolithos verticalis (Fenton and Fenton 1934, p. 345).

Many detailed studies have been made on the construction of polychaete, phoronid, and Skolithos tubes. Harding and Risk (1986, p. 685, 687) microprobed the margin of Skolithos tubes collected from the Lower Ordovician Nepean Formation in Ontario (Canada) and found anomalous concentrations of iron, aluminum, copper, and nickel. They interpreted this as the result of metal complexes by organic compounds, excreted by the tube builder, when seawater was pumped through the burrow during daily activity. Trace amounts of manganese and smaller amounts of nickel and cobalt have been reported from tubes constructed by the polychaete Serpula, but manganese is not associated with all tube-constructing polychaetes (Tasch 1973, p. 452-453). Sand grains, exhibiting at least 2:1 elongation, in the margin of 12 Skolithos tubes were preferentially oriented parallel to the tube wall in six thin sections orientated vertical to the tube, and tangentially around the tube wall margins in six thin sections orientated horizontal to the tube (Harding and Risk 1986, p. 685). This suggests the organism preferentially selected
and oriented sand grains in constructing its dwelling tube. Many modern polychaetes including some onuphinids, maldanids, sabellids, sabellariids, pectinariids, and nereids often employ fine- to coarse-grained sand in their dwelling burrows, and phoronids may use very fine-sand in their tubes (Ekdale et al. 1984, p. 84). A phoronid-like animal, because of its ‘primitive nature’ and dorsally distributed lophophore feeding structure, was suggested to have inhabited \textit{Skolithos linearis} tubes collected in siltstone float from the Jangle Limestone (Middle Cambrian) in California’s Nopah Mountains (Sundberg 1983, p. 148). Sundberg (1983, p. 148) suggests the animal protected itself in its burrow when the seawater became very turbid, probably to protect the animal from ingesting suspended sediment. The top of the tube would become buried as sediments settled out of suspension. Subsequently, the animal rose to break through the sediment cover and threw the covering sediment backwards (dorsally) as it lifted its lophophore. This created a small mound at the surface (Fig. 19). These ‘sediment mounds’ (disturbed zones in cross section) are rare structures associated with \textit{Skolithos} burrows (Fig. 20).

\textbf{Stratigraphic Range}

Trace fossils commonly span a wide range of geologic time, because in many instances ichnofossils reflect an animal’s behavior rather than its taxon. This can make identifying ichnospecies of \textit{Skolithos} and other trace fossils ‘hard or impossible’ (Lockley et al. 1994, p. 243). \textit{Skolithos} trace fossils have long been known to exist in American and European ‘primordial’ sandstones (Dana 1863, p. 82). It not only occurs in the latest Precambrian-age rocks, but it is also suggested to occur through most of the Phanerozoic (Häntzschel 1975, p. W108; Alpert 1977, p. 5; Crimes and Germs 1982, p. 893, 901; Crimes 1988, p. 10).
Figure 19. Reconstructions of a hypothetical phoronid organism making sedimentary structures associated with the *Skolithos linearis* tubes of the Carrara Formation (Cambrian) in southeast California. Figure (A) shows a suspension-feeding phoronid organism during a period of low turbidity with tentacles fully extended to gather food. The organism shifts its position downward during times of high turbidity with its tentacles folded inwards (B). The organism emerges and unfolds its tentacles after sedimentation (C). The arrow indicates the direction of tentacle and sediment movement forming the sediment mound (Sundberg 1983, Fig. 4).
Figure 20. Schematic cross section of the sedimentary structures associated with *Skolithos linearis* collected from the Cambrian Carrara Formation in southeast California. The labeled structures in the rock are disturbed zones (DiZ), distorted zones (DZ), sediment mound (M), and a *Skolithos* burrow (S). Horizontal lines represent bedding. No scale implied (Sundberg 1983, Fig. 3).
The abundance and, to some extent, the geologic range of *Skolithos* may be best exemplified by the number of *Skolithos* ‘piperocks’ that occur during the Paleozoic. *Skolithos* piperock is a particular ichnofabric caused by a dense assemblage of the trace fossil (Fig. 21) and occurs in some areas in the *Skolithos*-bearing sandstones of the Deadwood Formation. Its abundance generally decreases through the Paleozoic with only rare occurrences in post-Paleozoic rock units (Fig. 22). The decline in the distribution of *Skolithos* piperock may reflect fewer (preserved) sandy and shallow marine environments as well as biological factors resulting from new and better-adapted fauna that replaced the *Skolithos*-making organisms in evolutionary time as the dominant benthic infaunal organisms in this environment (Droser 1991, p. 321-322). In post-Paleozoic rock units a type of shrimp trace fossil, *Ophiomorpha*, dominates the *Skolithos* ichnofacies and *Skolithos* piperock is rare (Droser 1991, p. 316; e. g., Ekdale 1975). The earliest *Ophiomorpha* trace fossils are suggested to be Permian in age (Häntzschel 1975, p. W86). Therefore other biological, or geological events are necessary to account for the decrease in *Skolithos* piperock during the Paleozoic.

The initial decline of *Skolithos* piperock corresponds to the Ordovician diversification of marine metazoans (multicellular organisms with differentiated tissues for reproduction, respiration, digestion, etc.), when the number of families of metazoans with skeletons nearly tripled in a span of just 50 million years (Sepkoski 1979). Other organisms, also rapidly evolving during the early Paleozoic, most certainly affected the environment inhabited by the *Skolithos*-making organisms. For example, increases in tiering have been documented. Geologically, tiering is the establishment of a community structure in which different organisms are distributed above or below the substrate
Figure 21. Comparator for judging ichnofabric indices. Schematic diagrams of ichnofabric indices 1 through 5 for strata deposited in: (A) shelf environments; (B) high-energy nearshore sandy environments dominated by *Skolithos*; (C) high-energy nearshore sandy environments dominated by *Ophiomorpha*; and (D) deep-sea deposits. Piperock is defined as a rock fabric containing an ichnofabric index of 3 or more. Ichnofabric indices are defined as follows: (1) no bioturbation recorded [all original sedimentary structures]; (2) up to 10% of original bedding disturbed, discrete, isolated trace fossils; (3) approximately 10-40% of original bedding disturbed, burrows are generally isolated, but locally overlap; (4) last vestiges of bedding discernible, approximately 40-60% disturbed, burrows overlap and are not always well defined; and (5) bedding is completely disturbed, but burrows are still discrete in places and the fabric is not mixed. Ichnofabric index 6, for which there is no schematic diagram, is nearly totally homogenized sediment (from Bottjer and Droser 1991, Fig. 1).
Figure 22. The number of *Skolithos* piperock occurrences through the Paleozoic. The data displayed in the histogram are a function of age normalized to correct for differences in map area and duration such that the area and the duration of the Cambrian is set equal to one. Age along the X-axis is represented by (C) Cambrian, (O) Ordovician, (S) Silurian, (D) Devonian, (C) Carboniferous, and (P) Permian (from Droser 1991, Fig. 5).
surface (Ausich and Bottjer 1982, p. 173). Tiering by suspension-feeding infaunal and epifaunal communities in soft substrate from shallow subtidal shelf and epicontinental-sea settings, excluding reef complexes, exemplify an increase in ecospace utilization through the Phanerozoic (Ausich and Bottjer 1982). Infaunal suspension-feeding organisms (e.g., Skolithos-making animals) are predominantly sessile burrowers that acquire their food very close to the sediment-water interface. Epifaunal suspension-feeding organisms (e.g., stalked crinoids) are also predominantly sessile. The difference is epifaunal suspension feeders are attached to the seafloor (or to other objects on the seafloor) and acquire their food higher above the sediment-water interface. The characteristic tiering levels of infaunal and epifaunal suspension feeders in these shallow water environments, generally several meters below fair-weather wave base, has been divided into four phases (Fig. 23; Ausich and Bottjer 1991).

The complexity of epifaunal and infaunal suspension-feeding tiered communities increased during the Paleozoic. As a result, there were more suspension-feeding animals competing for the same resources like food and oxygen with each additional tier. A typical Middle Silurian community had four epifaunal tiers developed from 0 to +5 cm, +5 to +20 cm, +20 to +50 cm, and +50 to +100 cm and two infaunal tiers developed from 0 to -6 cm and -6 to -12 cm (Ausich and Bottjer 1991, p. 316; see also Ausich and Bottjer 1982; Bottjer and Ausich 1986; Bottjer and Droser 1994; Droser et al. 1995). A third infaunal suspension-feeding tier, developed from -12 to -100 cm below the substrate surface, was added later in Early Carboniferous time as part of Phase II (Ausich and Bottjer 1991, p. 317; see also Bottjer and Ausich 1986). These three infaunal tiers persisted through the Phanerozoic after their initial appearance. The increasingly
Figure 23. Four phase history of tiering among suspension feeders in the benthic marine ecosystem. Epifaunal tiers (above the substrate) are shown in the upper part and infaunal tiers (below the substrate) are shown in the lower part. The heaviest lines indicate the maximum epifaunal and infaunal tiering levels at any time. Other lines represent tier subdivisions. Solid lines represent data and dotted lines are inferred (from Ausich and Bottjer 1991, Fig. 1, as modified from Bottjer and Ausich 1986).
competitive nature of this ecosystem occurring throughout much of the Paleozoic may help explain why the number of *Skolithos* piperocks decreases from the Cambrian through the Carboniferous and the number of Permian *Skolithos* piperocks is slightly greater than the number of Carboniferous *Skolithos* piperock occurrences (see Fig. 22). This might be an effect of the terminal Paleozoic mass extinction, which severely reduced the height and complexity of epifaunal tiers, but left the infaunal tiers generally unaffected at the end of Phase II (Ausich and Bottjer 1991, p. 317).

An increase in the extent that mobile deposit feeders disrupted or bioturbated substratum in search of food has other implications for the decrease of the sessile suspension-feeding organisms responsible for making *Skolithos*. For example, an increase in bioturbation in a carbonate inner-shelf environment has been documented to occur during the Early Cambrian with a second dramatic increase occurring later between the Middle and Late Ordovician (Droser and Bottjer 1988; 1989, p. 851; Bottjer and Droser 1994, p. 157). It is reasonable to expect that similar deposit-feeding activities were occurring during these times in the sandy subaqueous environments typified by *Skolithos*. Pemberton and Jones (1988, p. 495) suggest the presence of *Skolithos*-making organisms is a response to hydrodynamic conditions. Therefore, the ichnofossils of some carbonate systems should be treated in a similar manner to their counterparts in siliciclastic settings. The documented increase in bioturbation is relevant, because deposit feeders in recent marine communities may exclude suspension-feeding organisms (Rhoads and Young 1970; Peterson 1977) by suspending excessive amounts of sediment and feces (Thayer 1979, p. 458), or by fluidizing mud substrata, which may foul the biological filtering systems of suspension feeders (Rhoads 1970). Deposit-feeding
animals may also accidentally ingest suspension feeders or their larvae (Thorson 1966), or they may ‘bulldoze’ through the sediment and bury suspension-feeding organisms, particularly juveniles (Thayer 1979, p. 458). It should be noted that the general increase in bioturbation during the Ordovician may have been influenced by an increase in organic matter washing into the seas (Thayer 1979, p. 460; Thayer 1983) beginning with the dispersal of land plants in Late Ordovician time (Dott and Prothero 1994, p. 282). This increase in available food close to shore possibly encouraged deposit feeders to settle the nearshore environments typically inhabited by the suspension-feeding organisms that made *Skolithos* tubes and is another apparent reason for the decline of *Skolithos* piperock.

Information from 50 stratigraphic units reported in 46 sources (Appendix A) referencing strata containing *Skolithos* trace fossils was collected in an attempt to better understand the stratigraphic range of *Skolithos* (Fig. 24). These sources were chosen to span the time from Precambrian to Recent; represent environments in which phoronids and/or polychaetes were the probable *Skolithos*-making animals (i.e., marine deposits); and include literature that gives details helpful in identifying the *Skolithos* ichnogenus. References describing *Skolithos* burrows occurring in modern carbonate settings were also included. *Skolithos*-making animals can thrive in this environment when certain hydrodynamic conditions are similar to those found in siliciclastic or nearshore environments where the suspension-feeding *Skolithos*-making organisms are more commonly found (Pemberton and Jones 1988, p. 495). Literature on fluvial deposits was additionally included because this was the only source that allowed identification of the *Skolithos* ichnospecies in Precambrian-age rocks. The ichnogenus was either identified by the author of the reference, or inferred by the present author from diameter
Figure 24. Apparent stratigraphic range of the characteristic Skolithos ichnospecies. The black areas in the figure (next page) represent times that polychaetes and/or phoronids could have made Skolithos tubes. The figure is based on an analysis of 46 studies listed in Appendix A. The Skolithos (S.) ichnospecies, coded across the top of the figure, are: (S. a.) S. annulatus (Howell 1957); (S. b.) S. bulbus (Alpert 1975); (S. i.) S. ingens (Howell 1945); (S. l.) S. linearis (Haldeman 1840); (S. m.) S. magnus (Howell 1944); and (S. v.) S. verticalis (Hall 1843).
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(Fig. 24)
measurements given. *Skolithos* length measurements are often incomplete, because the outcrop is poorly exposed and/or the tube length is prematurely terminated and juxtaposed against an eroded surface. Thus, tube length is often an unreliable criterion and so, when possible, should be avoided when determining *Skolithos* ichnospecies (Alpert 1974; 1975). Length measurements were considered only in distinguishing between *S. linearis* and *S. verticalis* when the diameter of the tube was 3 to 4 mm, because both ichnospecies can have this same diameter. However, *S. linearis* is generally larger, relative to *S. verticalis*, being between 3 to 12 mm in diameter and generally longer (up to 1 m).

Figure 24 shows that *S. linearis* (Haldeman 1840) is cited most commonly in the literature followed by *S. verticalis* (Hall 1843). This is no doubt due to the long stratigraphic range of both ichnospecies, which includes occurrences from the Late Precambrian units and Recent deposits, thus allowing more opportunities to study these trace fossils. *S. linearis* and *S. verticalis* were in fact the premier ichnospecies described in the *Skolithos* ichnogenus (Alpert 1974; 1975), and were identified 31 and 26 times, respectively, in Appendix A. *S. bulbus* (Alpert 1975) follows with dramatically fewer occurrences in the reviewed literature. It occurred in three Early Cambrian units and once each in Cambro-Ordovician and Middle Ordovician units. *S. annulatus* (Howell 1957), *S. ingens* (Howell 1945) and *S. magnus* (Howell 1944) were all rarely documented and occurred, respectively, in Early Cambrian, Cambro-Ordovician and Late Ordovician rock units. The few reports of these last three *Skolithos* ichnospecies cannot be attributed to a lack of recognition, because they are easily identifiable like the other *Skolithos* ichnospecies (Droser 1991, p. 322).
Crimes (1974; 1992) documented the change in the diversity of bathymetrically independent, shallow-water and deep-water types of trace fossils (Fig. 25). Interestingly, his results seem to reflect in some ways the increase in bioturbation that Droser and Bottjer (1989) discussed and the tiered community structures of suspension feeders recognized by Ausich and Bottjer (1991). Bathymetrically independent trace fossils increase in diversity from Precambrian to Cambrian and again from Cambrian to Ordovician time. Deep-water trace fossils, apparently not present during the Precambrian, increased in diversity first in Cambrian time and again later during the Ordovician. Trace fossils indicative of shallow marine environments increase in diversity during the Cambrian and decrease slightly after the Ordovician with a continued decline up through the Tertiary. These changes appear to correlate with changes in the complexity of tiering by suspension-feeding epifaunal and infaunal animals reported by Ausich and Bottjer (1982; 1991) and Bottjer and Ausich (1986). The increase in diversity of bathymetrically independent and deep-water types of trace fossils during the Cambrian and Ordovician may correspond to the documented increases in bioturbation that occurred in Early Cambrian and again later between Middle and Late Ordovician. However, there appears to be a lag in the Cambrian and Ordovician between the diversity and bioturbation increases. The slight decrease in the diversity of shallow-water forms from Ordovician to Silurian correlates better with the increase in bioturbation occurring in Late Ordovician time. This may help demonstrate the overall effect that new organisms and increases in ecospace utilization (like tiering) had on the Skolithos-making animals, implying that similar increases in bioturbation documented to occur in carbonate inner shelf environments also happened in the sandy, nearshore environments where the
Figure 25. Marine trace-maker diversity from Precambrian through Tertiary. A dramatic increase in the diversity of shallow-water trace makers occurring between the Precambrian and Cambrian as well as the absence of deep water types during the Precambrian and their subsequent increase in diversity suggest that marine trace-making organisms first inhabited shallow-marine regimes before deeper marine environments (Crimes 1974; 1992). The abbreviations are Precambrian (PC), Cambrian (C), Ordovician (O), Silurian (S), Devonian (D), Carboniferous (C), Permian (P), Triassic (T), Jurassic (J), Cretaceous (K), and Tertiary (Tr).
Skolithos-making animals lived.

The effect of the above changes is thought to have been detrimental to the Skolithos-making animal, and these resulted when other animals evolved to compete in the same environment. This seems to be reflected in Figure 24. The number of Skolithos ichnospecies increases from two (S. linearis and S. verticalis) in Precambrian units (although only two sources documenting Skolithos in Precambrian rocks were referenced) to four (adding S. annulatus and S. bulbus) in Early Cambrian units. This may correlate to the increase in the diversity of shallow-water trace fossils occurring during the Cambrian. The number of Skolithos ichnospecies decreases from these four back to the initial two ichnospecies by Middle Cambrian time, possibly correlating with the increase in bioturbation in this same environment according to Pemberton and Jones (1988) as well as reflecting the competition from other infaunal suspension feeders that developed a 0 to -6 cm tier by the Cambrian. The number of Skolithos ichnospecies increases from these two Middle Cambrian types to four (S. bulbus, S. ingens, S. linearis and S. verticalis) by the Cambro-Ordovician then it decreases to three by Middle Ordovician, apparently losing S. ingens. S. bulbus is not reported in the reviewed literature after Middle Ordovician time, but three Skolithos ichnospecies remain due to the initial appearance of S. magnus in Late Ordovician rocks. The changes during the Ordovician may correlate with the development of a deeper (-6 to -12 cm) infaunal suspension-feeding tier added in Ordovician or Late Cambrian time, and Middle Ordovician increases in the complexity and height of epifaunal suspension-feeding tiers. These changes may be also related to increased bioturbation occurring between the Middle and Late Ordovician by deposit-feeding organisms. The diversity of shallow-water trace
fossils decreases slightly after the Ordovician, as does the number of *Skolithos* ichnospecies. The fewer number of *Skolithos* ichnospecies reported in Silurian units (see Fig. 24) coincides with the addition of the highest epifaunal suspension feeder tier. The *Skolithos* ichnospecies (*S. linearis* and *S. verticalis*) occurring next in the literature after the Silurian were found in Middle Devonian units, Mesozoic units except for Triassic deposits, and Cenozoic units. The timing of bioturbation and tiering events discussed is shown along with changes in the number of *Skolithos* ichnospecies through the Tertiary in Figure 26. Overall, Cambrian and Ordovician age rock units exhibit greater diversity in the type of *Skolithos* ichnospecies they contain than the other rock units.

Some gaps in the stratigraphic range of *Skolithos* ichnospecies in Figure 24, representing an absence of data, are synchronous with extinction events, although no single event caused the complete extinction of all *Skolithos*-making organisms. Major extinction events (with probable causes) are the Late Ordovician (glaciation), Late Devonian (global cooling without glaciation), Late Permian (glaciation, changes in seawater chemistry due to increased volcanism, plus possible other factors), Late Triassic (climatic changes including increased precipitation), Cretaceous-Tertiary boundary (evidence for increased volcanism and especially bolide impact), and smaller scale extinction events during the Eocene, Oligocene and Pleistocene. Although no single extinction mechanism can be invoked to account for all of these events, some of them may have resulted from several coincident causes (Clarkson 1993, p. 71-74). More information is needed on the stratigraphic range of *Skolithos* ichnospecies in order to establish the relative importance of such factors as bioturbation, ecospace utilization, evolution, and extinction events on the *Skolithos*-making organisms.
Figure 26. Epifaunal and infaunal suspension feeder tiering complexity through the Phanerozoic (above from Ausich and Bottjer 1991, Fig. 1) with changes in the number of *Skolithos* ichnospecies (below). The lower figure accounts for all data in Figure 24 and Appendix A. Solid black and gray diamonds in the lower figure mark data (i.e., *Skolithos* bearing rock units, Early Cambrian, Middle Cambrian, etc.) used in Figure 24. Cambro-Ordovician age rock units, including the Aladdin sandstone, are indicated by the gray colored diamond. Arrows along the x-axis mark periods of increased bioturbation by infaunal deposit-feeding organisms in a carbonate inner-shelf environment (Droser and Bottjer 1988, 1989; see also Pemberton and Jones 1988, p. 495).
CHAPTER THREE

METHODOLOGY

Fieldwork

Before beginning fieldwork, the Late Cambrian-Early Ordovician contact in the northern Black Hills and southern Bear Lodge Mountains was transferred from the combined topographic and geologic map of Darton and Paige (1925) to 7.5 minute USGS topographic quadrangle maps. Locating the contact in this way aided in finding Aladdin sandstone outcrops, as did also the more detailed information from theses by McCoy (1952), Seeland (1961), Kulik (1962; 1965), Boyd (1975), and Stanley (1984). The study area in the northern Black Hills is shown in Figure 27. This can be separated into two parts, one containing the LCSS in the eastern portion and the other containing the EOSS in the central and western parts of the northern Black Hills. Each site was alphabetically assigned a one-letter code in the order the site was visited.

