

PALAEOENVIRONMENTAL INTERPRETATION OF A
VIRGILIAN (PENNSYLVANIAN) STROMATOLITE
BIOSTROME IN NORTHEASTERN KANSAS

200

by

ROBERT SCOTT SAWIN

B. S., Kansas State University, 1972

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

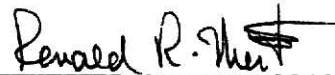
Department of Geology

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1977

Approved by:



Major Professor

Document
LD
2668
T4
1977
S29
C.2

ii

TABLE OF CONTENTS

	Page
Introduction.....	1
Purpose of Investigation.....	1
Location.....	1
Previous Investigations.....	1
Methods of Investigation.....	4
Field Procedure.....	4
Laboratory Procedure.....	6
General Statement.....	6
Vertical Slabs.....	6
Acetate Peel Analysis.....	6
Thin Sections.....	7
X-Ray Diffraction.....	7
Insoluble Residue.....	7
Disaggregation.....	7
Geologic Setting.....	8
Structure.....	8
Stratigraphy.....	8
Classification and Description of Stromatolites.....	10
Classification.....	10
Description.....	12
General Statement.....	12
Gross Morphology.....	12
Internal Structure.....	14
Biology, Morphology, and Distribution of Stromatolites.....	19
General Statement.....	19
Processes Involved in Stromatolite Construction.....	19
Morphology.....	20
Distribution.....	21
Detailed Analysis of the Stromatolite Biostrome and Its Relationship with Underlying and Overlying Lithologies: Locality SB-15.....	23
General Statement.....	23
Stromatolite Biostrome.....	23
Lithology.....	23
Argillaceous Dismicrite.....	23
Coated-grain Biosparrudite.....	28
Stromatolitic Biolithite.....	28

TABLE OF CONTENTS (Continued)

	Page
Biotic Components.....	30
Depositional Environment.....	34
Depositional Sequence.....	34
Depositional Gradient.....	37
Energy.....	37
Tidal Position.....	39
Salinity.....	39
Invertebrate Assemblage.....	40
Vertebrate Assemblage.....	40
Lateral Changes in Biostromal Development.....	41
Underlying and Overlying Lithologies.....	41
General Statement.....	41
Biotic Components.....	41
Depositional Environment.....	44
Lateral Integration of Measured Stratigraphic Sections.....	45
General Statement.....	45
Correlation.....	46
Interpretation.....	49
Comparison of the Soldier Creek Shale Stromatolites with the Holocene Example at Hamelin Pool, Shark Bay, Western Australia....	51
Physical, Chemical, and Biological Evolution.....	51
Comparison with Hamelin Pool Example.....	53
Hamelin Pool Setting.....	53
Comparison with the Soldier Creek Stromatolite Biostrome..	54
Internal Structure.....	54
Laminations.....	54
Surface Texture.....	55
Gross Morphology.....	55
Oncolites.....	55
Biotic Association.....	57
Depositional Gradient.....	57
Sediment Transport.....	58
Summary.....	58
Acknowledgments.....	61
References.....	62

LIST OF FIGURES

Figure	Page
1. Geologic Setting.....	2
2. Location of Measured Stratigraphic Sections.....	3
3. Map of Locality SB-15 Showing Location of Measured Stratigraphic Sections.....	5
4. Generalized Stratigraphic Section of the Bern Limestone.....	9
5. Diagrammatic Sketch of the Structural Formula for Soldier Creek Stromatolites Using Scheme of Logan <u>et al.</u> , 1964.....	12
6. Stages of Stromatolite Growth.....	13
7. Oncolites and Stromatolites.....	15
8. Surface Texture and Oncolite Laminae.....	16
9. Internal Structure: Digitate Branches and Interstitial Areas...	18
10. Outcrop at Locality SB-15, Sections A-H, West Exposure.....	24
11. Location of Samples, Stromatolite Biostrome, Locality SB-15, Sections A-H.....	25
12. Lithologies of the Stromatolite Biostrome.....	27
13. Boxwork Pattern, Dolomite Replacement of Calcite and Desiccation.....	29
14. Diagrammatic Sketch of Stromatolite Biostrome, Locality SB-15, West Exposure.....	35
15. Diagrammatic Summary of Environmental Interpretations, Locality SB-15, Sections A-H.....	38
16. Biostromal Distribution at Locality SB-15.....	42
17. Relative Diversity, Locality SB-15.....	43
18. North-South Correlation of Measured Stratigraphic Sections.....	47
19. East-West Correlation of Measured Stratigraphic Sections.....	48
20. Geographic Distribution of Vertebrate Skeletal Debris.....	50

LIST OF FIGURES (Continued)

Figure	Page
21. Geographic Distribution of "Topographic Highs".....	52
22. Comparison of Surface Texture and Gross Morphology of Pennsylvanian with Holocene Stromatolites.....	56

LIST OF TABLES

Table	Page
1. Average Grain Size and Insoluble Residues at Locality SB-15, Sections A-H.....	26
2. Biotic Components of the Argillaceous Dismicrite.....	30
3. Biotic Components of the Coated-grain Biosparrudite.....	31
4. Biotic Components of the Stromatolitic Biolithite.....	32
5. Stromatolite Biostrome Fossil Assemblage, Locality SB-15.....	34

LIST OF APPENDICES

Appendix	Page
I. Definition of Terms.....	68
II. Measured Stratigraphic Sections.....	69
III. Vertical Slabs of the Stromatolite Biostrome.....	104
IV. X-Ray Diffraction Data: Quartz, Calcite, Dolomite.....	117
V. Oncolite Measurements.....	118
VI. Biotic Components of the Stromatolite Biostrome: Locality SB-15, Sections A to H.....	120
VII. Biotic Components of Underlying and Overlying Mudstones at Locality SB-15.....	126

INTRODUCTION

Purpose of Investigation

This is a palaeoenvironmental investigation of an occurrence of Upper Pennsylvanian stromatolites. The principle objectives were to: 1) describe the gross morphology, internal structure, and biostromal relationships of these stromatolites, 2) determine their position in relation to sea level, 3) reconstruct the palaeogeography of the area, and 4) compare this occurrence with the Holocene example in Shark Bay, Western Australia.

Selection of this stromatolite occurrence was based on 1) its in situ preservation and absence of postdepositional compaction, 2) knowledge of the Shark Bay occurrence, and 3) most importantly, a desire to do a field-orientated palaeontologic investigation based on stratigraphy.

Location

The area includes approximately 60 square miles in the southeast corner of Brown County, Kansas (figs. 1 and 2). Twenty-five exposures of the stromatolite biostrome were chosen from available outcrops (fig. 2).

Previous Investigations

Moore and Mudge (1956) named the Bern Limestone for exposures near the town of Bern, Kansas. In ascending order the Bern consists of the Burlingame Limestone Member, Soldier Creek Shale Member, and Wakarusa Limestone Member. The type locality is in a roadcut in the SE $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 7, T.1 S., R. 13 E., Nemaha County, Kansas, one mile west and one-half mile north of Bern. Stratigraphy of the Bern Limestone and bioherms in the Soldier Creek Shale Member in Shawnee, Osage, and Lyon Counties, Kansas, were described by Owen (1959). He also summarized the stratigraphic

**THIS BOOK
CONTAINS
NUMEROUS PAGES
WITH DIAGRAMS
THAT ARE CROOKED
COMPARED TO THE
REST OF THE
INFORMATION ON
THE PAGE.**

**THIS IS AS
RECEIVED FROM
CUSTOMER.**

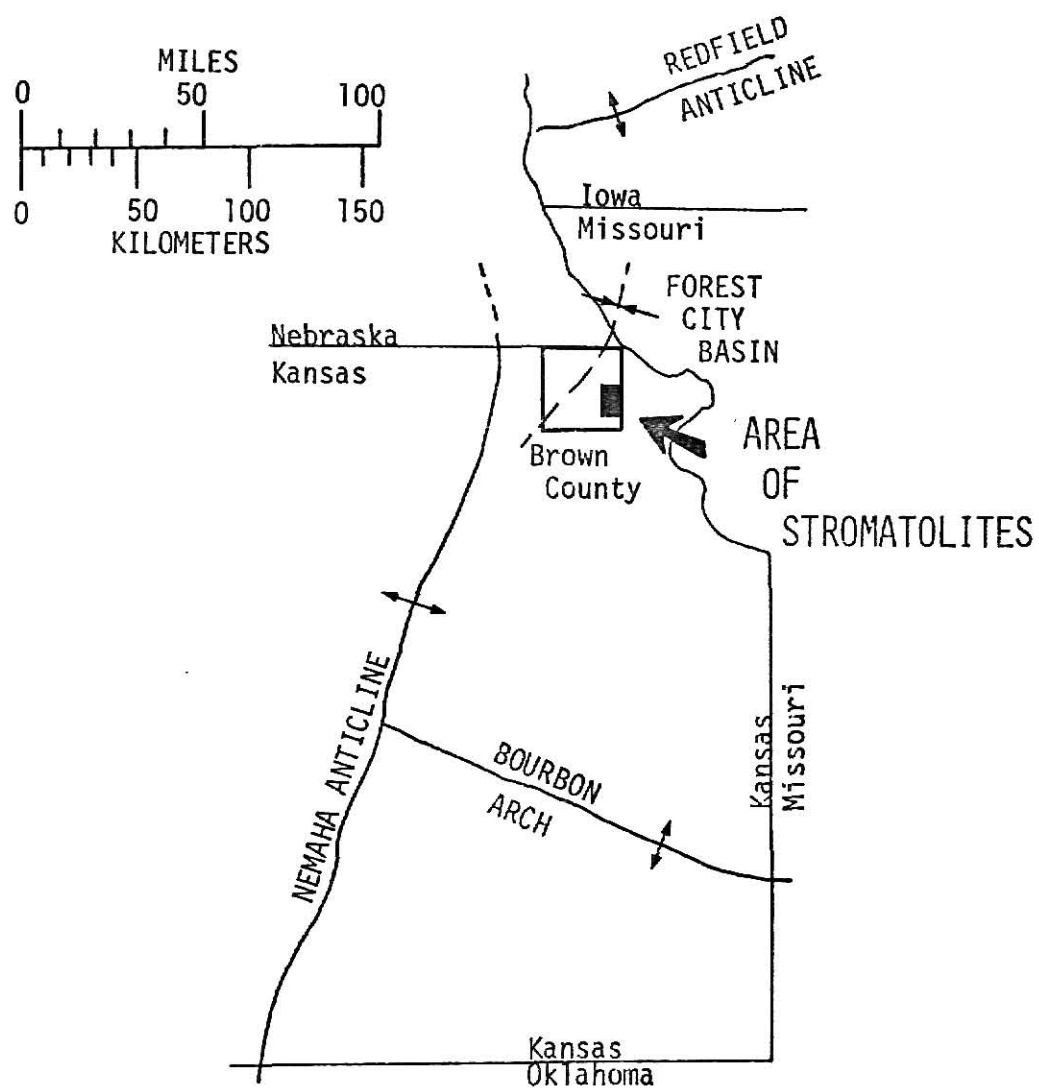


Figure 1. Geologic Setting (Sources: Lee, 1943; Jewett, 1951; Fagerstrom and Burchett, 1972).

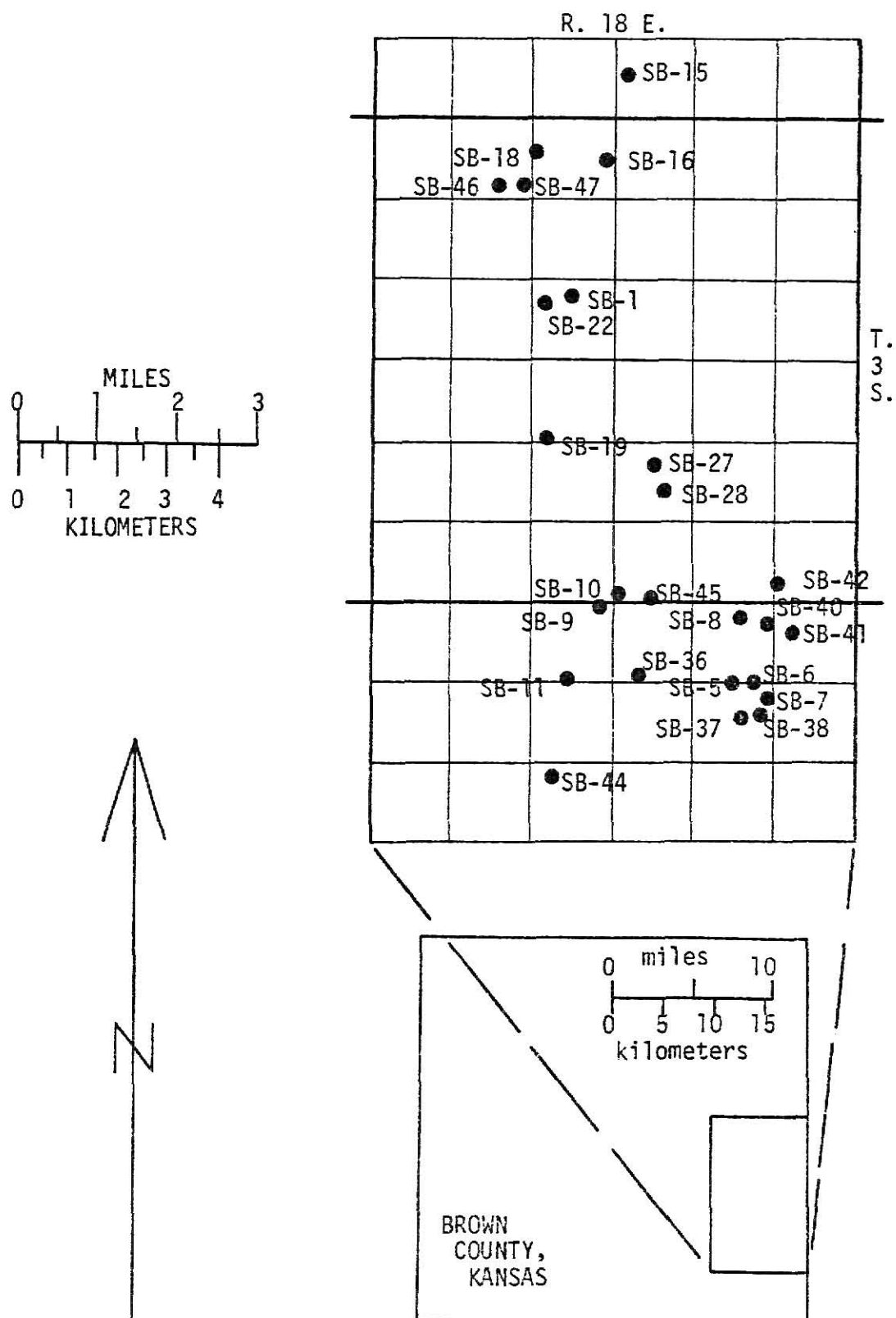


Figure 2. Location of Measured Stratigraphic Sections

investigations up to 1959. Beede (1899) first named the stromatolites Somphospongia multiformis (considering them sponges) from a locality northeast of Robinson, Kansas. Johnson (1946) collected specimens from this area and confirmed their algal affinities. More recently, Baird (1966) and Chorn and Conley (1977) have examined the vertebrate assemblage within this stromatolite biostrome (Appendix I).

METHODS OF INVESTIGATION

Field Procedure

A reconnaissance of Bern Limestone exposures in Brown, Atchison, and Doniphan Counties was made to determine the areal extent of stromatolites (Appendix I) and to locate in-place stromatolite outcrops. Suitable outcrops were located using geologic (Brown County: Bayne and Schoewe, 1967; Atchison County: Ward, 1973; Doniphan County: Bayne, 1973) and topographic maps. The stromatolite biostrome was exposed in stratigraphic position at 25 localities (fig. 2). Stromatolites occurred as "float" at fifteen other localities within this area but were not examined in detail.

At each locality 1) stratigraphic sections were measured and described (Appendix II), 2) a block representative of the stromatolite biostrome (laterally and vertically) was collected, 3) top surface, compass orientation, and sample number were marked on each sample, and 4) underlying and overlying mudstones in contact with the biostrome were sampled.

Locality SB-15 (fig. 3) was selected for detailed analysis because it provides an example of changes in stromatolite morphology along a continuous lateral exposure. This locality will be used as a model to delineate the palaeogeography of the area. Plane table and alidade were used to locate

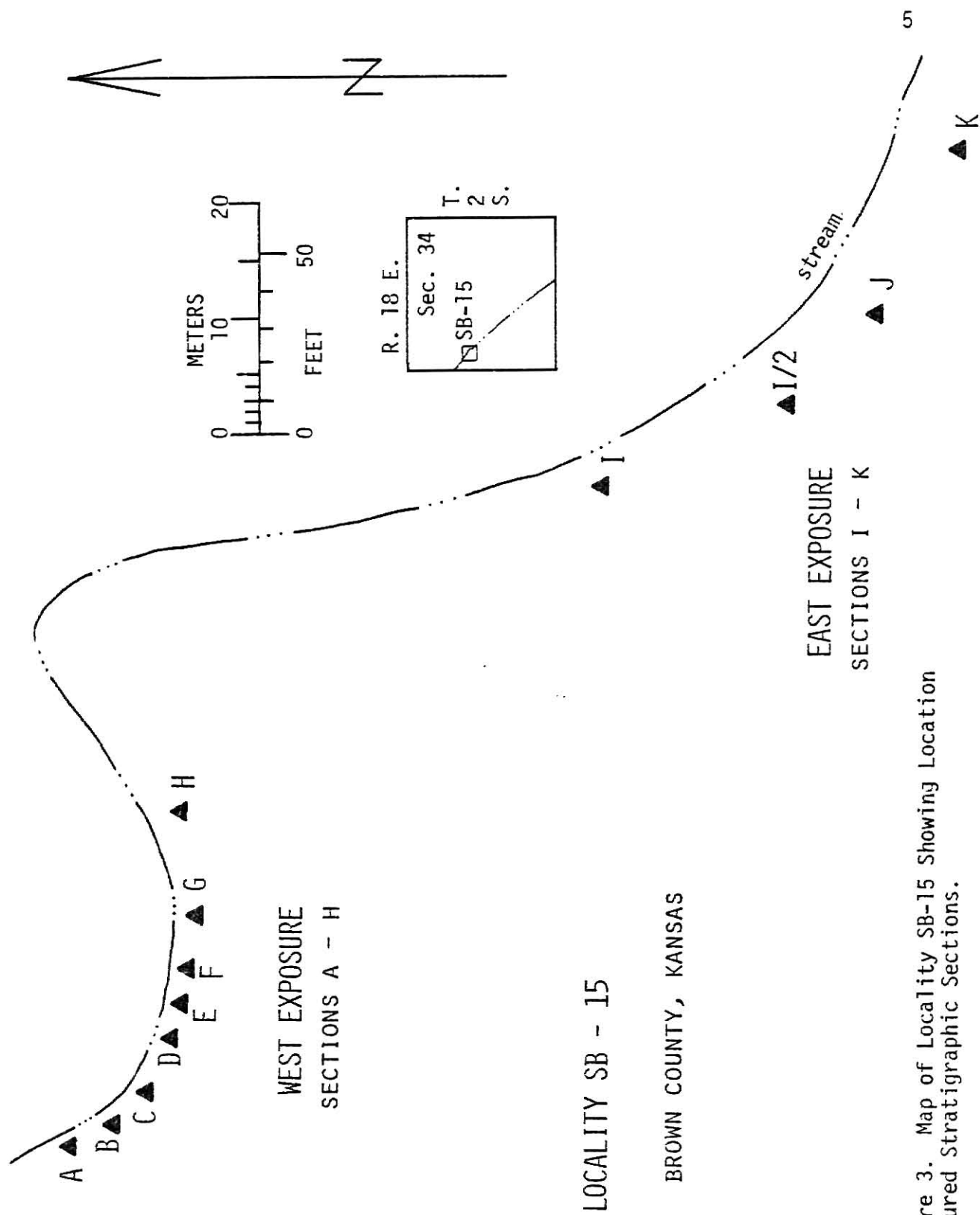


Figure 3. Map of Locality SB-15 Showing Location of Measured Stratigraphic Sections.

twelve measured sections and each measured section was sampled as previously described. Sections B, G, and J were sampled every half meter from 0.5 m below to 2.0 m above the stromatolite biostrome to obtain a better understanding of the vertical succession at this locality.

Laboratory Procedure

General Statement.--Laboratory analysis was confined to the stromatolite biostrome at all localities and the underlying and overlying mudstones at Locality SB-15. Detailed lithologic investigations were restricted to the stromatolite biostrome at Locality SB-15.

Vertical Slabs.--Blocks collected from each locality were vertically sectioned and polished. A 12-cm wide vertical strip representing the full block thickness was sketched to define biostromal lithologies (Appendix III).

Acetate Peel Analysis.--Acetate peels of vertical slabs were also used because 1) they can be prepared rapidly and 2) an area larger than standard thin section slides can be examined. Peels provide the same information, with the exception of mineralogy, that can be obtained from thin sections. Peels were prepared by 1) grinding the surface of the rock smooth, 2) etching the surface with 3N HCl for 15 seconds, 3) washing and drying the surface, 4) wetting the surface with acetone, 5) placing a 0.003 mm or 0.01 mm thick acetate sheet smoothly on it, and 6) peeling off the acetate sheet after it had dried for 30 minutes.

Peels from the stromatolite biostrome at Locality SB-15 were used to identify biotic components, and to determine grain to matrix ratios and grain parameters. These data were taken from a 4 cm by 6 cm area marked on each peel.

Thin Sections.--Petropoxy 154 epoxy was used to cement polished blanks to 50 mm by 75 mm glass slides and a Hillquist Thin Section Machine was used to prepare thin sections. Thin sections were examined to determine mineralogy and internal properties of the stromatolites.

X-Ray Diffraction.--Non-clay minerals in the stromatolite biostrome at Locality SB-15 were identified using random powder x-ray analysis (Appendix IV). Part of the sample crushed for insoluble residue analysis was sieved through a 230 mesh (4.0 ϕ) sieve and the -230 fraction x-rayed. Diffractometer settings were 1) 30 inches per hour chart speed, 2) 1 degree per minute scanning speed, 3) target, Ni, filtered Cu K alpha, 4) 1 degree divergent and antiscatter split, 5) 0.003 inch receiving slit, 6) kilovoltage setting at 35, 7) millamperage setting at 18, and 8) 2 seconds time constant. Samples were scanned from 0-62 degrees using a scale factor 1 K.

Insoluble Residue.--The procedure to obtain insoluble residues is a modification of the one used by Scott (1973). Approximately 50 grams of rock were crushed and dried. Part of this crushed sample was reserved for x-ray diffraction analysis. One gram of sample was weighed and placed in a weighed 150 ml beaker and covered with distilled water. Twenty-five milliliters of 1N HCl was added slowly. When the reaction ceased, more acid was added and allowed to stand for 24 hours. Residues were washed with distilled water and centrifuged to remove the acid, dried, and weighed. The percent insoluble residue was calculated to the nearest 0.1 percent.

Disaggregation.--Mudstones below and above the stromatolite horizon at Locality SB-15 were disaggregated to determine relative fossil diversity. Each sample was examined for megafossils, delicate specimens, and molds before it was disaggregated. A sample weighing approximately 400 grams was

prepared by 1) drying, 2) soaking in kerosene for 24 hours, 3) draining the kerosene and soaking in hot water for 24 hours, 4) washing the disaggregated sample through 10 mesh (-1.0 Ø) and 230 mesh (4.0 Ø) sieves with hot water, and 5) oven drying at 90°C. After drying, the residues were examined with a Bausch and Lomb stereozoom microscope.

GEOLOGIC SETTING

Structure

This area is east of the axis of the Forest City Basin (fig. 1) with the Nemaha Anticline to the west. The Redfield Anticline to the north and the Bourbon Arch to the south are associated minor structural features.

Stratigraphy

The Soldier Creek Shale is the middle member of the Bern Limestone (fig. 4) and can be traced from southwestern Iowa to northern Oklahoma (Condra, 1949). The stromatolite biostrome (Somphospongia multiformis) is part of the Soldier Creek Shale. The Wakarusa Limestone contains two or three limestones (the upper limestone is more persistent) separated by thin mudstones. Although not specifically stated, Owen's (1959) graphic sections place the contact between the Wakarusa and Soldier Creek at the base of the lower limestone (fig. 4). The lower contact of the Soldier Creek is placed at the top of the upper massive limestone in the Burlingame. The total thickness of the Soldier Creek ranges from 1.8 to 4.0 meters. Somphospongia multiformis was previously included as part of the Burlingame Limestone Member (Moore, 1935; Johnson, 1946; Zeller, 1968). Two thin (10-40 cm) limestones occur in the Soldier Creek, the upper one of which is the stromatolite biostrome (fig. 4).

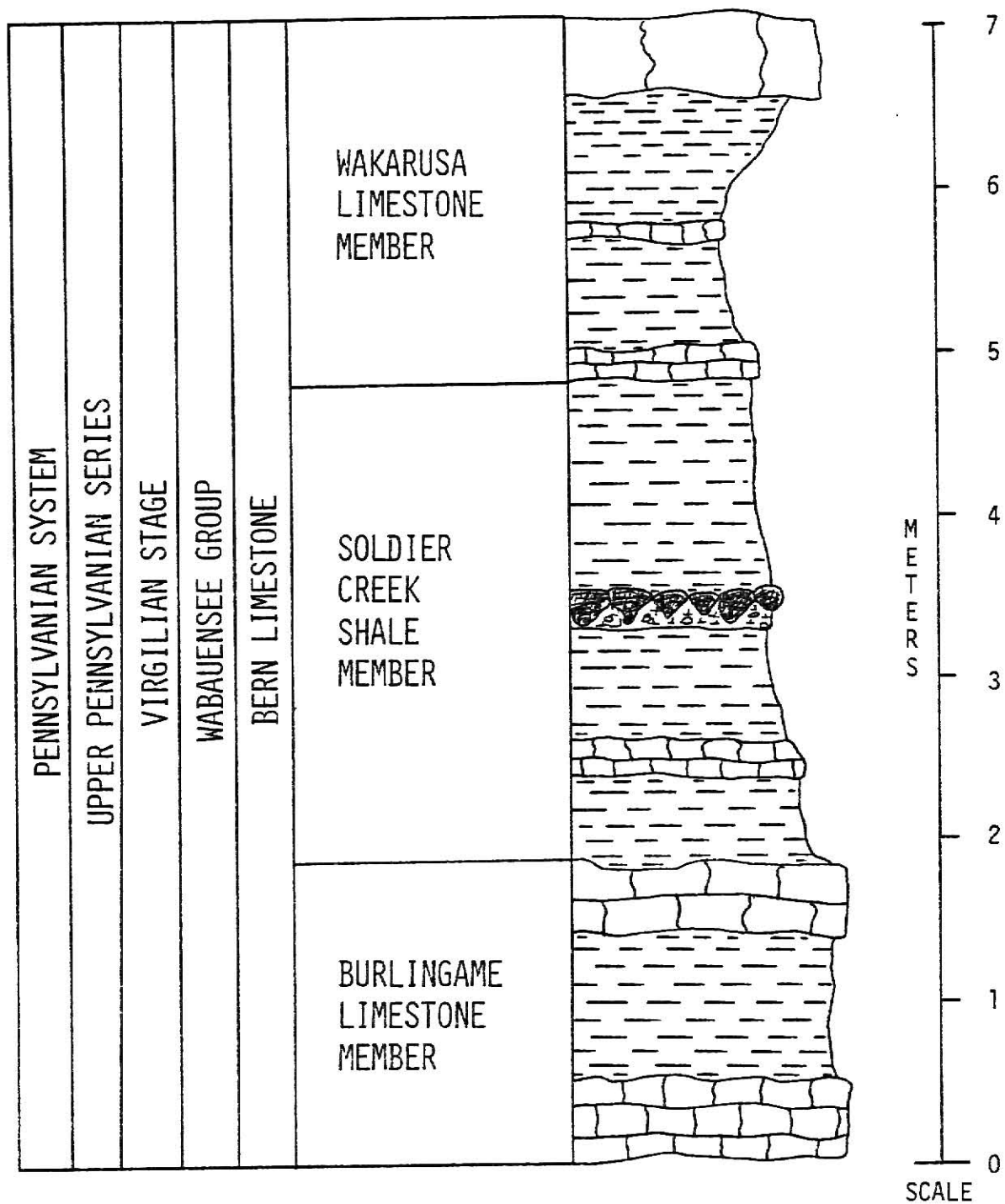


Figure 4. Generalized Stratigraphic Section of the Bern Limestone.