Site locations are described in more detail along with their ‘interval’ descriptions in Appendix B. The LCSS sites are named and coded as follows from southeast to northwest: Boxelder Creek (J), Little Elk Creek near Red Gate (E), Steamboat Rock (I), Dalton Lake (H), and Kirk Hill (G). The LCSS is well exposed in these areas but also
Figure 27. Locations of the LCSS and EOSS sites in the Black Hills (base map from Ladle 1972, Fig. 2). The bold, dashed-dotted line is drawn approximately between the southern LCSS and northern EOSS areas. The sites, in bold capital letters, are:

A. Spearfish Canyon  F. Iron Creek Lake  K. Warren Peaks  
B. Crow Peak  G. Kirk Hill  L. Sheep Mountain  
C. Deadwood  H. Dalton Lake  M. Cheyenne Crossing  
D. Whitewood Peak  I. Steamboat Rock  (no LCSS/EOSS found)  
E. Little Elk Creek  J. Boxelder Creek  N. Trojan
occurs in other southerly parts of the Black Hills. The EOSS sites are named and coded as follows from east to west: Whitewood Peak (D), Deadwood (C), and Trojan (N), Spearfish Canyon (A), Iron Creek Lake (F), Crow Peak (B), Sheep Mountain (L), and Warren Peaks (K). The LCSS and EOSS sites were chosen so as to represent, to the extent possible, all parts of the northern Black Hills. Fieldwork commenced May 25, 1998 and ended June 15, 1998.

Description of the rock units began by dividing each outcrop section into intervals based on one or more of the following criteria: predominant grain size, bedding characteristics, Skolithos characteristics, and/or overall composition and color of the rock. Bedding and Skolithos characteristics make up the interval descriptions in Appendix B. The bedding characteristics consist of thickness (classified using terminology from Boggs 1987, p. 138), color in general descriptive terms, variations in friability, presence or absence of cross-bedding (identified when possible as trough, tabular-planar, and planar with tangential bottomsets), and the nature of the upper and/or lower stratigraphic contacts. The orientation to bedding, shape, typical length and diameter, filling, and ‘density’ make up the Skolithos characteristics.

Skolithos density was calculated by counting the number of tubes that cross a 12 cm-long line oriented parallel to bedding and dividing this number by 12, giving the number of tubes per cm. The length, 12 cm, was chosen for convenience as a number of tubes could be quickly counted this way. These measurements were taken wherever Skolithos tubes could be easily seen in an interval. For this reason, they are somewhat biased observations. However, these measurements were made repeatedly at multiple levels within the interval until it was felt that the typical (horizontal) density was
determined for that portion of the section. The typical spacing of the tubes was recorded for multiple levels within an interval when there was a change in the number of *Skolithos* tubes occurring in the vertical direction. These levels represent the upper, middle and lower parts of the interval or, when changes are less apparent, only the upper and lower portions. A single density measurement, representing the typical number of *Skolithos* tubes for the entire interval, was made when there was no apparent change vertically.

After describing an interval, a representative fist-sized sample of the rock was collected and, when possible, this was chosen so as to contain *Skolithos* tubes. Samples were also collected above and below the stratigraphic bedding contacts when possible as were also other samples from outcrops that were either unusually hard (due to abundant quartz cement), consisted of silty interbeds, or contained no *Skolithos* tubes. The samples were described in terms of color, rock cement (using a hand lens to closely inspect the reaction of HCl acid), composition of framework grains, and the modal and maximum framework grain sizes (measured with an *American/Canadian Stratigraphic* visual grain-size comparator).

**Laboratory Work**

The rock samples were trimmed with a diamond-blade rock saw and sent to a commercial laboratory to be made into thin sections. A total of 33 petrographic thin sections were prepared, so that at least one thin section was available from each site (10 LCSS and 23 EOSS thin sections). The thin sections are oriented perpendicular to the *Skolithos* tubes, and so are also oriented approximately parallel to bedding. Their descriptions are found in Appendix C. Each thin section was divided into six contiguous
areas covering the entire slide. The percent abundance of framework grains, matrix, cement, and porosity in each area was visually estimated using a visual abundance comparator from Terry and Chilingar (1955, Figs. 1-4). The estimated abundances were converted to the following verbal ranges: none (zero percent), trace (less than one percent), scarce (one to five percent), common (five to 25 percent) or abundant (greater than 25 percent). Note that the thin section percentages are equivalent to volumetric percentages for the rock. Also, the modal grain size was judged in each area using the *American/Canadian Stratigraphic* grain-size comparator that groups grains into half phi size classes (see codes in Appendix C). In addition, modal sorting and roundness were estimated in each area from visual comparators in Harrell (1984, Figs. 2-6) and Powers (1953, Fig. 1), respectively. These ‘raw’ results (semi-quantitative abundances and qualitative descriptions of texture) were recorded, and then integrated into the ‘final’ results given in Appendix C. For example, trace amounts of orthoclase occurred in three different areas in sample D-8 and it also occurred in scarce amounts in three other areas in this sample. Therefore, the final result given in Appendix C shows that ‘trace to scarce’ amounts of orthoclase occurs in sample D-8.

*Skolithos* characteristics were documented from 30 thin sections, which contained 183 *Skolithos* cross sections. Their descriptions are given in Appendix D. Samples H-11, J-1 and J-5 do not contain *Skolithos*, and were selected instead to investigate other rock characteristics, especially cement. The *Skolithos* cross-sectional shapes are described in Appendix D as follows: ‘circular’ when the sample was cut perpendicular to *Skolithos* and approximately parallel to bedding; ‘oval’ when the sample was cut slightly tangential through mainly circular-shaped *Skolithos* tubes; ‘egg-shaped’ when the sample
was cut strongly tangential through the tubes, suggesting that the tubes were inclined to bedding; or ‘indeterminate’ when the tube exhibited no obvious shape in cross section, perhaps due to the surrounding grains being plucked-out during thin-sectioning. The grain size of the tube wall was also measured and recorded if it differed from the rock’s modal grain size. This was recorded as ‘ND’ if the tube-wall grains are not different from the rock’s modal grain size; ‘D’ if nearly all of the tube-wall grains differ in size from the rock’s modal grain size; or ‘.5D’ if roughly half of the tube-wall grains differed in size from the rock’s modal grain size. Elongated grains in the tube wall were categorized by the orientation of their long axis relative to the tube wall. These visually estimated categories are: ‘T’ if the long axis of most grains appeared to be tangent to the tube wall; ‘P’ if the long axis of most grains appeared to be approximately perpendicular to the tube wall; or ‘R’ if the long axis of most grains appeared to be randomly oriented with respect to the tube wall. The grain packing (spatial density of framework grains) and porosity (percentage of the rock that is void of material) in the tube wall and around the tube, respectively, was compared to the rock’s modal grain packing and porosity. This is noted as ‘L’ if the packing/porosity appeared to be less than rock’s modal grain packing/porosity; ‘M’ if the packing/porosity appeared to be more than the rock’s modal grain packing/porosity; or ‘ND’ if the packing/porosity was not different than the rock’s modal grain packing/porosity. The extent to which the tube was filled with some material was described as ‘N’ if there was no filling; ‘F’ if the tube was completely filled; or ‘P’ if the tube was partially filled. The material in partially filled tubes was distinguished as ‘L’ if the tube contained only a thin lining along the inside of the tube wall, or ‘S’ if the material filling part of the tube extended beyond the tube wall and into
the surrounding sand grains.
CHAPTER FOUR

RESULTS

Fieldwork

Introduction

The sites adjacent to major roads and easiest to access are the Dalton Lake and Boxelder Creek areas for the LCSS and Spearfish Canyon, Iron Creek Lake and Trojan for the EOSS. Longer walks are required to reach the other sites. The completeness, visibility and overall quality of the LCSS and EOSS vary from poor (e.g., Kirk Hill for the LCSS; Crow Peak and Warren Peaks for the EOSS) to excellent (e.g., Steamboat Rock for the LCSS; Deadwood, Trojan and Sheep Mountain for the EOSS). The upper and lower parts of the rock units at Little Elk Creek and Sheep Mountain, respectively, cannot be easily studied due to the topography (mainly cliffs) that makes accessing these parts very difficult.

Bedding characteristics can be quite similar throughout a particular locality, but sometimes they are also quite variable. It is easiest to select vertical intervals based on changes in bedding characteristics, such as those related to variations in friability (caused by changes in cement), grain size, and primary sedimentary structures like cross-bedding.
Skolithos trace fossils are usually easy to recognize and their characteristics are also useful for defining vertical intervals. However, the same intervals in one outcrop could not always be recognized in other outcrops at the same locality. A total of 40 LCSS intervals and 47 EOSS intervals are described in this study (see Appendix B).

**Composition and Color**

The LCSS is typically a siliceous, calcareous, ferruginous (hematitic) and dolomitic quartz arenite sandstone that is often dark or bright red in color due to its hematite cement. The sandstone frequently contains sand-sized glauconite grains. The dolomite cement is evident from the small reddish rhombs that react slightly with dilute HCl acid. The EOSS is typically a siliceous, less commonly calcareous, and ferruginous quartz arenite sandstone that is often tan, white or yellow-orange in color. Glauconite is not common among the framework grains of the EOSS except in interval D-8 at Whitewood Peak.

**Grain Size**

As seen in Figure 28, the modal grain sizes of the LCSS samples ranged between the lower fine and lower median sand size classes (3 to 1.5 phi) with most falling within the upper fine sand size (2 to 2.5 phi). The EOSS is generally finer-grained with modal grain sizes ranging between the upper very fine and upper fine sand size classes (3.5 to 2 phi). A weak trend in the stratigraphic distribution of the modal grain size occurs in both sandstone units at some sites as shown in Figure 29. The sand coarsens upwards from mainly upper fine- to lower medium-grained in the LCSS at Dalton Lake, and also coarsens upwards from lower fine- to upper fine-grained in the EOSS at Whitewood
Figure 28. Modal and maximum grain sizes of the LCSS and EOSS (estimated using a visual comparator). The sand size classes are coded as follows:

- lower coarse-grained (c L): 1 to 0.5 phi (0.50 to 0.71 mm)
- upper medium-grained (m U): 1.5 to 1 phi (0.35 to 0.50 mm)
- lower medium-grained (m L): 2 to 1.5 phi (0.25 to 0.35 mm)
- upper fine-grained (f U): 2.5 to 2 phi (0.177 to 0.25 mm)
- lower fine-grained (f L): 3 to 2.5 phi (0.125 to 0.177 mm)
- upper very fine-grained (v f U): 3.5 to 3 phi (0.088 to 0.125 mm)
<table>
<thead>
<tr>
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<th>Interval</th>
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<tr>
<td></td>
<td></td>
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<tr>
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<tr>
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<td>X</td>
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<tr>
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<td>C-5 (base)</td>
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Figure 29. Apparent trends in the stratigraphic distribution of modal grain size in the LCSS at Dalton Lake and EOSS at Whitewood Peak and Deadwood. An ‘X’ is placed in the column of the modal grain size for each interval. The interval numbers increase upward through a section.
Peak. These observations, however, are not based on complete sections, because the bedding contacts are not exposed at these localities. Grain size decreases upward from lower fine to upper very fine sand in the EOSS at Deadwood.

**Bedding Characteristics**

Bedding in the LCSS is usually massive (layers over 100 cm thick). Siltstone having discontinuous, thin (3 to 10 cm thick) to very thin (under 3 cm thick) laminations occurs locally at Boxelder Creek, Dalton Lake and Steamboat Rock. Planar cross-beds having tangential bottomsets and tabular-planar cross-beds are found at Dalton Lake and in the lowest part of the LCSS at Little Elk Creek. Trough cross-beds are seen at Dalton Lake, Steamboat Rock and Boxelder Creek.

In the EOSS, massive bedding occurs in all the intervals at Trojan, Spearfish Canyon, Crow Peak, Iron Creek Lake and Warren Peaks, and it occurs in one interval near the top of the sections at Whitewood Peak and Sheep Mountain. Intervals containing thin (3 to 10 cm thick), flaggy, bioturbated beds occur at Deadwood and Sheep Mountain. These beds often contain shale partings and no *Skolithos*. Medium (10 to 30 cm thick) to thin bedding occurs at Whitewood Peak. Thin, medium and thick (30 to 100 cm thick) bedding is found at Deadwood; and thick and medium bedding also occurs at Sheep Mountain and Warren Peaks, respectively. Trough-type cross-beds do not occur in the EOSS, but planar cross-beds with tangential bottomsets and tabular-planar cross-beds are seen at Crow Peak, Whitewood Peak, and Deadwood. Planar cross-beds with sloping bottomsets are noted at Trojan and in the upper part of the section at Iron Creek Lake. Interval F-3 at Iron Creek Lake contains cross-beds with especially
long foreset laminations (1.5 m) not seen in other intervals except C-10 at Deadwood. Tabular-planar cross-beds can be identified in the lowest interval at Spearfish Canyon.

Well-cemented zones (perhaps the beginning of concretions) and the friable rock that erodes more easily around them are prominent at Steamboat Rock and Boxelder Creek in the LCSS. These zones clearly developed during diagenesis as indicated by the *Skolithos* tubes and cross-bedding that cross-cut them (*Skolithos* tubes also pass through cross-beds; Fig. 30). There are three types of cemented zones that differ in shape and size: (1) small, flat irregular-shaped ‘patches’ of hard siliceous, ferruginous and calcareous cement, measuring a few centimeters across, which contain sand-sized glauconite grains (intervals I-7 and I-10 at Steamboat Rock with longer and more continuous patches found along the upper and lower contacts of these intervals); (2) rounded, concretion-like structures measuring 1 to 3 mm in diameter (intervals I-9, I-10 and I-12 at Steamboat Rock); and (3) harder, larger (2 to 19 cm in diameter) calcareous concretions (in intervals J-1, J-4 and J-5 at Boxelder Creek). The type 3 cemented zones commonly contain more glauconite than the more friable, surrounding sandstone, probably because the glauconite has been weathered away where it was not protected by cement. The EOSS is usually very well cemented throughout, and hence hard except for some intervals at Whitewood Peak (e.g., D-4 and D-9), whereas the LCSS at Boxelder Creek, Steamboat Rock and Dalton Lake is more friable with harder intervals occurring near the top at Boxelder Creek and Steamboat Rock.

**Bedding Contacts**

This study did not find a contact between the LCSS and EOSS anywhere in the northern Black Hills. The area where this contact is most likely to occur at the surface is
Figure 30. Well-cemented zones and *Skolithos* in the lower part of the LCSS at Boxelder Creek. These zones are more frequent near the top of the section where they are more spherical in shape and also more resistant to erosion. *Skolithos* trace fossils (S) can be seen cutting through the well-cemented zone (C) at the arrow in this picture.
between the Deadwood/Whitewood Peak localities and the Kirk Hill locality, where outcrops of the rock units are at their closest (about 13.5 km or 8 mi apart). The rock units are largely covered in this area except for poor quality exposures of the LCSS in Deadman Gulch and Vanocker Canyon (just south of Sturgis, about 10 km or 6 mi north of the Kirk Hill site). However, the lower contact of the LCSS is sharp and well exposed at Steamboat Rock. At Steamboat Rock, friable, dark red, calcareous and ferruginous quartz arenite sandstone (interval I-1) lies beneath the first massive sandstone interval (I-2) containing *Skolithos* trace fossils. Interval I-1 is thinly bedded, cross-bedded, flaggy in appearance, and recessed beneath the LCSS.

The lower contact of the EOSS is sharp at Deadwood, Trojan, Spearfish Canyon, and more gradational at Warren Peaks to the west. This contact occurs between thin to thickly bedded sandstone, which is usually friable near the top and contains green shale partings, and the first overlying *Skolithos*-bearing interval. The sandstone immediately beneath the lower EOSS contact is calcareous and flaggy in appearance at Deadwood; siliceous, calcareous and thinly bedded at Spearfish Canyon; and siliceous and thinly bedded at Trojan and Warren Peaks. The lower contact at Sheep Mountain could not be examined because it occurred in a steep cliff face.

The upper contact of the EOSS is usually covered by slopes of green shale from the overlying Icebox Member of the Winnipeg Formation in the northern Black Hills. This contact is placed between intervals C-15 and C-16 at Deadwood. It is found above the uppermost exposed interval (C-14) that contains *Skolithos* trace fossils by digging into the shallow cover. Interval C-14 (21.5 cm thick) is overlain by 4 cm of red-yellow, siliceous, ferruginous quartz arenite sandstone (C-15) containing shale partings and
exhibiting small local relief of about 1 cm on an otherwise sharp contact on its upper surface. Interval C-15 is immediately overlain by a thin (17 cm thick) transition zone of clean, poorly sorted, blue-gray, non-calcareous, siliceous quartz arenite sandstone (C-16, 1 cm thick) that grades upward into blue-gray, siliceous sandy shale (C-17, 14 cm thick) that in turn grades upward into blue-gray, siliceous quartz arenite sandstone (part of C-17, 2 cm thick). Brushing aside the thin cover of soil a short distance upslope from C-17 helps reveal the yellow-orange, siliceous, ferruginous quartz arenite sandstone that is interbedded with blue-gray sandstone (C-18, 35.5 cm thick). The rock is locally eroded back in step-like fashion where sample C-18 was collected. The upper contact is sharp with mainly red-brown or blue-gray sandy shale (15 cm thick) occurring at the base of the Winnipeg Formation (interval N-5) at Trojan. This material contains less shale in places in the lower part where bluish-white sand grains occur. The matrix holding these grains together is so friable the sand grains can be plucked from the outcrop by hand with little effort.

**Skolithos Characteristics**

**Orientation and Shape**

*Skolithos* occurs in most intervals, but their characteristics cannot be used to identify the same stratigraphic horizons at different localities in the study area. The tubes may be oriented nearly perpendicular to bedding (85 to 90 degrees) or inclined 55 to 85 degrees in the LCSS and 30 to 85 degrees in the EOSS. No interval exhibits *Skolithos* trace fossils consistently inclined in one direction, and both perpendicular and inclined orientations commonly occur in the same interval. The tubes can be either straight or slightly curved in shape, with both types commonly occurring in the same interval.
However, there are more curved *Skolithos* tubes in the EOSS than in the LCSS. Strongly curved tubes occur less frequently than the straight or slightly curved-shaped varieties.

**Length and Diameter**

The length of the *Skolithos* tubes cannot be depended on to determine the ichnosppecies. The original top or bottom end of the tube is often missing due to syndepositional erosion. This is seen where tubes are truncated at the upper or lower bounding margin of a cross-bed set as in Figures 31 and 32. *Skolithos* is also sometimes preserved in positive relief when the filling is hard, such as when filled by hematite or hematite-cemented sand grains, as is commonly the case at the Dalton Lake area (Fig. 33). However, sometimes the surrounding sandstone is as well well-cemented with hematite (particularly along cross-beds) as the *Skolithos* tubes, and so encloses and obscures parts of the tube (Fig. 34). Additionally, the tubes will also look shorter than they really are when the outcrop surface is not exactly parallel with the tube, which is often the case (Fig. 35). However, *Skolithos* tubes, at least the part that can be seen, are usually about 2 cm long. The longest tubes (10 cm) in the EOSS are found near the unit’s eastern and western limits in the northern Black Hills at Whitewood Peak and Sheep Mountain, respectively, while the longest tubes occurring near the southern margin of the unit at Iron Creek Lake and Trojan are much shorter (2.5 cm and 3 cm, respectively).