CLASSIFICATION AND DESCRIPTION OF STROMATOLITES

Classification

Stromatolite classifications are controversial and differ according to specific criteria used for each classification. In many examples, relating one classification to another is impracticable. Hofmann (1969) summarized seventeen classifications that have been used since stromatolites were first recognized as products of algal activity (Walcott, 1914). Krylov (1976) discussed twelve different approaches to stromatolite classification. Many classifications have been applied to Precambrian stromatolites which makes them unworkable when applied to Phanerozoic forms. Differences in gross morphology and internal structure make Precambrian and Phanerozoic stromatolite comparisons difficult.

Binomial "Linnéan" nomenclature was applied to fossil stromatolites when these structures were first interpreted as skeletal remains rather than organosedimentary structures. It later became apparent that stromatolites were not skeletal remains, nor were they strictly sedimentary structures, thus, the use of Linnean names became questionable. Cloud (1942) stated that the use of binomial nomenclature in naming stromatolites was not valid and so proposed a system of morphotypes that has never been widely accepted. Russian geologists have adopted binomial names that do not represent genera and species but rather identify "group" and "form" (Maslov, 1953) respectively, and treat them as palaeontologic taxa.

Johnson (1946, 1961), modifying Pia's (1927) classification, classified Somphospongia as follows:

Phylum Schizophyta (Falkenberg) Engler, 1892

"Section" Porostromata Pia, 1927

Class Cyanophyta

Family Spongiostroma

Genus Somphospongia Beede, 1899Species multiformis Beede

Logan et al. (1964) classified Holocene stromatolites on their geometric forms and related these forms to their sites of growth relative to sea level. This descriptive classification uses basic geometric units (hemispheroids and spheroids) and relates their stacking and lateral linkages in a structural formula. The classification of Logan et al. (1964) emphasizes synoptic morphology (Hofmann, 1969).

Following Logan et al. (1964), Somphospongia is classified according to three gross morphologies (Appendix I; oncolite, stromatolite, stromatolite biostrome) with different internal structure (Appendix I). The structural formula is written:

$$\begin{array}{ccccc} \text{SS-C} & & \text{SH-V} & & \text{LLH-C} \\ \hline \text{LLH-C} \longrightarrow \text{SH-C} & \longrightarrow & \text{SH-C} & \longrightarrow & \text{SH-C} \end{array}$$

This formula says that the concentrically stacked spheroids (SS-C), the oncolites, have an internal structure of close laterally linked hemispheroids (LLH-C) that pass ($\longrightarrow$) to stacked hemispheroids with constant basal radii (SH-C). The oncolite stage passes ($\longrightarrow$) to stacked hemispheroids with variable basal radii (SH-V), the stromatolite, which passes ($\longrightarrow$) to close laterally linked hemispheroids (LLH-C), the stromatolite biostrome, both of which have an internal structure of stacked hemispheroids with constant basal radii (SH-C) (fig. 5).

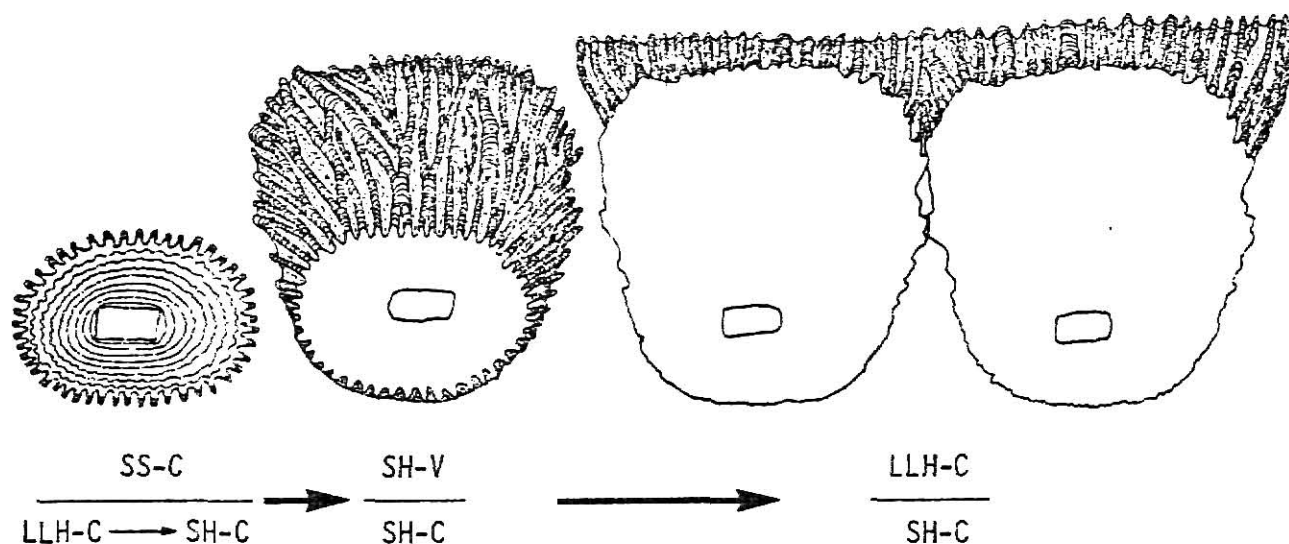


Figure 5. Diagrammatic Sketch of the Structural Formula for Soldier Creek Stromatolites Using Scheme of Logan et al., 1964.

Description

General Statement.--Soldier Creek stromatolites are compound structures that develop in three stages (fig. 6). The initial stage is oncolite growth. After stabilization of the oncolite algal growth on the upper surface creates a stromatolite. Stromatolites without an oncolitic stage have not been observed indicating that oncolites are essential to stromatolite development. Coalescence of crowded stromatolites form an almost continuous flat-topped biostrome in the final stage.

Gross Morphology.--Oncolites range from 1.0 to 7.0 cm in diameter (Appendix V) and approach a spherical shape (fig. 7, A and B). Oncolites

**THIS BOOK
CONTAINS SEVERAL
DOCUMENTS THAT
ARE OF POOR
QUALITY DUE TO
BEING A
PHOTOCOPY OF A
PHOTO.**

**THIS IS AS RECEIVED
FROM CUSTOMER.**

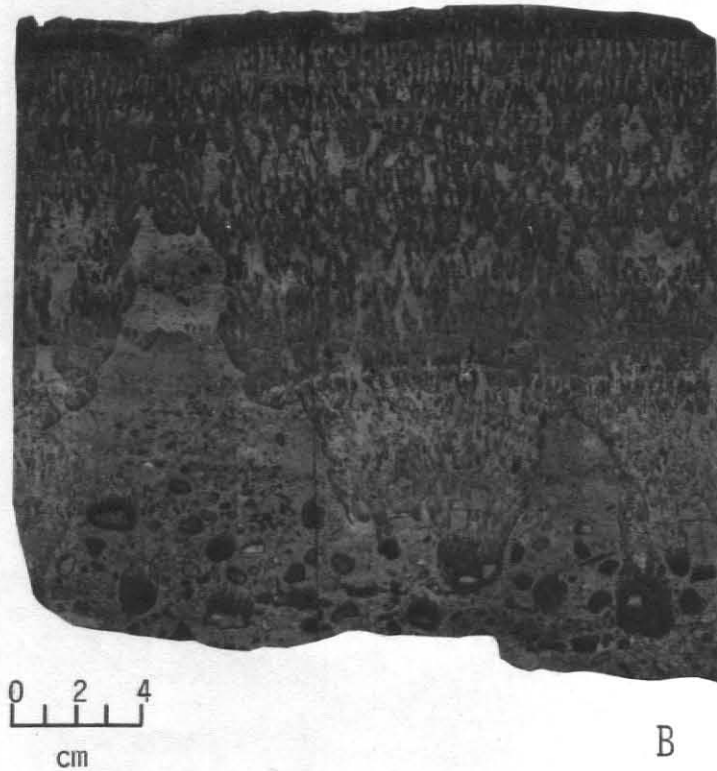
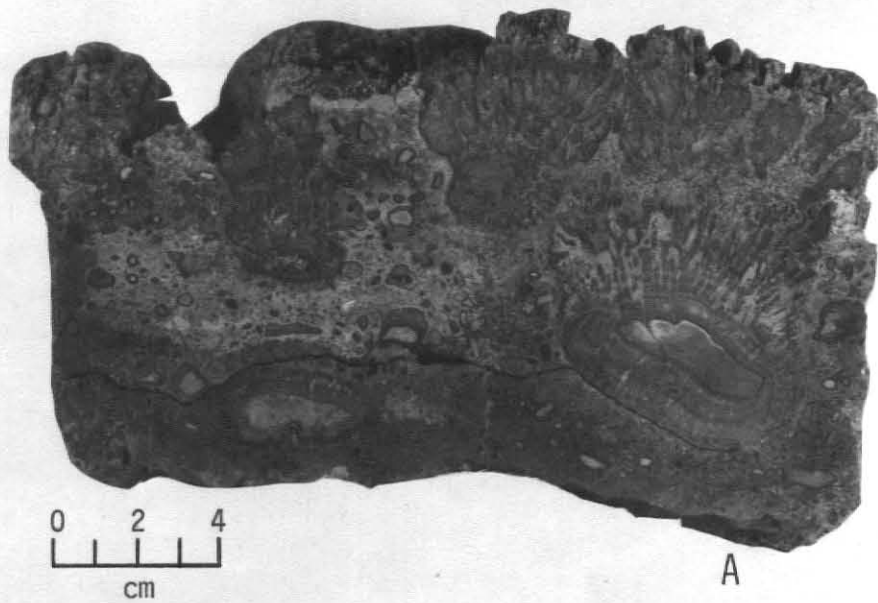


Figure 6. Stages of Stromatolite Growth. A. Oncolites and coalescing stromatolites, vertical slab, Locality SB-11. B. Oncolites, coalescing stromatolites, and continuous flat-topped stage, vertical slab, Locality SB-15, Section H.

that have stabilized to form stromatolites have an average diameter of 3.2 cm (Appendix V).

Discrete stromatolites (fig. 7, C and D) are cone-shaped (constricted at the base, expanded at the top) structures that are circular in plan. The structures are from 8 to 20 cm in diameter and have a height of 7 to 15 cm with domed tops and rounded edges. Surface texture (fig. 8A) is rough, crenulated, irregular, and reflects internal structure. Synoptic relief ranges from 0 to 6 cm. Coalescence of stromatolites develops as a result of upward expansion and crowding with growth. Confluence of discrete stromatolites initially forms laterally linked hemispheroids which may eventually decrease in relief to flat continuous tops (fig. 6B).

Internal Structure.--Oncolites consist of alternating light and dark laminated fabric (Appendix I), but boundaries between laminae are difficult to distinguish (fig. 8B). The light and dark laminated fabrics represent bands of spar and microspar. Average thickness of the light and dark laminae is 0.04 and 0.09 mm respectively. Combined laminae form a thickness that ranges from 0.3 to 7.0 mm before digitate growth begins. The laminae are initially smooth, taking the form of the object they encrust, and becoming undulatory before digitate growth starts. Initial algal growth encrusts a nucleus that is usually a fragment of argillaceous dismicrite, but vertebrate and invertebrate skeletal fragments may also serve as nuclei. The shape of the nucleus ranges from irregular to rectangular and ranges from 5 to 80 mm in diameter. Fossil microorganisms (Appendix I) were not recognized in the laminated fabric of oncolites.

When the oncolite reaches a size that is no longer easily "rolled" around, a transitional change from undulatory to pseudocolumnar laterally

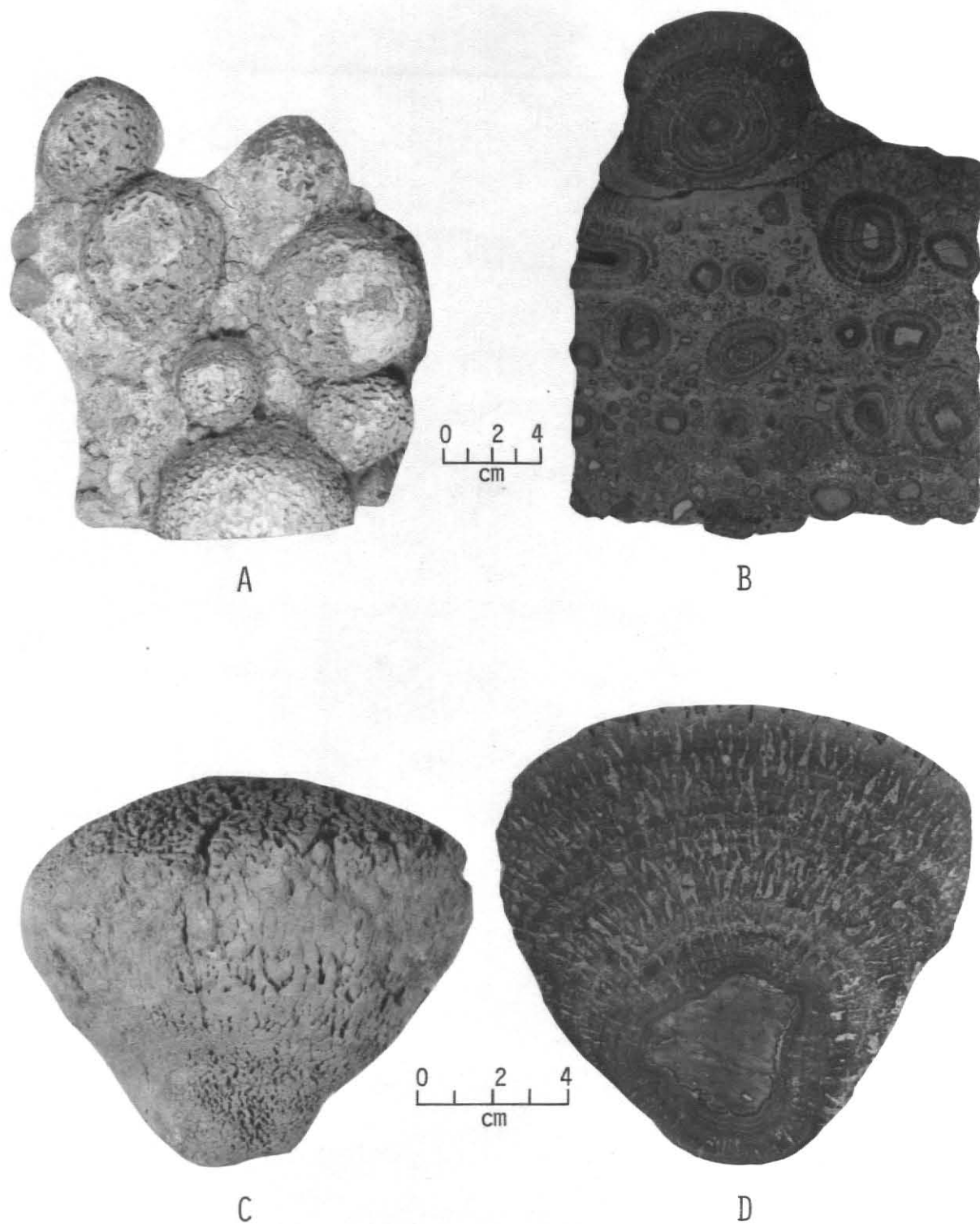


Figure 7. Oncolites and Stromatolites. A. Oncolites, top view, Locality SB-22. B. Oncolites, vertical slab, Locality SB-22. C. Stromatolite, lateral exterior view, Locality SB-22. D. Stromatolite, vertical slab, Locality SB-22.

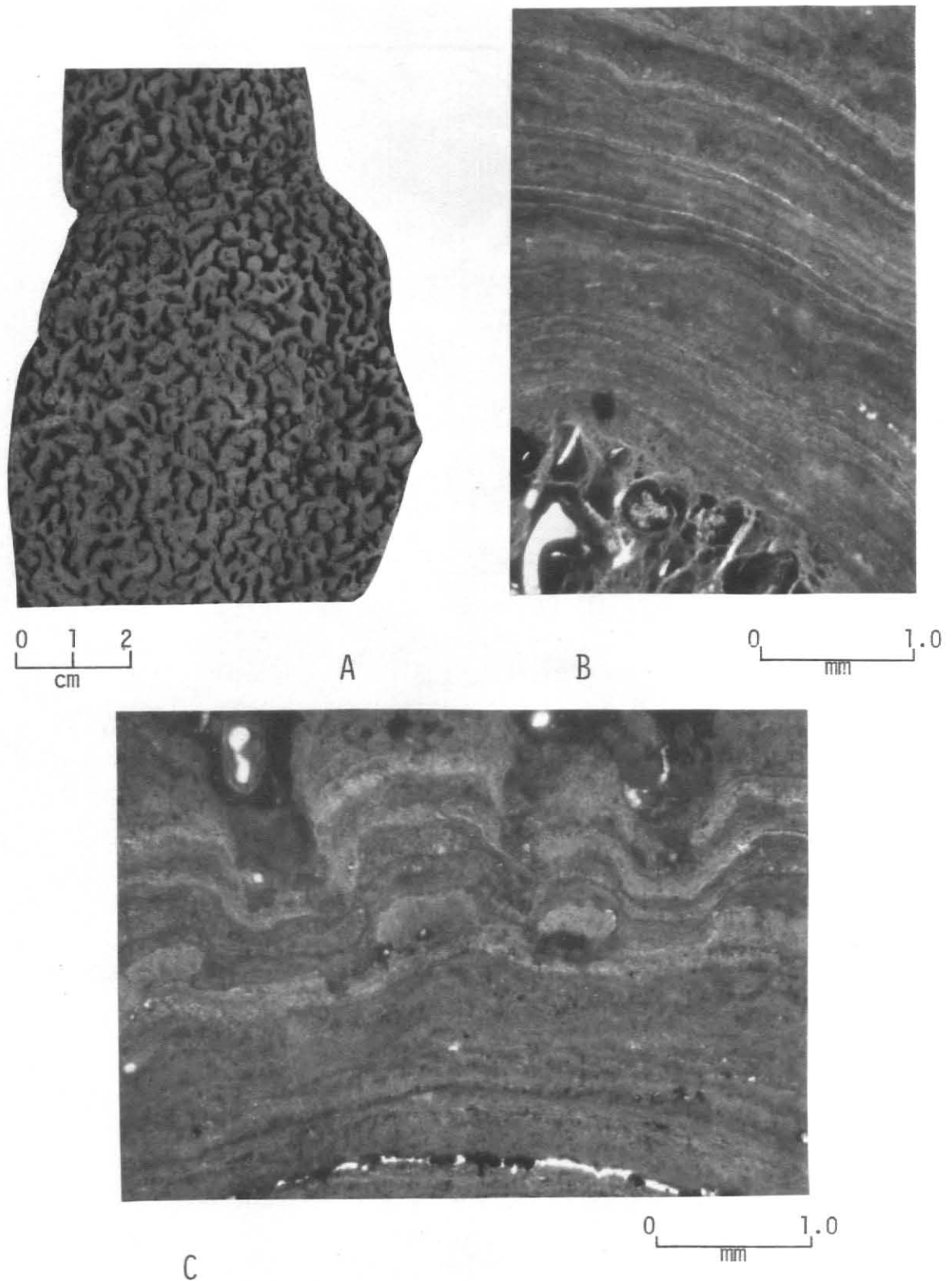


Figure 8. Surface Texture and Oncolite Laminae. A. Crenulated surface texture, top view, Locality SB-44. B. Initial concentric laminae around nucleus (nucleus in lower left corner), Locality SB-11. C. Undulatory to pseudocolumnar digitate development, Locality SB-11.

linked laminae to progressive upward growth of mammillary-shaped structures occurs (fig. 8C). These structures are the initial stage in the development of digitate branching. In vertical cross section, the elongate axes of the digits radiate outward normal to the concentric laminae of the oncolite (fig. 7D). In Hofmann's (1969) terms the style of branching is digitate and/or anastomosed with constricted variability. The digitate branches range in diameter from 1.0 to 4.2 mm with a synoptic relief of up to 5 mm. The digits in a section perpendicular to the elongate axis are lobate to sinuous (fig. 9A). As the synoptic relief of coalescing stromatolites approaches zero, digitate branches become erect and grow parallel to each other (fig. 6B). This final structure forms flat continuous surfaces. The interstitial spaces between branches (fig. 9, B and C) are filled with spar, clay-sized particles, sand-sized quartz, and small (0.66 mm) skeletal fragments. Terrigenous particles greater than 4 microns and skeletal grains are not found within the micritic digitate branches.

Continued growth of the digits was achieved by the superposition of successions of laminoid fabric (Appendix I). Laminations within the digitate branches are indistinct, but fenestrae and iron oxide stains outline the overall layering. Laminoid fabrics are wavy and rectangular to steeply convex. Digitate margins are smooth because the "laminae" bend over and envelope the lateral surface to form a wall. Concentrically arranged bands are not recognized in cross section. Fenestrae (Tebbutt et al., 1965) are recognized within the laminoid fabric (fig. 9 C), and according to Logan et al. (1974), develop as a result of interactions between algal mat, sediment, and diagenetic processes (mainly desiccation, oxidation, and lithification). Playford and Cockbain (1976) suggested that fenestral fabric in stromatolites

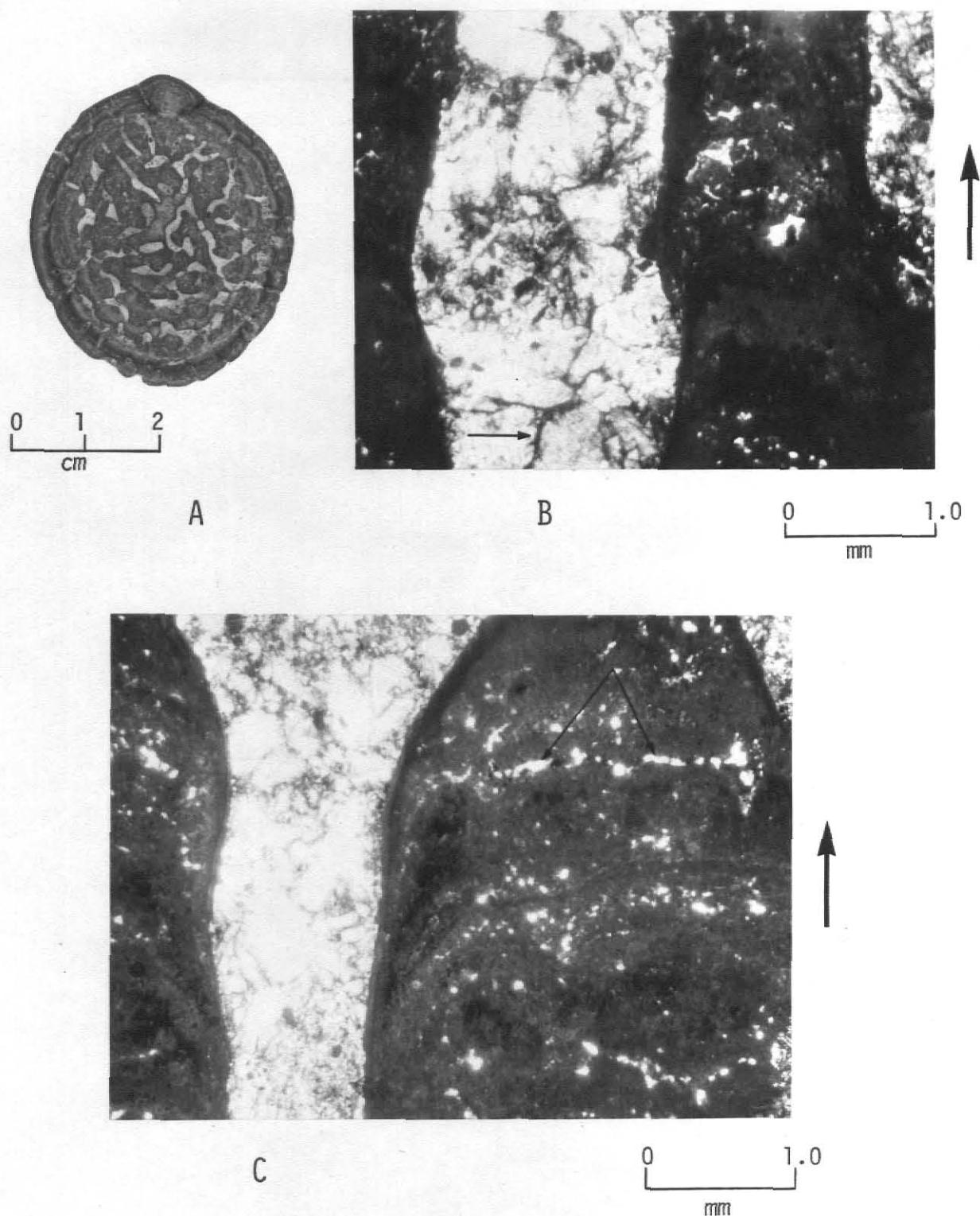


Figure 9. Internal Structure: Digitate Branches and Interstitial Areas. A. Sinuous outline of digits cut normal to their elongate axes, Locality SB-11. B. Photomicrograph of digits and interstitial areas. Clay (arrow) is forced to the edges of the spar mosaic in the interstitial areas. C. Fenestrae (arrow) in laminoid fabric of digits. B and C are from thin section cut parallel to elongate axes of digits, Locality SB-15, Section H.

at Hamelin Pool, Shark Bay, Western Australia, developed because of decomposition of enclosed algal debris.

Johnson (1946, p. 1105) described "laminae composed of fine branching algal threads" in Soldier Creek stromatolites he examined, however, they were not observed in this investigation.

BIOLOGY, MORPHOLOGY, AND DISTRIBUTION OF STROMATOLITES

General Statement

Stromatolites are biosedimentary structures produced by sediment-binding and/or carbonate-precipitation as a result of the growth and metabolic activity of microorganisms, mainly cyanophytes (Walter, 1976a). Microorganisms involved in the formation and preservation of Holocene stromatolites are cyanophytes, eucaryotic algae, photosynthetic bacteria, and various heterotrophic bacteria (Golubic, 1976b). Cyanophytes are the most significant group involved in the formation of stromatolites (Golubic, 1976b). Awramik et al. (1976) stated that

Cyanophytic diversity in extant mats commonly ranges from one or two to about eight dominant species (Golubic, 1973; Walter et al., 1973); however, as many as about 65 species have been found in some Recent mats from the Persian Gulf (Golubic, unpublished).

The gross morphology of the stromatolites results from the interaction of biological and physical controls.

Processes Involved in Stromatolite Construction

Trapping and binding loose sediment and calcium carbonate precipitation are two processes involved in the construction of stromatolites by non-skeletal

blue-green algae. Although both processes may interact to build stromatolites, one process is usually dominant (Riding, 1977). Golubic (1976a, 1976b) described modern microbial communities that build stromatolites and discussed the taxonomy of extant cyanophytes.

Particle laminations that build stromatolitic structures are a result of agglutination or trapping of sediment by mucilaginous blue-green algae (Gebelein, 1969). Ancient stromatolites that have been constructed by trapping and binding sediment are described by Hoffman (1967), Szulczewski (1967), Davis (1968), Horodyski (1975), Haslett (1976), Horodyski (1976), and Playford and Cockbain (1976). Holocene examples are described by Logan (1961), Logan et al. (1964), Monty (1967), Kendall and Skipwith (1968), Gebelein (1969), Walter et al. (1973), Logan et al. (1974), and Gebelein (1976a).

Direct or indirect precipitation of calcium carbonate is the result of metabolic activity of the microbiota (Hofmann, 1969). Removal of carbon dioxide and/or bicarbonate from the water by microorganisms causes the precipitation of calcium carbonate. Korolyuk (1963), Komar (1966), Krylov (1971), Horodyski (1975), Donaldson (1976), and Horodyski (1976) gave examples of ancient stromatolites formed by carbonate precipitation. Holocene examples of algal induced precipitation of calcium carbonate are documented by Carozzi (1962), Monty (1967), Horodyski and Vonder Haar (1975), and Halley (1976).

Morphology

Stromatolites are the product of the interaction between mat building organisms and the physical environment. Internal structure appears to be

biologically controlled (Monty, 1967; Hoffman et al., 1972; Golubic, 1973; Gebelein, 1974; Awramik et al., 1976; Hoffman, 1976), yet no relationship between the gross morphology and its internal structure has been demonstrated (Awramik et al., 1976). Some feel (Logan et al., 1964) that gross morphology is dominated by physical factors rather than biological factors. In reality, the interaction of physical and biological factors probably determines gross morphology (Awramik et al., 1976; Hoffman, 1976; Golubic, 1976a).

Distribution

The most important factors controlling distribution and morphology of Holocene subtidal and intertidal stromatolites are 1) grazing and burrowing metazoans that destroy or prevent stromatolite growth and 2) lithification rates that are not rapid enough to build stromatolitic structures (Gebelein, 1976a).

Diversification of grazing and burrowing metazoans probably caused the decline in stromatolite diversity through the Phanerozoic (Garrett, 1970). Distribution of stromatolites at Shark Bay, Western Australia, is controlled by burrowing and grazing metazoans with stromatolites growing where metazoans are controlled by hypersaline waters (Hoffman, 1976). Hypersaline water in Shark Bay is defined by Playford and Cockbain, 1976 as having salinities of 55-70 ‰. Shallow subtidal algal mats in Florida, the Bahamas, and Bermuda are restricted by grazers, burrowers, and sediment movement (Gebelein, 1976a).

Environments that favor organic or inorganic carbonate precipitation (hypersaline, brackish, or freshwater environments) are directly related to

conditions that reduce the affects of burrowing and grazing metazoans. Rapid cementation is important in stromatolite construction because it 1) reduces erosion, 2) reduces the effect of burrowers, and 3) allows the structures to support their bulk. Precipitated structures produced by blue-green algae suggest hypersaline, fresh, or brackish waters (Halley, 1976).

Gebelein (1976b) discussed why Phanerozoic stromatolites might be restricted to freshwater or hypersaline environments. Hypersaline environments are favorable because 1) some invertebrates are eliminated by abnormal salinity, and 2) cementation occurs because of algal induced precipitation. Freshwater conditions favor stromatolite growth because 1) the level of invertebrate activity is much lower in freshwater than in normal marine waters, and 2) the lack of a buffering system in freshwater allows carbonate precipitation by blue-green algae to occur more readily.

Holocene stromatolites are generally restricted to supratidal, intertidal, and shallow subtidal environments. Stromatolites most often occur in shallow marginal waters of marine basins and saline lakes (Wray, 1977). Playford and Cockbain (1969) have demonstrated that columnar stromatolites in Devonian fore-reef facies developed in water at least 45 m deep. Wray (1977) stated that

Algal stromatolites are most likely to have formed in low-latitude environments...not necessarily because of any ecological restriction of blue-green algal mats, but rather because marine, shallow-water, carbonate deposition predominates in these regions.

DETAILED ANALYSIS OF THE STROMATOLITE BIOSTROME
AND ITS RELATIONSHIP WITH
UNDERLYING AND OVERLYING LITHOLOGIES: LOCALITY SB-15

General Statement

The outcrop at Locality SB-15 is exposed at two sites (fig. 3). Eight measured sections within the western exposure (Sections A to H) and four within the eastern exposure (Sections I, I/2, J, and K) were examined. Sections A to H (fig. 10) provided 31 m of continuous horizontal outcrop that was sampled as in figure 11.

Carbonate classification and rock names are from Folk (1962). Size range of orthochemical constituents are: micrite, less than 4 microns; microspar, 4-10 microns; spar, 10 microns or more.

Stromatolite Biostrome

Lithology.--The stromatolite biostrome is divided into three lithologic units: 1) argillaceous dismicrite, 2) coated-grain biosparrudite, and 3) stromatolitic biolithite (fig. 12, A and B). Contacts between the biostrome and underlying and overlying mudstones are conformable.

Argillaceous Dismicrite.--This lithology is characteristically a dark yellowish orange (10YR6/6) argillaceous limestone with a grain to matrix ratio of less than 10 percent (visual estimate). Allochems (coated and uncoated skeletal fragments) comprise less than one percent except where "patches" contain up to 10 percent. Insoluble residues (Table 1) ranging from 21 to 26 percent are composed of angular quartz (0.07-0.10 mm), clay minerals, and secondary pyrite. Micrite, the original orthochemical constituent, has been replaced by very finely crystalline (2-12 microns) dolomite.

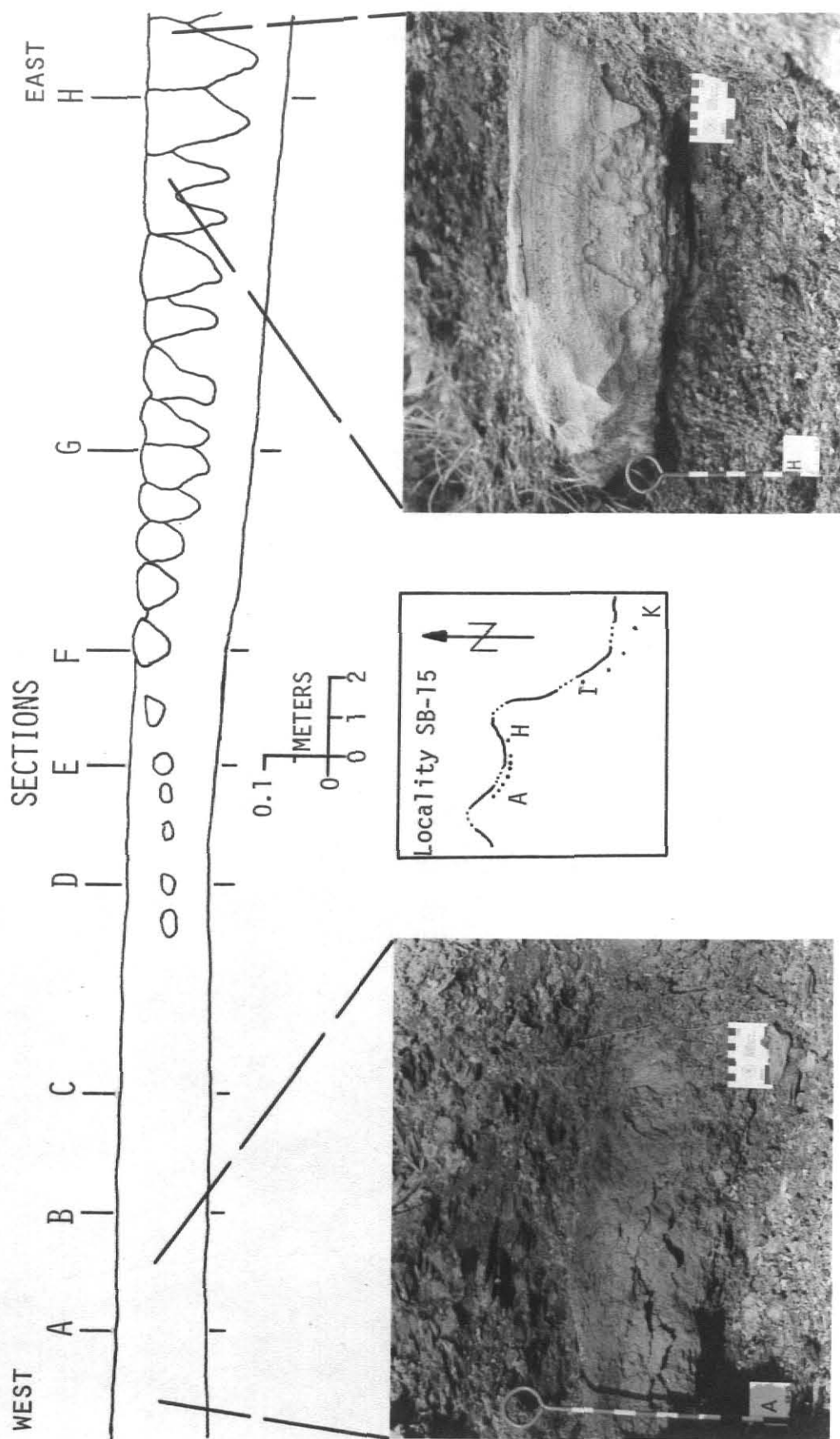


Figure 10. Outcrop at Locality SB-15, Sections A - H, West Exposure.

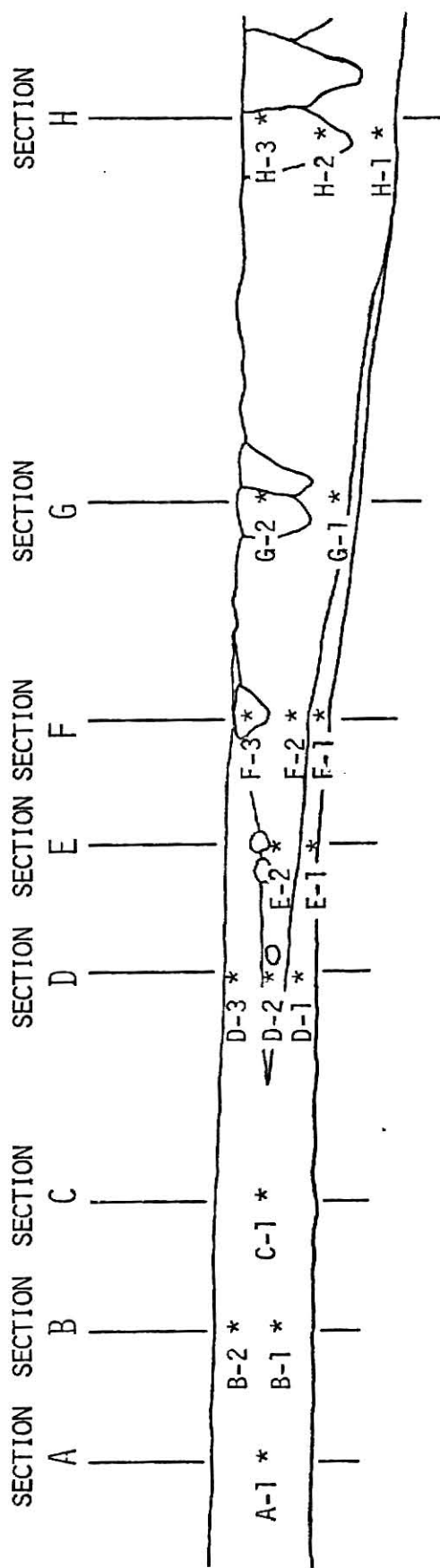
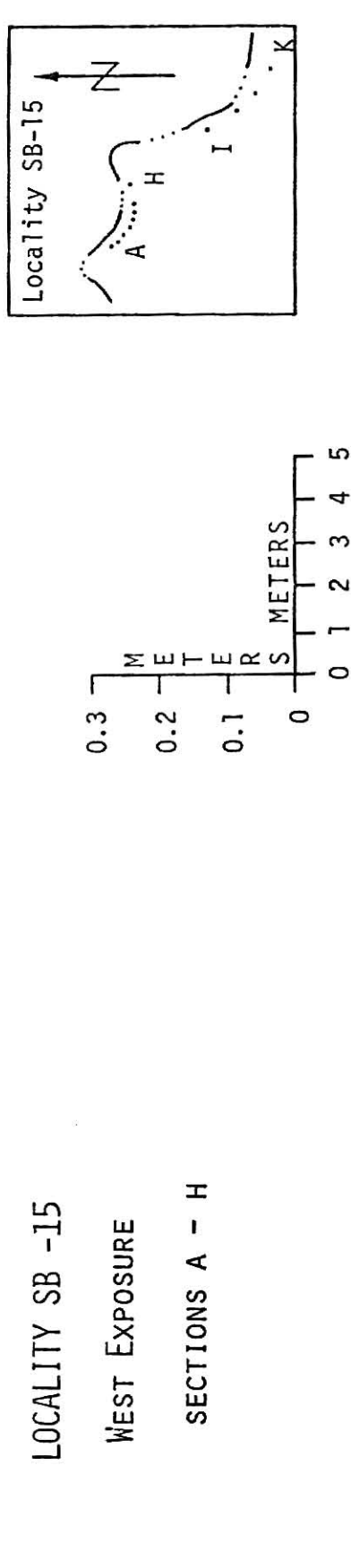


Figure 11. Location of Samples, Stromatolite Biostrome, Locality SB-15, Sections A - H.

Table 1

Average Grain Size and Insoluble Residues at Locality SB-15, Sections A-H

Sample Number	Average Grain Size (mm)	Insoluble Residue Weight Percent
Argillaceous Dismicrite		
A-1	0.66	25.9
B-1	-	26.3
B-2	-	20.5
C-1	0.67	-
D-1	-	24.6
D-3	-	22.6
F-1	-	22.4
$\bar{x} =$		0.665 mm
Coated-grain Biosparrudite		
D-1	1.45	13.9
F-2	1.38	12.2
H-1	0.97	12.1
$\bar{x} =$		1.27 mm
Stromatolitic Biolithite		
F-3	0.53	17.2
H-2	-	13.1
H-3	0.36	15.9
$\bar{x} =$		0.44 mm

Grain Size from Acetate Peels (100 grains per sample were measured)

Differential cementation of the argillaceous dismicrite has created "voids" that are filled with spar (fig. 12C). Spar filled "voids" constitute 50 percent of the rock (point count determination of 400 points). Clay minerals in the spar have been forced to the edges of the mosaic (fig. 12D) by crystal growth. Evidence of desiccation is not found in this lithology. Calcite-

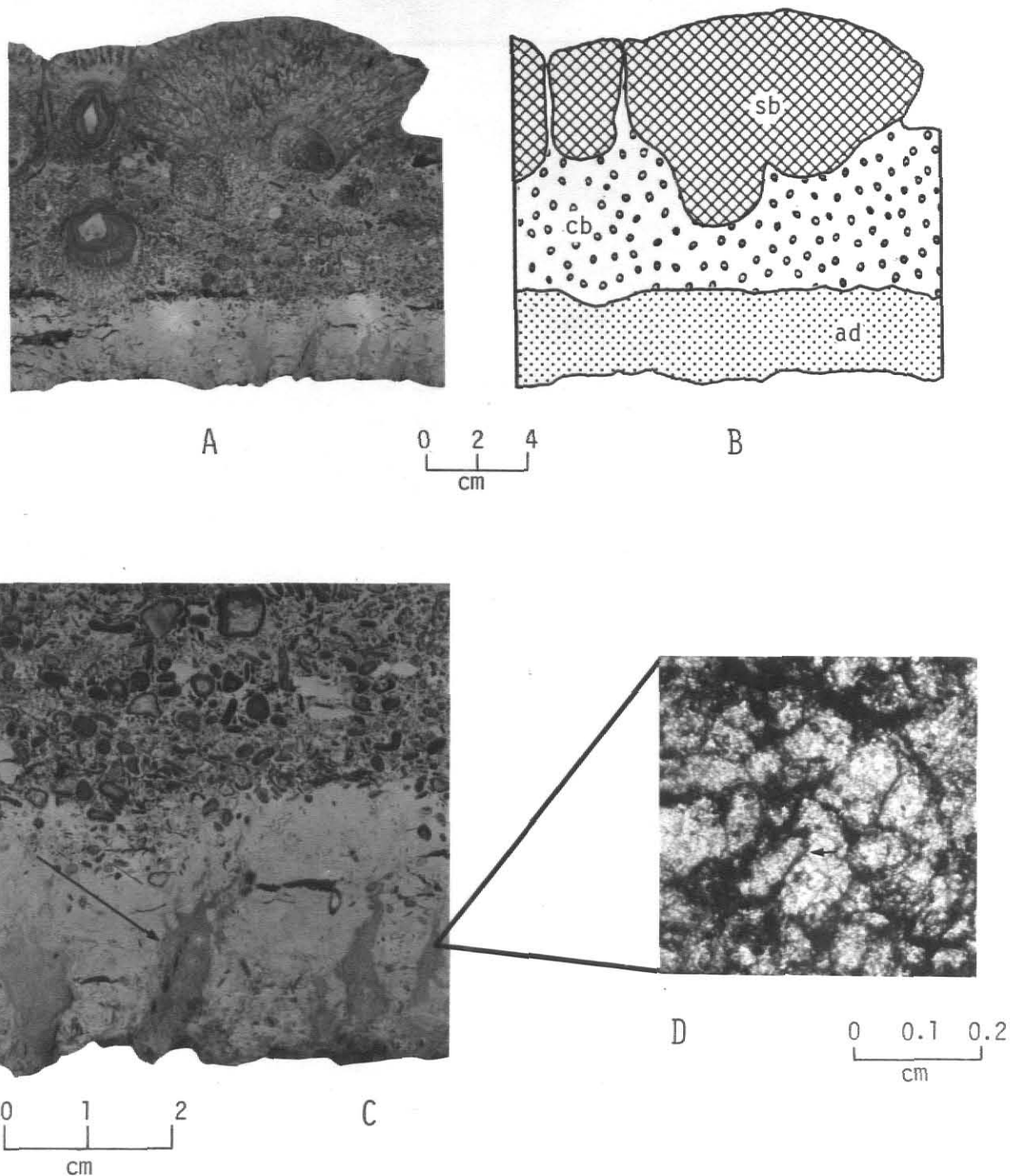


Figure 12. Lithologies of the Stromatolite Biostrome. A and B. Three lithologies at Locality SB-15, Section F: ad = argillaceous dismicrite; cb = coated-grain biosparrudite; sb = stromatolitic biolithite. C. Spar filled "voids" (arrow) in the argillaceous dismicrite, Locality SB-15, Section F. D. Clay minerals at edges of spar mosaic (arrow).

filled fractures in some samples cause this lithology to weather into a boxwork pattern (fig. 13A).

Coated-grain Biosparrudite.--Initial oncolitic growth and subsequently filled areas between stromatolites constitute this lithology. Allochems in this grain-supported rock are predominately coated-grains with nuclei of intraclasts of argillaceous dismicrite and skeletal fragments. Terrigenous components are angular quartz (0.07 mm) and clay minerals. Pyrite occurs as a secondary mineral. Average grain size (Table 1) of the coated-grain biosparrudite is 1.27 mm. Insoluble residues of quartz, clay minerals, and secondary pyrite range from 12 to 14 percent. Spar that fills voids created by loosely packed grains is being replaced by dolomite (fig. 13B). Dessication in this lithology occurs in two isolated samples as 1) desiccated coated-grains near the contact between the argillaceous dismicrite and coated-grain biosparrudite at Section F, and 2) desiccation of argillaceous dismicrite clasts within the coated-grain biosparrudite at Section D (fig. 13, C and D). These clasts have V-shaped vertical cracks that are filled with sand-sized quartz and skeletal grains.

Stromatolitic Biolithite.--Calcareous digits of algal construction and their interstitial spaces comprise the stromatolite. The ratio of digits to interstitial space is 1.5:1 (point count determination of 400 points). Digitate branches are micrite and fenestrae are filled with microspar. Allochemical grains in the interstitial spaces average 0.44mm (Table 1) in size. Terrigenous components are angular quartz (0.04 mm) and clay minerals. The orthochemical component of the interstitial spaces is spar that is being replaced by dolomite (similar to fig. 13B). Clay minerals in the spar have been forced to the edges of the mosaic (fig. 9B) as in the

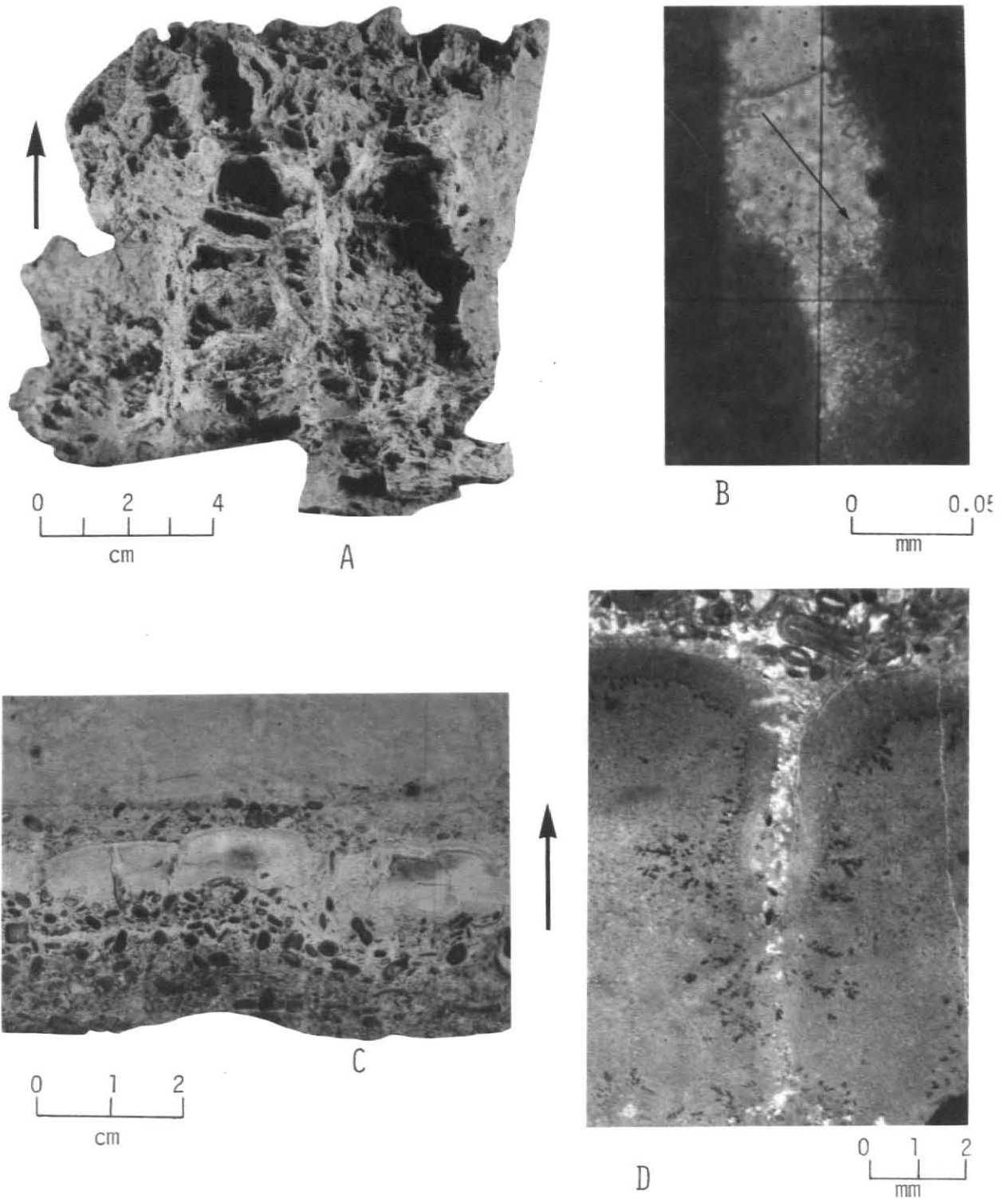


Figure 13. Boxwork Pattern, Dolomite Replacement of Calcite, and Desiccation. A. Boxwork pattern in the argillaceous dismicrite is a result of calcite-filled fractures (Locality SB-47). B. Dolomite replacing spar in coated-grain biosparrudite (arrow points to dolomite rhomb) at Locality SB-15, Section F. C and D. Desiccation of argillaceous dismicrite clasts within the coated-grain biosparrudite at Locality SB-15, Section D.

argillaceous dismicrite. Insoluble residues of the stromatolitic biolithite range from 13 to 17 percent and contain angular quartz, secondary pyrite, and clay minerals.

Biotic Components.--The fossil assemblage of the stromatolite biostrome has been compiled from all three lithologies, however, most fossils occur in the coated-grain biosparrudite (Appendix VI). Bivalves (Phestia bellistriata, ?Permophorus, Aviculopecten, and small (5 mm) unidentifiable bivalves), brachiopods (Crurithyris, Neochonetes, and an unidentifiable punctate brachiopod), and vertebrate skeletal debris dominate this assemblage (Tables 2, 3, and 4). The vertebrate assemblage in the stromatolite

Table 2
Biotic Components of the Argillaceous Dismicrite

Taxa	Percent of Total Skeletal Components						
	A-1	B-1	C-1	D-1	D-3	E-1	F-1
Mollusca							
Bivalve, fragment	50.0	57.1	50.0	100.0	14.3	66.7	25.6
Brachiopoda							
Impunctate, fragment	16.6	42.9	50.0			16.7	46.5
Bryozoa							
Unidentifiable							9.3
Arthropoda							
Trilobite							18.6
Vertebrata							
Debris	33.3				85.7	16.7	
Total Percent	99.9	100.0	100.0	100.0	100.0	100.1	100.0
Number of Specimens	6	7	4	2	7	6	43

Data from Appendix VI

Table 3
Biotic Components of the Coated-grain Biosparrudite

Taxa	Percent of Total Skeletal Components				
	D-2	E-2	F-2	G-1	H-1
Mollusca					
Bivalve, fragment	44.3	40.0	32.1	39.8	25.0
Bivalve, whole			2.7		6.3
Planispiral gastropods			0.5		3.1
High spired gastropods				0.5	1.0
Unidentifiable gastropods	1.3	4.2	4.9	2.0	6.3
Brachiopoda					
Impunctate, fragment	31.6	24.8	14.7	24.0	10.4
Impunctate, whole			1.1		1.0
Pseudopunctate, fragment			1.6	3.6	7.3
Punctate, fragment				0.5	
Bryozoa					
Ramose	3.8	4.8	1.1	2.0	3.1
Unidentifiable			3.3		
Echinodermata					
Crinoid	1.3	1.2	0.5	0.5	3.1
Echinoid		1.2	1.6	0.5	
Unidentifiable	2.5	5.5	2.7		
Arthropoda					
Trilobite	6.3	7.3	10.9	11.7	3.1
Ostracode			0.5		2.1
Vertebrata					
Debris	8.9	10.9	21.7	14.8	28.1
Total Percent	100.0	99.9	99.9	99.9	99.9
Number of Specimens	79	165	184	196	96

Data from Appendix VI

Table 4
Biotic Components of the Stromatolitic Biolithite

Taxa	Percent of Total Skeletal Components		
	F-3	G-2	H-2
Mollusca			
Bivalve, fragment	19.7	13.9	51.8
Bivalve, whole		1.3	
Planispiral gastropods	1.6		
High spired gastropods	1.6		
Unidentifiable gastropods	9.8	7.6	3.6
Brachiopoda			
Impunctate, fragment	13.1	12.7	3.6
Impunctate, whole			
Pseudopunctate, fragment		3.8	5.4
Punctate, fragment		1.3	
Bryozoa			
Ramosa			5.4
Unidentifiable	6.6		
Echinodermata			
Crinoid	1.6	5.1	1.8
Echinoid		3.8	
Unidentifiable	8.2		
Arthropoda			
Trilobite	3.3	5.1	
Ostracode	1.6	1.3	
Vertebrata			
Debris	32.8	44.3	28.6
Total Percent	99.9	100.2	100.2
Number of Specimens	61	79	56

Data from Appendix VI

biostrume has been identified by Chorn & Conley (1977) and Chorn (1977, per. comm.). Vertebrates include fish (Acanthodes, a paleoniscoid, and a coelacanth), sharks (Cladodus, Xenacanthus, Hybodus, and Petalodus; Petalodus is classified Elasmobranchii Incertae Sedis), lungfish (Sagenodus and Gnathorhiza), amphibians (Isodectes, a labyrinthodont, and a lepospongy), and a reptile (pelycosaur?). Gastropods include Euphemites, Glabrocingulum (?Ananias), Straparollus (?Amphiscapha), ?Trepostira, ?Euconospira, and small (1 mm) unidentifiable gastropods. Crinoids, echinoids, bryozoans, trilobites, ostracodes, corals, and charcoal also occur.