With rare exception, the diameter of *Skolithos* tubes in the LCSS and EOSS is constant along the entire length of the tube and is a more reliable indicator of the organism’s size than the apparent length of the tube. For this reason, the identification of *Skolithos* ichnospecies is based mainly on the tube diameters. No tubes in the study area
Figure 31-A. *Skolithos* in EOSS interval C-8 at Deadwood. The tubes are rarely longer than 3 cm and vary from straight to slightly curved. The tubes are typically 1.5 to 2 mm in diameter, thus indicating *Skolithos verticalis*. Note the planar (or tabular-planar) cross-bedding within this interval.
Figure 31-B. Same image as Figure 31-A, but with bold lines added to mark *Skolithos* tubes in EOSS interval C-8 at Deadwood.
Figure 32. The LCSS at the Dalton Lake site containing hematite-filled *Skolithos* tubes. The bright red tubes (S) are most abundant near the top of the picture where they are very short, ending at areas representing erosional surfaces marked by the white arrows. Fewer tubes occur in the lower half of the picture where scour and fill structures or trough cross-bedding occurs. A quarter appears in the middle of the picture for scale.
Figure 33. *Skolithos* (S) tubes in positive relief in LCSS interval H-8 at the Dalton Lake site. A dime appears in the picture for scale.
Figure 34. *Skolithos* (S) tubes in positive relief from the friable sandstone at the Dalton Lake site. Note how the harder sandstone encloses portions of these tubes, concealing part of the tube length. A quarter appears in the picture for scale.
Figure 35. *Skolithos* tubes in EOSS interval D-4 at Whitewood Peak.
have a funnel-shaped top, which is characteristic of another trace fossil, *Monocraterion* that otherwise looks virtually the same as straight *Skolithos* tubes. The tubes that are slightly wider at one end are most likely artifacts of their orientation (i.e., inclined to the outcrop surface). The common (interquartile) ranges in *Skolithos* diameter are 1 to 2 mm in the EOSS and 2 to 3 mm in the LCSS, and are very consistent throughout the study area (Fig. 36-37). The average diameter is slightly larger (2.5 mm) in the LCSS than the EOSS (2 mm). The maximum diameter in the LCSS is 5 mm. It occurred just once in interval I-2 at Steamboat Rock and twice in intervals J-1 and J-3 at Boxelder Creek. The maximum diameter in the EOSS is 10 mm. It occurred just once in interval B-2 at Crow Peak. The next largest *Skolithos* diameter in the EOSS is 5 mm and it occurred just once at Sheep Mountain (interval L-4).

The observed diameters and other characteristics of the *Skolithos* tubes indicate that both *S. linearis* (Haldeman 1840) and *S. verticalis* (Hall 1843) occur in the LCSS and EOSS. Note, however, these different tubes are not necessarily made by different organisms. The tubes measuring 1 to 2.5 mm are *S. verticalis*, those measuring 3 to 4 mm can be either *S. verticalis* or *S. linearis*, and those measuring more than 4 mm are *S. linearis* (see Table 4). Applying this information to the 166 *Skolithos* diameter measurements (77 and 89 measurements in the LCSS and EOSS, respectively) in Appendix B shows that *S. verticalis* is the predominant ichnospecies in the EOSS (82 percent of the tubes measured). It may be just as common in the LCSS, but this rock unit contains more tubes (44 percent) that are 3 to 4 mm in diameter, which may be either *S. linearis* or *S. verticalis*. Tubes 3 to 4 mm in diameter occur less frequently (16 percent) in the EOSS. *S. linearis* can be clearly identified (i.e., diameter is more than 4 mm) in
Figure 36. Box-and-whisker plots of *Skolithos* diameters measured in the LCSS and EOSS. ‘Boxes’ (rectangular sections) enclose the middle 50 percent of each data group (interquartile range). Small crosses (+) mark the mean of each data group with triangles (△) marking the mode and a vertical line marking the median, which is the same as a box edge in this case. The ‘whiskers’ are horizontal lines with short vertical lines at the ends. The lower (left) whisker is drawn from the 25th percentile (lower quartile) to the smallest diameter within 1.5 interquartile ranges from the lower quartile. The other whisker is drawn from the 75th percentile (upper quartile) to the largest diameter within 1.5 interquartile ranges from the upper quartile. Diameters that fall beyond the whiskers, but within three interquartile ranges (outliers), are marked by individual small squares. Small squares with crosses mark diameters that are more than three interquartile ranges below the lower quartile or above the upper quartile. Plots created using the computer program *Statgraphics Plus* version 4.1 (Manugistics, Inc., Rockville, MD). The mean *Skolithos* diameter is 2.5 mm in the LCSS and 2 mm in the EOSS. The modal *Skolithos* diameter is 2 mm in both rock units. The median of each data set is 2 mm. Outliers are at 5 mm in the LCSS and at 4, 5 and 10 mm in the EOSS.

<table>
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*Skolithos Diameter by Rock Unit*
Figure 37. Box-and-whisker plots of *Skolithos* diameters measured at each site. LCSS sites are in italics and EOSS sites in plain print. See Figure 36 for an explanation of the symbols used on this plot.
only 4 percent and 2 percent of the tubes measured in the LCSS and EOSS, respectively. *S. linearis* occurs in intervals at Crow Peak (B-2, one tube 10 mm in diameter), Steamboat Rock (I-2, one tube 5 mm in diameter), and Boxelder Creek (J-1 and J-3, one tube in each, 5 mm in diameter), and Sheep Mountain (L-4, one tube 5 mm in diameter).

**Spacing**

The modal *Skolithos* density is 0.4 tubes per cm in the LCSS and 0.5 tubes per cm in the EOSS, which is also close to the average of each unit (Fig. 38). Unlike *Skolithos* diameters, these measurements do show more variation at the site level (Fig. 39). Interval H-7 at Dalton Lake in the LCSS has an unusually high density (1 tube per cm) that is noticeably larger than the site’s overall *Skolithos* density. It was just as high in intervals L-6 and L-8 at Sheep Mountain in the EOSS. Each of these unusually high *Skolithos* densities was observed just once in the mentioned intervals where other lower *Skolithos* densities also occurred. Overall *Skolithos* density is typically high in the EOSS at Deadwood and Iron Creek Lake, but no one measurement was much larger than the others at that particular site. The modal *Skolithos* density in the LCSS is 0.6 at Dalton Lake and Little Elk Creek, 0.4 at Steamboat Rock, and 0.3 at Boxelder Creek. In the EOSS, these values are 1 at both Deadwood and Iron Creek Lake, 0.6 at Whitewood Peak, 0.5 at both Crow Peak and Sheep Mountain, 0.4 at Warren Peaks and 0.3 at Spearfish Canyon. A modal *Skolithos* density is not available for Trojan because just three measurements were recorded (0.3, 0.6, 0.8) and none were the same. In general, the LCSS contains thicker portions (roughly 1 m or more in thickness) that do not contain any *Skolithos* tubes than the EOSS.
Figure 38. Box-and-whisker plots of *Skolithos* densities measured in the LCSS and EOSS. See Figure 36 for an explanation of the symbols used on this plot.
Figure 39. Box-and-whisker plots of *Skolithos* densities measured at each site. LCSS sites are in italics and EOSS sites in plain print. See Figure 36 for an explanation of the symbols used on this plot.
Filling

Although the material filling *Skolithos* in the LCSS and EOSS is usually different, the same type of filling occurs at different sites within the same rock unit with a few exceptions. Very fine-grained hematite is the prominent filling in *Skolithos* in the LCSS sections at Boxelder Creek, Steamboat Rock, Dalton Lake and Little Elk Creek. The filling is usually brighter or darker in color than the surrounding sandstone (see Fig. 32). The hematite-filled *Skolithos* are harder and more resistant to erosion than the more friable surrounding sandstone in the middle part of the Dalton Lake section, causing the filled tubes to be preserved in positive relief and making them highly visible. Although the majority of the burrows are filled in the LCSS, some intervals in the lower part of Boxelder Creek and Steamboat Rock are not because the filling has been weathered from the tube. Hematite or limonite filling occurs in interval E-3 at the base of the LCSS in Little Elk Creek, and some *Skolithos* in float at the Kirk Hill area are filled by limonite or hematite while some tubes have had their filling weathered away.

Limonite usually fills the EOSS tubes. Hematite or limonite filling occurs at Trojan in the south-central part of the northern Black Hills and the lower intervals at Whitewood Peak. Hematite filling also occurs in the second interval from the top (K-9) at Warren Peaks in the western Black Hills. A pale green, or white colored silt fills tubes in one interval (D-6) in the middle part of the Whitewood Peak section and the lower two intervals at Spearfish Canyon. Sample RUB from the top of the EOSS in Rubicon Gulch, located approximately 0.8 km (0.5 mi) northeast of the Spearfish Canyon site, is stained dark red by hematite that also fills some *Skolithos*. Overall, the EOSS contains more *Skolithos* tubes that are not filled than the LCSS. Tubes containing no filling in the
EOSS are usually stained yellowish-brown with a darker stain occurring in the uppermost interval (A-5) at Spearfish Canyon.

**Other Trace Fossils**

Dense assemblages of fadinichnia (feeding) or pascichnia (grazing) trace fossils preserved in hyporelief or hypichnia (Fig. 40), occur on the lower surface of interval C-18 in yellow-orange sandstone. The complete size of this trace fossil cannot be measured; however, the visible portions are 2 to 3 cm long and as wide as 5.5 mm, but most commonly 3 mm wide. Trace fossils looking similar to these ‘sandy knobs’ are preserved in epiorelief or epichnia, in the uppermost EOSS interval (L-9) at Sheep Mountain. These trace fossils are significantly different than the vertical *Skolithos* tubes seen in the LCSS and EOSS, and are believed to be the result of a deposit-feeding organism very different from the polychaetes or phoronids making the *Skolithos*.

**Laboratory Work**

**Rock Characteristics**

The compositions of both the LCSS and EOSS are fairly simple. These sandstone units are primarily composed of quartz and can be classified as quartz arenites that differ only in the abundance of feldspar and glauconite. Appendix C contains the thin section petrography descriptions for the 10 LCSS and 23 EOSS samples discussed below.

**LCSS Thin Sections**

Modal grain size, modal sorting and modal roundness in the LCSS thin section samples are predominantly upper fine- to lower medium-grained, well sorted, and
Figure 40. Terminology for the preservation of trace fossils (modified from Ekdale et al. 1984, Fig. 2-6).
subangular, respectively. Monocrystalline quartz is abundant (defined as greater than 25 percent), glauconite is scarce (defined as 1 to 5 percent) to common (defined as 5 to 25 percent), orthoclase is scarce, and polycrystalline quartz occurs in trace (defined as less than 1 percent) to scarce amounts. Occasionally a discontinuous coating of ‘dirt’, forming ‘dust rings’ within quartz overgrowths, marks the edge of the original (detrital) quartz framework grains in samples from the upper and lower parts of the rock unit. Trace to scarce amounts of glauconite are ‘crushed’ between framework grains in samples (G-7, G-8, I-5) from the upper and lower parts of the unit. Orthoclase is most common (roughly 4 percent) in samples from the upper part of the rock unit at Boxelder Creek (samples J-1, J-2, J-5) and Dalton Lake (H-11), and less abundant (roughly 2 percent) in samples (G-7 and G-8) from the upper part of the Kirk Hill site. The relative stratigraphic position of each thin-sectioned sample is shown in Table 5. A few orthoclase grains appear to have flame-shaped microperthite.

Mica is present in trace amounts with muscovite being more common than biotite. Biotite is noted in samples from Little Elk Creek, Dalton Lake and Boxelder Creek. These samples come from the lower part of the LCSS at Little Elk Creek (sample E-3), the middle part (sample H-4) and the upper part (sample H-11) of the LCSS at the Dalton Lake area, and the upper part of the LCSS at Boxelder Creek (samples J-1 and J-2). Chert rock fragments occur in trace amounts in at least one thin section from each locality. Other rock fragments, consisting of a quartz-orthoclase intergrowth, are rarely seen, but occur in scarce amounts in sample H-11 from Dalton Lake and trace amounts in sample G-8 from the Kirk Hill area. These grains are probably igneous rock fragments. Other minerals occurring in trace amounts are tourmaline, zircon, apatite and hornblende.
Table 5. Relative stratigraphic positions of the thin-sectioned samples.*

<table>
<thead>
<tr>
<th>Relative Stratigraphic Position in Rock Unit</th>
<th>LCSS Samples</th>
<th>EOSS Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper part</td>
<td>G-7, G-8, H-11, J-1, J-2, J-5</td>
<td>C-12, K-10, L-8, N-3 (upper part) RUB</td>
</tr>
<tr>
<td>middle part</td>
<td>H-4</td>
<td>B-1, C-9, C-10, D-6, D-8, F-3, K-9, L-4, L-6, L-7, N-3 (middle part)</td>
</tr>
<tr>
<td>lower part</td>
<td>E-3, I-3, I-5</td>
<td>A-3, C-5, D-3, K-6, K-7, K-8, N-3 (lower part)</td>
</tr>
</tbody>
</table>

* Sample name corresponds to the interval the sample was taken from.
Tourmaline crystals are usually subhedral, zircon is typically subhedral or anhedral, apatite is typically subhedral or euhedral, and hornblende is typically anhedral or subhedral. Tourmaline is the most common of these trace minerals and is frequently brown in color (probably dravite) and less frequently green (probably elbaite).

Porosity is usually due to common intergranular voids and scarce dissolution of carbonate cement. Pore space formed from *Skolithos* tubes lacking filling cause trace to scarce amounts of additional porosity in samples from the upper part of the LCSS, while adding trace amounts of porosity to samples from the lower part of the rock unit. Quartz, dolomite, calcite and hematite, in order of declining abundance, are the most common cements in the LCSS samples. These samples rarely contain a clayey matrix.

**EOSS Thin Sections**

In the EOSS samples, model grain size, modal sorting and modal roundness in thin section are predominantly lower to upper fine-grained, well sorted, and subround, respectively. Monocrystalline quartz is abundant; polycrystalline quartz is trace to common, followed by trace to scarce amounts of orthoclase. Microcline and plagioclase can both occur in trace amounts. The detrital quartz grains, outlined by dust rings, are usually subround to round in shape. Orthoclase is most abundant in scarce amounts (roughly 2 to 3 percent) in samples from the lower, middle and upper parts of the unit at Trojan. Here the plagioclase and microcline grains are typically smaller than other framework grains, but they are not heavily weathered. The few plagioclase and microcline grains seen occur mainly in samples from the lower and middle parts of the unit.
Muscovite and biotite are both present in trace amounts. Muscovite occurs in most samples. Biotite occurs in just four samples from the middle and upper parts of the EOSS sampled at Deadwood and Spearfish Canyon. Rock fragments include chert in trace abundance in six samples from all different parts of the unit. Metamorphic and igneous rock fragments are less commonly seen and occur in trace amounts, in samples from mainly the middle part of the EOSS. Sample N-3 from the upper part of the Trojan section contains metamorphic fragments looking similar to the mica-quartz schist grains seen in sample F-3 from the middle part of the Iron Creek Lake section. Igneous rock fragments are composed of quartz and/or K-feldspar and/or mica or sericite (samples B-1 and C-10). Other minerals seen in trace amounts are tourmaline (subhedral), zircon (subhedral), and hornblende (anhedral).

Porosity is usually scarce and due to either intergranular voids or hollow *Skolithos* tubes. Quartz, carbonate (both calcite and dolomite) and hematite, in order of declining abundance, are the most common cements, but carbonate and hematite cements are less common in the EOSS than the LCSS. The EOSS does contain more microcrystalline quartz (both ordinary quartz and chalcedony) cements than the LCSS. These chert-like cements grew from the edge of framework grains in samples D-6 and D-8, toward the center of intergranular pore spaces, which are not completely filled. Less than half the samples contain a clayey matrix, and this occurs in trace to scarce amounts.

**Skolithos Characteristics**

Although an effort was made to cut the thin sections parallel to bedding and, thus, perpendicular to the *Skolithos* tubes, only 38 percent of the tube cross sections are circular in shape. Almost as many tubes (35 percent) are oval or egg-shaped due to
inclined cuts. This should not be surprising, because field results show that the tubes are commonly inclined with no one orientation being predominant. The other *Skolithos* cross sections (27 percent) have no systematic shape. It appeared that grains had been plucked from the tube walls during thin sectioning in 58 percent of the circular cross sections, 68 percent of the oval cross sections, and 63 percent of the indeterminate cross sections. In all, 62 percent of the *Skolithos* cross sections had grains missing from the tube walls.

The *Skolithos* characteristics suggest the tubes represent simple burrows. However, a great deal of information appears to be missing due to grain plucking. Although tube wall grains are normally the same size as the rock’s modal grain size, 23 percent of the EOSS *Skolithos* cross sections are constructed of smaller grains. The entire tube wall is made of grains smaller than the rock’s modal grain size in 13 percent of the *Skolithos* cross sections, and at least half of the tube wall is made of grains smaller than the rock’s modal grain size in 10 percent of the *Skolithos* cross sections. The sand in the walls of these tubes is predominately lower to upper very fine grained. All EOSS thin-sectioned samples, except those from Spearfish Canyon and Iron Creek Lake, have these types of tubes. Such tubes occur most frequently in samples from Deadwood, Whitewood Peak and Warren Peaks. They occur in 32 percent of the *Skolithos* from Deadwood and in 40 percent of the *Skolithos* from Whitewood Peak and Warren Peaks. No LCSS thin sections contained *Skolithos* tubes like these. The elongated grain-orientation in the tube wall appears to be random in 82 percent of the *Skolithos* cross sections. Elongated grains are arranged with most of their long axes tangent to the tube wall in 16 percent of the *Skolithos* cross sections, and 2 percent have elongated grains oriented with most of their long axes perpendicular to the tube wall. Grain packing in the
tube wall was less than the rock’s modal grain packing in 65 percent of the *Skolithos* cross sections, and it was not different from the rock’s modal grain packing in 35 percent of *Skolithos* cross sections. The porosity around the tube wall did not differ from the rock’s modal porosity in 83 percent of the *Skolithos* cross sections, and it was more than the rock’s modal porosity in 17 percent of the *Skolithos* cross sections. A thin (0.01 to 0.07 mm thick) clay lining averaging 0.03 mm thick occurs along the inside of the tube wall in 15 percent of the *Skolithos* cross sections. These linings are most common in *Skolithos* from Deadwood, particularly interval C-9. The tubes range in the amount of filling they contain from no filling (16 percent of the *Skolithos* cross sections) to being completely filled (47 percent of the *Skolithos* cross sections).
CHAPTER FIVE

DISCUSSION

The results of the present study largely agree with those of previous investigations by McCoy (1952), Seeland (1961), Kulik (1962; 1965), Ladle (1972) and Stanley (1984), but provide additional details on how the rock and Skolithos characteristics reflect the depositional environments of the LCSS and EOSS. The LCSS and EOSS seafloors were susceptible to strong, frequently shifting currents, which are characteristic of the Skolithos ichnofacies. This is indicated by mainly trough cross-bedding in the LCSS, planar and tabular-planar cross-bedding in the EOSS, and Skolithos tubes that terminate at the upper boundaries of cross-bed sets.

Thick sandstones containing abundant Skolithos tubes, like portions of the LCSS and almost all of the EOSS, were formed by repetitive successions of burrowing, erosion and deposition. The Skolithos-making animal burrowed vertically into the sandy substrate to secure a position from which it could extend its suspension-feeding mouthparts just above the seafloor. The bottom currents keeping the animal’s food in suspension would have occasionally swept away some animals from their tubes. Some of these animals would have survived to establish new Skolithos tubes in another nearby area whereas others were probably buried while in their tube. Some of the buried animals
may have pushed the overlying sediment out of the way as Sundburg (1983, p. 148) has suggested and escaped upwards. Bedding that was deflected both upward and downward at the margins of the *Skolithos* tubes would mark the resulting escape structures. However, bedding in the LCSS and EOSS is usually too thick to identify such structures if they are present. The animals died that did not escape, and their soft bodies easily decomposed in the fully oxygenated bottom and interstitial waters where *Skolithos* burrows are found (see Fig. 13).

The Black Hills were located approximately five degrees north of the equator during LCSS and EOSS time according to maps in Dott and Prothero (1994, p. 233). Cross-bed orientation measurements (in present-day coordinates) show the currents were bimodal south-southwest and north-northwest in the LCSS and unimodal due west in the EOSS (Seeland 1961, Figs. 16-17). The mean cross-bed current directions calculated by Seeland (1961, p. 56, 84) seem to correlate with a westward-prevailing wind direction (the tropical ‘trade winds’), which would be expected given the Black Hills’ paleogeographic location and orientation during the Cambro-Ordovician. The bimodal current directions indicated by the LCSS cross-beds suggest at least portions of the LCSS were deposited under tidal influences within the intertidal zone. This interpretation agrees with that of Ladle (1972, p. 145) who suggested the high tide line of the LCSS sea trended northeast-southwest, about 16 mi (26 km) south of the Boxelder Creek locality. It is certainly possible, however, parts of the LCSS were deposited within the upper shoreface, just below the intertidal zone, because sediment transport in this region is also dominated by bi-directional, shore-normal oscillatory waves as well as by unidirectional longshore currents and rip currents (McCubbin 1982, p. 255). This latter possibility
agrees with Kulik’s (1965, p. 94) suggestion that longshore and other currents produced the cross-bedding in the LCSS. In addition, fecal matter, preserved as glauconite in the LCSS, can be abundant within the upper shoreface environment according to McCubbin (1982, p. 255). Based on the interpretations of McCoy (1952, p. 20), Seeland (1961, p. 74-75), Kulik (1965, p. 93-94), Ladle (1972, p. 145) and this study, the LCSS is similar to the late Lower Ordovician Monkman Quartzite studied by Jansa (1975) in the Main Range of the Canadian Rocky Mountains.

The EOSS sands were deposited further from shore in somewhat deeper water under the influence of stronger and more variable currents as indicated by the cross-bed current directions measured by Seeland (1961, p. 59) and the unit’s smaller modal grain size. It was probably deposited in the upper shoreface throughout most of the study area. These deposits generally show cycles of erosion and deposition related to changing wave conditions whereas physical processes in the lower shoreface are mostly inferred from characteristics of the sediments themselves (McCubbin 1982, p. 255). The shaley, bioturbated intervals interbedded with *Skolithos* sandstone in the lower part of the EOSS at Sheep Mountain may represent a transition to deeper, lower shoreface deposits. These interpretations agree with the previous findings of McCoy (1952, p. 20), Kulik (1962, p. 43), Kulik (1965, p. 13, 133) and Stanley (1984, p. 189).

Vertical profiles compiled using the ichnofabric index method developed by Droser and Bottjer (1986) have the potential to distinguish lower intertidal from upper intertidal beds as well as shoreface deposits in the LCSS based on the results of Harrison et al. (1994), Skoog et al. (1994) and Simpson et al. (1991). However, the modal *Skolithos* density is nearly the same in the LCSS (0.4 tubes per cm) and EOSS (0.5 tubes
per cm). In other work by Davies et al. (1971), the upper, middle and lower parts of shoreface deposits have been identified in barrier environments based on quartz grain size and abundance, but this method requires more rigorous petrographic work than was conducted for the present study.

The thicker intervals, particularly in the LCSS, containing few or no *Skolithos* were probably deposited too quickly to allow the animals to construct burrows. Cross-bedded intervals with *Skolithos* tubes indicate the rate of deposition was greater than the rate of burrowing in order for the cross-beds to be preserved. The bioturbated beds that are flaggy in appearance and contain shale and siltstone partings, or streaks, in the EOSS at Deadwood and Sheep Mountain contain neither cross-beds nor abundant *Skolithos*. This indicates the rate of burrowing was greater than the rate of deposition. The dominant organism in these finer-grained deposits must have been a deposit feeder that ingested the organic matter that tends to accumulate in muddy sediment. The shaley, bioturbated beds at Sheep Mountain apparently indicate the transition to lower shoreface deposits positioned just below the fair-weather wave base with interbedded *Skolithos* sandstones representing sand swept in by storms from shallower water depths that were opportunistically burrowed by *Skolithos*-making animals.

Rock composition indicates different source rocks and relative rates of sedimentation for the LCSS and EOSS. LCSS samples contain scarce amounts of orthoclase whereas trace amounts typically occur in EOSS samples, but the latter has more (although still mostly trace amounts) of microcline and plagioclase. Overall, the petrographic results agree with those of Ladle (1972, p. 137), Owens (1975, p. 63-64) and Connors (1996, p. 70). The only exception is an EOSS sample described by Connors
(1996, p. 70-71), which contained anomalously large amounts of feldspar (16.8 percent orthoclase, 2.6 percent microcline, and 1.0 percent plagioclase). This one sample suggests that the feldspar was eroded from source rocks and quickly buried in order to escape destruction by chemical weathering. This led Connors to conclude that Precambrian basement rocks were exposed in the Black Hills during EOSS time. Samples collected from the Whitewood Peak, Trojan, Iron Creek Lake, and Sheep Mountain sections contained scarce amounts of feldspar, more than any other EOSS samples collected during the present study. Although this amount is small in comparison to that reported by Connors (1996), the trace amounts of quartz-mica schist rock fragments found in Trojan (N-3 upper part) and Iron Creek Lake (F-3) samples further support the idea that metamorphic basement rocks were exposed in the Black Hills during EOSS time.

The *Skolithos* trace fossils in the LCSS and EOSS appear to be simple burrows, as sand grains in the tube walls usually do not differ from the surrounding rock’s modal grain size. There are exceptions (23 percent of all *Skolithos* studied in the thin-sectioned samples) from the EOSS, where the tubes contain smaller-sized grains that are predominantly very fine-grained. Phoronids may use very fine-grained sand in their tubes whereas many polychaetes (including some onuphinids, maldanids, sabellids, sabellariids, pectinariids and nereids) often employ fine- to coarse-grained sand in their dwelling burrows (Ekdale et al. 1984, p. 84). Thin clay linings (0.01 to 0.07 mm thick) were another structure associated with some (15 percent) of the tubes. These typically occur in EOSS samples, but they are common only in some of those from Deadwood and are much thinner than the 0.1 mm thick clay linings found in *Skolithos* tubes from a
Cretaceous storm deposit described by Vossler and Pemberton (1988, p. 353). The Skolithos tubes described by these authors represent the Arenicolites ichnofacies where clay-sized sediments, deposited offshore under fair-weather conditions, washed into the tubes under normal depositional conditions following the coarser-grained, storm deposited, burrowed sands. The LCSS and EOSS Skolithos tubes represent the Skolithos ichnofacies rather than the Arenicolites ichnofacies, because these units were deposited nearshore. The very thin clay linings seen in the LCSS and EOSS Skolithos tubes are probably diagenetic rather than depositional because of the paucity of clay-sized sediments in these units. Therefore, the occurrence of seemingly homogeneous thin sandstones with several Skolithos-rich intervals is an indication of amalgamated storm beds, since each burrowed zone probably represents a single storm event (Vossler and Pemberton 1988, p. 360). Thick nearshore Cretaceous sandstones (more than 2 m thick) with vertical burrows exhibit evidence of amalgamated storm events as well (Bourgeois 1980, p. 689-690). Also, elongated sand grains in the tube walls of LCSS and EOSS samples were randomly oriented and this contrasts markedly with the findings of Harding and Risk (1986, p. 685), who found elongated grains preferentially oriented parallel to the tube wall in six thin sections cut vertical to the tube, and elongated grains oriented tangentially around the tube wall margins in thin-sections cut horizontal to Skolithos in a Lower Ordovician sandstone.

This study concurs with Stanley (1984) that S. linearis and S. verticalis are the Skolithos ichnospecies occurring in the LCSS and EOSS. However, S. verticalis appears to predominate based on characteristics of these ichnospecies reported by Alpert (1974; 1975). Although the modal Skolithos density is low (0.4 tubes per cm in the LCSS and
0.5 tubes per cm in the EOSS), the tubes can be spaced as densely as 1.4 per cm. This is consistent with Alpert’s (1974, p. 663-664) claim that \textit{S. linearis} can occur close together or widely spaced, but \textit{S. verticalis} is never ‘extremely’ crowded.

The lower bedding contacts of the LCSS and EOSS found in this study match the descriptions given by Kulik (1962, p. 50; 1965, p. 92, 133). No studies, including this one, found any marker horizons in either sandstone. The upper bedding contact of the LCSS was not observed at any of the sites visited, but the upper bedding contact of the EOSS can be seen at Deadwood based on the rock’s color and cementation as described by Carlson (1960, p. 38-39) for occurrences in North Dakota. Carlson (1960) calls the lowermost sandstone of the Winnipeg Formation the Black Island member. However, the blue-gray, siliceous sandstone that is similar in appearance to this unit in interval C-16 at Deadwood may be reworked sand from the EOSS rather than an extension of the Black Island sandstone (Moore 1960, p. 13, 20).

Trace fossils apparently similar to those Moore (1960, p. 14) found at the base of the Winnipeg Formation at Sheep Mountain, and generically called ‘fucoids’, occur on the lower surface of interval C-18 above the EOSS at Deadwood and on the upper surface of interval L-9 in the EOSS at Sheep Mountain. These trace fossils could be the feeding traces of deposit-feeding organisms and may correlate to a worldwide increase in bioturbation known to occur between Middle and Late Ordovician as documented by Droser and Bottjer (1989, p. 151).
CHAPTER SIX

CONCLUSIONS

The following conclusions are reached regarding the Late Cambrian *Skolithos* Sandstone (LCSS) and Early Ordovician *Skolithos* Sandstone (EOSS) in the northern Black Hills.

1. The LCSS and EOSS represent nearshore, sandy marine environments with strong bottom currents, a condition characteristic of the *Skolithos* ichnofacies. The fine-to medium-grained LCSS sands accumulated in either intertidal or upper shoreface settings whereas the very fine- to fine-grained EOSS sands represent both upper and lower shoreface deposits.

2. Bedding is typically massive in these units with trough cross-bedding common in the LCSS, and planar and tabular-planar cross-bedding common in the EOSS.

3. *Skolithos* burrows are oriented nearly perpendicular to bedding (85 to 90 degrees) or inclined 55 to 85 degrees in the LCSS and 30 to 85 degrees in the EOSS. The tube-like burrows are usually straight or slightly curved, and can be preserved in positive relief or may contain no filling. Observed lengths are usually less than 2 cm, but these may be incomplete due to their orientation or erosional termination at bedding planes. Diameters (commonly 2 to 3 mm in the LCSS and 1 to 2 mm
in the EOSS) and other tube characteristics indicate that both *S. linearis* (Haldeman 1840) and *S. verticalis* (Hall 1843) occur in the LCSS and EOSS; however *S. verticalis* predominates in both rock units. Modal *Skolithos* density is essentially the same in both units (0.4 tubes per cm in the LCSS and 0.5 tubes per cm in the EOSS) but varies somewhat among the sites. The maximum *Skolithos* density is 1 tube per cm in the LCSS and 1.4 tubes per cm in the EOSS.

4. EOSS beds containing only *Skolithos* trace fossils were apparently deposited during storm events and quickly colonized by the *Skolithos*-making animals. Finer-grained, lower energy deposits with deposit-feeding animals followed these beds as normal, slower sedimentation resumed. The thick sandstone intervals with few or no *Skolithos*, which are especially common in the LCSS, probably represent times when sand deposition was too rapid for borrowing animals to flourish.

5. Variously-shaped fodinichnia or pascichnia trace fossils (2 to 3 cm long and 3 mm wide commonly) preserved in epirelief (epichnia) and hyporelief (hypichnia) appear as sandy knobs on some bedding surfaces near the top of the EOSS. Their presence marks an environmental change at the end of EOSS time and may represent the burrowing activity of a possibly new deposit-feeding animal.
6. An analysis of petrographic thin sections oriented approximately perpendicular to the LCSS and EOSS Skolithos tubes produced no insights into how the Skolithos-making organism constructed its burrow.

7. The factors affecting the abundance and diversity of the infaunal suspension-feeding polychaetes and/or phoronids likely responsible for making Skolithos include bioturbation by deposit-feeding organisms, ecospace utilization by other infaunal and epifaunal suspension-feeding organisms, evolution of new organisms, and extinction events. Over time these factors reduced the Skolithos-making organisms to two predominant ichnospecies: *S. linearis* and *S. verticalis.*
RECOMMENDATIONS

FOR FURTHER WORK

The following recommendations are suggested to improve our understanding of the *Skolithos* ichnofacies, and its characteristics in the Late Cambrian *Skolithos* Sandstone (LCSS) and Early Ordovician *Skolithos* Sandstone (EOSS).

1. Consult additional references on the *Skolithos* ichnofacies to better define the stratigraphic range of this trace fossil.

2. Research the stratigraphic range of *Skolithos*-making polychaete and phoronid organisms to understand their relationships with changes in the abundance and diversity of the *Skolithos* ichnospecies through time.

3. Plot locations of *Skolithos* sandstones on paleogeographic maps to see if the latitudinal range of these rocks correlates with regions prone to major storm events.

4. Use the ichnofabric index method (together with *Skolithos* density) to create a vertical profile through the LCSS and EOSS to refine the environmental interpretations of these rock units.
5. Examine *Skolithos* trace fossils in the Harding Sandstone in the upper part of the Gallatin Formation in Wyoming, which correlates with the EOSS in the northern Black Hills.
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APPENDIX A

DATA FOR FIGURE 24
Listed below, in stratigraphic order, are the rock units, localities and references used to define the stratigraphic range of *Skolithos*. The geologic ages are given as reported in the references. The *Skolithos* ichnospecies are either identified by the authors of these references or by the present author (indicated in brackets with a question mark). In the later case, the ichnospecies were identified primarily on the basis of tube diameter as discussed in Alpert (1974; 1975). The length of the tube was used to identify ichnospecies when the *Skolithos* characteristics matched both *S. linearis* and *S. verticalis*.

**HOLOCENE**

1. **Rock Unit**
   a modern size-graded shelf in northwestern Gulf of Mexico off the coast of south-central Texas

   **Location**
   between Corpus Christi and Baffin bays

   **Skolithos ichnospecies**
   
   *S. linearis?* and *S. verticalis?* ranges in diameter from 1 to 3 mm with length up to 20 cm

   neoichnofossils identified as ‘trace B’ having a tube-shaped shaft that averages 1 to 1.5 mm in diameter and an overall diameter of about 3 mm burrow walls are 1 mm thick and comprised of mucus-agglutinated grains

   **Interpretation**
   nearshore marine to a depth of about 180 m (sublittoral zone)

   **Reference**
   Hill (1985, p. 197-198)

**PLEISTOCENE**

2. **Rock Unit**
   ‘Current Unit’

   **Location**
   Aurora in eastern North Carolina

   **Skolithos ichnospecies**
   *S. linearis* and *S. verticalis?* ranges in diameter from 2 to 6 mm with length up to 75 cm

   *Onuphis microcephala* (a polychaete) is considered a modern analogue to *S. linearis* traces

   **Interpretation**
   intertidal and shallow subtidal environments

   **Reference**
   Curran and Frey (1977, p. 148, 150)
### CENOZOIC

<table>
<thead>
<tr>
<th></th>
<th>Rock Unit</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Rock Unit (not named)</td>
<td>San Salvador in the Bahama Islands</td>
</tr>
<tr>
<td></td>
<td>Skolithos ichnospecies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S. linearis$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interpretation</td>
<td>subtidal, tubes occur in medium- to very coarse-grained, cross-bedded calcarenites</td>
</tr>
<tr>
<td></td>
<td>Reference</td>
<td>Curran (1984, p. 318)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Rock Unit</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Ironshore Formation</td>
<td>Grand Cayman Island (British West Indies)</td>
</tr>
<tr>
<td></td>
<td>Skolithos ichnospecies</td>
<td>$S. linearis$ and $S. verticalis?$ range in diameter from 2 to 6 mm with length up to 7 cm</td>
</tr>
<tr>
<td></td>
<td>Interpretation</td>
<td>depositional environment is not specified, but portions of this formation have previously been described as tidal channels in a carbonate setting</td>
</tr>
<tr>
<td></td>
<td>Reference</td>
<td>Pemberton and Jones (1988, p. 505)</td>
</tr>
</tbody>
</table>

### CRETACEOUS

<table>
<thead>
<tr>
<th></th>
<th>Rock Unit</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>sands of the Sandhills region</td>
<td>upper coastal plain of North and South Carolina</td>
</tr>
<tr>
<td></td>
<td>Skolithos ichnospecies</td>
<td>$S. verticalis?$ range in diameter from 1.5 to 2 cm with length up to 15 cm</td>
</tr>
<tr>
<td></td>
<td>Interpretation</td>
<td>tide-dominated, shallow marine environment</td>
</tr>
<tr>
<td></td>
<td>Reference</td>
<td>Cabe (1986, p. 570)</td>
</tr>
</tbody>
</table>

### CRETAEOUS

<table>
<thead>
<tr>
<th></th>
<th>Rock Unit</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Englishtown Formation (middle unit of the Matawan Group)</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>north bank of the Chesapeake and Delaware Canal in Delaware</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td><em>Skolithos</em> ichnospecies</td>
<td><em>S. linearis</em> and <em>S. verticalis?</em></td>
<td></td>
</tr>
<tr>
<td>Interpretation</td>
<td>the latter is vertical to steeply inclined, straight to gently curving to somewhat meandering, and subcylindrical in shape; diameter is commonly 1 to 1.5 mm with length up to 6 cm; branching occurs but is not common and has no regular pattern; burrow walls are formed of agglutinated fine-sand and silt sized grains; burrow filling is usually lighter in color than the surrounding material</td>
<td></td>
</tr>
<tr>
<td>7. Rock Unit</td>
<td>Star Point Formation (Panther Member)</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Coal Creek Canyon in Utah</td>
<td></td>
</tr>
<tr>
<td><em>Skolithos</em> ichnospecies</td>
<td><em>S. linearis</em></td>
<td></td>
</tr>
<tr>
<td>Interpretation</td>
<td>Landward-most shore face zone and upper off-shore zone</td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Frey and Howard (1985, p. 391, 400)</td>
<td></td>
</tr>
<tr>
<td>8. Rock Unit</td>
<td>Cardium Formation</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>core from the Pembina-Carrot Creek oilfield in west-central Alberta (Canada)</td>
<td></td>
</tr>
<tr>
<td><em>Skolithos</em> ichnospecies</td>
<td><em>S. verticalis?</em> diameter is 2 to 3 mm (length not given)</td>
<td></td>
</tr>
<tr>
<td>Interpretation</td>
<td>storm deposited sand</td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Vossler and Pemberton (1988, p. 353)</td>
<td></td>
</tr>
</tbody>
</table>
**JURASSIC** (Early-Middle ?)

9. **Rock Unit**  & Skloby Formation  
**Location**  & Holy Cross Mountains in Poland  
**Skolithos ichnospecies**  & \([S. \text{linearis}? \text{ and } S. \text{verticalis}?]\) diameter ranges from 2 to 8 mm with length up to 20 cm  
**Interpretation**  & brackish and nearshore marine environment  
**Reference**  & Pienkowski (1985, p. 39, 41)

**PERMIAN** (Epoch not specified)

10. **Rock Unit**  & Wasp Head Formation  
**Location**  & Sydney Basin in eastern Australia  
**Skolithos ichnospecies**  & \(S. \text{verticalis}\)  
**Interpretation**  & mainly foreshore marine environments and less commonly open shoreface zones  
**Reference**  & McCarthy (1979, p. 360, 346)

11. **Rock Unit**  & Phosphoria Formation (Tosi Chert Member) and Shedhorn Formation (upper member)  
**Location**  & northwestern Wyoming and southwestern Montana
Skolithos ichnospecies

*S. verticalis* and *S. linearis*? diameter ranges from 3 to 7 mm with length up to 20 cm

*S. grandis* (author’s suggested new ichnospecies) diameters range from 3 x 4 cm to 5 x 6 cm with length up to 6 m (typically 2 to 4 m long)

*S. verticalis* and *S. grandis* were interpreted to be made by suspension-feeding animals

Interpretation nearshore environment (loose carbonate substrate setting)

Reference Andersson (1982)

**EARLY PERMIAN**

12. Rock Unit Pietermaritzburg Formation (lower Ecca Group)

Location Newlands Estate in Durban (South Africa)

Skolithos ichnospecies

*[S. linearis]*? diameter up to 8 mm with length up to 22 cm

diameter includes a pale axial part up to 8 mm wide bordered by a darker colored ‘halo’, measuring up to 10 mm wide

halo area in cross section is made of ‘shallowly-concave spreiten, which curve sharply upward in their distal direction at their margins’, interpreted as resulting from layers of mucus-like substances that served as a grain binding adhesive to strengthen the burrow wall

organism occupied the axial part of the tube

Interpretation sediment deposited in shallow nearshore marine waters of up to about 10 m deep, derived by storm wave action

Reference Travener-Smith (1980)
LATE CARBONIFEROUS

13. Rock Unit: Upper Fentress Formation (Crab Orchard Mountains Group)
   Location: northern Cumberland Plateau in eastern Tennessee
   *Skolithos* ichnospecies
   - three broad *Skolithos* groups are recognized:
     - *[S. verticalis?]* diameter less than 1 mm (length not specified)
       - These are unlined burrows occurring in thin zones, surrounding sediments are disrupted in vertical sections
     - *[S. verticalis?]* diameter 2 to 3 mm on average (length not specified)
     - *[S. linearis?]* diameter 7 to 8 mm on average (length not given)
       - The larger tubes may be lined or partially lined with clay or carbonaceous material
   Interpretation: lagoon and tidal channel environments
   Reference: Miller and Knox (1985, p. 89)

EARLY CARBONIFEROUS

14. Rock Unit: Tar Springs Sandstone
   Location: southern Illinois
   *Skolithos* ichnospecies
   - *[S. linearis?]* diameter ranges from 6 to 11 mm with lengths up to 11 cm
   Interpretation: intertidal sandflat

15. Rock Unit: Riddlesburg Shale Member (Prince Formation)
   Location: Bowden in West Virginia
**Skolithos ichnospecies**

$[S. \text{linearis}?]$ diameter less than 1 cm with length up to 36 cm (averaging less than 30 cm long)

tubes are unbranched, straight and slightly inclined to slightly undulose in shape

**Interpretation**
nearshore (shore face zone) marine

**Reference**
Bjerstedt (1987, p. 883)

16. **Rock Unit**
Price Delta

**Location**
southeast West Virginia

**Skolithos ichnospecies**

$[S. \text{linearis}?]$ diameter is less than 5 mm with lengths up to 30 cm

**Interpretation**
outer shelf, inner shelf, lower shore face, bar-washover, foreshore, interdistributary bay, and distributary mouth-bar environments frequently containing sedimentary structures attributed to storm deposition