This assemblage is classified as an exotic fossil assemblage (Craig and Hallam, 1963) because it is derived from different, but contemporaneous environments. Marine, terrestrial, and freshwater habitats are represented in this mixed assemblage (Table 5). According to Johnson (1960), this would be a model III assemblage based on 1) ecologically noncoherent organisms, 2) high disassociation of articulated organisms, 3) high breakage (low proportion of single whole valves and high proportion of fragments), 4) high abrasion, 5) homogenous size and shape, and 6) exposure time that allows grains to become coated.

Table 5
Stromatolite Biostrome Fossil Assemblage, Locality SB-15

Taxa	Probable Environment of Origin	Percent Articulated	Percent Fragments	Percent Coated	Number of Specimens Counted
Bivalves	marine or ?brackish	0.3	96.6	75.4	353
Gastropods	marine or ?brackish	-	83.7	32.7	49
Brachiopods					
Impunctate	marine	0.5	98.5	73.5	200
Pseudopunctate	marine	0.0	100.0	82.6	23
Punctate	marine	0.0	100.0	100.0	2
Bryozoans	marine	-	100.0	83.8	37
Echinoderms	marine	0.0	100.0	84.1	44
Arthropods	marine	0.0	100.0	76.8	82
Vertebrates	freshwater	0.0	-	22.4	201
Plants	terrestrial	-	-	-	1

Data from Appendix VI

Depositional Environment.--The stromatolite biostrome was deposited in a transgressive-progradational sequence near the wave "break" zone in low intertidal or shallow subtidal waters. The stromatolites possibly inhabited a shallow lagoon or embayment that was connected to normal marine environments, but influenced by a freshwater source.

Depositional Sequence.--Lithologies at Sections A to H represent a transgressing-prograding vertical sequence of sedimentation. The west end (Section A) and east end (Section H) represent respectively, nearshore and offshore directions of stromatolite morphologies and sedimentation. Figure 14 is a diagrammatic reconstruction of the stromatolite biostrome at

Locality SB-15, Sections A to H. The sequence of deposition is interpreted as follows. Initially, the coated-grain biostromalite was deposited in the offshore with contemporaneous nearshore deposition of the argillaceous dismicrite. Transgression of the biostromalite shoreward caused the argillaceous dismicrite to "pinch-out" in the offshore direction. As transgression continued, oncolitic growth occurred at the offshore end. The initial oncolites became stabilized and stromatolites formed as the oncolite producing environment migrated shoreward over the biostromalite. Maximum transgression occurred when the active oncolitic zone had migrated to Section E. Near the upper part of the biostrome the argillaceous dismicrite overlaps the stromatolite biolithite as a prograding wedge. Progradation of the argillaceous dismicrite near the top of the stromatolitic biolithite may be explained by the landward movement of carbonate mud environments as suggested in depositional models proposed by Ginsburg (1971), Lucia (1972), and Matti and McKee (1976). Carbonate mud is produced offshore by 1) precipitation and 2) disintegration of organic skeletons (Ginsburg, 1971). This mud is moved shoreward by tidal currents, storms, and wind-driven circulation and "trapped" on shallow-water carbonate flats. Continued carbonate production will result in seaward progradation if the rate of accumulation is greater than the rate of relative sea-level rise (Lucia, 1972) and subsidence does not exceed production (Matti and McKee, 1976). Progradation was halted by the sudden deposition of the overlying mudstone (terrigenous "drowning"). Rapid burial is suggested by a non-erosional contact and a continuous iron oxide (oxidized pyrite) zone on top of the stromatolitic biolithite. The original pyrite was probably a result of algal decomposition.

Depositional Gradient.--Relatively sudden appearance and rapid increase in stromatolite thickness suggests an increase in bottom gradient. The slope upon which the stromatolites built themselves can be roughly estimated by calculating changes in thickness at Sections F, G, and H and equals 7 mm per meter, decreasing in an offshore direction. This slope estimation is not accurate, but it does suggest a relatively sudden change in gradient. The depositional gradient for the argillaceous dismicrite could not be calculated, but its uniform thickness suggests deposition on a nearly horizontal surface.

Energy.--Relative energy and energy distributions are a direct result of change in gradient. Figure 15 is a summary of relative energy at Locality SB-15. The highest energies correspond to the change in gradient which produces a "break" zone for waves. Low energy in the nearshore direction is indicated by micrite, clay, and the low percentage of allochems. In the offshore direction, energies take a moderate position between high in the "break" zone and low over the mud flat. Spar, intraclasts, quartz sand, and large grain size support a higher energy interpretation. Oncolites also provide a relative estimate of turbulence of the environment. Concentrically laminated oncolites are restricted to areas that are continually under water and highly agitated (Ginsburg, 1960; Logan et al., 1974). Occasional extreme or storm generated energies are reflected in the movement of stabilized oncolites, production of intraclasts, and the occurrence of coated-grains in the argillaceous dismicrite. Movement of temporarily stabilized oncolites occurs from time to time as suggested by oncolites with asymmetrical digitate growth that are upside down in the coated-grain biosparrudite. Intraclasts of argillaceous dismicrite occur as coated-

← NEARSHORE		OFFSHORE →	
RELATIVE ENERGY	LOW	HIGH ("break" zone)	MODERATE
GRAIN SIZE	less than 4 microns	Average 1.45mm	Average 0.36mm
	coated-grains and skeletal fragments	intraclasts and stable oncolites moved	
STABILIZED ONCOLITES	DECREASE	30.0mm	23.8mm
GRADIENT	nearly horizontal	48.6mm	14.6mm
		7 m/km	
ORTHOCHEMS	micrite	spar, intraclasts	
ALLOCHEMS	vertebrate skeletal debris	coated-grains, marine invertebrates, freshwater vertebrates	
TERRIGENOUS	clay	quartz sand	
INSOLUBLE RESIDUE	26%	14%	12%

Synoptic Profile at Maximum Transgression

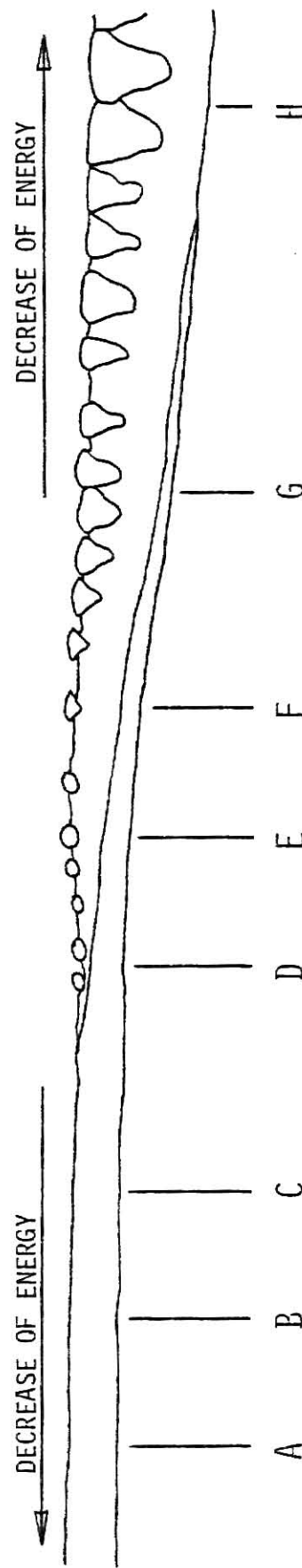


Figure 15. Diagrammatic Summary of Environmental Interpretations, Locality SB-15, Sections A - H.

grains in the coated-grain biosparrudite. Storm related energies would probably be required to rip-up these intraclasts. Isolated "patches" of coated and skeletal grains in the argillaceous dismicrite may also be the result of storms. Energy distributions corresponding to tidal position have been determined by Logan (1961) and Gebelein (1969) for Holocene occurrences and by Peryt and Piatkowski (1977) for a Permian example. The interpretation of energy distributions for the Soldier Creek stromatolite biostrome is compatible with those reported by Logan (1961), Gebelein (1969), and Peryt and Piatkowski (1977).

Tidal Position.--A low intertidal to shallow subtidal environmental interpretation is based on 1) the requirements of concentrically laminated oncolites, and 2) isolated incidents of desiccation. A subtidal environment is necessary for the formation of concentrically laminated oncolites (Ginsburg, 1960; Logan et al., 1964). The spherical shape, concentric laminations, and lack of desiccation cracks suggests that oncolitic growth occurred in a high energy underwater environment.

Evidence of desiccation is too rare to suggest that this area was subaerially exposed at frequent intervals. Minor evidence of desiccation (Sections E and F) does, however, place the stromatolites in a position that could have occasionally been subaerially exposed.

Salinity.--Lack of terrigenous laminae indicates algal-induced precipitation of calcium carbonate was responsible for stromatolite construction. Although precipitation may have been the dominate process involved in digitate construction, these features may have been the result of trapping and binding of carbonate mud. Fresh, brackish, or hypersaline waters provide favorable conditions for such precipitation (Gebelein, 1976b; Golubic, 1973). The

salinity of the water during deposition of the stromatolite biostrome is interpreted as brackish. Precipitation of calcium carbonate is favored in other than normal (35 ‰) marine salinities and the freshwater vertebrate assemblage suggests a fluvial influence that would produce brackish conditions.

Invertebrate Assemblage.--The transported invertebrate assemblage of the stromatolite biostrome suggests a shoreward position. Bellerophontacean and pleurotomariacean gastropods may have grazed on algae (Knight, 1960), but they seemingly were not detrimental to algal growth. Most of the invertebrate fossil assemblage was probably derived from an offshore normal marine environment and transported shoreward. Invertebrates such as crinoids, trilobites, corals, and bryozoans suggest an association with normal marine water.

Vertebrate Assemblage.--Vertebrate fossils are significant to the interpretation because of their preservation, abundance, and freshwater origin. The vertebrate assemblage is almost entirely of freshwater origin (Chorn and Conley, 1977). Baird (1966) also stated that freshwater habitats were characteristic of vertebrates in this assemblage. Although practically all bones are disarticulated (except skull plates and jaw bones), the rapid encrustation by algae and protection from compaction has preserved delicate bone specimens. Large bones are common and vertebrate skeletal debris makes up 20.3 percent of all skeletal grains (Appendix VI).

The postulated freshwater origin of these vertebrates raises a question as to their proximity and/or association with the stromatolites. Abundance, lack of abrasion, and minimum breakage suggests these animals were transported a relatively short distance from their habitat (lake or stream?). Fresh water must have entered the sea relatively close to the stromatolite occurrence making the water within which the stromatolites grew slightly

brackish. The irregular distribution and relief of the stromatolites may have provided an unusual "trap" that stranded floating vertebrate carcasses.

Lateral Changes in Biostromal Development.--Sections I, I/2, J, and K (fig. 3) fit into the sequence described for Sections A to H (Section I = Section H; Section I/2 = between C and D; Section J = between Sections F and G; Section K = between Sections E and F). Figure 16 demonstrates the irregularity of stromatolite distribution within this small geographic area. The biostromes dependence upon specific environmental conditions (gradient, tidal position, energy distribution) permits it to develop only where these conditions occur. Rapid lateral as well as some vertical changes are apparently characteristic of this biostrome.

Underlying and Overlying Lithologies

General Statement.--Olive gray, silty calcareous mudstones underlie and overlie the stromatolite biostrome at Locality SB-15. Contacts between the mudstones and stromatolites are conformable. Samples were collected 1) 5 cm above and below the biostrome at Sections A to K, and 2) vertically every 0.5 m at Sections B, G, and J (fig. 17). Laterally, these samples are lithologically and palaeobiologically consistent with each other.

Biotic Components.--Relative organism diversity (fig. 17) is higher in the mudstone below the stromatolite biostrome than it is in the upper mudstone. Brachiopods (Crurithyris, Punctospirifer, Derbyia, productaceans, chonetids, and ?Dielasma), bivalves (myalinids, permophorids, ?Phestia, ?Aviculopecten, and unidentifiable bivalves), gastropods (Worthenia, ?Glabrocingulum, ?Trepospira, bellerophontids, and several small 1 mm unidentifiable gastropods), bryozoans (ramose and fenestrate), ostracodes

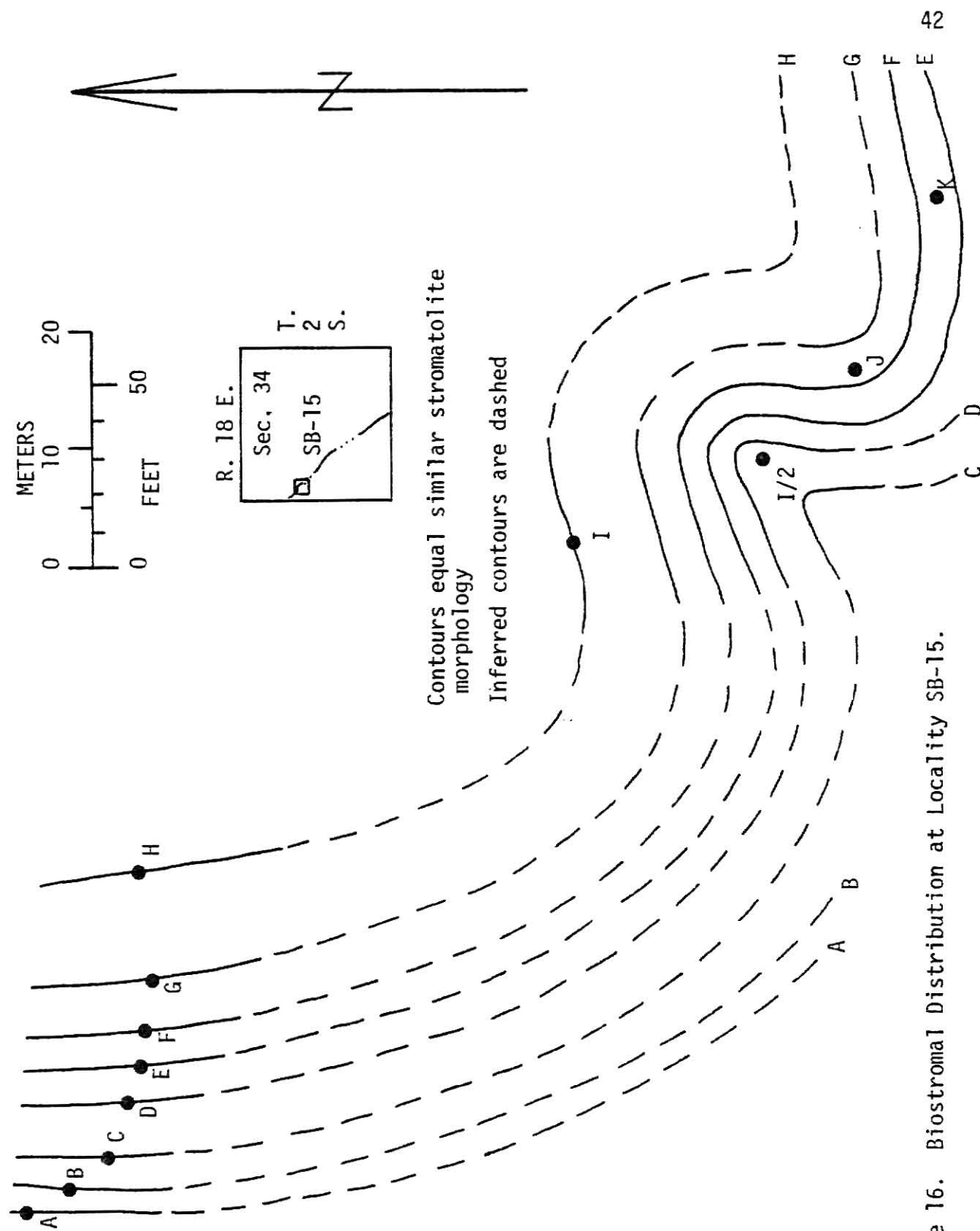


Figure 16. Biostromal Distribution at Locality SB-15.

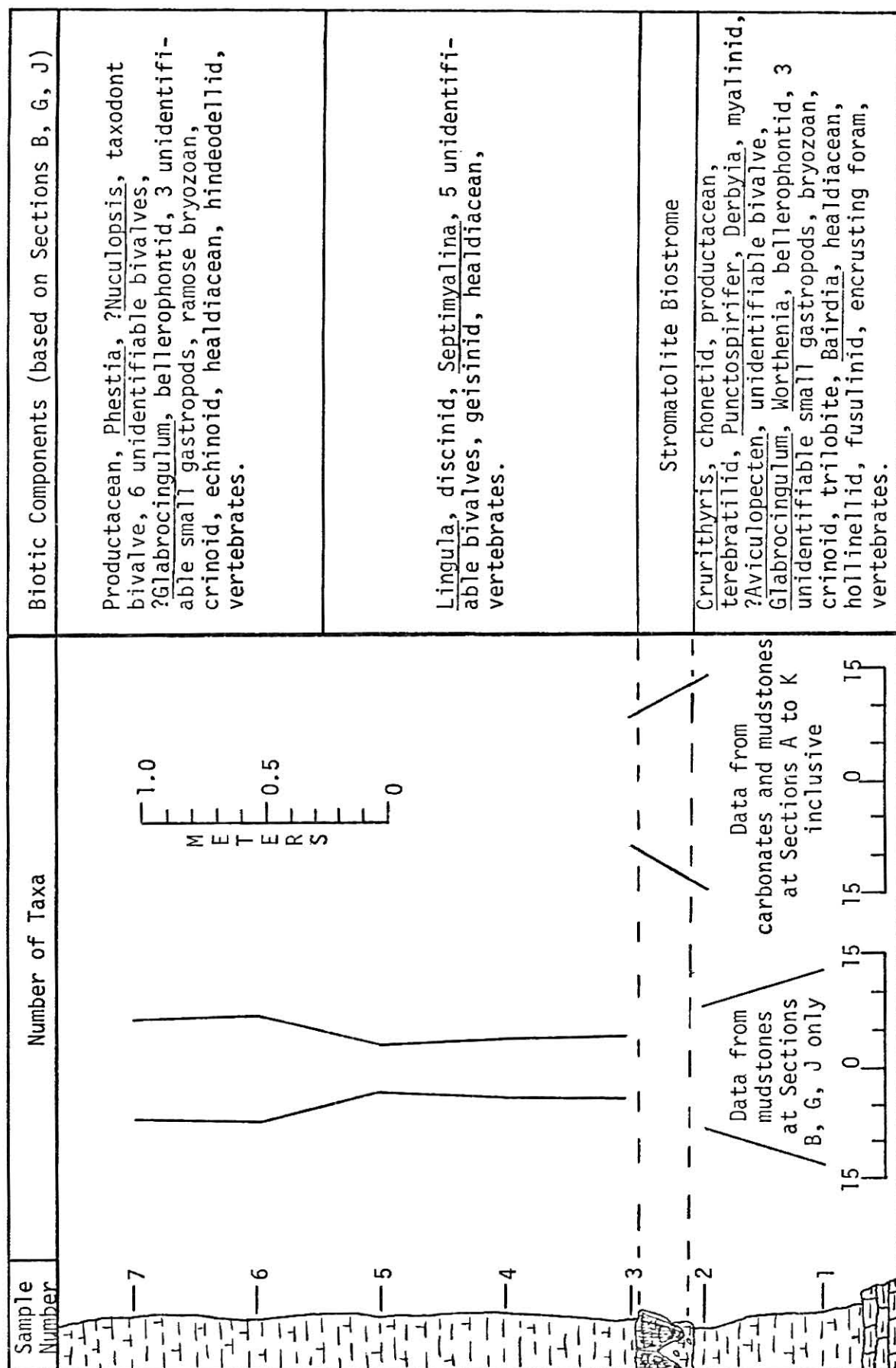


Figure 17. Relative Diversity, Locality SB-15.

(Carbonate data from Appendix VI)
(Mudstone data from Appendix VII)

(Bairdia, hollinellids, healdiaceans), a hindeodellid conodont, trilobites, crinoids, echnoids, encrusting foraminifers, a fusulinid, and vertebrate skeletal debris occur in the underlying mudstone. In the mudstone above the stromatolite biostrome brachiopods (Lingula and discinids), bivalves (myalinids, unidentifiable bivalves), ostracodes (geisinids, healdiaceans), and vertebrate skeletal debris are the common biotic components.

The fossil assemblages in the mudstone represent model I or model II assemblages as defined by Johnson (1960). Criteria for this interpretation are 1) ecologically coherent organisms, 2) most specimens are articulated, 3) high proportion of whole valves, low proportion of fragments, 4) low abrasion (delicate shells preserved), and 5) heterogenous size and shape. Although quantitative data were not collected, impressions of these factors were obtained from sample examination before disaggregation.

Depositional Environment.--The mudstone below the stromatolite biostrome was deposited in normal marine offshore waters. Brackish salinities are postulated for the mudstone above the stromatolites. Based on types of fossils and relative diversity the vertical section represents a transition from normal marine environment upward to brackish environments.

Invertebrates found in samples 1 and 2 (fig. 17) suggest an offshore marine environment. Moore (1964, p. 308) interpreted corals, bryozoans, some brachiopods, crinoid skeletal remains, gastropods, bivalves, and possibly fusulinids as typical marine invertebrates belonging to an offshore association. More specifically he named Derbyia, Myalina or Septimyalina, and Aviculopecten as members of this association. Fossil assemblages in samples 1 and 2 contain bryozoans, crinoid skeletal remains,

gastropods, bivalves, a fusulinid, Derbyia, a myalinid, and ?Aviculopecten. Corals are absent from these assemblages. Highest relative diversities, expected of normal marine environments (Gunter, 1947), also occur in samples 1 and 2.

Mudstones above the stromatolite biostrome (samples 3, 4, 5) seem to represent deposition in a brackish environment. Lingula and discinid brachiopods, along with fresh to brackish water geisinid ostracodes (the only ostracode in sample 5), represent part of a brackish water association (Moore, 1964; Lane, 1964). Normal marine organisms are absent from this interval and it has the lowest relative diversity (fig. 17).

The stromatolite biostrome has a relative diversity intermediate between the mudstones above and below (fig. 17, Sections A to K) indicating it fits well as a transitional sequence. "Disaggregation" methods used to estimate diversity in mudstone and carbonate samples are comparable. Mudstones were disaggregated and examined as described on page 7. Weathered surfaces and residues from vertebrate preparations (loaned by John Chorn) were examined to obtain carbonate diversities.

Return of marine conditions is suggested by an increase in diversity upward (samples 6 and 7) and a normal marine assemblage of fossil invertebrates (brackish water forms are lacking).

LATERAL INTEGRATION OF MEASURED STRATIGRAPHIC SECTIONS

General Statement

The 25 localities of this investigation represent all known exposures of in-place stromatolites in southeastern Brown County, Kansas. Beede (1899)

reported stromatolites (Somphospongia) in northwest Atchison and western Doniphan Counties, but this was not confirmed. Outcrops are limited by thick glacial cover. North-south (fig. 18) and east-west (fig. 19) cross sections were used to 1) define lateral changes in the stratigraphic sequence, 2) portray changes in thickness of the Soldier Creek Shale, and 3) provide the framework necessary for a palaeogeographic delineation of the area.

Correlation

All lithologic units (fig. 4) comprising the Bern Limestone (including the stromatolite biostrome) are traceable over the area. The Soldier Creek Shale thins to the south (fig. 18) and east (fig. 19). In the southern part of the area the mudstone directly below the stromatolite biostrome thickens to the southwest. The thickness of this mudstone remains constant in the northern part of the area but the narrow north-south alignment of localities (fig. 2) makes east-west trends difficult to establish.

Locality SB-15 is the only surface exposure of the stromatolite biostrome that can be examined for a significant distance (31 m) laterally. The vertical sequence is available at other localities, but thick glacial cover precludes observing lateral changes. In addition, the stromatolite biostrome cannot be correlated from one locality to another because of 1) irregular horizontal distribution (as shown at Locality SB-15 by Sections I, I/2, J, K) and 2) rapid lateral changes (Sections A to H, Locality SB-15). Locality SB-15 is used as a model (fig. 14) to infer the relative lateral position of the other vertical sequences. At some localities the sequences represent a complex combination of two or three stages of stromatolitic biostrome development. Each stage can be assigned a position corresponding

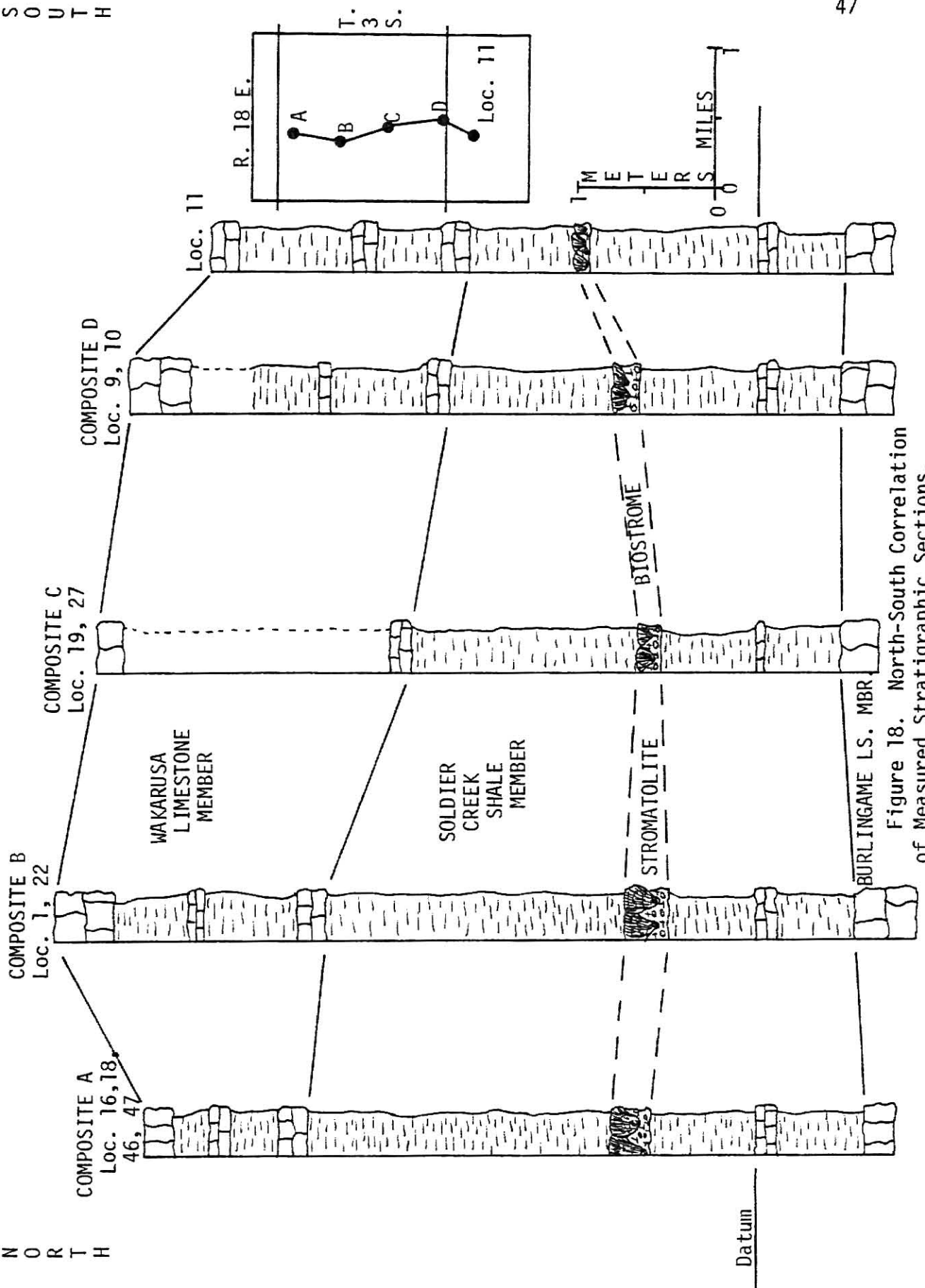


Figure 18. North-South Correlation of Measured Stratigraphic Sections.