**Reference**
Bjerstedt (1988, p. 517)

**LATE DEVONIAN**

17. **Rock Unit**
Oswaygo Member (Price Formation)

**Location**
Rowlesburg in West Virginia

**Skolithos ichnospecies**

$[S. \text{linearis}?]$ diameter less than 1 cm with length up to 36 cm (averaging less than 30 cm long)

tubes are unbranched, straight and slightly inclined to slightly undulose in shape

**Interpretation**
lower- to upper-shore face environment

**Reference**
Bjerstedt (1987, p. 865, 883)

18. **Rock Unit**
Binem Formation

**Location**
Jebel Asba in southeast Libya
Skolithos ichnospecies \( S. \text{linearis} \)

Interpretation tidal and beach zones

Reference Turner and Benton (1983, p. 457)

**MIDDLE TO LATE DEVONIAN**

19. Rock Unit Tully Limestone

Location east-central New York state

Skolithos ichnospecies \([S. \text{linearis}]?\) diameter ranges from 5 mm to 3 cm with length up to 10 cm

‘type A’ Skolithos tubes occur in fine- to very fine-grained sandstone and siltstone beds

[S. \text{linearis}? and S. \text{verticalis}?] diameter ranges from 1 to 5 mm with length up to 10 cm

‘type B’ Skolithos tubes are more abundant than Type A Skolithos and are found in medium- to very fine-grained sandstone, siltstone and shale

Interpretation type A tubes occur in alluvial, tidal, nearshore, and offshore environments

Type B tubes occur in units representing the same environments including distal offshore settings

Reference Miller (1979, p. 129, 136)

**MIDDLE SILURIAN**

20. Rock Unit Thorold Formation

Location southern Ontario in Canada

Skolithos ichnospecies \( S. \text{linearis} \)

Interpretation offshore storm deposits

Reference Pemberton and Risk (1982)
<table>
<thead>
<tr>
<th></th>
<th>Rock Unit</th>
<th>Location</th>
<th>Skolithos ichnospecies</th>
<th>Interpretation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>Rock Unit Georgian Bay Formation</td>
<td>Southern Ontario in Canada</td>
<td><em>S. magnus</em> <em>S. verticalis</em></td>
<td>Storm dominated shelf environment</td>
<td>Stanley and Pickerill (1998)</td>
</tr>
<tr>
<td>22</td>
<td>Rock Unit Ely Springs Dolomite</td>
<td>southern Nevada</td>
<td>[S. verticalis? and S. linearis?] diameter ranges from 2 to 5 mm (length not specified)</td>
<td>shoal, partially tidal dominated</td>
<td>Miller (1977, p. 1331)</td>
</tr>
<tr>
<td>23</td>
<td>Rock Unit ‘Stage 5 b’</td>
<td>Oslo-Asker region in southern Norway</td>
<td><em>S. linearis</em></td>
<td>nearshore environment (water depth 1-16 m)</td>
<td>Stanistreet (1989, p. 351, 353)</td>
</tr>
</tbody>
</table>

**MIDDLE ORDOVICIAN**

<table>
<thead>
<tr>
<th></th>
<th>Rock Unit Swan Peak Formation (upper member) and Eureka Quartzite</th>
<th>Location</th>
<th>Skolithos ichnospecies</th>
<th>Interpretation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>Swan Peak Formation (upper member) and Eureka Quartzite</td>
<td>northern Utah</td>
<td>[S. verticalis? and S. linearis?] diameter is less than 5 mm (length not specified)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Interpretation: shallow subsiding shelf environment
Reference: Francis (1972, p. 42, 51)

25. Rock Unit: Eureka Quartzite
Location: Lone Mountain in central Nevada
Skolithos ichnospecies: *S. verticalis*
Interpretation: marine
Reference: Chamberlain (1977, p. 5, 18)

26. Rock Unit: Eureka Quartzite
Location: southern Nevada
Skolithos ichnospecies: *S. bulbus?* diameter ranges from 7 to 14 mm with round or elliptical areas 5 to 14 mm in longest dimension (length not specified)
Interpretation: Shore-face environment
Reference: Miller (1977, p. 1330)

27. Rock Unit: St. Peter Sandstone
Location: Governor Dodge Park in southwestern Wisconsin
Skolithos ichnospecies: *S. verticalis?* and *S. linearis?* diameter is usually 2 mm with length from 10 to 30 cm
tubes occur as massive burrowed zones that are sharply truncated by flat erosional surfaces
Interpretation: nearshore marine environment
Reference: Dott et al. (1986, p. 359)

**EARLY ORDOVICIAN**

28. Rock Unit: Monkman Quartzite
Location: northeast British Columbia in Canada
<table>
<thead>
<tr>
<th><strong>Skolithos ichnospecies</strong></th>
<th>[S. <em>linearis</em>?] length ranges from 15 to 30 cm (diameter not given)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpretation</td>
<td>sand barriers and tidal deposits</td>
</tr>
<tr>
<td>Reference</td>
<td>Jansa (1975, p. 156)</td>
</tr>
</tbody>
</table>

29. **Rock Unit** Amorican Quartzite

<table>
<thead>
<tr>
<th>Location</th>
<th>central Portugal and western Spain (Central Iberian Zone)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Skolithos ichnospecies</strong></td>
<td><em>S. linearis</em></td>
</tr>
<tr>
<td>Interpretation</td>
<td>cold-water shelf sea</td>
</tr>
<tr>
<td>Reference</td>
<td>Romano (1991, p. 194, 197)</td>
</tr>
</tbody>
</table>

30. **Rock Unit** Nepean Formation

<table>
<thead>
<tr>
<th>Location</th>
<th>Kingston Ontario, in Canada</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Skolithos ichnospecies</strong></td>
<td>[S. <em>verticalis</em>? and <em>S. linearis</em>?] diameter ranges from 3 to 5 mm and length commonly ranges from 4 to 8 cm</td>
</tr>
<tr>
<td>Interpretation</td>
<td>nearshore marine environment</td>
</tr>
<tr>
<td>Reference</td>
<td>Harding and Risk (1986, p. 684)</td>
</tr>
</tbody>
</table>

**CAMBRO-ORDOVICIAN**

31. **Rock Unit** (basal) Bynguano Formation

<table>
<thead>
<tr>
<th>Location</th>
<th>New South Wales (Mootwingee area in Australia)</th>
</tr>
</thead>
</table>
Skolithos ichnospecies

[S. linearis?] diameter ranges from 5 to 10 mm (length not specified)

‘type A Skolithos forms piperock in this rock unit

[S. bulbus? and/or S. ingens?] diameter up to 2 cm (length not specified)

‘type B’ Skolithos is very common, diameter variable in width throughout the burrow depth

type B Skolithos does not occur in dense assemblages in this rock unit and the two Skolithos groups seldom occur together in the same bed

Interpretation shallow-marine shelf environment above storm wave base

Reference Droser et al. (1994, p. 276)

32. Rock Unit Theresa Formation

Location Thousand Island area of northwest Adirondacks in New York state

Skolithos ichnospecies

[S. verticalis?] diameter averages 2 to 3 mm and length commonly ranges from 3 to 6 cm

Interpretation subtidal and peritidal environments

Reference Bjerstedt and Erickson (1989, p. 223)

33. Rock Unit (basal) Bliss Formation

Location Silver City Range in southwest New Mexico

Skolithos ichnospecies

[S. verticalis?] diameter averages 2 to 3 mm and length commonly ranges from 1 to 5 cm

Interpretation shallow-transgressive marine environment

Reference Chafez et al. (1986, p. 205)

34. Rock Unit Upper Deadwood Formation including the Aladdin sandstone
Location: northern Black Hills in South Dakota

*Skolithos* ichnospecies: *S. verticalis* and *S. linearis*

Interpretation: nearshore marine environment

Reference: Stanley (1984, p. 182-183)

### MIDDLE CAMBRIAN

35. Rock Unit: Oville sandstone

Location: Cantabrian Mountains in northern Spain

*Skolithos* ichnospecies: *S. linearis* and [*S. verticalis*?] diameter ranges from 3 to 11 mm (length not specified)

Interpretation: intertidal (including lower delta, tidal channel, and tidal delta settings), sand flat, beach, and barrier beach environments

Reference: Legg (1985, p. 152, 161)

36. Rock Unit: Tintic Quartzite

Location: North of Ogden Canyon near Ogden (Weber County) in Utah

*Skolithos* ichnospecies: [*S. verticalis*?] and *S. linearis*? diameter ranges from 2 to 5 mm with length up to 10 mm

*Skolithos* found in one thin piece of float

author states that *Skolithos* tubes measuring up to 12 cm have been reported to occur in this formation based on previous studies

Interpretation: shallow marine environment (mixed *Skolithos* and *Cruziana* ichnofacies).


37. Rock Unit: Carrara Formation

Location: Nopah Range in California
**Skolithos ichnospecies**  
*S. linearis*

**Interpretation**: shallow-subtidal environment

**Reference**: Sundberg (1983, p. 145)

**EARLY CAMBRIAN**

38. **Rock Unit**: Campito Formation  
**Location**: White-Inyo Mountains in eastern California  
*S. linearis* diameter ranges from 4 to 6 mm (length not specified)

**Interpretation**: shallow-marine environment

**Reference**: Alpert (1975, p. 510-511)

39. **Rock Unit**: lower and middle Harkless Formation  
**Location**: White-Inyo Mountains in eastern California

*S. linearis*

**Interpretation**: shallow-marine environment

**Reference**: Alpert (1975)

40. **Rock Unit**: Upper Member of the Poleta Formation  
**Location**: White-Inyo Mountains in eastern California

*S. bulbus*

**Interpretation**: shallow-marine environment

**Reference**: Alpert (1975)

41. **Rock Unit**: Hardeberga Formation  
**Location**: Bornholm in Denmark
<table>
<thead>
<tr>
<th><strong>Skolithos ichnospecies</strong></th>
<th><strong>S. linearis</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpretation</td>
<td>shallow-marine environment</td>
</tr>
<tr>
<td>Reference</td>
<td>Claussen and Vilhjámssson (1986, p. 64)</td>
</tr>
</tbody>
</table>

| Rock Unit | (not specified) |
| Location   | Asturias and Cantabica in Spain |

<table>
<thead>
<tr>
<th><strong>Skolithos ichnospecies</strong></th>
<th>[<strong>S. linearis</strong>? and subordinate <strong>S. verticalis</strong>?]</th>
</tr>
</thead>
<tbody>
<tr>
<td>diameter ranges from 3 to 9 mm averaging 6 mm</td>
<td>(length not specified)</td>
</tr>
<tr>
<td>Interpretation</td>
<td>shallow-marine environment</td>
</tr>
<tr>
<td>Reference</td>
<td>Crimes et al. (1977, p. 125)</td>
</tr>
</tbody>
</table>

| Rock Unit | Wood Canyon Formation |
| Location   | Daylight Pass area of Death Valley in California |

<table>
<thead>
<tr>
<th><strong>Skolithos ichnospecies</strong></th>
<th><strong>S. bulbus</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpretation</td>
<td>shallow-marine environment</td>
</tr>
<tr>
<td>Reference</td>
<td>Cornwall and Kleinhampfl (1964, p. J 2)</td>
</tr>
</tbody>
</table>

| Rock Unit | ‘Pipe Rock’ |
| Location   | Southern Lock Eribol in the northwest Scottish Highlands |

<table>
<thead>
<tr>
<th><strong>Skolithos ichnospecies</strong></th>
<th><strong>S. linearis</strong> diameter ranges from 3 to 15 mm with lengths sometimes exceeding 1 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpretation</td>
<td>nearshore marine environment</td>
</tr>
<tr>
<td>Reference</td>
<td>Hallem and Swett (1966, p. 102)</td>
</tr>
</tbody>
</table>

<p>| Rock Unit | Zabriskie Quartzite |
| Location   | Nopah Range in California |</p>
<table>
<thead>
<tr>
<th>Rock Unit</th>
<th>Location</th>
<th>Skolithos ichnosppecies</th>
<th>Interpretation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harding Sandstone</td>
<td>Reading in Pennsylvania</td>
<td><em>S. bulbus</em></td>
<td>shallow-marine environment</td>
<td>Hazzard (1937, p. 310)</td>
</tr>
<tr>
<td>Chapel Island Formation</td>
<td>southeastern Newfoundland in Canada</td>
<td><em>S. linearis</em> and <em>S. verticalis</em></td>
<td>shallow nearshore marine</td>
<td>Howell (1943, p. 20)</td>
</tr>
<tr>
<td>Bradore Formation</td>
<td>southern Labrador in Canada</td>
<td><em>S. linearis</em></td>
<td>delta front</td>
<td>Landing et al. (1988, p. 37-38)</td>
</tr>
</tbody>
</table>

*Skolithos* occurs in river-dominated, storm-influenced gray-green sandstones with siltstone interbeds that exhibit evidence for high rates of sedimentation.
<table>
<thead>
<tr>
<th>Rock Unit</th>
<th>Location</th>
<th>Skolithos ichnospecies</th>
<th>Interpretation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dabis Formation</td>
<td>south of Osis, Namibia in southwest Africa</td>
<td>[S. verticalis?] diameter averages 1 to 2 mm, none larger than 3 mm</td>
<td>braided-fluvial environment</td>
<td>Crimes and Germs (1982, p. 890, 893, 901)</td>
</tr>
<tr>
<td><strong>49.</strong> Rock Unit</td>
<td></td>
<td>Skolithos occurs as circular protuberances (1 mm high) closely spaced on bedding planes known or assumed to be soles</td>
<td></td>
<td>Alpert (1974, p. 664) states that S. verticalis is never extremely crowded</td>
</tr>
<tr>
<td><strong>50.</strong> Rock Unit</td>
<td>northern Australia</td>
<td>S. linearis</td>
<td>(not specified)</td>
<td>Häntzschel (1975, p. W106-W108)</td>
</tr>
</tbody>
</table>
APPENDIX B

SITE LOCATIONS AND

INTERVAL DESCRIPTIONS
Location A: Spearfish Canyon, SD

Maurice 7.5’ USGS topographic sheet, T5N / R2E / Section 9, SW quarter of NW quarter; approximately 0.5 mile west of Bridal Veil Falls on US Highway 14A (i.e., Spearfish Canyon Road). The exposure, located at ground surface on north side of highway, is fractured and dips westward.

DEADWOOD FORMATION

Upper Member

**Interval A-1**: thickness not measured

Tan, calcareous, glauconitic quartz arenite sandstone.

**Interval A-2**: 51 cm

Thin- to thick-bedded, friable, tan, siliceous, calcareous quartz arenite sandstone with green shale partings.

Aladdin Member [EOSS]

**Interval A-3**: 1.85 m

Friable, white in color in the upper part, tan colored in the lower part, siliceous quartz arenite sandstone, cross-bedding type is difficult to identify due to fractures, tabular-planar type cross-beds may be more common near the bottom of the interval. The modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi in the upper part of interval, and 3.0 to 2.5 phi and 2.0 to 1.5 phi, respectively in the lower part of interval.

_Skolithos_ description –

Orientation: perpendicular to inclined at 80 degrees.

Shape: mainly straight; longer tubes have strongly curved ends.

Length: 7.7 cm, 6 cm, 5 cm, 4.7 cm, and 1.6 cm for five typical tubes.

Diameter: ranges between 1 to 3 mm with most closer to 1 mm.

Ichnospecies: _S. verticalis_. 
Skolithos per cm: 0.5 in the upper part, 2 in the middle part, and typically ranging from 0.3 to 0.5 in the lower part of the interval.

Filling: stained yellowish-green in the top half of the interval and filled with brown limonite in the lower half of the interval.

**Interval A-4: 3.37 m**

Very hard, white, siliceous quartz arenite sandstone containing vertical tubes. Stained yellow-green on freshly exposed surfaces; modal grain size is 3.5 to 3.0 phi and the maximum grain size is 3.0 to 2.5 phi.

**Skolithos description** –

Orientation: perpendicular to inclined, similar angles as interval A-3.

Shape: mainly straight; longer tubes have strongly curved ends.

Length ranges from 2 to 4 cm for five tubes visible on fresh surface of interval.

Diameter ranges between 1 to 2 mm, typically 1.5 mm.

Ichnospecies: *S. verticalis*.

Skolithos per cm: not measured in the upper and middle parts of the interval, 0.3 near the bottom of the interval.

Filling: stained greenish-yellow, yellow clay fills tubes in the top of interval.

**Interval A-5: 40 cm**

Friable, white, siliceous quartz arenite sandstone. *Skolithos* tubes are clearly seen and stained black or yellowish-green. The modal grain size is 3.0 to 2.5 phi and the maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined, similar angles as interval A-3.

Shape: mainly straight; longer tubes have strongly curved ends.
Length: ranges from 2.5 to 4.5 cm for five typical tubes.

Diameter: ranges between 1 to 3 mm with most closer to 1 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: not measured in the upper part of the interval. It typically ranged from 0.3 to 0.5 in the middle part and was 0.1 in the lower part of interval.

Filling: *Skolithos* tubes are stained black in the upper half of the interval and yellowish-green in the lower half of interval.

**Location B: Crow Peak, SD**

Maurice 7.5’ USGS topographic sheet, T6N / R1E / Section 23, SW quarter of NE quarter. The outcrop dips steeply and is located on south side of the Crow Peak intrusion in the ‘bowl area’.

**DEADWOOD FORMATION**

**Aladdin Member [EOSS]**

**Interval B-1: 1.9 m**

Yellowish-brown, siliceous quartz arenite sandstone; the rock is white in color where sand grains are larger. Quartz fractures occur throughout the interval, cross-bedding is probably tabular-planar and most common in the upper part; the modal grain size is 3.0 to 2.5 phi and the maximum grain size is 2.0 to 1.5 phi.

*Skolithos* description –

Orientation: perpendicular to bedding.

Shape: straight, some are slightly curved.

Length: 5 cm for six typical tubes, three tubes are 5 cm and one tube is 5.5.

Diameter: typically 2 mm.

Ichnospecies: *S. verticalis*. 
*Skolithos* per cm: 0.5, 0.6 and 1.4 for three measurements in the dipping interval.

Filling: stained or occasionally filled by limonite.

**Interval B-2:** 2.1 m

Interval description same as interval B-1, planar type cross-beds may be seen.

*Skolithos* description –

Orientation: perpendicular to bedding.

Shape: straight, some are slightly curved.

Length: 5 cm for three typical tubes.

Diameter: ranges from 1 to 10 mm.

Ichnospecies: *S. verticalis* and *S. linearis*.

*Skolithos* per cm: 0.2, 0.4 and 0.5 for three measurements in the dipping interval.

Filling: hematite filling occurs near the top of the interval and limonite stains or fills the tubes.

**Location C: Deadwood, SD**

Deadwood North 7.5’ USGS topographic sheet, T5N / R3E, / Section 14, SE corner of NE quarter of SW quarter, Deadwood Formation type locality, massive cliff overlooking the town of Deadwood, South Dakota. Accessed by a short, north by northeast trending trail located at the western end of Burnham Avenue (north side of town adjacent to Texaco gas station and Highway 85/14A).

**DEADWOOD FORMATION**

**Upper Member**

**Interval C-1:** thickness not measured
Red, sandy limestone with sand grains typically 2.0 to 1.5 phi. The upper contact is sharp.

**Interval C-2: 61 cm**

Yellowish-orange sandy limestone with sand grains typically 3.5 to 3.0 phi. The upper contact is sharp.

**Interval C-3: 30.5 cm**

Orange-yellow, calcareous sandstone. Modal grain size is 3.5 to 3.0 phi and maximum grain size is 3.0 to 2.5 phi. The upper contact is gradational.

**Interval C-4: 30.5 cm**

Thin-, wavy-bedded, orange-yellow, calcareous quartz arenite sandstone with shale partings. Modal grain size is 3.5 to 3.0 phi and maximum grain size is 3.0 to 2.5 phi. The upper contact is sharp.

**Aladdin Member [EOSS]**

**Interval C-5: 22 cm**

Well-sorted, pink, calcareous quartz arenite sandstone with black sand-size grains scattered throughout rock. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined at 70 to 80 degrees.

Shape: straight, some are slightly curved.

Length: typically 3 cm.

Diameter: typically 1.5 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.8, more densely spaced in the lower 10 cm of interval.

Filling: limonite with a black sand-sized grain occurring in both the rock and tube filling.
**Interval C-6:** 38 cm

Same as interval C-5, no *Skolithos*, modal grain size is 3.5 to 3.0 phi and maximum grain size is 3.0 to 2.5 phi.

**Interval C-7:** 22 cm

Pinkish-white, siliceous quartz arenite sandstone. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi. Interval contains tabular-planar type cross-beds (N45°E).

*Skolithos* description –

Orientation: perpendicular to inclined at 80 degrees.

Shape: straight, very few are slightly curved, some have oval-shaped upper ends that are slightly wider than the main tube.