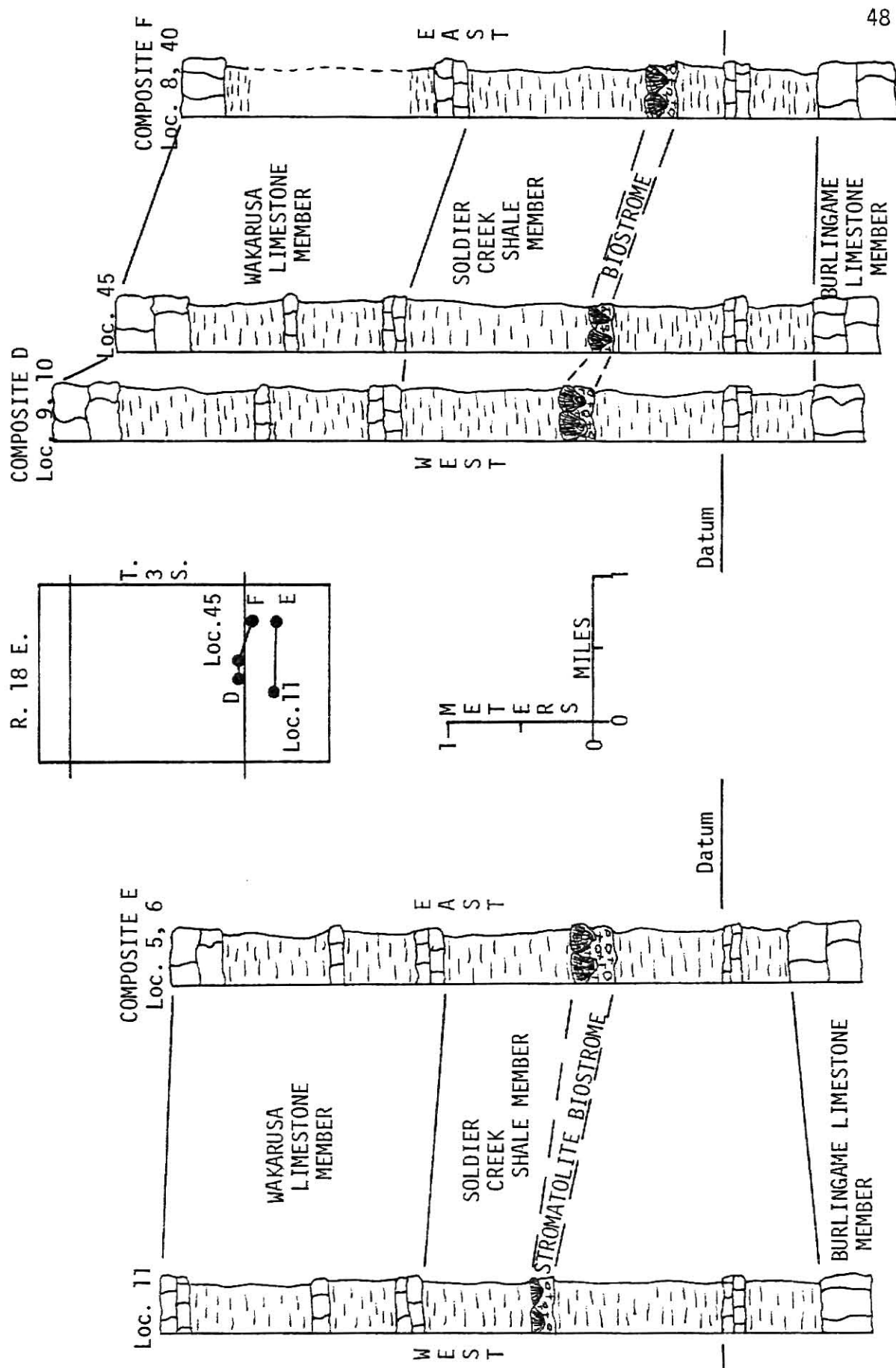


Figure 19. East-West Correlation of Measured Stratigraphic Sections.

to a section in the SB-15 model.

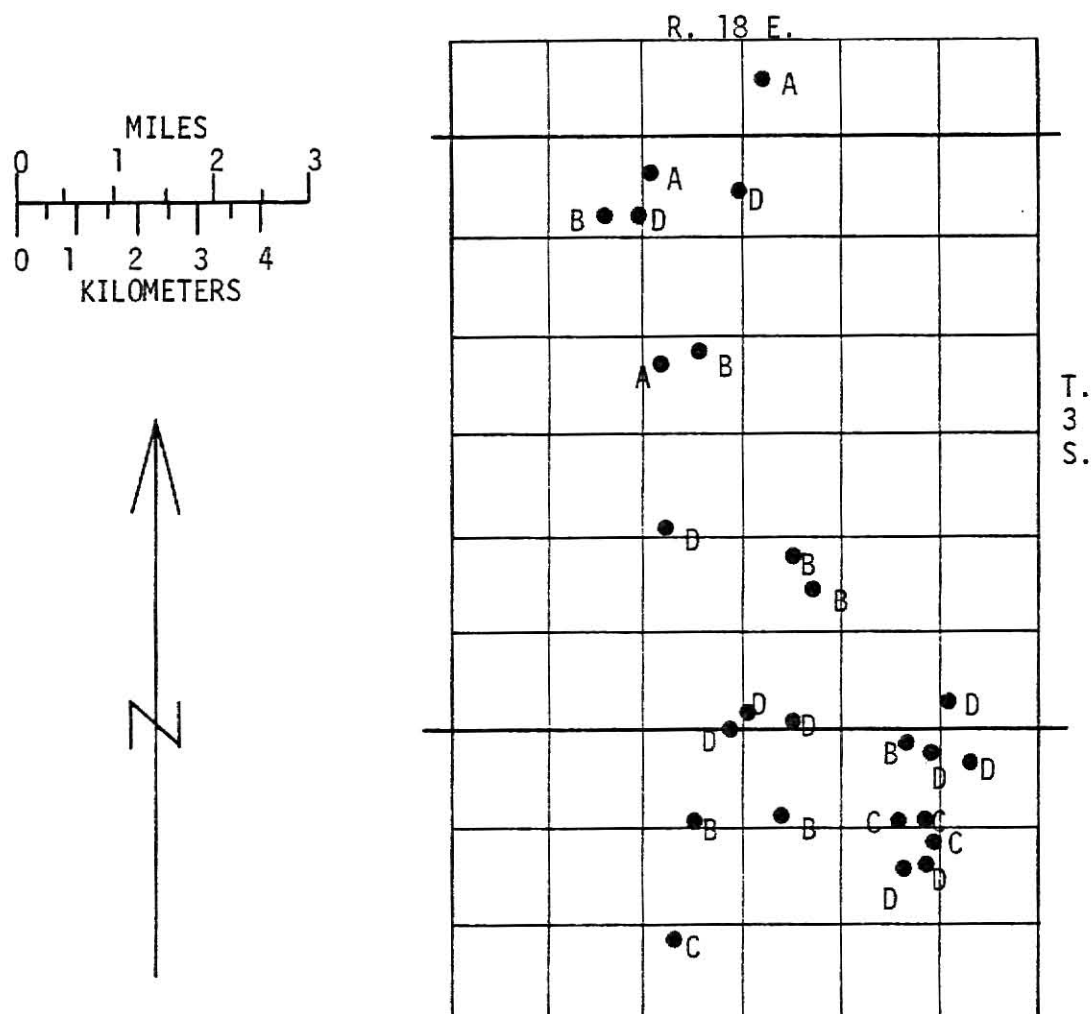
The size and abundance of vertebrate skeletal debris has been visually estimated. General trends show larger specimens and greater quantities concentrated in the northern part of the area (fig. 20).

Interpretation

Southeastern thinning of the Soldier Creek Shale suggests sediment was transported into the area from the northwest. The distribution of vertebrate debris indicates a northern source for transported animal remains. A freshwater origin for the vertebrate assemblage and the thickening of the Soldier Creek Shale to the north might suggest a fluvial influence from a north or northwestern direction.

Owen (1959) described two marine bioherms in the Soldier Creek Shale, one in east-central Lyon County and the other on the Shawnee County-Osage County line. The bioherms have been interpreted by Owen (p. 96) as having formed on the southwest edge of the Forest City Basin. Coal and non-marine shales are reported in the Soldier Creek Shale in Shawnee, Osage, and Lyon Counties. Owen (1959, p. 78) described unfossiliferous argillaceous "punk beds" in Shawnee County as "very earthy, yellowish orange limestone that weathers into a limestone boxwork". He thought the "punk beds" represented freshwater or lagoonal deposits to the west and normal marine deposits to the east as it became an algal-molluscan limestone. The "punk beds" may compare to the argillaceous dismicrite of the stromatolite biostrome suggesting that both were deposited in nearshore areas influenced by freshwater run-off.

The argillaceous dismicrite is interpreted as representing water



VOLUME VERTEBRATE SKELETAL DEBRIS - VISUAL ESTIMATE

Classification	Percent Vertebrate Debris	Size Range
Class A	1-3%	0.1-100 mm
Class B	0.1-1%	0.1-20 mm
Class C	less than 0.1%	0.1-5 mm
Class D	0%	-

Figure 20. Geographic Distribution of Vertebrate Skeletal Debris.

depths too shallow for stromatolite growth. Areas outlined in figure 21 may represent topographic highs around which stromatolites grew by providing nearshore brackish conditions and gradient "break" zones favorable to stromatolite development.

COMPARISON OF THE SOLDIER CREEK SHALE STROMATOLITES
WITH THE HOLOCENE EXAMPLE AT
HAMELIN POOL, SHARK BAY, WESTERN AUSTRALIA

Physical, Chemical, and Biological Evolution

The application of Holocene environments to the interpretation of ancient environments depends on an understanding of the evolution of physical, chemical, and biological factors that affect these environments. Gebelein (1976b) discussed the evolution of physical, chemical, and biological factors in considering the application of Holocene examples to the interpretation of ancient stromatolites. The conclusions he reached were:

1. Physical environments for stromatolite development have had a distinctly "modern" aspect since the beginning of the Proterozoic.
2. Major changes in seawater chemistry (except redox reactions) seem unlikely since at least 2 b.y. before present.
3. Carbonate equilibria have not changed markedly since at least the beginning of the Early Proterozoic.
4. Controls on distribution, phototactic and chemotactic responses, and the types of blue-green algae and their associations and communities should be similar to the Holocene since the Proterozoic.
5. The distribution, abundance, and diversity of stromatolites has been controlled by the activities of metazoan burrowers and grazers since the Late Proterozoic.

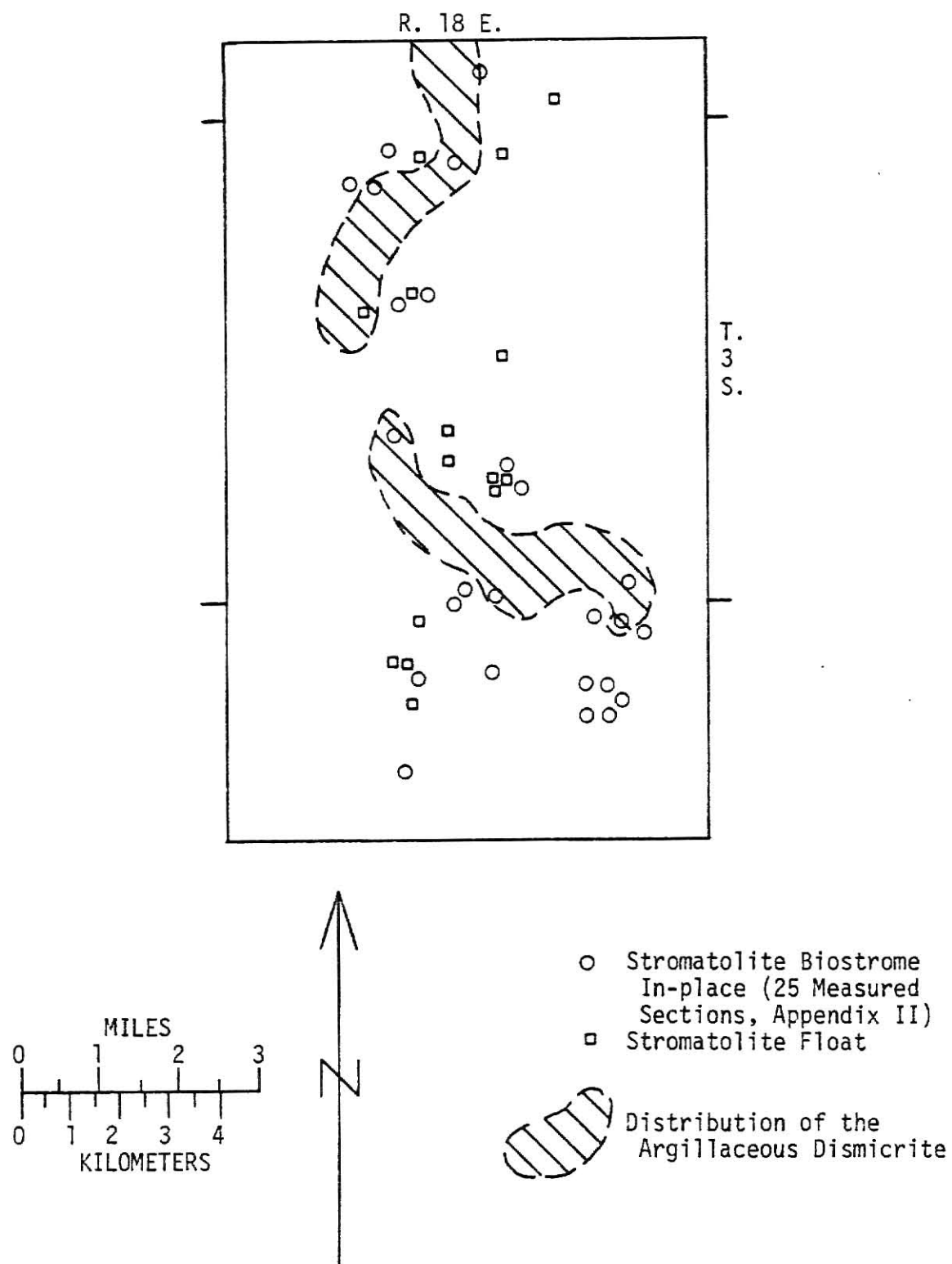


Figure 21. Geographic Distribution of "Topographic Highs".

6. Stromatolite building biotas were restricted to the very margins (hypersaline, brackish, and freshwater environments) of their potential ecological hyperspace since the beginning of the Ordovician (one exception being the role of blue-green algae in biohermal and reef-like deposits).
7. Holocene principles of stromatolite distribution may be applied with some confidence throughout the Phanerozoic.

Comparison with Hamelin Pool Example

Hamelin Pool Setting.--Modern algal stromatolites at Hamelin Pool, Shark Bay, Western Australia, are the most diverse and abundant shallow water stromatolites known from Holocene seas (Playford and Cockbain, 1976). Hamelin Pool is a hypersaline marine basin that is "barred" at its mouth by a sea-grass barrier. The restriction of oceanic waters combined with low precipitation and high evaporation produce hypersaline (55-70 ‰) conditions (Playford and Cockbain, 1976) which restrict species diversity and eliminate algae consuming organisms. These parameters allow flat algal mats and algal stromatolites to form on the intertidal and subtidal platforms. Living stromatolites are found from depths of at least 3.5 m below sea level to about high-water-spring tide level (Playford and Cockbain, 1976). Physical environments ranging from high stress wave-raked shorelines to low stress tidal ponds affect the gross morphology of stromatolites at Hamelin Pool. Columnar stromatolites are products of the high stress environment where their form is controlled by physical processes (Hoffman, 1976). Biotic processes dominate the gross morphology of low stress environments where flat cryptalgal mats or small stromatolites occur (Hoffman, 1976).

Stromatolites at Hamelin Pool were first described by Logan (1961) and later investigated by Logan et al. (1964) and Logan et al. (1974). The following discussion is summarized from Logan et al. (1974). Cryptalgal structures at Hamelin Pool are built by sediment binding and trapping blue-green algae that interact with a variety of mechanical and diagenetic processes. The algal mat tends to cover intertidal, supratidal, and some shallow subtidal surfaces and is differentiated into seven intergradational types. The sediments that are trapped and/or bound by the algal mat produce a distinctive fabric that can be related to specific mat types.

Comparison with the Soldier Creek Stromatolite Biostrome.--The Soldier Creek stromatolite biostrome is compared to the Hamelin Pool example on the basis of stromatolite morphology and environmental relationships.

Internal Structure.--The internal structure of the Soldier Creek stromatolites resembles the digitate structure characteristic of the colloform mat type (Logan et al., 1974) at Hamelin Pool. Stromatolitic structures built by colloform mats at Hamelin Pool are restricted to lower intertidal and subtidal zones (Logan et al., 1974). The colloform mat type is restricted to zones rarely exposed to desiccation (Hoffman, 1976). The internal structure of the Soldier Creek stromatolites suggests they inhabited low intertidal to shallow subtidal environments which are only rarely desiccated.

Laminations.--Stromatolite laminations are built by algal trapping and binding of sediment particles and cryptocrystalline aragonite at Hamelin Pool (Logan et al., 1974). The laminations of Soldier Creek stromatolites are probably a result of carbonate precipitation. Although terrigenous silt and sand sized particles occur in interstitial areas, they are not within or between laminae.

Surface Texture.--The surface texture of the Soldier Creek stromatolites and the colloform mat type at Hamelin Pool are similar. Both have an irregular crenulated surface (fig. 22 A and B).

Gross Morphology.--Soldier Creek stromatolites resemble some forms in Hamelin Pool (Fig. 22 C and D). The gross morphology of the Soldier Creek stromatolites is comparable to stromatolite forms found in the low intertidal-shallow subtidal bight areas of Hamelin Pool. Bight areas have a subtidal shelf that is relatively broad and shallow (Hoffman, 1976) and intertidal sand flats of moderate to low gradient (Logan et al., 1974). Waves are refracted due to gradual shoaling offshore resulting in moderate wave attack (Logan et al., 1974). Stromatolites in the low intertidal-shallow subtidal zone are produced by colloform and smooth mat types forming complex associations of structures (coalescing columns, crowded growth) with moderate relief (less than 20 cm) (Logan et al., 1974). The associated sediments are fine to medium grainstones (Logan et al., 1974). The Soldier Creek stromatolites form coalescing structures less than 20 cm high and have been interpreted to inhabit a low intertidal-shallow subtidal environment. The coated-grain biosparrudite (average grain size is 1.27 mm) lithology associated with Soldier Creek stromatolites may be similar to the medium grainstone reported by Logan et al. (1974) in Hamelin Pool. Unfortunately, Logan et al. (1974) do not define the size of "medium".

Oncolites.--Oncolites at Hamelin Pool are minor components of stromatolite growth. At Hamelin Pool, the algae usually colonize objects such as lithoclasts, intraclasts, shells, or scaled fragments of nearby columns and form columns that are not usually disturbed. Columns that do originate

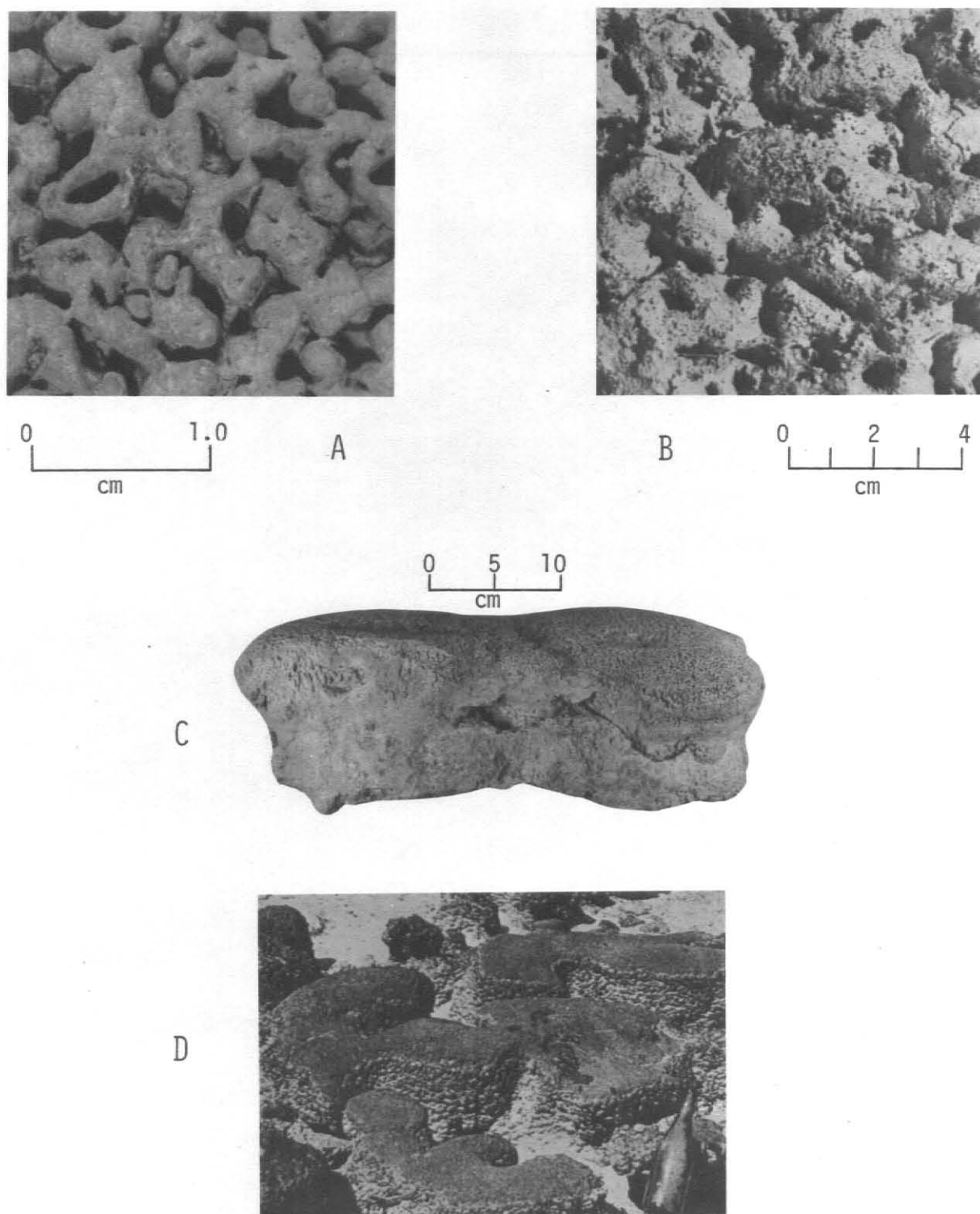


Figure 22. Comparison of Surface Texture and Gross Morphology of Pennsylvanian with Holocene Stromatolites. A. Crenulated surface texture of Soldier Creek stromatolites, Locality SB-44. B. Surface texture of colloform mat type in Hamelin Pool, Holocene (from Logan *et al.*, 1974, p. 147, fig. 4). C. Gross morphology of stromatolites from Locality SB-8. D. Holocene stromatolites in Hamelin Pool (from Logan, 1961, Plate 1, fig. 3).

from oncolites are formed the same way stromatolites develop in the Soldier Creek. Algae are not able to establish a mat on the mobile sediment, thus, stromatolitic structures are built on the stable nuclei (Logan et al., 1974). In some turbulent areas small stromatolitic structures are overturned and mats grow on both sides to produce disconcoidal structures (Logan et al., 1974). Because of size or rapid burial these oncolites are soon stabilized and accretion proceeds on the upper surface as usual (Logan et al., 1974). The oncolite stage in the Soldier Creek biostrome is essential to the development of stromatolites. Stromatolitic growth starting from oncolites has been reported by Playford and Cockbain (1969; conical caps that grew on some subtidal oncolites) and Aitken (1967; two examples of oncolites prolonged upward as digitate stromatolites). The Soldier Creek occurrence is the only known example of stromatolite dependence on an initial oncolite stage.

Biotic Association.--The biota of both occurrences have low diversity. The fauna of Hamelin Pool has not been studied in detail, but organisms include peneroplid and miliolid foraminifers, sea snakes, a few species of fish, and the small bivalve Fragum hamelini Iredale which can be very abundant (Playford and Cockbain, 1976). Epiphytic organisms that inhabit the sides of subtidal colloform columns are Acetabularia, serpulids, and the small bivalve Irus irus (Linne') (Playford and Cockbain, 1976).

Depositional Gradient.--Depositional gradients interpreted at Locality SB-15 are similar to gradients described by Logan et al. (1974) for bight areas at Hamelin Pool. In bight areas, a gentle slope (0.3 to 0.6 m/km) extends from the supratidal zone to the intertidal zone and then the gradient increases into the subtidal zone (Logan et al., 1974). At

Locality SB-15 the gradient corresponding to the increase into the subtidal zone was calculated to be 7 m/km. Logan et al. (1974) stated:

The steeper "face" coincides with the "break" zone for prevailing waves, where wave currents change from predominantly oscillatory (with small shoreward component) to translatory.

A similar change in gradient has been recognized at Locality SB-15. Stromatolite growth might be dependent on this change of gradient. The most intense wave action occurs in shallow subtidal and lower intertidal environments at Hamelin Pool (Logan et al., 1974). Similar energy estimates for the Soldier Creek stromatolites have been inferred (fig. 15).

Sediment Transport.--At Hamelin Pool, there is a net shoreward transport of sediment from the subtidal platform and an overall seaward progradation over shallow subtidal facies (Logan et al., 1974). A similar situation is suggested at Locality SB-15; offshore organisms are in the associated sediments (net shoreward movement) and a prograding wedge migrates seaward over the stromatolites.

SUMMARY

The palaeoenvironment of the Soldier Creek stromatolite occurrence has been reconstructed and compared to the Holocene example at Hamelin Pool, Shark Bay, Western Australia. These relationships are summarized as follows:

1. Stromatolitic development takes place in three stages. The initial stage is oncolite growth. Stabilization of the oncolite allows algal growth on the upper surface to form a stromatolite. Coalescing stromatolites create the stromatolitic biostrome.

2. The digitate internal structure formed by laminoid fabric is probably the result of algal induced precipitation of calcium carbonate.

3. The stromatolite biostrome is composed of three lithologic components that record transgressing (shoreward) and prograding (seaward) directions of sediment transport.

4. The Soldier Creek stromatolites probably developed in low intertidal or shallow subtidal environments. Stromatolitic development corresponds to a gradient increase near the wave "break" zone. The wave "break" zone constitutes the highest energy relative to low energy in the nearshore direction and moderate energy offshore.

5. The salinity of the water during development of the stromatolite biostrome is interpreted as brackish.

6. Stromatolites may have inhabited a shallow lagoon or embayment that was linked to normal marine environments but influenced by a freshwater source. The mudstone below the stromatolite biostrome represents deposition in a normal marine environment. The depositional environment of the stromatolite biostrome is intermediate between this and the mudstone above which is interpreted as a brackish deposit.

7. Invertebrate fossils associated with the stromatolitic biostrome were probably transported from farther offshore by the landward movement of water. The vertebrate assemblage is probably of freshwater origin (Chorn and Conley, 1977). Preservation and abundance suggests the vertebrate (lungfish, amphibians, sharks, fish) skeletal fragments were transported a relatively short distance with the stromatolites acting as a "trap" that stranded floating carcasses. Abundance of vertebrate skeletal debris in the

northern part of the area, thickening of the Soldier Creek Shale to the northwest, and the freshwater origin of the vertebrates may suggest a fluvial influence from a north or northwestern direction. Argillaceous dismicrite was deposited on topographic highs around which stromatolites developed.

8. The Soldier Creek stromatolites morphologically resemble forms that develop in the wave "break" zone of bight areas in Hamelin Pool, Shark Bay, Western Australia. The wave "break" zone coincides with the gradient change at the lower intertidal-shallow subtidal zone. The colloform mat type builds stromatolites in the low intertidal and shallow subtidal zone at Hamelin Pool. The surface texture and internal structure built by the colloform mat are characteristic of the Soldier Creek stromatolites. A net shoreward transport of sediment and an overall seaward progradation occurs at Hamelin Pool. Shoreward transport and seaward progradation are recognized in the stromatolite biostrome at Locality SB-15.

ACKNOWLEDGMENTS

This investigation was under the supervision and direction of Dr. R. R. West whose guidance and advice is gratefully acknowledged.

Sincere appreciation is extended to the committee members, Dr. C. W. Shenkel, Dr. C. C. Smith, and Dr. P. C. Twiss, who reviewed the manuscript and offered helpful suggestions and discussions.

This investigation was partly supported by a Grant-in-Aid of Research from Sigma Xi, The Scientific Research Society of North America.

REFERENCES

- Aitken, J. D., 1967, Classification and environmental significance of cryptalgal limestones and dolomites, with illustrations from the Cambrian and Ordovician of southwestern Alberta. *Jour. Sed. Petrology*, v. 37, p. 1163-1178.
- Awramik, S. M., Margulis, L., and Barghoorn, E. S., 1976, Evolutionary processes in the formation of stromatolites, in Walter, M. R., (ed.), *Stromatolites*: Amsterdam, Elsevier, p. 149-162.
- Baird, D., 1966, New Labyrinthodon amphibian from the Pennsylvanian of Kansas: *Geol. Soc. America Special Paper* 101, p.8-9.
- Bayne, C. K., 1973, Geohydrology of Doniphan County, northeastern Kansas: *U.S. Geol. Survey Hydrol. Inv. Atlas* HA-462.
- Bayne, C. K., and Schoewe, W. H., 1967, Geology and ground-water resources of Brown County, Kansas: *Kansas Geol. Survey Bull.* 186, 68 p.
- Beede, J. W., 1899, New fossils from the Kansas Coal Measures: *Kansas Univ. Quart.*, v. VIII, no. 3, Univ. of Kansas, Lawrence, Kansas, p. 123-130.
- Carozzi, A. V., 1962, Observations on algal biostromes in the Great Salt Lake, Utah: *Jour. Geology*, v. 70, no. 2, p. 246-252.
- Chorn, J., and Conley, C. D., 1977, A Late Pennsylvanian vertebrate assemblage from stromatolites in the Bern Formation, northeastern Kansas: *Kansas Academy of Science*, 109 th. Annual Meetings Abstracts, p. 10.
- Cloud, P. E., 1942, Notes on stromatolites: *Am. Jour. Sci.*, v. 240, p. 363-379.
- Condra, G. E., 1949, The nomenclature, type localities, and correlation of the Pennsylvanian subdivisions in eastern Nebraska and adjacent states: *Nebraska Geol. Survey*, ser. 2, Bull. 16, 67 p.
- Craig, G. Y., and Hallam, A., 1963, Size-frequency and growth-ring analyses of Mytilus edulis and Cardium edule, and their paleoecological significance: *Palaeontology*, v. 6, p. 731-750.
- Davis, R. A., 1968, Algal stromatolites composed of quartz sandstone: *Jour. Sed. Petrology*, v. 38, p. 953-955.
- Donaldson, J. A., 1976, Paleoecology of Conophyton and associated stromatolites in the Precambrian Dismal Lakes and Rae Groups, Canada, in Walter, M. R., (ed.), *Stromatolites*: Amsterdam, Elsevier, p. 523-534.
- Fagerstrom, J. A., and Burchett, R. R., 1972, Upper Pennsylvanian shoreline deposits from Iowa and Nebraska: their recognition, variation, and significance: *Geol. Soc. America Bull.* 83, p. 367-387.

- Folk, R. L., 1962, Spectral subdivision of limestone types, in Ham, W. E., (ed.), Classification of carbonate rocks: a symposium: Am. Assoc. Petroleum Geol., Memoir 1, p. 62-84.
- Garrett, P., 1970, Phanerozoic stromatolites; non-competitive ecological restriction by grazing and burrowing animals: Science, v. 169, p. 171-173.
- Gebelein, C. D., 1969, Distribution, morphology, and accretion rate of Recent subtidal algal stromatolites, Bermuda: Jour. Sed. Petrology, v. 39, p. 49-69.
- Gebelein, C. D., 1974, Biologic control of stromatolite microstructure: implications for Precambrian time stratigraphy: Am. Jour. Sci., v. 274, no. 6, p. 575-598.
- Gebelein, C. D., 1976a, Open marine subtidal and intertidal stromatolites (Florida, the Bahamas and Bermuda), in Walter, M. R., (ed.), Stromatolites: Amsterdam, Elsevier, p. 381-388.
- Gebelein, C. D., 1976b, The effects of the physical, chemical and biological evolution of the earth, in Walter, M. R., (ed.), Stromatolites: Amsterdam, Elsevier, p. 499-515.
- Ginsburg, R. N., 1960, Ancient analogues of Recent stromatolites: 21st. International Geol. Congress, Copenhagen, 1960, pt. 22, p. 26-35.
- Ginsburg, R. N., 1971, Landward movement of carbonate mud: new model for regressive cycles in carbonates: Am. Assoc. Petroleum Geol. Bull. 55, no. 2, p. 340.
- Golubic, S., 1973, The relationship between blue-green algae and carbonate deposits, in Carr, N. G. and Whitton, B. A., (eds.), The biology of blue-green algae: Oxford, Blackwell Scientific, p. 434-472.
- Golubic, S., 1976a., Organisms that build stromatolites, in Walter, M. R., (ed.), Stromatolites: Amsterdam, Elsevier, p. 113-126.
- Golubic, S., 1976b, Taxonomy of extant stromatolite-building cyanophytes, in Walter, M. R., (ed.), Stromatolites: Amsterdam, Elsevier, p. 127-140.
- Goddard, E. N., et al., 1963, Rock Color Chart: New York, Geol. Soc. America.
- Gunter, G., 1947, Paleoecological import of certain relationships of marine animals to salinity: Jour. Paleontology, v. 21, p. 77-79.
- Halley, R. B., 1976, Textural variation within Great Salt Lake algal mounds, in Walter, M. R., (ed.), Stromatolites: Amsterdam, Elsevier, p. 435-445.

- Haslett, P. G., 1976, Lower Cambrian stromatolites from open and sheltered intertidal environments, Wirrealpa, South Australia, in Walter, M. R., (ed.), *Stromatolites*: Amsterdam, Elsevier, p. 565-584.
- Hoffman, P., 1967, Algal stromatolites: use in stratigraphic correlation and paleocurrent determination: *Science*, v. 157, p. 1043-1045.
- Hoffman, P., 1976, Stromatolite morphogenesis in Shark Bay, Western Australia, in Walter, M. R., (ed.), *Stromatolites*: Amsterdam, Elsevier, p. 261-271.
- Hoffman, P. F., Logan, B. W., and Gebelein, C. D., 1972, Algal mats, cryptalgal fabrics, and structures, Hamelin Pool, Western Australia: *Am. Assoc. Petroleum Geol. Bull.* 56, p. 628 (abstract).
- Hofmann, H. J., 1969, Attributes of stromatolites: *Geol. Survey Canada Paper*, 69-39, 58 p.
- Horodyski, R. J., 1975, Stromatolites of the Lower Missoula Group (Middle Proterozoic), Belt Supergroup, Glacier National Park, Montana: *Precambrian Research*, v. 2, p. 215-254.
- Horodyski, R. J., 1976, Stromatolites from the Middle Proterozoic Altyn Limestone, Belt Supergroup, Glacier National Park, Montana, in Walter, M. R., (ed.), *Stromatolites*: Amsterdam, Elsevier, p. 585-597.
- Horodyski, R. J., and Vonder Haar, S. P., 1975, Recent calcareous stromatolites from Laguna Mormona (Baja California) Mexico: *Jour. Sed. Petrology*, v. 45, no. 4, p. 894-906.
- Jewett, J. M., 1951, Geologic structures in Kansas: *Kansas Geol. Survey Bull.* 90, pt. 6, 172 p.
- Johnson, J. H., 1946, Lime-secreting algae from the Pennsylvanian and Permian of Kansas: *Geol. Soc. America Bull.* v. 57, p. 1087-1120.
- Johnson, J. H., 1961, Limestone-building algae and algal limestones: Colorado School of Mines, Johnson Publishing Co., Boulder, Colorado, 297 p.
- Johnson, R. G., 1960, Models and methods for the analysis of the mode of formation of fossil assemblages: *Geol. Soc. America Bull.*, v. 71, p. 1075-1086.
- Kalkowsky, E., 1908, Oolith und Stromatolity im norddeutschen Buntsandstein: *Deutsche geol. Gesell. Zeitschr.*, v. 60, p. 68-125.
- Kendall, C. G., St. C., and Skipwith, Sir P. A. d'E., 1968, Recent algal mats of a Persian Gulf lagoon: *Jour. Sed. Petrology*, v. 38, p. 1040-1058.

- Knight, J. B., 1960, Systematic descriptions, in Moore, R. C., (ed.), Treatise on invertebrate paleontology, Part I, Mollusca 1: Geol. Soc. Am. and Kansas Univ. Press, p. 1169-1330.
- Komar, V. A., 1966, Stromatolity verkhnedokembriiskikh otlozhenii severa sibirskoi platformy i ikh stratigraficheskoe znachenie (Upper Precambrian stromatolites in the northern part of the Siberian Platform and their stratigraphic significance): Akad. nauk S.S.S.R., Geol. Inst., Tr., v. 154, 122 p.
- Korolyuk, I. K., 1963, Stromatolity verkhnego dokembriya (Stromatolites of the Late Precambrian), in Keller, B. M., (ed.), Stratigrafiya S.S.S.R., Verkhniy dokembriy, Gosgeoltekhizdat, Moscow, p. 479-498.
- Krylov, I. N., 1971, The significance of stromatolites for the Upper Precambrian stratigraphy of Kazakhstan and central Asia, in Stratigrafiya dokembriya Kazakhstana i Tien-Shanya. Nauka, Moscow, p. 24-31.
- Krylov, I. N., 1976, Approaches to the classification of stromatolites, in Walter, M. R., (ed.), Stromatolites: Amsterdam, Elsevier, p. 31-43.
- Lane, N. G., 1964, Paleoecology of the Council Grove Group (Lower Permian) in Kansas, based upon microfossil assemblages. Kansas Geol. Survey Bull. 170, no. 5, p. 1-23.
- Lee, W., 1943, Stratigraphy and structural development of the Forest City Basin in Kansas: Kansas Geol. Survey Bull. 51, 142 p.
- Logan, B. W., 1961, Cryptozoon and associate stromatolites from the Recent, Shark Bay, Western Australia: Jour. Geology, v. 69, no. 5, p. 517-533.
- Logan, B. W., Rezak, R., Ginsburg, R. N., 1964, Classification and environmental significance of algal stromatolites: Jour. Geology, v. 72, p. 68-83.
- Logan, B. W., Hoffman, P., and Gebelein, C. D., 1974, Algal mats, cryptalgal fabrics, and structures, Hamelin Pool, Western Australia: Am. Assoc. Petroleum Geol., Memoir 22, p. 140-194.
- Lucia, F. J., 1972, Recognition of evaporite-carbonate shoreline sedimentation, in Rigby, J. K., and Hamblin, W. K., (eds.), Recognition of ancient sedimentary environments: Soc. Econ. Paleontologists and Mineralogists, Spec. Publ 16, p. 160-191.
- Maslov, V. P., 1953, Printsipy nomenklatury i sistematiki stromatolitov (Principles of nomenclature and systematics of stromatolites): Akad. nauk S.S.S.R., Izvestia, Ser. Geol., 1953, no. 4, p. 105-112.

- Matti, J. C., and McKee, E. H., 1976, Stable eustacy, regional subsidence, and a carbonate factory: a self-generating model for onlap-offlap cycles in shallow-water carbonate sequences: *Geol. Soc. America Abst.*, v. 8, no. 6, p. 1000-1001.
- Monty, C. L. V., 1967, Distribution and structure of Recent stromatolitic algal mats, Eastern Andros Island, Bahamas: *Société Géologique de Belgique, Annales*, v. 90, p. 55-100.
- Monty, C. L. V., 1976, The origin and development of cryptalgal fabrics, in Walter, M. R., (ed.), *Stromatolites*: Amsterdam, Elsevier, p. 193-249.
- Moore, R. C., 1935(1936), Stratigraphic classification of the Pennsylvanian rocks of Kansas: *Kansas Geol. Survey Bull.* 22, 256 p.
- Moore, R. C., 1964, Paleoecological aspects of Kansas Pennsylvanian and Permian cyclothems: *Kansas Geol. Survey Bull.* 169, p. 287-380.
- Moore, R. C., and Mudge, M. R., 1956, Reclassification of some Lower Permian and Upper Pennsylvanian strata in northern mid-continent. *Am. Assoc. Petroleum Geol. Bull.*, v. 40, no. 9, p. 2271-2278.
- Owen, D. E., 1959, Stratigraphy of bioherms and other deposits of the Upper Pennsylvanian Bern Limestone in east central Kansas: Univ. of Kansas, M.S. thesis, 185 p.
- Peryt, T. M., and Piatkowski, T. S., 1977, Stromatolites from the Zechstein Limestone (Upper Permian) of Poland, in Flügel, E., (ed.), *Fossil Algae*: Berlin, Springer-Verlag, p. 124-135.
- Pia, J., 1927, Thallophyta, in Hirmer, M., (ed.), *Handbuch der Paläobotanik*, v. 1, p. 31-136.
- Playford, P. E., and Cockbain, A. E., 1969, Algal stromatolites: deepwater forms in the Devonian of Western Australia: *Science*, v. 165, p. 1008-1010.
- Playford, P. E., and Cockbain, A. E., 1976, Modern algal stromatolites at Hamelin Pool, a hypersaline barred basin in Shark Bay, Western Australia, in Walter, M. R., (ed.), *Stromatolites*: Amsterdam, Elsevier, p. 389-411.
- Riding, R., 1977, Skeletal stromatolites, in Flügel, E., (ed.), *Fossil Algae*: Berlin, Springer-Verlag, p. 57-60.
- Scott, D. R., 1973, Marine benthic communities of the Reading Limestone (Upper Pennsylvanian) Atchison County, Kansas: Kansas State Univ., M.S. thesis, 135 p.

- Szulczewski, M., 1967, Stromatolitic structures within Middle Jurassic transgressive deposits at Wolo Morawicka (southern margins of the Holy Cross Mountains, central Poland): *Ann. Soc. Geol. Pol.*, v. 37, p. 515-528.
- Tebbutt, G. E., Conley, C. D., and Boyd, D. W., 1965, Lithogenesis of a distinctive carbonate rock fabric: *Wyoming Univ. Contrib. Geol.*, v. 4, p. 1-13.
- Walcott, C. D., 1914, Cambrian geology and paleontology III: Precambrian Algonkian algal flora: *Smithsonian Inst. Misc. Coll.*, v. 64, no. 2, p. 77-156.
- Walter, M. R., 1976a, Introduction, in Walter, M. R., (ed.), *Stromatolites*: Amsterdam, Elsevier, p. 1-3.
- Walter, M. R., 1976b, Appendix I. Glossary of selected terms, in Walter, M. R., *Stromatolites*: Amsterdam, Elsevier, p. 687-692.
- Walter, M. R., Golubic, S., and Preiss, W. V., 1973, Recent stromatolites from hydromagnesite and aragonite depositing lakes near the Coorong Lagoon, South Australia: *Jour. Sed. Petrology*, v. 43, no. 4, p. 1021-1030.
- Ward, J. R., 1973, Geohydrology of Atchison County, northeastern Kansas: *U.S. Geol. Survey Hydrol. Inv. Atlas HA-467*.
- Wray, J. L., 1977, *Calcareous Algae*: Amsterdam, Elsevier, 185 p.
- Zeller, D. E., 1968, The stratigraphic succession in Kansas: *Kansas Geol. Survey Bull.* 189, 81 p.

APPENDIX I

Definition of Terms

- cryptalgal - Term applied to sediments and rock structures that result from sediment binding and/or carbonate precipitating activities of non-skeletal blue-green algae (Aitken, 1967). Includes 1) laminated structures such as stromatolites (Kalkowsky, 1908) and oncolites (Pia, 1927) and, 2) unlaminated structures such as thrombolites (Aitken, 1967). (from Logan et al., 1974)
- stromatolite biostrome - refers to the overall deposit. (from Monty, 1976)
- stromatolite - refers to the individual cryptalgal structures constituting the deposit (biostrome). (from Monty, 1976)
 - organosedimentary structures produced by sediment trapping, binding and/or precipitation as a result of the growth and metabolic activity of microorganisms, principally cyanophytes. (from Walter, 1976a, p. 1)
 - in nonskeletal stromatolites, the microorganisms are not calcified. (modified from Riding, 1977)
- oncolite - unattached stromatolite with encapsulating laminae. (Walter, 1976b, p. 691)
- gross morphology - refers to the external form of the individual stromatolite. (modified from Hofmann, 1969)
 - macrostructure. (from Awramik et al., 1976)
- internal structure - features within a stromatolite (laminations, branching)
 - fabric. (from Monty, 1976)
- laminations - layered fabric (Monty, 1976). Two main types:
 1) laminated fabrics - microstratification resulting from the superposition of well-defined individual layers or laminae of similar or different composition, microstructure, origin and/or color, separated, in most places, by clear physical discontinuity, or microdiastem; 2) laminoid fabric - laminae are absent, but the presence of well or poorly aligned structural features tend to outline an overall layering. (from Monty, 1976)
- fossil microorganisms - fossil remains identifiable with biological affinities, found only in skeletal stromatolites. (modified from Riding, 1977)

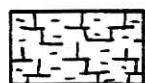
APPENDIX II

Measured Stratigraphic Sections

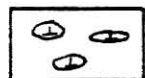
Localities are designated SB and a number. Example: SB-15-A

S = stromatolite
 B = Brown County
 15 = locality number
 A = Section within that locality

Symbols and Abbreviations:



Calcareous Mudstone



Calcareous Nodules



Cover



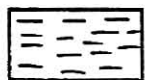
Stromatolites



Coal



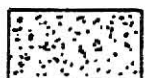
Limestone



Mudstone



Bedded Sandstone



Massive Sandstone

approx. - approximate

calc. - calcareous

cm - centimeter

cg. - conglomerate

encrust. - encrusting

equiv. - equivalent

frag. - fragment

indet. - indeterminable

irreg. - irregular

lt. - light

Ls. - limestone

med. - medium

mbr. - member

m - meters

No fossils - no fossils were
observed

skel. - skeletal

strom. - stromatolites

Bedding Descriptions

fissile = less than 3 mm

platy = 3-12 mm

v. thin bedded = 12-50 mm

thin bedded = 5-10 cm

med. bedded = 10-30 cm

thick bedded = 30-100 cm

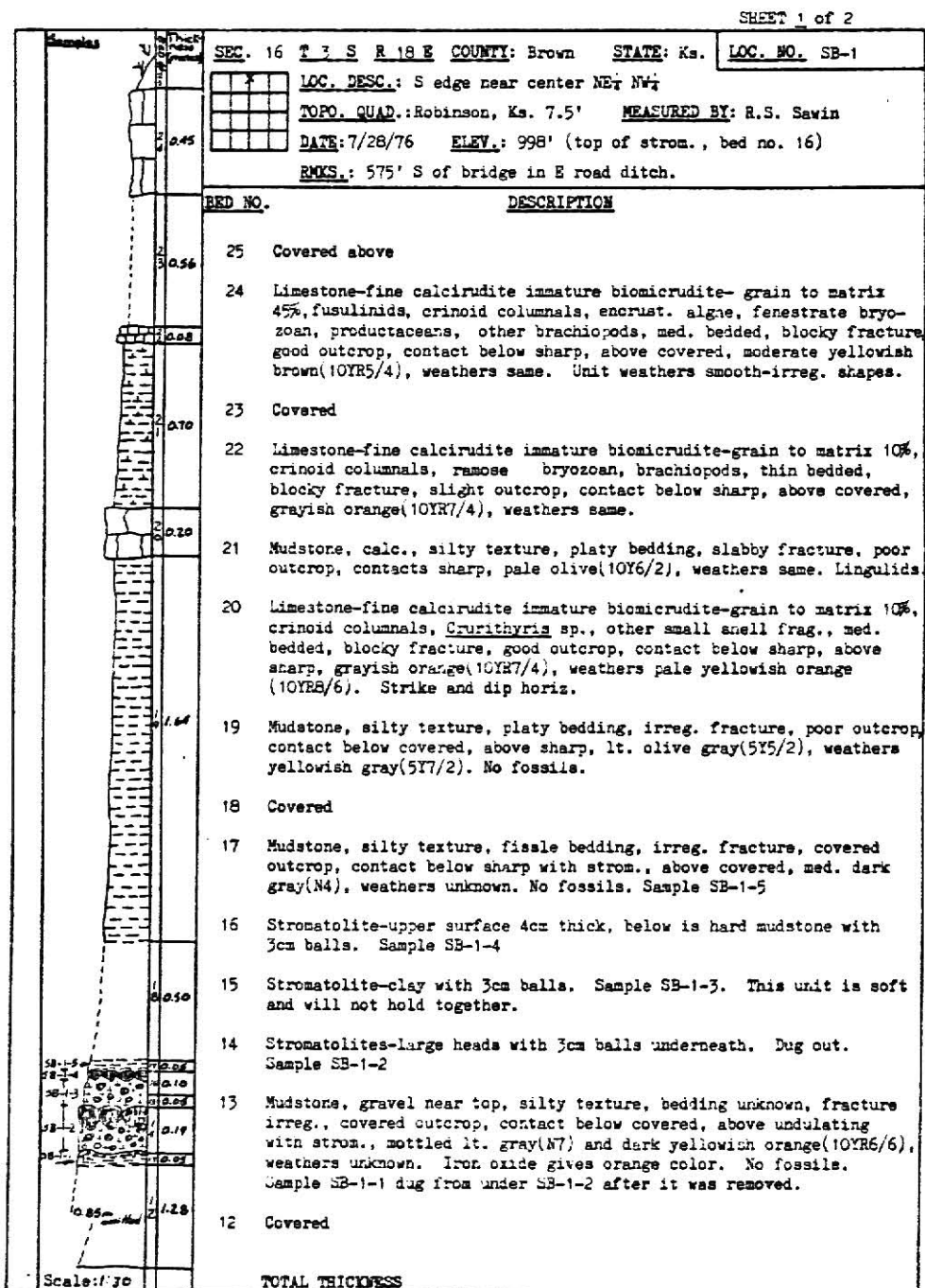
massive = greater than 1 m

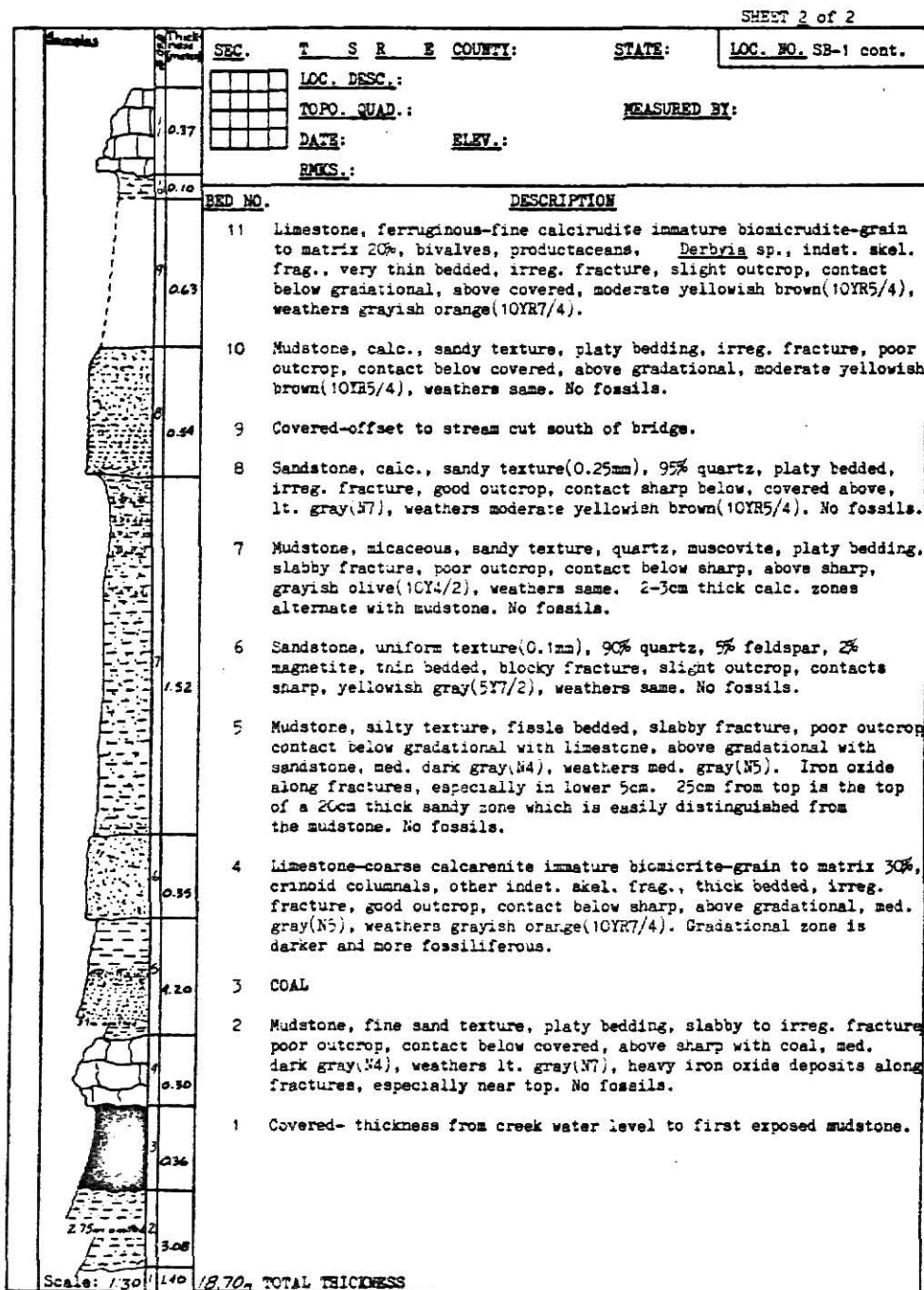
Outcrop Descriptions

- weathering characteristics of
units relative to each other in
order of increasing resistance

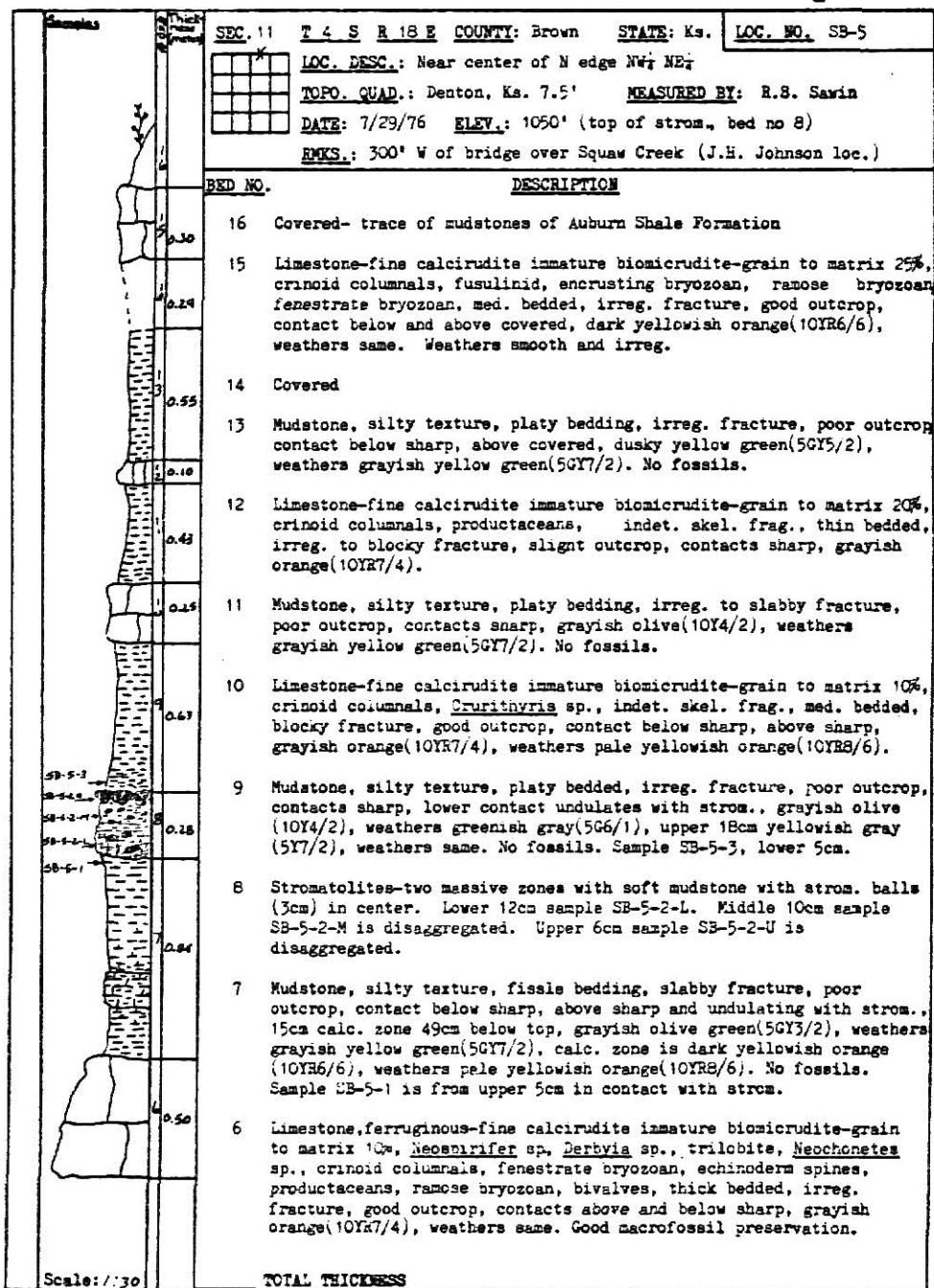
↓
 covered
 poor
 slight
 good
 ledge forming

Color designations according to Goddard, et al., 1963.