Length: ranges typically from 2 to 4 cm.

Diameter: ranges from 1 to 2.5 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.5 in the upper part, 0.3 in the middle part and 0.5 in the lower part of the interval.

Filling: Tubes are stained by limonite.

**Interval C-8:** 24 cm

Tan to white, siliceous quartz arenite sandstone containing tabular-planar cross-beds (N45°E), *Skolithos* tubes occur most densely near the lower part of the interval with the tops of tubes commonly terminating along the lower plane of cross-beds, few tubes are seen in the cross-bedded portion. The bottom ends of *Skolithos* tubes immediately overlying the cross-bedded area are commonly terminated by the upper plane of cross-beds. The modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

*Skolithos* description –

Orientation: perpendicular to inclined.
Shape: straight to slightly curved, but the ends of tubes are never extremely curved.

Length: ranges from 2 to 5.5 cm, typically 3 cm, the longer tubes occur near the lower part of the interval.

Diameter: ranges from 1 to 3 mm, typically 1.5 to 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.4 in the upper part, 0.8 in the middle part and 1 in the lower part of the interval.

Filling: limonite or nothing.

**Interval C-9: 22 cm**

White, siliceous quartz arenite sandstone containing planar type cross-beds (N39°E). The interval is more severely weathered along cross-beds where small holes or pits occur. A black colored sand-sized grain occurs with the framework grains. Modal grain size is 2.5 to 2.0 phi in the upper half and 3.0 to 2.5 phi in the lower half of the interval, maximum grain size is 2.0 to 1.5 phi in the upper half and 2.5 to 2.0 phi in the lower half.

*Skolithos* description –

Orientation: perpendicular to inclined at 71 degrees.

Shape: straight to slightly curved, typically straight.

Length: ranges from 2 to 4.5 cm.

Diameter: ranges from 1.5 to 3 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically ranged from 0.6 to 1 in the upper portion of the interval, 1 to 1.2 in the middle part of the interval and 0.8 in the lower part of the interval.

Filling: tubes are stained by limonite.

**Interval C-10: 30.5 cm**
Very hard, white, siliceous quartz arenite sandstone that is slightly calcareous immediately above cross-beds (N54˚E) that become nearly tangential with the lower bounding surface. Cross-beds are more weathered than other parts of the interval. Cross-beds are long and inclined 20 degrees from the horizontal. Thickness of an individual cross-bed is 1 to 1.5 cm. *Skolithos* tubes are scarcely visible on the interval surface, but are clearly seen on freshly exposed surfaces. It is difficult to break the hard, well-cemented interval in order to view the *Skolithos* tubes and collect a hand sample. The modal grain size is 3.5 to 3.0 phi and maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined at 75 degrees.

Shape: straight, some exhibit strongly curved bottoms.

Length: ranges from 2 to 5.5 cm, some tubes terminate at upper and lower margins of the cross-bedded area.

Diameter: ranges from 1 to 2 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.8, measured in one small area of a fresh interval surface. The interval is too hard to break to view more tubes.

Filling: limonite.

**Interval C-11:** 2.5 to 5 cm

Yellowish-tan, calcareous, ferruginous quartz arenite sandstone interbedded in the upper part with thin grayish-white shale or silt. The interval is wavy- and thinly-bedded. Contains no *Skolithos*. Modal grain size is 3.5 to 3.0 phi and maximum grain size is 3.0 to 2.5 phi.

**Interval C-12:** 35.5 cm

White, yellow or pink, calcareous, ferruginous, siliceous, well-sorted quartz arenite sandstone. Modal grain size is 3.5 to 3.0 phi and maximum grain size of 3.0 to 2.5 phi.

**Skolithos description** –
Orientation: perpendicular to inclined at 75 degrees.

Shape: mainly straight, some are slightly curved.

Length: ranges from 2 to 3 cm, typically 2 cm.

Diameter: typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically ranges in the upper part of the interval from 0.3 to 0.6, 1 to 1.2 in the middle part of the interval, and is 1.2 in the lower part of the interval.

Filling: limonite.

**Interval C-13:** 13 cm

Orange-yellow, calcareous, ferruginous, siliceous quartz arenite sandstone with a small percentage of clay matrix containing shale partings. The interval is thinly-bedded and weathers to thin pieces that form small slopes. Modal grain size is 3.5 to 3.0 phi and maximum grain size is 3.0 to 2.5 phi.

*Skolithos* description –

Orientation: perpendicular, rarely inclined at 40 degrees.

Shape: straight to slightly curved.

Length: typically 2.5 cm, two rare inclined tubes were measured and ranged from 3.7 to 4 cm.

Diameter: typically 1 mm, the rare inclined tubes measured 2 mm in diameter.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically scarce, rarely as dense as 0.4 per cm.

Filling: limonite.

**Interval C-14:** 21.5 cm
Hard, pink to white, siliceous quartz arenite sandstone containing tabular-planar cross-beds (N65°E) in the upper part with *Skolithos* tubes mainly occurring below the cross-beded area. Modal grain size is 3.5 to 3.0 phi and maximum grain size is 3.0 to 2.5 phi.

*Skolithos* description –

Orientation: perpendicular to inclined.

Shape: straight.

Length: ranges from 2 to 3 cm, typically 2 cm.

Diameter: ranges from 1 to 2 mm, typically 1 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.6 in the upper part and 1 in the lower part.

Filling: limonite.

**Interval C-15:** 4 cm

Red-yellow, siliceous, ferruginous quartz arenite sandstone that contains small silt lenses. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi. This is the top of the EOSS at this locality. The upper contact is sharp with minor relief (about 1 cm).

**WINNIPEG FORMATION**

**Black Island Member (?)**

**Interval C-16:** 1 cm

Poorly-sorted, blue-gray, siliceous quartz arenite sandstone. Modal grain size in the upper part is 1.0 to 1.5 phi and 2.0 to 2.5 phi in the lower part. This is considered the base of the Winnipeg Formation at this locality.

**Interval C-17:** 16 cm

Blue-gray, siliceous, sandy shale measuring about 14 cm thick. About 6 percent of the rock is sand-sized quartz grains. Grades
upwards into blue-gray, siliceous quartz arenite sandstone measuring about 2 cm thick.

**Interval C-18:** 35.5 cm

Yellow-orange, siliceous, ferruginous quartz arenite sandstone. Modal grain size is 3.0 to 2.5 phi and the maximum gain size is 2.5 to 2.0 phi. This sandstone is interbedded with blue-gray, siliceous quartz arenite sandstone. Modal grain size is 2.0 to 2.5 phi occurring near the top of the blue-gray sandstone and the maximum grain size is 1.0 to 1.5 phi occurring near the bottom of the blue-gray sandstone. Sandy knobs or burrow portions of an unidentified trace fossil, preserved in hyporelief, occur on the lowermost surface of the interval. The knobs of the incomplete trace fossil are 2 to 3 cm long and as wide as 5.5 mm, commonly 3 mm wide. Strike and dip of the interval is N39°W and 17° NE.

**Location D: Whitewood Peak, SD**

Deadwood North 7.5’ USGS topographic sheet, T5N / R3E / Section 12, NE quarter of SW quarter of SE quarter. Outcrop is about 124 feet (37 m) above Whitewood Creek and can be reached by walking up a steep hillside. See geologic map by Boyd (1975).

**DEADWOOD FORMATION**

**Aladdin Member [EOSS]**

**Interval D-1:** 20 cm

Yellow-tan, siliceous quartz arenite sandstone. Cross-beds become nearly tangential to the lower bounding surface. Lower contact covered. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

**Interval D-2:** 22 cm

Tan, siliceous quartz arenite sandstone. Cross-beds become nearly tangential to the lower bounding surface. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.5 to 1.0 phi.

**Interval D-3:** 15 cm

Yellow-brown, siliceous quartz arenite sandstone. Cross-beds become nearly tangential to the lower bounding surface. Modal
grain size is 3.0 to 2.5 and maximum grain size is 2.5 to 2.0 phi. The lowermost bedding plain contains unidentified horizontal burrows preserved in positive relief. These burrows are straight or slightly curved in shape, do not branch and are sometimes cross cut by each other.

**Skolithos description** –

Orientation: perpendicular to inclined at 75 degrees.

Shape: straight or slightly curved in no preferred direction.

Length: ranges from 1.5 to 3.5 cm, typically 3 cm.

Diameter: ranges from 1 to 2 mm, typically 1 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.4.

Filling: limonite fills some tubes and stains other tubes where the filling has weathered out of the rock.

**Interval D-4:** 21.5 cm

Friable to hard, mottled red and light brown, siliceous, ferruginous quartz arenite sandstone. Planar cross-beds are seen in the lower part. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined at 65 degrees.

Shape: straight, some with strongly curved lower ends.

Length: ranges from 2 to 6 cm, typically 2 cm.

Diameter: ranges from 1 to 2 mm, typically 1 mm, but diameter of longer tubes is typically 2 mm, the lower ends of some tubes are slightly wider than the general diameter of the tube.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.5 in the upper part, 0.6 in the middle part and scarce in the lower part.
Filling: limonite and hematite.

**Interval D-5: 63.5 cm**

Orange, yellow, red (white near top of interval), siliceous quartz arenite. Planar cross-beds occur throughout entire interval. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

*Skolithos description* –

Orientation: perpendicular to slightly inclined; tubes in the lower part are more strongly inclined at 30 degrees.

Shape: straight or slightly curved.

Length: not measured

Diameter: ranges from 1 to 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.3 in the upper part and 0.6 in the lower part of the interval.

Filling: limonite and hematite.

**Interval D-6: 45.7 cm**

Clean white, siliceous quartz arenite sandstone. Cross-beds become nearly tangential to the lower bounding surface near the top of the interval. Small areas of the rock, including around some *Skolithos* tubes, are stained green. No glauconite grains are seen. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

*Skolithos description* –

Orientation: mainly perpendicular, longer tubes are commonly inclined.

Shape: mainly straight, longer tubes are commonly curved.

Length: ranges from 2 to 10 cm, the longest tubes occur in the middle part of the interval.
Diameter: ranges from 2 to 3 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.6 in the upper part, 0.2 in the middle and scarce in the lower part.

Filling: a yellow-orange stain occurs around the outside of the white-gray silt filling.

**Interval D-7: 38 cm**

Tan, siliceous and calcareous quartz arenite sandstone, cross-bedded. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.5 to 1.0 phi.

*Skolithos* description –

Orientation: perpendicular to slightly inclined.

Shape: straight to curved in the lower part of the tube.

Length: ranges from 2 to 4.5 cm, typically 2.5 cm.

Diameter: ranges from 1 to 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.4 in the upper part, 0.5 in the middle and 0.3 in the lower part.

Filling: stained brown.

**Interval D-8: 91.4 cm**

Thin- to medium-bedded, white, siliceous and calcareous quartz arenite sandstone. Contains green colored sand-sized glauconite grains. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

*Skolithos* description –

Orientation: perpendicular to inclined at 77 degrees.

Shape: straight or curved.
Length: ranges from 1.5 to 9.2 cm.

Diameter: ranges from 1 to 2 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.9 in the upper part, 0.4 in the middle and 0.5 in the lower part.

Filling: limonite or not filled.

**Interval D-9:** 30.5 cm

Thin- and wavy-bedded, friable, glauconitic, white, siliceous quartz arenite sandstone. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

*Skolithos* description –

Orientation: perpendicular to inclined.

Shape: straight or curved.

Length ranges from 1 to 2 cm.

Diameter: ranges from 2 to 3 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 0.6 in the upper part.

Filling: limonite.

**Interval D-10:** 1.27 m

Massive bedding, white, siliceous and calcareous quartz arenite sandstone. Cross-bedding is not clearly distinguishable but occurs in the middle part. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

*Skolithos* description –

Orientation: perpendicular to inclined.

Shape: straight or curved.
Length ranges from 2 to 6 cm, typically 3 cm, the longest tubes most commonly occur in the lower part.

Diameter: ranges from 1 to 3 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 1 in the upper part, 0.6 and 0.8 for two measurements in the middle part in which *Skolithos* is less noticeable where cross-bedding occurs, and 0.4 in the lower part.

Filling: limonite.

**Location E: Little Elk Creek, SD**

Piedmont 7.5’ USGS topographic sheet, T3N / R6E / Section 7, NE quarter of SW quarter of NW quarter. Area is referred to as the Red Gate in Little Elk Creek Canyon accessed from US Highway 79 South, to Little Elk Creek Canyon Road, take first dirt road on left. Other exposures of the Upper Member of the Deadwood Formation occur as cliffs high above Little Elk Creek and were not investigated. Large blocks of float, thicker than the measured section also occur but were not studied.

**DEADWOOD FORMATION**

**Upper Member**

**Interval E-1:** 30.5 cm

Brown, calcareous shale containing brown calcareous concretions occurring above glauconitic sandstone and shale, thickness was not measured for the latter.

**Interval E-2:** not measured

Flat pebble limestone conglomerate, upper contact is covered.

[LCSS]

**Interval E-3:** 2.9 m

White, red siliceous, ferruginous, calcareous quartz arenite sandstone containing yellow-green sand-sized glauconite grains, hematite fractures that commonly parallel bedding, and planar
cross-beds in areas that trend N23°W. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.5 to 1.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined.

Shape: straight or curved.

Length: ranges from 3 to 4 cm, typically 3 cm.

Diameter: ranges from 1 to 4 mm, typically 3 mm.

Ichnospecies: *S. verticalis* and (?) *S. linearis*.

*Skolithos* per cm: typically 0.6 in the upper part, 0.6 in the middle part (not measured in the lower part). It is sometimes difficult to distinguish hematite fractures from *Skolithos* tubes.

Filling: hematite and limonite.

**Interval E-4: 2.1 m**

Same as interval E-3, fractures make it difficult to recognize bedding characteristics, *Skolithos* tubes are easier to recognize from hematite fractures then in the underlying interval. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description** –

Orientation: perpendicular to inclined.

Shape: straight or curved.

Length: typically 4 cm.

Diameter: ranges from 1 to 4 mm, typically 3 mm.

Ichnospecies: *S. verticalis* and (?) *S. linearis*.

*Skolithos* per cm: typically 0.6.

Filling: hematite.
**Interval E-5: 1.6 m**

Medium- to thick-bedded, dark red, siliceous, ferruginous, calcareous quartz arenite sandstone. Contains long cross-beds that become nearly tangential to the lower bounding surface. Hematite may be more concentrated in some areas of the rock than others. More weathered than other intervals. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

*Skolithos description –*

Orientation: perpendicular to inclined.

Shape: straight.

Length ranges from 3 to 5 cm, typically 3 cm.

Diameter: ranges from 2 to 4 mm.

Ichnospecies: *S. verticalis* and (?) *S. linearis*.

*Skolithos* per cm: typically 0.2.

Filling: hematite.

**Location F: Iron Creek Lake, SD**

Maurice 7.5’ USGS topographic sheet, T5N / R1E / Section 23, north-central portion of SW quarter. Outcrop is 0.25 mile north of intersection of National Forest Road 135 and National Forest Road 122. Igneous rock is visible north of the outcrop from road 122. Top surface of outcrop is stained red by hematite to a depth of 1 to 8 cm and has well-developed joint sets. Measured joints are: N80°E, N87°W, N77°W, N85°E, N82°E, N88°E; N42°E, N46°E, N53°E, N53°E, N52°E, N44°E; and N50°W, N50°W, N50°W, N37°W, N54°W, N59°W. The strike and dip of the measured outcrop is N90°E and 12°S, an adjacent Aladdin outcrop orientated N19°W and 50°E is located approximately 36 to 46 meters southeast of the measured outcrop. Float containing many *Skolithos* tubes occurs further west on right side of road.

**DEADWOOD FORMATION**

Aladdin Member [EOSS]

**Interval F-1: 1.57 m**
White to gray, siliceous quartz arenite sandstone. *Skolithos* is visible in the lower part. Lower contact is covered. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined.

Shape: straight or curved.

Length: ranges from 1.5 to 2 cm, typically 2 cm.

Diameter: ranges from 1 to 2 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos per cm*: ranges in the lower part from 0.2 to 1 for two typical measurements, not measured in the upper part.

Filling: hematite.

**Interval F-2**: 96 cm

Same as interval F-1. Both intervals contain rock areas that are more easily eroded than others. These more friable areas thin and appear to pinch out into the massive-bedded intervals. Surface of cross-beds in interval F-2 contain white, thin layers probably derived from water flowing through the rock and over outcrop surfaces dissolving soluble minerals in the rock and later depositing them. Hand specimen contains parts of horizontal burrows that are unidentifiable, may be inclined *Skolithos* tubes. *Skolithos* can be difficult to see due to lichens that cover most of the outcrop surface. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular.

Shape: straight.

Length: ranges from 1 to 2.5 cm, typically 2.5 cm.

Diameter: ranges from 1 to 2 mm, typically 2 mm.

Ichnospecies: *S. verticalis*. 
Skolithos per cm: typically 1 in the lower part, not measured in the upper part.

Filling: limonite.

**Interval F-3: 1.52 m**

Hard, white to gray, siliceous quartz arenite sandstone containing fine-sized limonite colored grains. Long cross-beds occur throughout the interval and are prominent near the top of the interval. Individual cross-beds can be traced for a distance of about 1.5 m. Cross-beds become nearly tangential to the lower bounding surface. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description** –

Orientation: perpendicular.

Shape: straight or curved.

Length: ranges from 1 to 2 cm.

Diameter: is typically 2 mm.

Ichnospecies: *S. verticalis*.

Skolithos per cm: ranges from 0.3 to 0.5 in the upper part.

Filling: limonite.

**Interval F-4: 2.13 m**

Same as interval F-3. Cross-bedding is not as prevalent. Skolithos tubes clearly seen. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular.

Shape: straight or curved.

Length: typically 2 cm.
Diameter: ranges from 2 to 3 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.6 in the middle part.

Filling: limonite.

**Interval F-5:** 1.37 m

Same interval F-4. Upper surface of interval/outcrop is fractured. Rock contains a very small black-colored grains. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

*Skolithos* description –

Orientation: perpendicular.

Shape: straight or curved.

Length: typically 2 cm.

Diameter: ranges from 1 to 3 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: scarce.

Filling: limonite or sometimes black colored iron oxides.

**Location G: Kirk Hill Area, SD**

Deadman Montain 7.5’ USGS topographic sheet, T4N / R5E / Section 7, SE quarter of SW quarter and Section 18, NE quarter. Exposure is mainly float that varies in color; traverse follows National Forest Road 541 and commences at small outcrop juxtaposed against igneous rock, no *Skolithos* density (*Skolithos* per cm) measurements were made.

**DEADWOOD FORMATION**

**Upper Member [LCSS]**

**Interval G-1:** 1.7 m
Interval is poorly exposed outcrop of brown, siliceous quartz arenite sandstone with glauconite grains. Partially covered in the upper and lower parts. *Skolithos* tubes are common in hand specimen. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Interval G-2:** 60 cm

Float, blackish-red, siliceous quartz arenite sandstone containing silty limonite colored areas. *Skolithos* common in float in upper part and decreasing in abundance downward. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

**Interval G-3:** 50 cm

Float, dark red, siliceous quartz arenite sandstone appearing silvery-gray in color on freshly exposed surfaces. *Skolithos* is common and filled by brown silt. Modal grain size is 3.5 to 3.0 phi and maximum grain size is 2.5 to 2.0 phi.

**Interval G-4:** 1.3 m

Covered (thickness is about 30 cm). Float same as interval G-2 with cross-bedding apparent for the first time (thickness is about 60 cm). Slight break in slope and then float same as above (thickness about 40 cm).

**Interval G-5:** 50 cm


**Interval G-6:** 2.1 m

Float, dark red, siliceous quartz arenite, cross-bedded. *Skolithos* filled by silt-sized hematite. *Skolithos* diameter ranges in size from 5 to 6 cm (*S. linearis*). Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Interval G-7:** 60 cm

Float, same in composition as interval G-3, cross-bedded. *Skolithos* is abundant and filled by limonite or have no filling and are hollow. Length of *Skolithos* in float ranges from 2 to 4 cm and is typically 3 cm long, but probably incomplete. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.
Interval G-8: 40 cm

Float, red, siliceous quartz arenite sandstone containing hematite filled \textit{Skolithos} tubes. \textit{Skolithos} is common to abundant and ranging in diameter from 1 to 2 mm, typically 2 mm (\textit{S. verticalis}). Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

Interval G-9: 1 m

Medium-bedded outcrop, brownish-red, siliceous quartz arenite containing small limonite colored areas. Planar cross-beds occur throughout interval. \textit{Skolithos} is scarce. Two \textit{Skolithos} tubes seen that measure 3 and 5 cm long. Diameter is 2 mm (\textit{S. verticalis}). Upper contact covered by green shale float. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

Location H: Dalton Lake Area, SD

Nemo 7.5’ USGS topographic sheet, T3N / R5E / Section 15, SW quarter of NW quarter. Exposure is on the north side of National Forest Road 26 approximately 1.8 miles south of the Dalton Lake entrance.