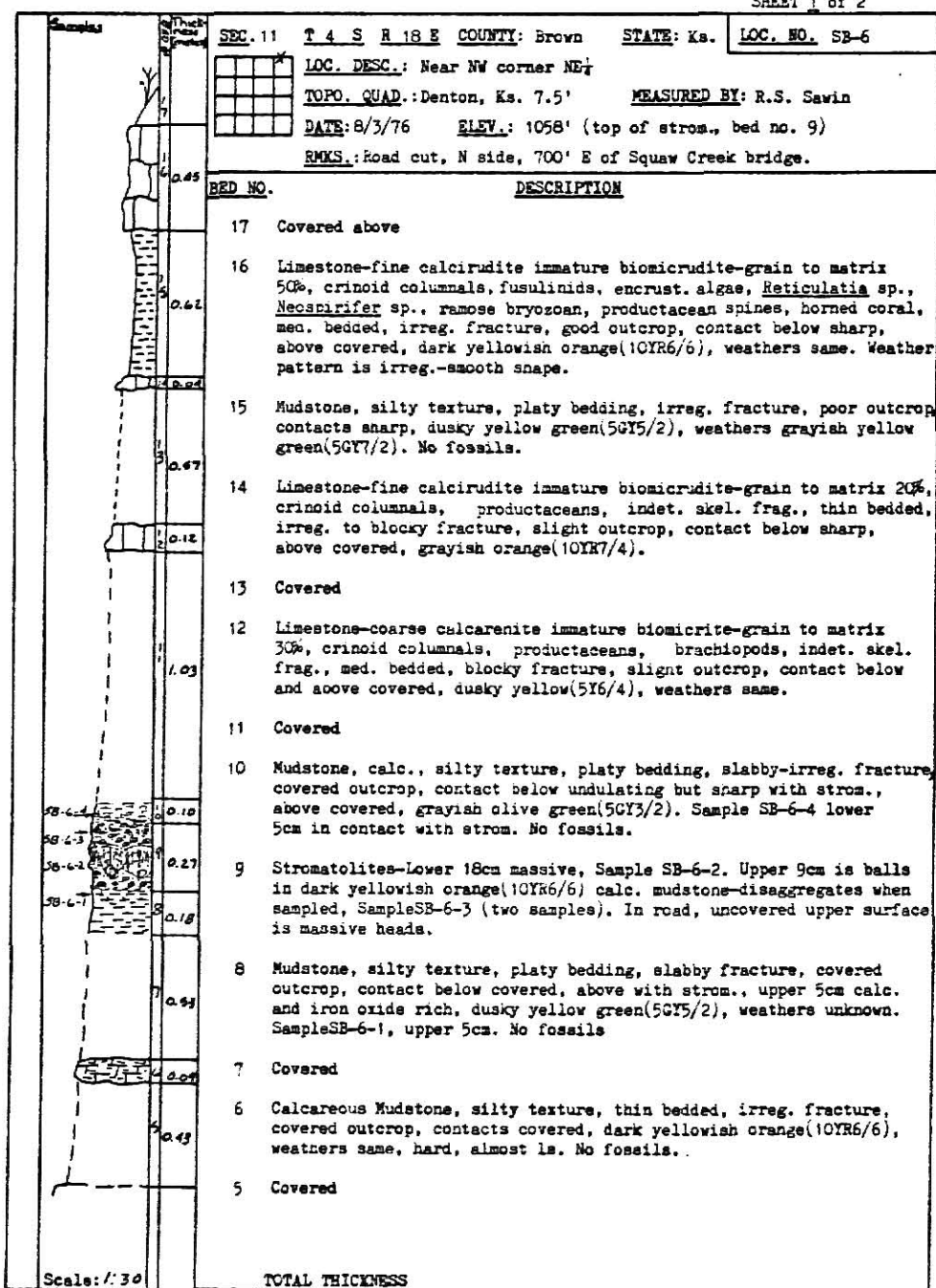
SHEET 1 of 2



SHEET 2 of 2

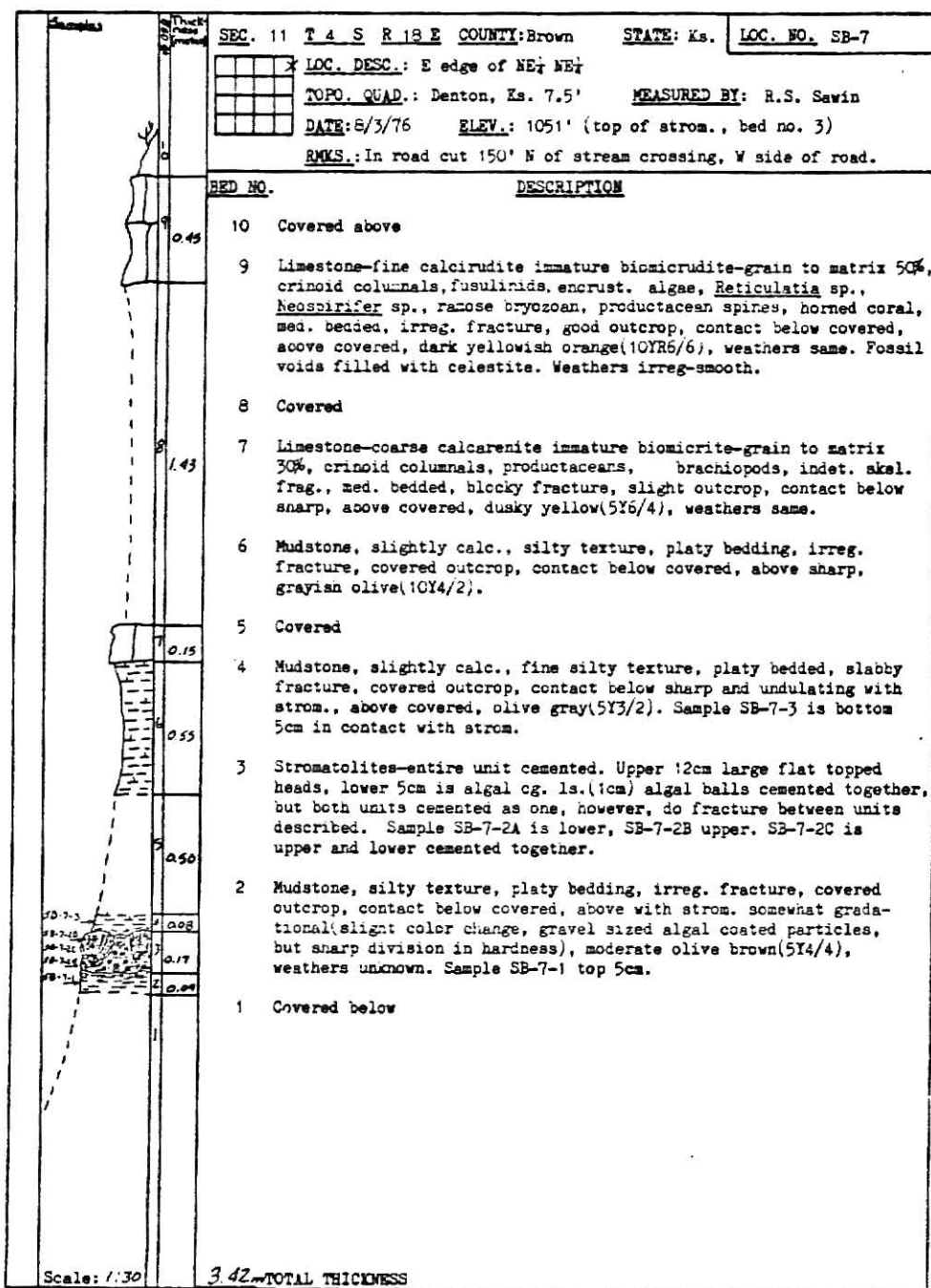
Samples 	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 10%;">SEC.</td> <td style="width: 40%;">T S R E COUNTY:</td> <td style="width: 10%;">STATE:</td> <td style="width: 40%;">LOC. NO. SB-5 cont.</td> </tr> <tr> <td rowspan="3"> </td> <td colspan="3">LOC. DESC.:</td> </tr> <tr> <td colspan="3">TOPO. QUAD.:</td> </tr> <tr> <td colspan="3">MEASURED BY:</td> </tr> <tr> <td colspan="2">DATE:</td> <td colspan="2">ELEV.:</td> </tr> <tr> <td colspan="4">RMKS.:</td> </tr> </table> <table border="1" style="width: 100%; border-collapse: collapse; margin-top: 5px;"> <thead> <tr> <th style="width: 10%;">BED NO.</th> <th style="width: 90%;">DESCRIPTION</th> </tr> </thead> <tbody> <tr> <td style="text-align: center;">5</td> <td>Mudstone, silty texture, platy bedding, irreg. fracture, poor outcrop, contacts sharp, grayish olive green(5GY3/2), weathers greenish gray (5GY6/1), upper 30cm lt. olive gray(5Y5/2), weathers pale olive (10Y6/2). No fossils.</td> </tr> <tr> <td style="text-align: center;">4</td> <td>Limestone, ferruginous-fine calcirudite immature biomicrudite-grain to matrix 25%, indet. skel. frag., iron oxide bearing(5C6), med. bedded, blocky fracture, good outcrop, contact below covered, above sharp, very lt. gray(8B), weathers very pale orange(10YR8/2). Celestite, pyrite, iron oxide in cavities. This unit is thicker than measured, base covered.</td> </tr> <tr> <td style="text-align: center;">3</td> <td>Covered</td> </tr> <tr> <td style="text-align: center;">2</td> <td>Mudstone, very sandy near middle, grades to fine silt near top, platy bedding, thin slabby fracture, poor outcrop, contacts covered, pale olive(10Y6/2), weathers pale greenish yellow(10YB/2), iron oxide on bedding planes and fractures. Sandy zone near center is micaceous. No fossils.</td> </tr> <tr> <td style="text-align: center;">1</td> <td>Covered below</td> </tr> </tbody> </table> Scale: 1/30 796m TOTAL THICKNESS	SEC.	T S R E COUNTY:	STATE:	LOC. NO. SB-5 cont.		LOC. DESC.:			TOPO. QUAD.:			MEASURED BY:			DATE:		ELEV.:		RMKS.:				BED NO.	DESCRIPTION	5	Mudstone, silty texture, platy bedding, irreg. fracture, poor outcrop, contacts sharp, grayish olive green(5GY3/2), weathers greenish gray (5GY6/1), upper 30cm lt. olive gray(5Y5/2), weathers pale olive (10Y6/2). No fossils.	4	Limestone, ferruginous-fine calcirudite immature biomicrudite-grain to matrix 25%, indet. skel. frag., iron oxide bearing(5C6), med. bedded, blocky fracture, good outcrop, contact below covered, above sharp, very lt. gray(8B), weathers very pale orange(10YR8/2). Celestite, pyrite, iron oxide in cavities. This unit is thicker than measured, base covered.	3	Covered	2	Mudstone, very sandy near middle, grades to fine silt near top, platy bedding, thin slabby fracture, poor outcrop, contacts covered, pale olive(10Y6/2), weathers pale greenish yellow(10YB/2), iron oxide on bedding planes and fractures. Sandy zone near center is micaceous. No fossils.	1	Covered below
SEC.	T S R E COUNTY:	STATE:	LOC. NO. SB-5 cont.																																
	LOC. DESC.:																																		
	TOPO. QUAD.:																																		
	MEASURED BY:																																		
DATE:		ELEV.:																																	
RMKS.:																																			
BED NO.	DESCRIPTION																																		
5	Mudstone, silty texture, platy bedding, irreg. fracture, poor outcrop, contacts sharp, grayish olive green(5GY3/2), weathers greenish gray (5GY6/1), upper 30cm lt. olive gray(5Y5/2), weathers pale olive (10Y6/2). No fossils.																																		
4	Limestone, ferruginous-fine calcirudite immature biomicrudite-grain to matrix 25%, indet. skel. frag., iron oxide bearing(5C6), med. bedded, blocky fracture, good outcrop, contact below covered, above sharp, very lt. gray(8B), weathers very pale orange(10YR8/2). Celestite, pyrite, iron oxide in cavities. This unit is thicker than measured, base covered.																																		
3	Covered																																		
2	Mudstone, very sandy near middle, grades to fine silt near top, platy bedding, thin slabby fracture, poor outcrop, contacts covered, pale olive(10Y6/2), weathers pale greenish yellow(10YB/2), iron oxide on bedding planes and fractures. Sandy zone near center is micaceous. No fossils.																																		
1	Covered below																																		

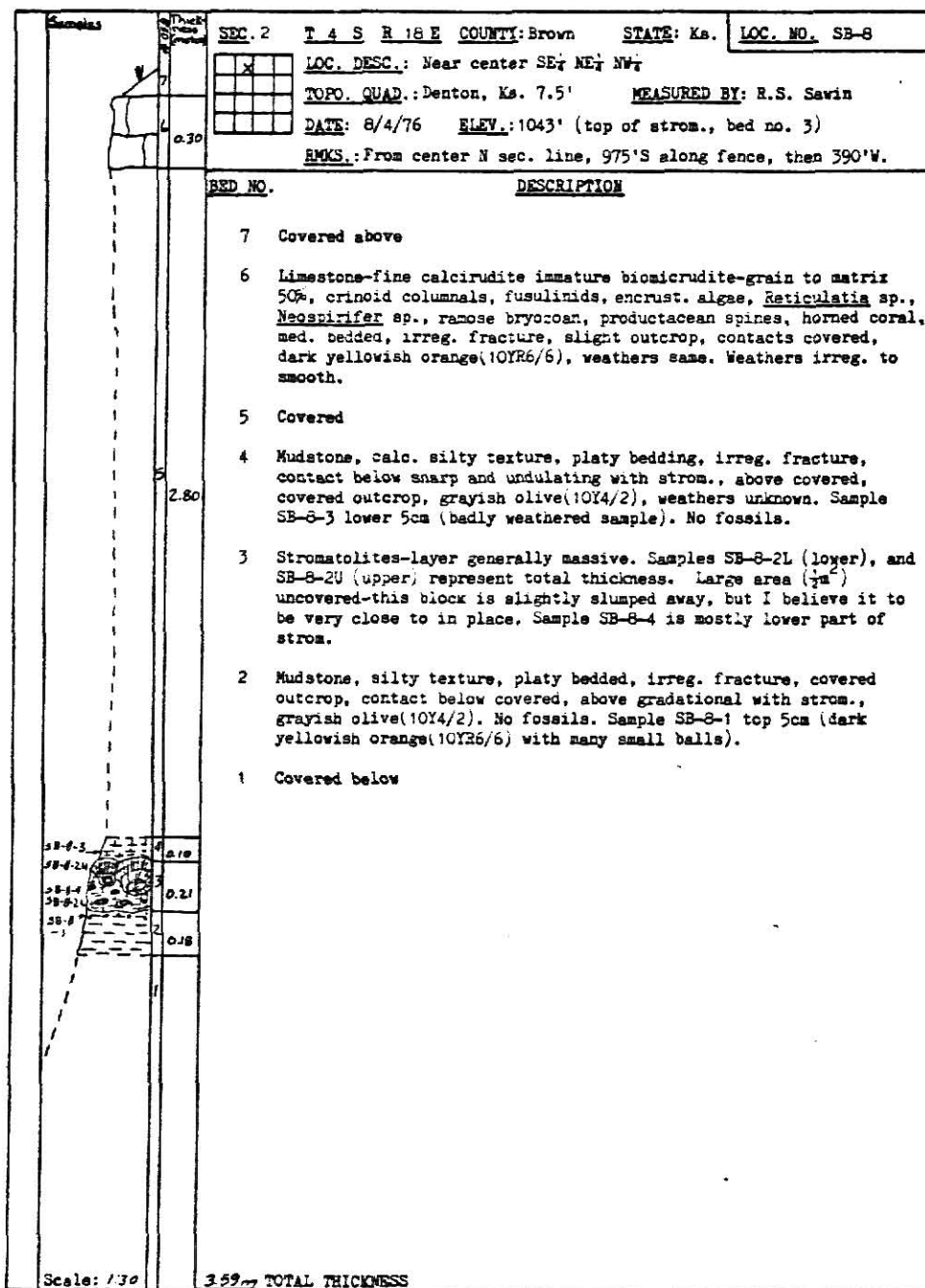
SHEET 1 of 2

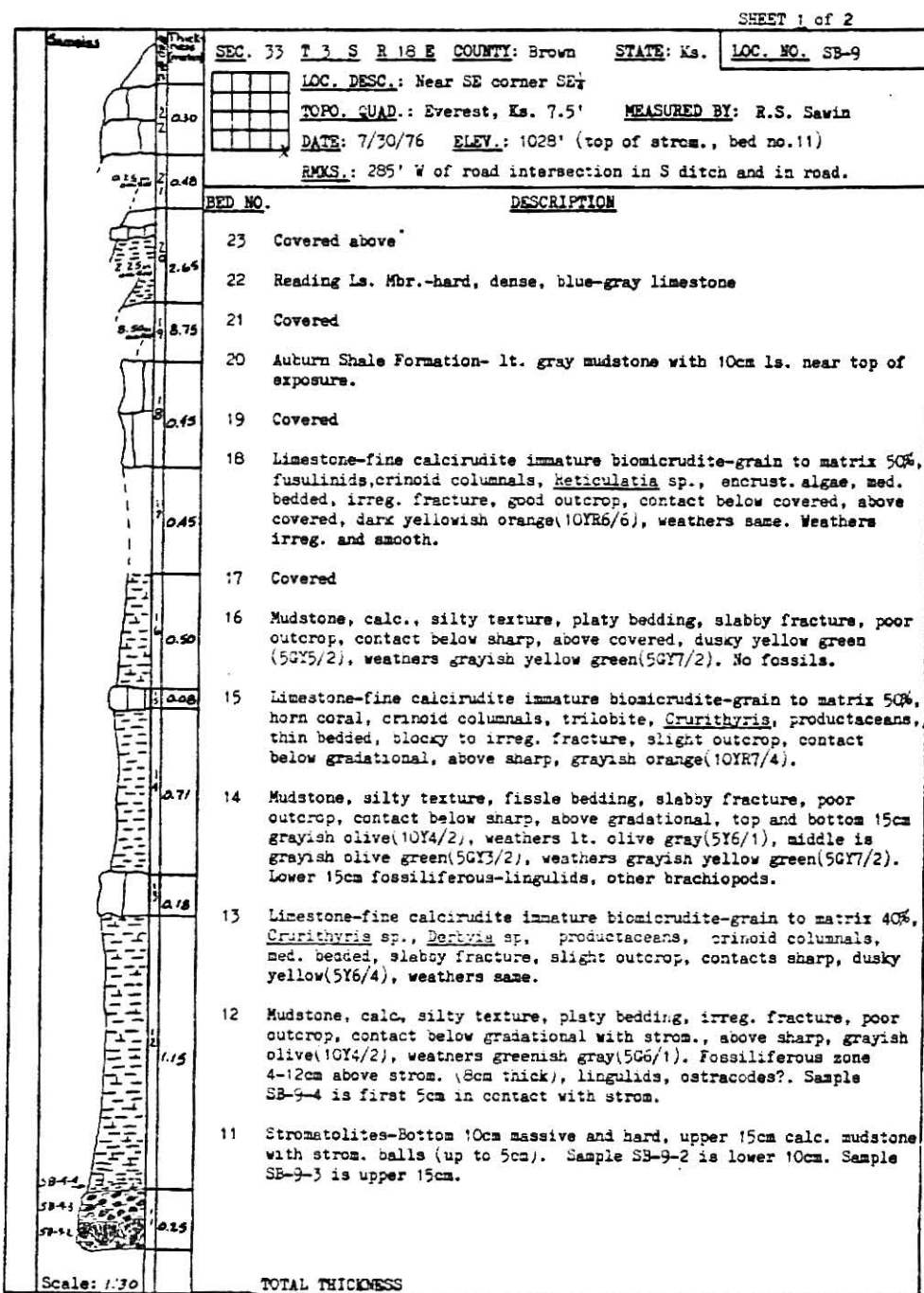


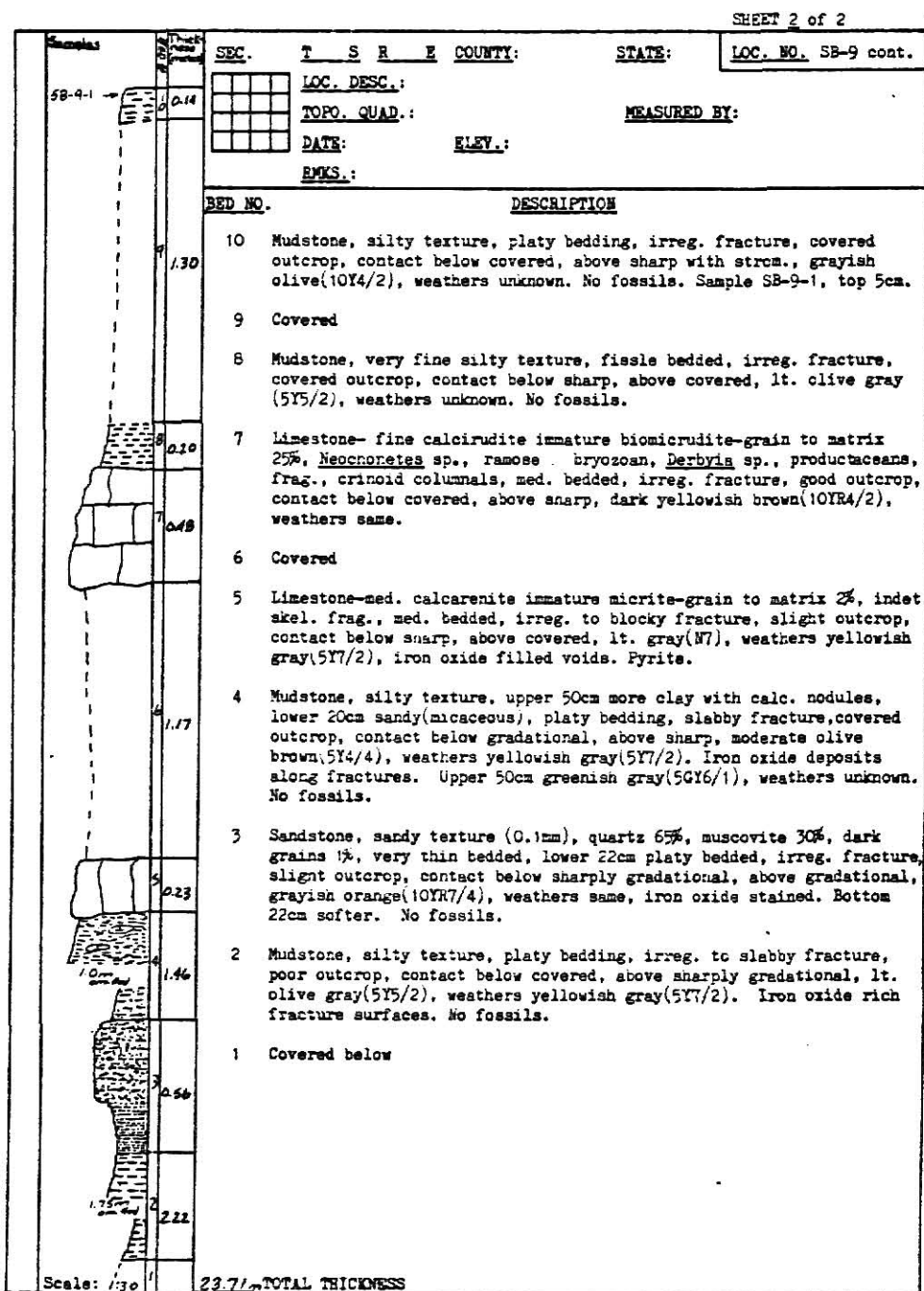
SHEET 2 of 2

Samples		SEC. T S R E COUNTY: STATE: LOC. NO. SB-6 (cont)											
LOC. DESC.: TOPO. QUAD.: DATE: ELEV.: RMKS.:		MEASURED BY:											
		<table border="1"> <thead> <tr> <th>BED NO.</th> <th>DESCRIPTION</th> </tr> </thead> <tbody> <tr> <td>4</td> <td>Limestone-fine calcirudite immature biomicrudite-grain to matrix 40%, crinoid columnals, fenestrate bryozoans, ramose bryozoan, <i>Neospirifer</i> sp., <i>Neocnometes</i> sp., <i>Linoproductus</i> sp., <i>Derbyia</i> sp., med. bedded, irreg. fracture, good outcrop, contact below covered, above covered, dark yellowish orange(10YR6/6), weathers same.</td> </tr> <tr> <td>3</td> <td>Covered</td> </tr> <tr> <td>2</td> <td>Limestone-fine calcirudite immature biomicrudite-grain to matrix 40%, crinoid columnals, brachiopods, indet. skel. frag., thick bedded, irreg. fracture, slight outcrop, contact above and below covered, very light gray(N8), weathers lt. gray(N7). Iron oxide void fillings.</td> </tr> <tr> <td>1</td> <td>Covered below</td> </tr> </tbody> </table>		BED NO.	DESCRIPTION	4	Limestone-fine calcirudite immature biomicrudite-grain to matrix 40%, crinoid columnals, fenestrate bryozoans, ramose bryozoan, <i>Neospirifer</i> sp., <i>Neocnometes</i> sp., <i>Linoproductus</i> sp., <i>Derbyia</i> sp., med. bedded, irreg. fracture, good outcrop, contact below covered, above covered, dark yellowish orange(10YR6/6), weathers same.	3	Covered	2	Limestone-fine calcirudite immature biomicrudite-grain to matrix 40%, crinoid columnals, brachiopods, indet. skel. frag., thick bedded, irreg. fracture, slight outcrop, contact above and below covered, very light gray(N8), weathers lt. gray(N7). Iron oxide void fillings.	1	Covered below
BED NO.	DESCRIPTION												
4	Limestone-fine calcirudite immature biomicrudite-grain to matrix 40%, crinoid columnals, fenestrate bryozoans, ramose bryozoan, <i>Neospirifer</i> sp., <i>Neocnometes</i> sp., <i>Linoproductus</i> sp., <i>Derbyia</i> sp., med. bedded, irreg. fracture, good outcrop, contact below covered, above covered, dark yellowish orange(10YR6/6), weathers same.												
3	Covered												
2	Limestone-fine calcirudite immature biomicrudite-grain to matrix 40%, crinoid columnals, brachiopods, indet. skel. frag., thick bedded, irreg. fracture, slight outcrop, contact above and below covered, very light gray(N8), weathers lt. gray(N7). Iron oxide void fillings.												
1	Covered below												
Scale: 1/30		6.20m TOTAL THICKNESS											