DEADWOOD FORMATION

Upper Member [LCSS]

Interval H-1: 90 cm

Friable, dark red, siliceous, ferruginous quartz arenite sandstone containing common glauconite. Cross-bedded. \textit{Skolithos} tubes are difficult against the dark colored outcrop. Only the tops of tubes are seen, so shape description is incomplete and length cannot be measurable. Lower contact is covered. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 1.5 to 1.0 phi.

\textit{Skolithos} description –

Orientation: perpendicular.

Shape: circular, convex-up tube tops are visible.

Length: not measurable.
Diameter: ranges from 1 to 2 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 0.6 in the middle part.

Filling: hematite.

**Interval H-2: 50 cm**

Dark red, calcareous, siliceous, ferruginous quartz arenite sandstone containing less glauconite than underlying interval. Also, less friable than interval H-1. Cross-bedded. Interval is very hard in the lower half where *Skolithos* tubes are most common. Rock becomes more friable toward the top where few *Skolithos* tubes are seen. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.5 to 1.0 phi.

*Skolithos* description –

Orientation: perpendicular to slightly inclined.

Shape: straight.

Length: typically 2 cm.

Diameter: ranges from 2 to 3 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 0.2 in upper part, 0.3 in the middle and 0.5 in the lower part.

Filling: hematite.

**Interval H-3: 50 cm**

Dark red, siliceous, calcareous, ferruginous quartz arenite sandstone containing scarce amounts of fine-grained glauconite. Cross-beds become nearly tangential to lower bounding surface. Only the top of *Skolithos* tubes are visible, so shape description is incomplete and length cannot be measured. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.5 to 1.0 phi. Overlying 60 cm is covered.
**Skolithos description** –

Orientation: perpendicular.

Shape: circular, convex-up tube tops are visible.

Length: not exposed.

Diameter: ranges from 1 to 2 mm, typically 1 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 0.3 in the upper part.

Filling: hematite.

**Interval H-4:** 1.87 m

Massive-bedded, dark to light red, calcareous, ferruginous quartz arenite sandstone containing glauconite. Tabular-planar cross-beds occur in some areas in positive relief. Contains one large (approximately 2 to 2.5 m long and 25 cm tall), red colored, calcareous siltstone lens that has mostly weathered away from the surrounding competent sandstone. Other silty lenses occur, but are much smaller; measuring only a few centimeters in length and a 1 to 3 cm thick. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.5 to 1.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined at 80 degrees.

Shape: straight.

Length is typically 2 cm.

Diameter: ranges from 1 to 3 mm, typically 2 mm but commonly 3 mm in upper part.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 0.6 in upper part and 0.4 in the lower part.

Filling: *Skolithos* preserved as hematite cemented sand casts.

**Interval H-5:** 15 cm
Dark to bright red, calcareous, siliceous, ferruginous quartz arenite sandstone. Planar cross-beds. Siliceous cemented areas are silvery-gray in color. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description** –

Orientation: perpendicular, rarely inclined.

Shape: straight.

Length: ranges from 2 to 3 cm, typically 2 cm.

Diameter: typically 2 mm

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: ranges typically from 0.4 to 0.5.

Filling: hematite.

**Interval H-6**: 80 cm

Lower 70 cm is dark red, calcareous, ferruginous quartz arenite sandstone, upper 10 cm is same as interval H-5. Cross-bedded. Modal grain size is 2.0 to 1.5 phi and maximum grain size is 1.5 to 1.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined at 60 degrees.

Shape: straight.

Length: ranges from 1 to 4 cm, typically 2 cm, tube length is usually incomplete.

Diameter: ranges from 1 to 4 mm, typically 3 mm.

Ichnospecies: *S. verticalis* and (?) *S. linearis*.

*Skolithos* per cm: ranges from 0.4 to 0.6 in upper part.

filling: *Skolithos* preserved as hematite-cemented sand casts in positive relief.
**Interval H-7:** 80 cm

Friable, dark red, calcareous, ferruginous quartz arenite sandstone. Contains scarce amounts of glauconite. Cross-beds may be planar and usually hard. *Skolithos* sometimes cuts through cross-beds. Modal grain size is 2.0 to 1.5 phi and maximum grain size is 1.5 to 1.0 phi.

*Skolithos description* –

Orientation: perpendicular.

Shape: straight.

Length: ranges from 2 to 3.5 cm, typically 2 cm.

Diameter: ranges from 2 to 3 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 1 in upper part and 0.2 in the lower part.

Filling: hematite. Tubes commonly occur as hematite cemented sandy knobs 2 to 3 mm in relief.

**Interval H-8:** 1.10 m

Dark red to white, calcareous, ferruginous quartz arenite sandstone. Friable in white colored areas especially in the upper part. Contains scarce amounts of glauconite. Calcareous cement more common in cross-beds. Cross-beds become nearly tangential to the lower bounding surface in the lower part. Tabular-planar cross-beds seen in the upper part.

*Skolithos description* –

Orientation: perpendicular to inclined.

Shape: straight, sometimes with slightly curved lower ends.

Length: ranges from 2.5 to 9 cm, typically 4 cm.

Diameter: ranges from 1 to 4 mm, typically 3 mm.

Ichnospecies: *S. verticalis* and (?) *S. linearis*. 
*Skolithos* per cm: typically 0.6 and may be more dense near the bottom of the interval.


**Interval H-9:** 2.20 m

Friable, dark red, pink, white calcareous, ferruginous quartz arenite sandstone. Glauconite is abundant. Siltstone lenses occur in the upper part. Interval is cross-bedded and weathers to smooth, convex surfaces. Grain size is typically smaller in cross-beds. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

*Skolithos description* –

Orientation: perpendicular to inclined.

Shape: typically straight, few tubes have slightly curved lower ends.

Length: ranges from 2.5 to 6 cm, typically 3 to 3.5 cm.

Diameter: ranges from 1 to 2 mm, typically 1.5 to 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.6 in the upper part and 0.4 in the lower part.

Filling: hematite-cemented sand (very-fine grained) with scarce amounts of glauconite.

**Interval H-10:** 45 cm

Friable, dark red, calcareous, ferruginous quartz arenite sandstone. Contains glauconite. Modal grain size is 2.0 to 1.5 phi and maximum grain size is 1.0 to 0.5 phi.

*Skolithos description* –

Orientation: perpendicular to inclined.

Shape: straight, rarely with slightly curved lower ends.
Length: not measured, very short/incomplete.

Diameter: not measured.

Ichnospecies: not determined.

*Skolithos* per cm: typically 0.4.

Filling: hematite and fine-grained quartz sand.

**Interval H-11:** 1.30 m

Dark red, calcareous, ferruginous quartz arenite sandstone. Contains trace amounts of glauconite. Cross-beds are hard and form resistant ridges in places. Larger sand-sized grains not stained red like smaller sand grains. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.0 to 0.5 phi.

*Skolithos description* –

Orientation: perpendicular to inclined.

Shape: straight.

Length: typically ranges from 2 to 4 cm.

Diameter: ranges from 1 to 4 mm, typically 1 to 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.4.

Filling: hematite.

**Interval H-12:** 1.20 m

Friable, bright red to dark red, white, pale green, calcareous, ferruginous quartz arenite sandstone. Contains a pale green silt in areas. No glauconite grains are seen. Interval weathers to a convex shaped ledge. Modal grain size is 2.0 to 1.5 phi and maximum grain size is 1.5 to 1.0 phi.

*Skolithos description* –

Orientation: perpendicular to inclined.
Shape: straight.

Length: ranges from 2 to 6 cm, typically 4 cm.

Diameter: ranges from 2 to 4 mm

Ichnospecies: *S. verticalis* and (?) *S. linearis*.

*Skolithos* per cm: typically 0.6.

Filling: hematite and sand-sized quartz grains.

**Interval H-13:** 60 cm

Friable to hard, dark red, calcareous, ferruginous quartz arenite sandstone. Contains bright green glauconite grains and pale green silt. Rock fizzes less than underlying interval when tested with HCl. Interval is cross-bedded and weathered to a gentle slope. Upper contact covered. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

*Skolithos* description –

Orientation: perpendicular.

Shape: straight.

Length: typically ranges from 2 to 6 cm.

Diameter: typically ranges from 2 to 3 mm.

Ichnospecies: *S. verticalis* and (?) *S. linearis*.

*Skolithos* per cm: typically 0.3, tubes are scarce or difficult to see.

Filling: hematite and fine-grained quartz sand.

**Location I: Steamboat Rock, SD**

Piedmont 7.5’ USGS topographic sheet, T2N / R5E / Section 1, NE quarter of SW quarter. Exposure is adjacent to the National Forest picnic area adjacent to National Forest Road 26, just south of Nemo and north of Boxelder Creek on a high cliff reachable by a short hike.
DEADWOOD FORMATION

Upper Member

**Interval I-1:** 50 cm

Thinly-bedded, dark red, calcareous, ferruginous, glauconitic quartz arenite sandstone. Bedding is flaggy in appearance. Interval is cross-bedded. Hematite mostly seen in cross-beds. Interval contains horizontal burrows on bedding surfaces. No vertical burrows are seen. Elongated vug measuring 21 mm in length and 4 mm wide contains calcite crystals. Contact with overlying *Skolithos*-bearing sandstone is sharp. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

[LCSS]

**Interval I-2:** 1.70 m

Massive, dark to pale red, siliceous quartz arenite sandstone. Contains very fine-grained glauconite. Trough cross-bedding in the lower half. Ripple marked uppermost surface. *Skolithos* seen easiest in the upper and lower parts of the interval, middle of interval is slightly more friable having a pitted weathered surface. A seam of calcite crystals measuring 16 cm long and 1 cm wide occurs near the bottom of the interval. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description**

Orientation: perpendicular to inclined.

Shape: straight to slightly curved.

Length: ranges from 2 to 5 cm, typically 2 cm.

Diameter: ranges from 2 to 5 mm, typically 2 mm.

Ichnospecies: *S. verticalis* and *S. linearis*.

*Skolithos* per cm: typically 0.4 in the upper part, 0.6 in the middle and 0.4 in the lower part.

Filling: hematite.

**Interval I-3:** 13 cm
Thinly-bedded, friable, dark red with pale white areas, siliceous, slightly calcareous quartz arenite sandstone. Contains abundant very fine-grained glauconite. Bedding is flaggy in appearance toward the top. Interval is cross-bedded. Horizontal burrows seen in positive relief on bedding surfaces. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined.

Shape: straight.

Length: typically 1.5 mm.

Diameter: typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.4.

Filling: hematite and sand-sized quartz grains.

**Interval I-4:** 1.02 m

Medium bedded, friable, dark red to orange-red, siliceous quartz arenite sandstone. Contains abundant very fine-grained glauconite. Trough cross-beds more prevalent in the lower part. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined.

Shape: mainly straight, slightly curved tubes are scarce. Extremely curved tubes are rare.

Length: ranges from 1 to 3 cm, typically 2.5 cm.

Diameter: ranges from 1.5 to 3.5 mm, typically 1.5 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.3 in the upper part.
Filling: most tubes are not filled but some are lined with hematite.

**Interval I-5: 73 cm**

Friable to hard, dark red to orange-yellow, calcareous, ferruginous quartz arenite sandstone. Contains common amounts of fine-grained glauconite. Rock gives stronger fizz with HCl then any underlying interval. Thin calcareous deposits occur locally like interval F-2 at Iron Creek Lake. Interval harder along cross-beds. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description** –

Orientation: perpendicular to inclined.

Shape: straight to slightly curved.

Length: ranges from 2 to 3.5 cm, typically 2.5 to 3 cm

Diameter: ranges from 2 to 3 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: typically 0.3 in the middle part and scarce in the upper part.

Filling: hematite.

**Interval I-6: 1.35 m**

Massive, friable, pale red to yellow-orange, calcareous quartz arenite sandstone. Contains common amounts of upper fine-grained glauconite. Interval surface is slightly concaved and is pitted from weathering. Dark red to bright red colored lenses of very fine-grained quartz sand and hematite occur locally. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.0 to 0.5 phi.

**Skolithos description** –

Orientation: perpendicular to inclined.

Shape: mainly straight, a few tubes are slightly curved.

Length: ranges from 2.5 to 4.5 cm, typically 3 cm.
Diameter: ranges from 2 to 4 mm, typically 2.5 to 3 mm.

Ichnospecies: \textit{S. verticalis}.

\textit{Skolithos} per cm: typically 0.3 in the middle part, scarce in the upper and lower parts.

Filling: hematite, more resistant to weathering then other parts of the interval.

\textbf{Interval 1-7:} 1.80 m

Massive, friable to hard, dark red, yellow-orange, calcareous, ferruginous quartz arenite sandstone. Contains fine-grained glauconite. Green colored silt occurs between some framework grains. Trough cross-beds seen. Interval is more resistant to erosion than intervals 1-6 and 1-8. Calcite-lined vugs occur locally. Hard, dark red areas differentially cemented by siliceous, ferruginous and calcareous cement. Hard areas contain common amounts of glauconite. Hard areas occur as small patches throughout the interval and are more continuous along the upper and lower boundaries of the interval. Both \textit{Skolithos} and cross-beds cut through these cemented areas. Modal grain size is 2.0 to 1.5 phi and maximum grain size is 1.0 to 0.5 phi. Same grain sizes occur in the harder areas.

\textit{Skolithos} description –

Orientation: perpendicular to inclined at 55 degrees.

Shape: straight to slightly curved.

Length: ranges from 1.5 to 4 cm, typically 3 cm.

Diameter: ranges from 2 to 3 mm, typically 3 mm.

Ichnospecies: \textit{S. verticalis}.

\textit{Skolithos} per cm: typically ranges from 0.2 to 0.4 in the middle part and is 0.2 in the lower part.

Filling: hematite.

\textbf{Interval 1-8:} 1.18 m
Friable, light pink with cross-beds being a darker shade of red, calcareous, ferruginous, siliceous quartz arenite sandstone. Contains common amounts of glauconite in areas slightly harder than other parts of the interval. Interval surface is weathered with a pitted texture. Grains are typically larger in size in friable parts. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular to inclined.

Shape: straight.

Length: typically ranges from 1.5 to 2 cm.

Diameter: typically 3 mm.

Ichnospecies: *S. verticalis* and/or *S. linearis*.

*Skolithos* per cm: typically 0.2 in the middle part.

Filling: hematite.

**Interval I-9:** 3.57 m

Massive, friable, tan to black, calcareous, ferruginous quartz arenite sandstone. Contains fine-grained glauconite with green-yellow silt occurring between some framework grains. Concentrated ferruginous and fine-sand areas occur as small lenses locally and are slightly harder than other parts of the interval. Interval surface is weathered with pits and vertical concave shapes. Differential weathering occurs in the shape of small domes that are more densely spaced than the *Skolithos* tubes. Small domes are 1 mm wide near the bottom of the interval. Hand sample is white to green-yellow in color. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description** –

Orientation: perpendicular to inclined.

Shape: straight to slightly curved, some tubes are strongly curved toward their lower ends.

Length: ranges from 2 to 5 cm, typically 3 cm.
Diameter: ranges from 2 to 4 mm, typically 3 mm.

Ichnospecies: *S. verticalis* and (?) *S. linearis*.

*Skolithos* per cm: typically 0.4.

Filling: tubes near the bottom are filled with hematite and quartz sand forming bright red colored casts in positive relief. More poorly preserved hematite filled tubes occur in the middle and upper parts of the interval.

**Interval I-10:** 2.90 m

Massive, friable to hard, dark red to black, calcareous, ferruginous quartz arenite sandstone. Contains common amounts of glauconite. Cross-bedded. Harder areas throughout the interval, which are more continuous along the upper and lower boundaries of the interval. Differentially weathering occurs in the shape of small domes 2 mm wide near the bottom of the interval like interval I-9. No *Skolithos* tubes can be clearly identified. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi. Same grain sizes in the hard areas.

**Interval I-11:** 2.70 m

Medium-bedded, friable, porous, dark red grading to a brownish-red in the upper 80 cm, calcareous quartz arenite sandstone. Contains common amounts of glauconite and cross-beds. Beds weather to rounded, convex edges. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

*Skolithos* description –

Orientation: perpendicular.

Shape: straight to slightly curved.

Length: ranges from 3 to 4 cm.

Diameter: ranges from 3 to 4 mm.

Ichnospecies: *S. verticalis* and/or *S. linearis*.

*Skolithos* per cm: 0.2 in the upper part and 0.5 in the middle part.
Filling: mainly empty tubes, some tubes filled by hematite and sand.

**Interval I-12:** 73 cm

Friable, porous, dark red to pink, siliceous quartz arenite sandstone. Contains glauconite, scarce amounts of hematite, and cross-beds. Glauconite occurs with quartz sand grains in calcareous dome-shaped differential weathering features. Surface is pitted. Differential weathering occurs in the form of small domes 2 to 3 mm in width that are more densely spaced than the *Skolithos* tubes. Framework grains are well-sorted and well-rounded. Modal grain size is 2.0 to 1.5 and maximum grain size is 1.5 to 1.0 phi.

*Skolithos description –*

Orientation: incomplete.

Shape: incomplete.

Length: typically 2 cm, probably incomplete because of erosion of the friable rock.

Diameter: typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 0.4.

Filling: none.

**Interval I-13:** 21 cm

Ledge forming, dark red, siliceous, ferruginous quartz arenite sandstone. Upper 3 cm is dark red to purple, siliceous, ferruginous quartz arenite sandstone containing trace amounts of glauconite and small limonite colored areas. Interval is cross-bedded, ripple marks occur on the upper surface. Upper contact is covered. Modal grain size is 2.0 to 1.5 phi and maximum grain size is 1.5 to 1.0 phi. Modal grain size of upper 3 cm is 2.5 to 2.0 phi and maximum grain size of upper 3 cm is 2.0 to 2.5 phi.

*Skolithos description –*

Orientation: slightly inclined.
Shape: slightly curved.
Length: typically 3.5 cm.
Diameter: typically 3 mm.
Ichnospecies: *S. verticalis* and/or *S. linearis*.

*Skolithos* per cm: scarce.
Filling: hematite.

**Location J: Boxelder Creek, SD**

Piedmont 7.5’ USGS topographic sheet, T2N / R6E / Section 17, NW corner of SE quarter. Site located 0.45 mile south of National Forest Road 26, County Road T238, and County Road T234 intersection. Outcrop contains large concretions that increase in density up-section.

**DEADWOOD FORMATION**

*Upper Member [LCSS]*

**Interval J-1:** 1.75 m

Massive, friable with harder concretions that measure 2 to 19 cm in diameter, reddish-orange, pale red to light purple, calcareous quartz arenite sandstone. Contains common to abundant amounts of very fine-grained glauconite and trough cross-beds. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

Concretions are silvery-white in color on fresh surfaces, calcareous, siliceous quartz arenite sandstone. Contains common to abundant amounts of very fine-grained glauconite, cross-bedded. Sometimes *Skolithos* tubes intersect the concretions. Hand specimen of concretion rock contains a seam of dark red, sandy, silty, calcareous material measuring 2.5 cm long and 0.9 cm wide. Modal grain size is the same as above and maximum grain size is larger, 1.0 to 0.5 phi.

*Skolithos* description –

Orientation: perpendicular to inclined, typically perpendicular.
Shape: straight to slightly curved.

Length: ranges from 1.5 to 5.5 cm, typically 3 cm.

Diameter: ranges from 1.5 to 5 mm, typically 3 mm.

Ichnospecies: *S. verticalis* and *S. linearis*.

*Skolithos* per cm: 0.3 in the upper part, 0.6 in the middle part and 0.5 in the lower part.

Filling: hematite, not apparent in all tubes due to weathering.

**Interval J-2:** 70 cm

Dark red, siliceous, calcareous, ferruginous quartz arenite sandstone, harder than interval J-1. Cross-bedded, probably trough cross-beds exposed along their longitudinal section. Bedding is thin in the lower part and becomes thicker (medium-bedded) in the upper part. Concretions similar to those in interval J-1 occur in the lower part. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description** –

Orientation: perpendicular.

Shape: straight or slightly curved.

Length: ranges from 2 to 7 cm, typically 2 to 3 cm.

Diameter: typically 3 to 4 mm.

Ichnospecies: *S. verticalis* and/or *S. linearis*.

*Skolithos* per cm: ranges from 0.2 to 0.4 in the lower part

Filling: hematite.

**Interval J-3:** 1.88 m

Friable, dark red to bright red like typical construction bricks, calcareous, ferruginous quartz arenite sandstone. Interval is cross-bedded and flaggy in appearance in the middle and lower part. Bedding is more parallel, but still cross-bedded in the upper part.
Modal grain size is 1.5 to 1.0 phi and maximum grain size is 1.0 to 0.5 phi.

**Skolithos description** –

Orientation: perpendicular.

Shape: straight.

Length: ranges from 3 to 4 cm, typically 2 cm.

Diameter: ranges from 3 to 5 mm, typically 3 mm.

Ichnospecies: *S. linearis* and (?) *S. verticalis*.

*Skolithos* per cm: 0.3 in both the middle and lower parts.

Filling: has weathered away but some tubes are lined with hematite.

**Interval J-4:** 1.20 m

Similar to interval J-1, but darker in color. Contains more concretions than interval J-1 and less glauconite. Glauconite is fine-grained, occurring in scarce amounts. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.0 to 0.5 phi.

Concretions are pale greenish-white, calcareous quartz arenite sandstone containing a greater abundance of fine-grained glauconite than the surrounding rock. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description** –

Orientation: perpendicular to inclined at 75 degrees.

Shape: straight to slightly curved.

Length: ranges from 1 to 5 cm.

Diameter: ranges from 1 to 3mm, typically 3 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: scarce or poorly preserved.
Filling: hematite.

**Interval J-5: 1.35 m**

Hard, brown to friable and pale green, siliceous, calcareous, ferruginous quartz arenite sandstone. Contains scarce to common amounts of fine-grained glauconite, common amounts of hematite and a black colored grain in the harder areas. Friable, pale green colored areas are typically calcareous and only slightly siliceous. Interval is cross-bedded and contains concretions from 0.8 to 1.2 m from the bottom. Thinly-bedded sandstone measuring 15 cm thick has a blocky appearance above the concretions. Modal grain size is 2.0 to 1.5 phi and maximum grain size is 1.5 to 1.0 phi.

**Skolithos description** –

Orientation: perpendicular to slightly inclined.

Shape: straight.

Length: ranges from 1 to 4 cm, typically 2.5 cm.

Diameter: typically 1 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 0.4.

Filling: none, stained black by iron oxides.

**Interval J-6: 1.85 m**

Friable to hard in concretions, light red, porous, weakly calcareous quartz arenite sandstone. Contains trace amounts of fine-grained glauconite and concretions. Concretions are white in color with fine-grained to silt-sized pale green glauconite. *Skolithos* tubes are difficult to see, if they are present. Rock surface is weathered. Modal grain size is 2.0 to 1.5 phi and maximum grain size is 1.5 to 1.0 phi.

**Interval J-7: 90 cm**

Hard, white to pale green, calcareous, siliceous quartz arenite sandstone. Contains common amounts of fine-grained glauconite and trough cross-beds. Top of interval is purple, siliceous quartz arenite sandstone containing common amounts of fine-grained to
silt-sized glauconite. *Skolithos* tubes are difficult to see, if present. Surface is weathered and covered by moss. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.5 to 1.0 phi.

**Interval J-8: 42 cm**

Red, pink to brown, calcareous, ferruginous, siliceous quartz arenite sandstone. Contains scarce amounts of fine-grained glauconite. Brownish to pink areas are calcareous and more friable than dark red colored, ferruginous and siliceous areas. Interval contains scattered concave-bowl shapes about the size of the concretions seen in previous intervals. *Skolithos* tubes occur as hematite filled circular shapes in positive relief on the uppermost surface. Modal grain size is 2.0 to 1.5 phi and maximum grain size is 1.0 to 0.5 phi.

**Skolithos description** –

Orientation: only tops of tubes preserved in epirelief occur on uppermost surface.

Shape: circular in map view of uppermost surface.

Length: not measurable.

Diameter: ranges from 2 to 3 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: ranges from 0.3 to 0.5, typically 0.3, in the upper part.

Filling: hematite.

**Location K: Warren Peaks, WY**

Sundance West 7.5’ USGS topographic sheet, T52N / R63W / Section 33, SE corner of SE quarter of SW quarter of SW quarter. Road cut located 2.1 miles north of entrance to Reuter Campground on National Forest Road 838 in the Bear Lodge Mountains. The exposure on east side of road is split by a sill or low angle dike that is absent in the exposure on the west side of road. Outcrop is heavily fractured, which obscures bedding characteristics; orientation N60°E, 55°SW.

**DEADWOOD FORMATION**
Upper Member

Interval K-1: 3.8 m

Thick- to thinly bedded, brown sandstone. Lower contact is covered. Contains shale partings. Sandstone grades upwards to medium- to thickly-bedded light brown quartz arenite sandstone that is cross-bedded.

Interval K-2: 16 cm

Friable, reddish-brown, siliceous quartz arenite sandstone. Contains no shale partings.

Interval K-3: 7 cm

Hard, light brown, siliceous quartz arenite sandstone.

Interval K-4: 4 to 7 cm

Hard, brown, siliceous quartz arenite sandstone with interbedded friable, light brown to tan, siliceous quartz arenite sandstone. Contains small and thin pale green clay between quartz sand-sized grains.

Interval K-5: 40 cm

Thinly- to medium-bedded, hard, yellow-red to white, siliceous quartz arenite sandstone with interbedded friable sandstone similar to interval K-4. Contains a greater abundance of the thin, green clay partings. Interval is transitional into the overlying Skolithos-bearing sandstone.

[EOSS]

Interval K-6: 1.06 m

Medium-bedded, light pink, siliceous quartz arenite sandstone. Contains cross-beds. Modal grain size is 3.5 to 3.0 phi and maximum grain size is 3.0 to 2.5 phi.

Skolithos description –

Orientation: slightly inclined at 85 degrees.
Shape: slightly curved.
Length: typically 2 cm.
Diameter: ranges from 2.5 to 3 mm.
Ichnospecies: *S. verticalis*.

*Skolithos* per cm: sparse to 0.1.
Filling: none.

**Interval K-7: 1.74 m**

Medium- to thinly bedded, light brown with pink areas locally, siliceous quartz arenite sandstone. Contains cross-beds. Fractured pieces form sharp-pointed blocks. Modal grain size is 3.0 to 2.5 phi and maximum grain size 2.5 to 2.0 phi.

*Skolithos* description –

Orientation: mainly slightly inclined, rarely perpendicular.

Shape: straight to slightly curved, rarely curved in lower part causing the lower end of the tube to be horizontal with apparent bedding.

Length: typically 1.5 cm.

Diameter: ranges from 1 to 4 mm, typically 1 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 0.3 in the upper part, 0.4 in the middle and 0.2 in the lower part.

Filling: most tubes are not filled, minority of tubes are filled with fine-grained sand that is stained brown.

**Interval K-8: 1.69 m**

Medium- to thickly bedded, light pink to white, dark red in cross-beds, siliceous quartz arenite sandstone. Weathering similar to interval K-7. Modal grain size is 3.5 to 3.0 phi and maximum grain size is 3.0 to 2.5 phi.
Skolithos description –

Orientation: perpendicular to inclined at 60 degrees, inclined tubes typically inclined at 80 degrees.

Shape: straight to slightly curved.

Length: ranges from 1 to 6 cm, typically 2 cm but usually 1 to 1.5 cm near top.

Diameter: ranges from 1 to 4 mm, typically 2 mm.

Ichnospecies: S. verticalis.

Skolithos per cm: 0.6 in the upper part, 0.8 in the middle and 0.4 in the lower part.

Filling: most tubes not filled, some tubes are stained brown and contain little hematite.

Interval K-9: 7.60 m

Massive, fractured, hard, pale pink, with white or yellow areas locally, siliceous quartz arenite sandstone. Contains cross-beds. More resistant to weathering than underlying intervals. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

Skolithos description –

Orientation: perpendicular to slightly inclined.

Shape: straight to slightly curved.

Length: ranges from 1.5 to 4 cm, typically 2 to 2.5 cm.

Diameter: ranges from 1 to 3 mm, typically 2 mm.

Ichnospecies: S. verticalis.

Skolithos per cm: ranges from 0.5 to 1 in the middle part, typically 0.6 in the upper and middle parts and 0.5 in the lower part.

Filling: brown silt and hematite.

Interval K-10: 5.90 m
White, pink near top, siliceous quartz arenite sandstone appearing similar to interval K-9 but lighter in color. Upper contact is covered. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description** –

Orientation: perpendicular to slightly inclined.

Shape: straight to slightly curved.

Length: ranges from 1 to 2 cm, typically 1 to 1.5 cm.

Diameter: ranges from 1 to 2 mm, typically 1 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: ranges from 0.4 to 0.5 in the upper part and 0.3 to 0.4 in the middle. It is 0.3 in the lower part.

Filling: most tubes not filled, some tubes are stained brown.

**Location L: Sheep Mountain, WY**

Sundance East 7.5’ USGS topographic sheet, T52N / R63W / Section 13, NW quarter of SE quarter of NW quarter of SE quarter of NW quarter. Access the summit of Sheep Mountain from National Forest Road 838, turn right on National Forest Road 851, turn left on National Forest Road 841, turn right on National Forest Road 831, and a short hike.

**DEADWOOD FORMATION**

**Upper Member**

**Interval L-1**: not measured

Steep cliff. Appears to be thinly-bedded sandstone interbedded with shale or thinly-bedded limestone.

**Interval L-2**: 1.60 m
Medium- to thickly bedded, white quartz arenite sandstone. Contains silty brown colored calcareous areas. Contains cross-beds. Near vertical cliff below interval.

**Interval L-3**: 85 cm

White to pale green, calcareous, sandy-silty shale and interbedded yellow-brown, calcareous quartz arenite sandstone. Sandstone contains pale green shale partings and trace to common amounts of fine-grained glauconite. Bedding appears wavy. Modal grain size of quartz sand-sized grains is 3.0 to 2.0 phi.

[EOSS]

**Interval L-4**: 77 cm

White, calcareous quartz arenite sandstone. Contains light brown colored silty areas similar to interval L-2. Contains cross-beds. *Skolithos* tubes concentrated in rows similarly seen at Deadwood. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.0 to 1.5 phi.

*Skolithos* description –

Orientation: perpendicular to inclined at 70 degrees.

Shape: straight or slightly curved.

Length: ranges from 2.5 to 6 mm, typically 3 cm.

Diameter: ranges from 1 to 5 mm, typically 2 mm.

Ichnospecies: *S. verticalis* and *S. linearis*.

*Skolithos* per cm: 0.5 in both the upper and middle parts and 0.2 in the lower part.

Filling: brown, calcareous silt and very fine-grained quartz sand.

**Interval L-5**: 90 cm

Yellow-brown, calcareous quartz arenite sandstone. Thinly-interbedded with brown, calcareous sandy-silty shale. The shale material occurs most commonly toward the bottom of the interval and decreases in abundance upward as the sandstone bedding becomes thick. Shale is pale green in color and wavy-bedded in
the upper 4 to 5 cm of the interval. *Skolithos* tubes are longest and most densely occurring near the top where sandstone beds are thickest. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.5 to 2.0 phi.

**Skolithos description** –

Orientation: perpendicular to slightly inclined.

Shape: straight or slightly curved.

Length: ranges from 1.5 to 3 cm, typically 3 cm.

Diameter: ranges from 1 to 2 mm, typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 0.3 to 0.4 in the upper part.

Filling: light brown, calcareous silt.

**Interval L-6: 50 cm**

Light brown, calcareous quartz arenite sandstone. Contains cross-beds. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description** –

Orientation: perpendicular to slightly inclined.

Shape: straight or slightly curved.

Length: typically 3 cm.

Diameter: typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: ranges from 0.6 to 1.

Filling: none.

**Interval L-7: 70 cm**
Pale red and yellow, calcareous, ferruginous quartz arenite sandstone. Contains a fine sand-sized black colored grain in trace abundance and light brown, calcareous silt with abundant hematite. Cross-bedded. Interval is slightly more friable then interval L-6. Weathers to the same degree as L-6. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Skolithos description** –

Orientation: perpendicular to inclined at 65 degrees.

shape: straight or slightly curved

Length: ranges from 1 to 4 cm, typically 2.5 cm.

Diameter: typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: ranges from 0.2 to 0.5 in the upper part, typically 0.2.

Filling: none.

**Interval L-8**: 1.65 m

Tan to white, brown to red locally near top, siliceous quartz arenite sandstone. Interval is hard where is white in color, becoming more friable where it is brown. Contains cross-beds. Modal grain size is 3.5 to 3.0 phi and maximum grain size is 3.0 to 2.5 phi.

**Skolithos description** –

Orientation: perpendicular to slightly inclined.

shape: straight or slightly curved

Length: ranges from 2 to 9.5 cm, many tubes are greater than 4 cm, typically 3 to 4 cm.

Diameter: typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: ranges from 0.5 to 1, typically 0.5 to 0.6 near the bottom.
Filling: white colored silt, stained brown or empty.

**Interval L-9:** 15 cm

Thinly-bedded, bioturbated, yellow-orange or reddish-orange to brown, siliceous, ferruginous, calcareous quartz arenite sandstone. Contains a brown silty matrix. Burrows preserved in epirelief (epichnia) and appear as ferruginous or siliceous sandy knobs. Lower contact is gradational and upper contact is covered by green to gray shale. No Skolithos. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 1.5 to 1.0 phi.

**Location M: Cheyenne Crossing, SD**

Lead 7.5’ USGS topographic sheet, T4N / R2E / Section 22. Outcrop located on northwest side of US Highway 85 about one mile south of the road's intersection with US Highway 14A at Cheyenne Crossing, about four miles south Trojan. The typical Skolithos Sandstone was not found here or during a brief stop at Hanna Camp Ground located southeast about one mile.

**DEADWOOD FORMATION**

**Upper Member**

**Interval M-1:** 45.5 cm

Pale green to brown, siliceous sandstone. Contains a brown colored silt; fine-grained, dark colored glauconite and green shale partings. Glaucenicite shale and sandstone lies immediately below.

**Interval M-2:** 66 cm

Brown, siliceous sandstone. Contains silt-sized grains; fine-grained and bright green colored glauconite; horizontal and inclined burrows. Cross-beds typically occurs in the upper part. Contact with the overlying interval is sharp. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Interval M-3:** 4.61 m

Brown, calcareous sandstone in the lower part. Contains abundant amounts of fine-grained glauconite. Cross-bedded. Modal grain size is 2.5 to 2.0 phi. Thinly- to wavy-bedded, brown, calcareous sandstone in the middle part. Contains fine-sand sized black-
colored grains and light-colored silt between some framework grains. Cross-bedded. Modal grain size is 3.5 to 3.0 phi and maximum grain size is 3.0 to 2.5 phi. Upper part is dark brown, calcareous sandstone that contains thin veins of calcite and calcite lined vugs. Cross-bedded. Upper contact is covered.

**Location N: Trojan, SD**

Lead 7.5’ USGS topographic sheet, T4N / R2E / Section 2, SW quarter of NE quarter of NE quarter. Site located near the town of Trojan. Outcrop is accessed by travel 3.2 miles on a paved road that follows Nevada Gulch accessed from Highway 85. The exposure is on the west side of road near where paving terminates.

**DEADWOOD FORMATION**

Upper Member

**Interval N-1:** not measured

Dark brown, calcareous, ferruginous, glauconitic quartz arenite sandstone. Lower contact is covered.

**Interval N-2:** 3 to 4 cm

Friable, harder near bottom, yellow-brown, siliceous quartz arenite sandstone. Contains some silt and green or white shale partings. Contact is sharp with the overlying, massive-bedded *Skolithos* sandstone.

[EOSS]

**Interval N-3:** 1.88 m

Massive, hard, reddish-brown to dark brown, siliceous, ferruginous quartz arenite sandstone in the extreme lower part. Modal grain size is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi. Middle part is typical of the interval; hard, white, locally stained red or purple, siliceous quartz arenite sandstone. Contains cross-beds that become nearly tangential to the lower bounding surface. Modal grain size is 3.0 to 2.5 phi and maximum grain size is 2.5 to 2.0 phi. Extreme upper part is lighter in color than towards the base of the interval; similar in appearance to the middle part but *Skolithos* tubes are filled with a brown colored silt. Modal grain
size is 3.0 to 2.5 phi and maximum grain size is 2.0 to 1.5 phi. Upper contact is sharp with the overlying Winnipeg Formation.

**Skolithos description** –

Orientation: perpendicular to slightly inclined.

Shape: straight or slightly curved.

Length: ranges from 2 to 8 cm, typically 2.5 to 3 cm.

Diameter: typically 2 mm.

Ichnospecies: *S. verticalis*.

*Skolithos* per cm: 0.3 in the upper part, 0.8 in the middle part and 0.6 in the lower part.

Filling: typically brown, red or purple-stained silt and hematite.

**WINNIPEG FORMATION**

**Black Island Member (?)**

**Interval N-4:** 15 cm

Thinline-bedded, friable, brown to dark red locally, siliceous, ferruginous quartz arenite sandstone. Interbedded with friable, blue-gray or pale green colored, non-calcareous quartz arenite sandstone that is sandy shale to more shale-like in areas; forms a thin transition zone having a sharp upper and lower contact between the underlying *Skolithos* sandstone and the overlying Winnipeg shale. Modal grain size of sand-sized grains is 2.5 to 2.0 phi and maximum grain size is 2.0 to 1.5 phi.

**Icebox Member**

**Interval N-5:** 1.11 m

Red, brown, blue-gray sandy shale that is transitional into overlying green shale. A friable, pale purple to white, siliceous, dolomitic (?) silty sandstone, 42 cm thick, occurs locally within the green shale and could not be found laterally.
APPENDIX C

THIN SECTION PETROGRAPHY
### ABBREVIATIONS AND CODES

<table>
<thead>
<tr>
<th>ABUNDANCE</th>
<th>CEMENT</th>
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<td>blank space</td>
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#### FRAMEWORK GRAINS

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<tr>
<th>mq</th>
<th>monocrystalline quartz</th>
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<tr>
<td>pq</td>
<td>polycrystalline quartz</td>
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<tr>
<td>ortho</td>
<td>orthoclase feldspar</td>
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<tr>
<td>micro</td>
<td>microcline feldspar</td>
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<tr>
<td>plag</td>
<td>plagioclase feldspar</td>
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<tr>
<td>mm</td>
<td>mica muscovite</td>
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<td>mb</td>
<td>mica biotite</td>
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<tr>
<td>r f</td>
<td>rock fragments</td>
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<tr>
<td>glauc</td>
<td>glauconite</td>
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#### POROSITY

| inter | intergranular         |
| diss  | dissolution           |
| skolith | hollow Skolithos   |
| frac  | fracture              |

#### TEXTURE

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<th>m g s</th>
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APPENDIX D

SKOLITHOS THIN SECTION DESCRIPTIONS
## ABBREVIATIONS AND CODES

<table>
<thead>
<tr>
<th>SKOLITHOS CROSS SECTION SHAPE</th>
<th>ELONGATED-GRAIN ORIENTATION IN TUBE WALL</th>
<th>GRAIN PACKING IN TUBE WALL COMPARED TO THE SAMPLE’S MODAL GRAIN PACKING</th>
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<tbody>
<tr>
<td>C circular</td>
<td>T long axis of most grains is tangent to tube wall</td>
<td>L less than</td>
</tr>
<tr>
<td>O/E oval or egg-shaped</td>
<td>P long axis of most grains long is perpendicular to tube wall</td>
<td>M more than</td>
</tr>
<tr>
<td>IND indeterminate</td>
<td>R long axis of most grains is randomly oriented with respect to tube wall</td>
<td>ND no difference</td>
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<thead>
<tr>
<th>GRAIN SIZE IN TUBE WALL COMPARED TO THE SAMPLE’S MODAL GRAIN SIZE</th>
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<tbody>
<tr>
<td>ND no difference; tube-wall grains are the same size as sample’s modal grain size</td>
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<tr>
<td>D nearly all tube-wall grains are different in size than the sample’s modal grain size</td>
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<tr>
<td>.5D roughly half of the tube-wall grains are different in size than the sample’s modal grain size</td>
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<tr>
<th>POROSITY AROUND THE TUBE COMPARED TO THE SAMPLE’S MODAL POROSITY</th>
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<tr>
<td>L less than</td>
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<td>M more than</td>
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<td>ND no difference</td>
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<tr>
<th>EXTENT OF TUBE FILLING</th>
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<tr>
<td>N tube has no filling material</td>
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<tr>
<td>F tube is completely filled</td>
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<tr>
<td>P tube is partially filled</td>
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<tr>
<td>L tube contains only a thin lining along the inside of the burrow wall</td>
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<td>S tube filling material extends beyond the tube into surrounding sand</td>
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| (lower part) |   |   |   |
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| 159 | ND | ND | N |
| 160 | ND | ND | P |
| 161 | ND | ND | P |
| 162 | ND | ND | P |
| 163 | ND | L | P |
| 164 | ND | L | P |
| 165 | ND | ND | P |
| 166 | ND | L | P |
| 167 | ND | L | L | 0.03 |
| 168 | ND | L | P |
| 169 | ND | L | S |
| 170 | ND | L | S |
| 171 | ND | ND | F |
| 172 | ND | ND | F |
| 173 | ND | L | F |
| 174 | ND | L | F |
| 175 | ND | L | F |
| 176 | ND | L | F |
| 177 | ND | ND | F |
| 178 | ND | ND | F |
| 179 | ND | ND | F |
| 180 | ND | ND | F |
| 181 | ND | ND | F |
| 182 | ND | ND | P |
| 183 | ND | L | P |