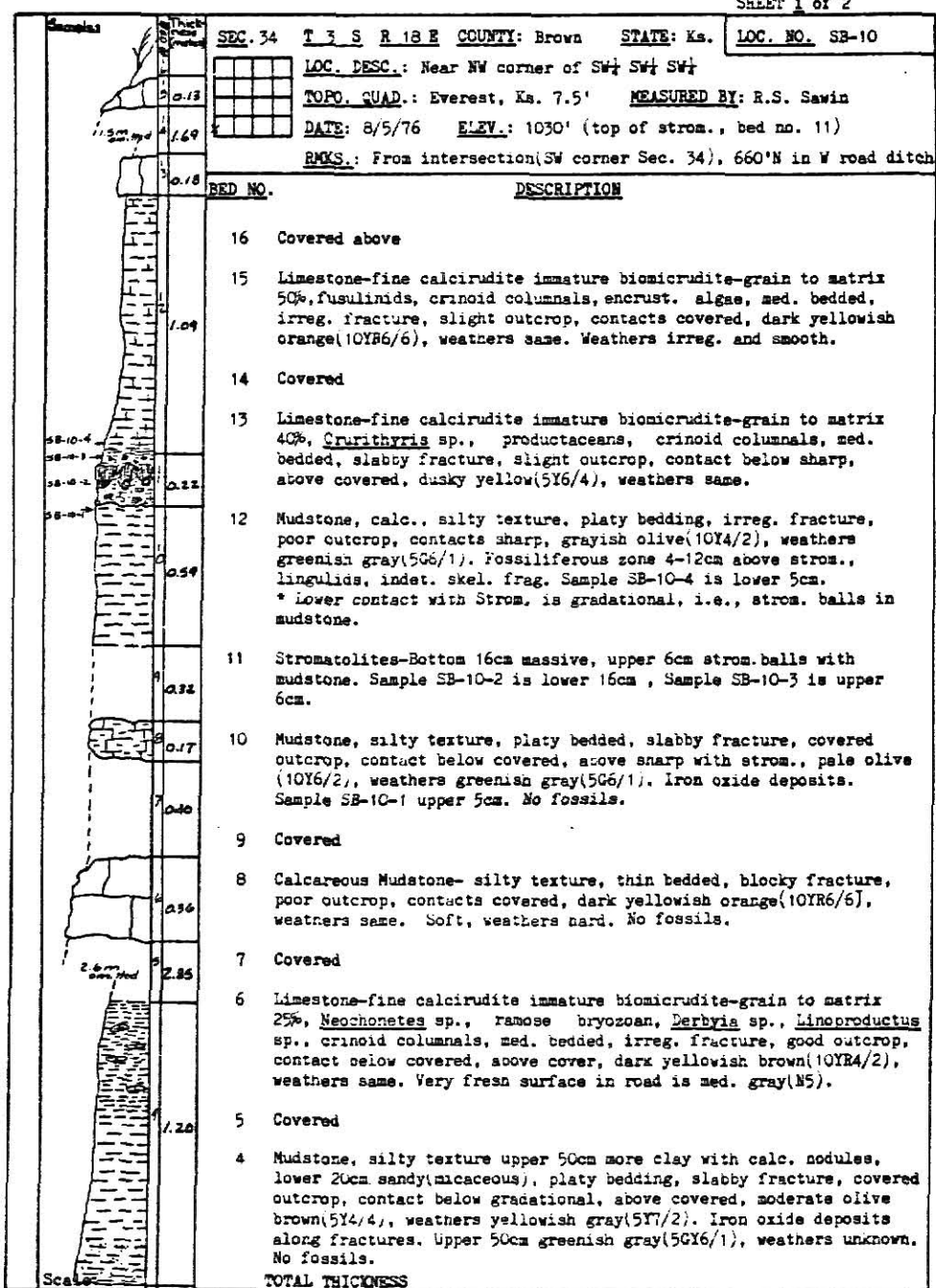








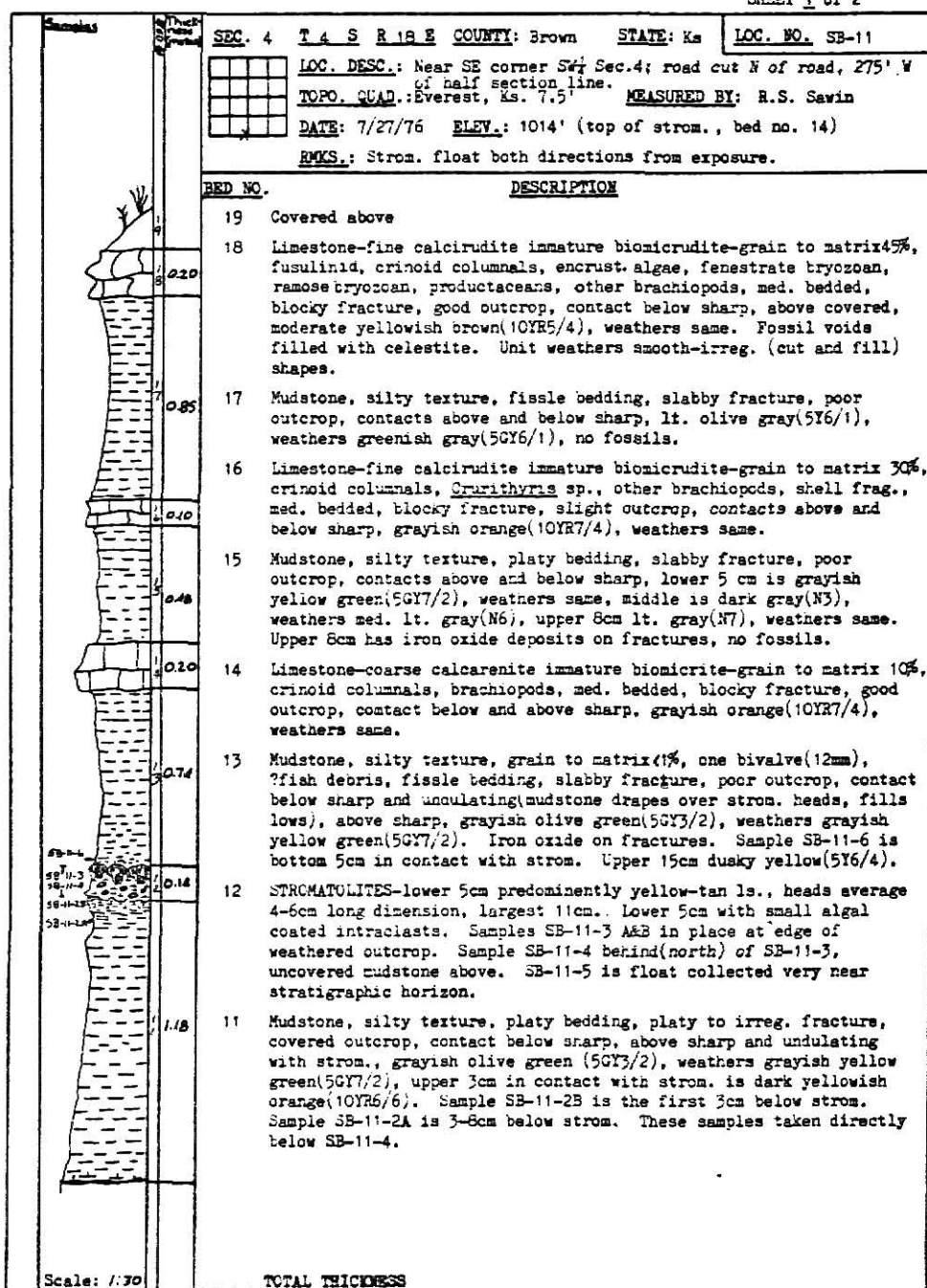
SHEET 1 of 2



SHEET 2 of 2

Sample:		SEC. T S R E COUNTY: STATE: LOC. NO. SB-10 (cont)
		LOC. DESC.: TOPO. QUAD.: MEASURED BY: DATE: ELEV.: RMKS.:
BED NO.	DESCRIPTION	
3	Sandstone, sandy texture(0.1mm), quartz 65%, muscovite 30%, dark grains 1%, very thin bedded, lower 22 cm platy bedded, irreg. fracture, slight outcrop, contact below sharply gradational, above gradational, grayish orange(10YR7/4), weathers same, iron oxide stained. Bottom 22cm softer. No fossils.	
2	Mudstone, silty texture, platy bedding, irreg. to slabby fracture, poor outcrop, contact below covered, above sharply gradational, lt. olive gray(5Y5/2), weathers yellowish gray(5Y7/2). Iron oxide rich fracture surfaces. No fossils.	
1	Covered below	
Scale: 1:30		11.9m TOTAL THICKNESS

SHEET 1 of 2



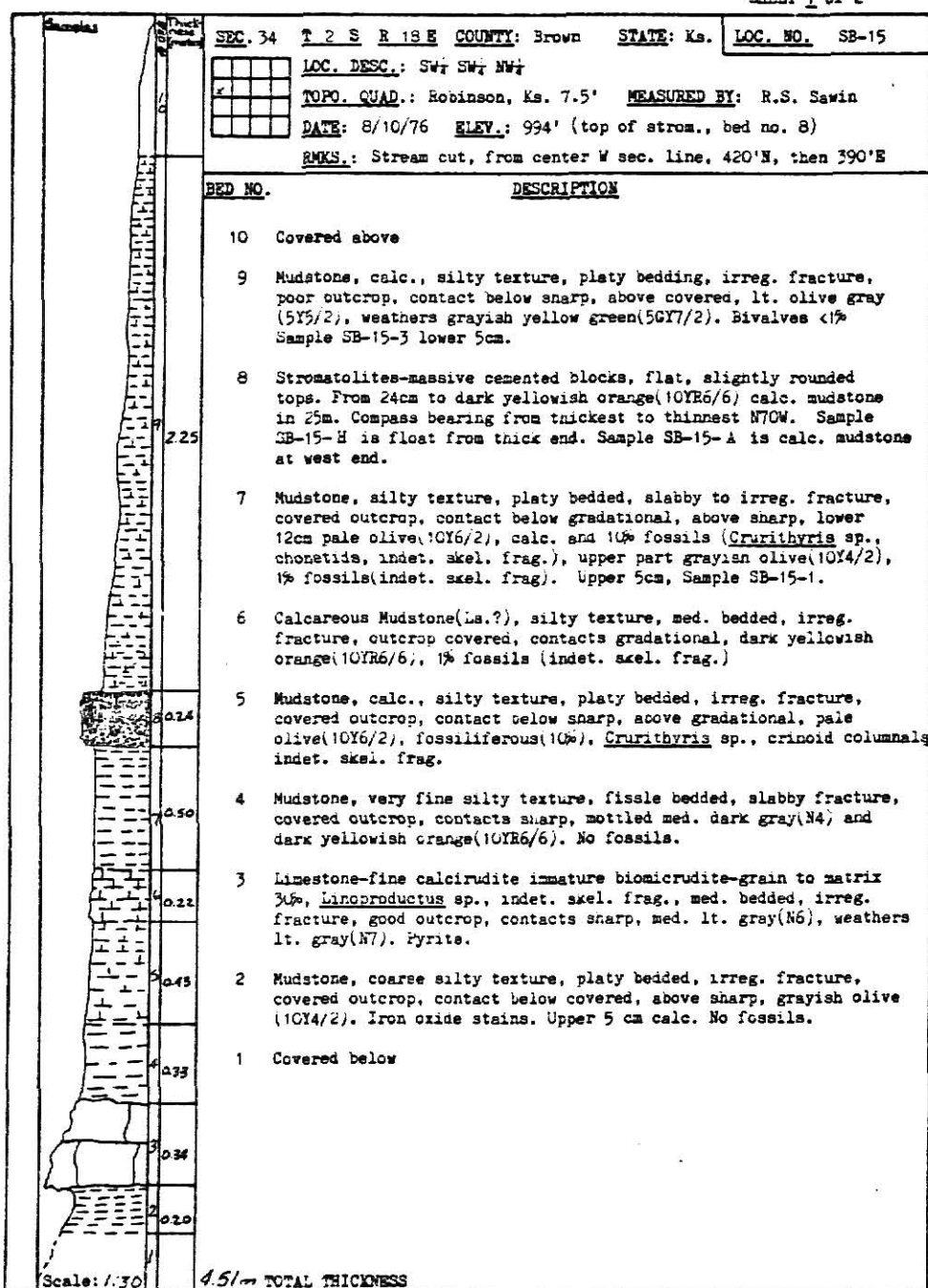
SHEET 2 of 2

SEC. <u> </u> T <u> </u> S <u> </u> R <u> </u> E COUNTY: <u> </u> STATE: <u> </u> LOC. NO. SB-11con't.	
LOC. DESC.: TOPO. QUAD.: DATE: <u> </u> ELEV.: <u> </u> RMKS.: <u> </u> MEASURED BY: <u> </u>	
BED NO.	DESCRIPTION
10	Limestone, ferruginous-fine calcirudite immature biomicrudite-grain to matrix 10%, crinoid columnals, ?bivalves, productaceans, med. bedded, irreg. fracture, poor outcrop, contact below gradational, above sharp, dark yellowish orange(10YR6/6), weathers grayish orange (10YR7/4). This unit appears softer when unexposed, gets harder when exposed to weathering. This is similar to mudstones seen in sections without strom. Sample SB-11-1.
9	Mudstone, silty texture, grain to matrix 10%, crinoid columnals, <i>Crurithyris</i> sp., productaceans, <i>Derbyia</i> sp., indet. skel. frag., platy bedding, irreg. fracture, covered outcrop, contact below covered, above gradational. 10cm from top contact is a 3cm calc. zone. Lower 10cm is grayish olive(10Y4/2), weathers unknown, 3cm calc. zone is med. lt. gray(N6), upper 10cm is lt. olive gray(5Y5/2). 3cm calc. zone is much harder than mudstone above and below.
8	Covered
7	Mudstone, very fine silty texture, fissile bedding, irreg. fracture, covered outcrop, contact below sharp, above covered, grayish olive (10Y4/2), weathers pale olive(10Y6/2). No fossils.
6	Limestone, ferruginous-fine calcirudite immature biomicrudite, grain to matrix 10%, brachiopods (<i>Neochonetes</i> sp., <i>Juresania</i> sp., <i>Derbyia</i> sp.), pectens, crinoid columnals, fenestrate bryozoan, ramose bryozoan, very thin bedded (cut and fill bedding), irreg. fracture, slight outcrop, contact below sharp and undulating, above sharp, dark yellowish orange(10YR6/6), weathers grayish orange(10YR7/4). One joint set N55°E, vertical.
5	Mudstone, upper 5cm calc., silty texture, platy to irreg. bedding, irreg. fracture, covered outcrop, contact below covered, contact above undulating but sharp, olive gray(5Y3/2), weathers unknown, upper 5cm lt. olive gray(5Y5/2), weathers unknown. Thin (1mm) carbonaceous layer separates color change at 5cm from top. No fossils.
4	Covered
3	Limestone-fine calcarenite immature micrite-grain to matrix <1%, ostracodes?, platy bedding, irreg. fracture, poor outcrop, contact below irreg., above covered, lt. gray(N7), weathers very lt. gray(NS), iron oxide, dendrites, celestite in fractures and voids.
2	Mudstone, calc., silty texture, irreg. bedded, irreg. fracture, covered outcrop, contact above irreg., below covered, grayish orange (10YR7/4), weathers unknown. Iron oxide fills voids and fractures. No fossils.
1	Covered below

Scale: 1:30

5.88m TOTAL THICKNESS

SHEET 1 of 2

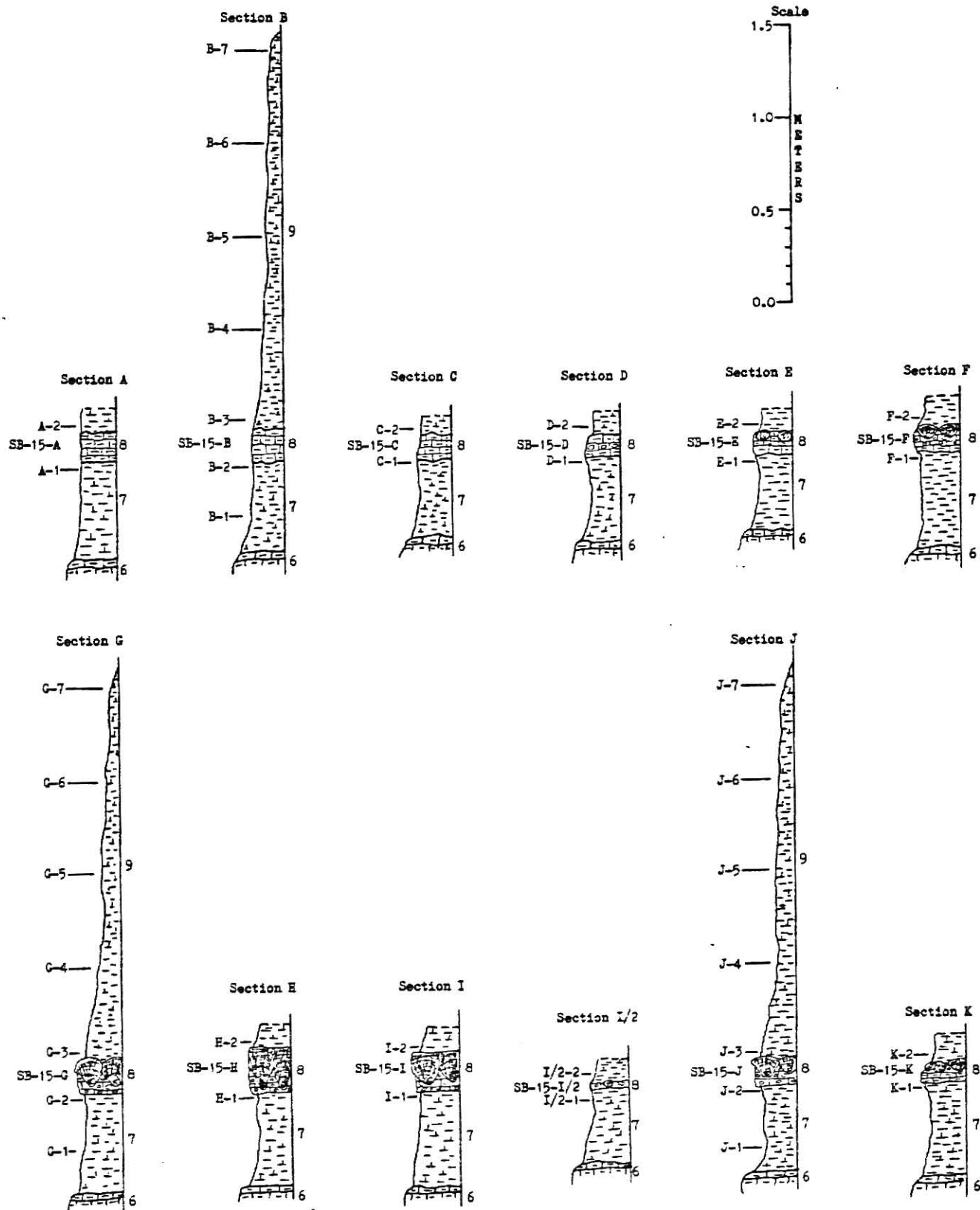


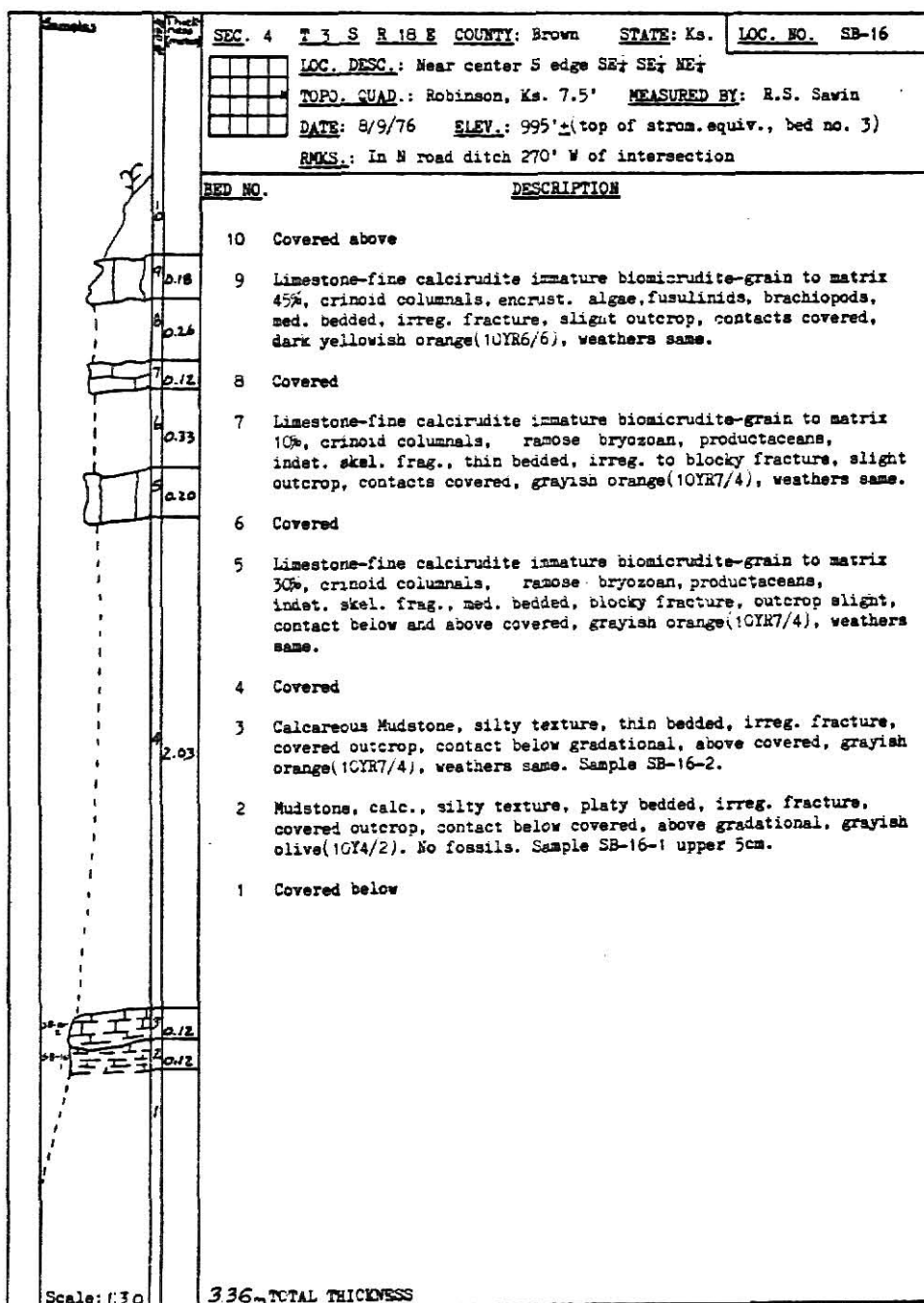
Locality SB-15, Sections A to K

Sections A to H = West Exposure

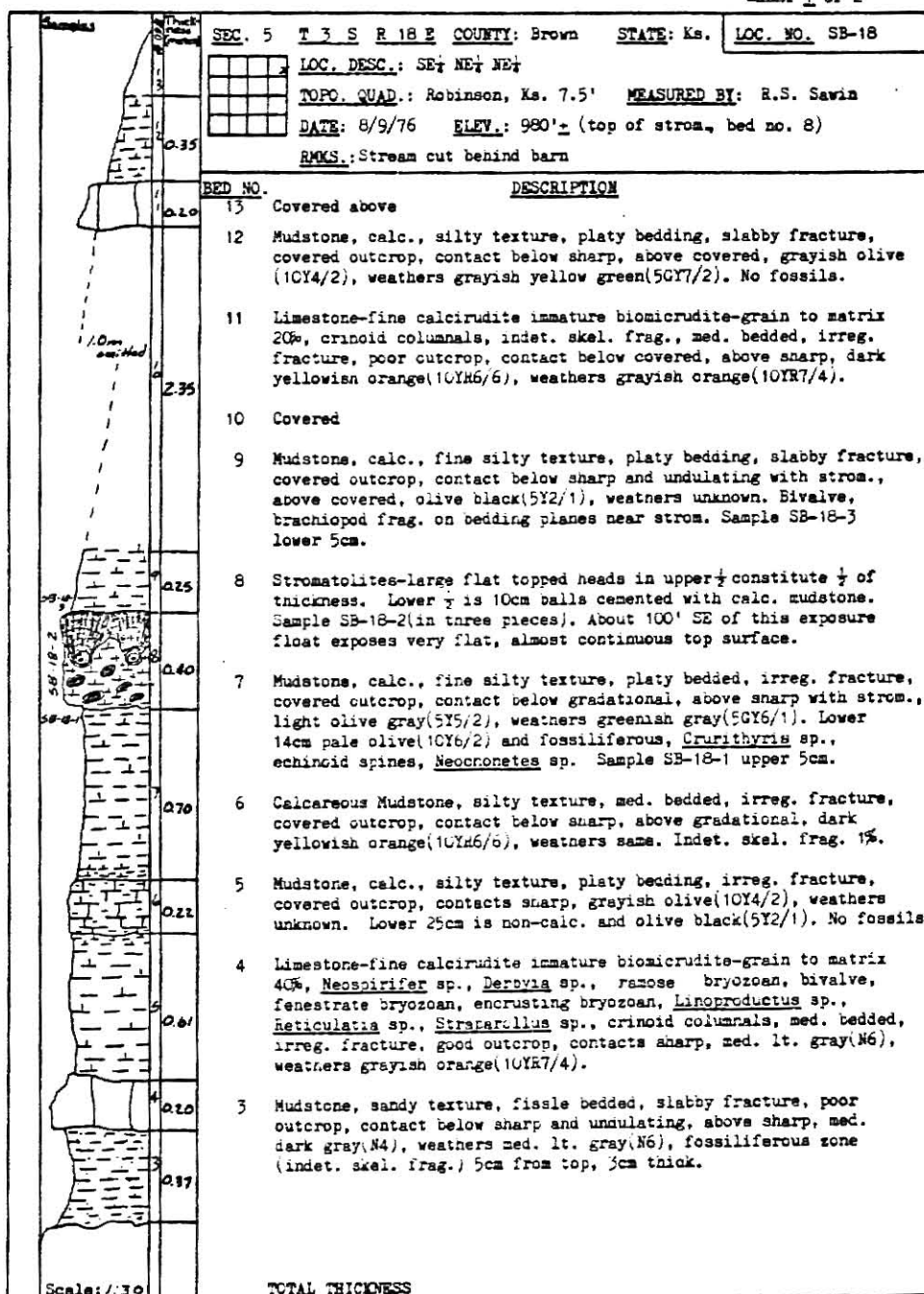
Sections I to K = East Exposure

Refer to Sheet 1 for lithologic descriptions





SHEET 1 of 2

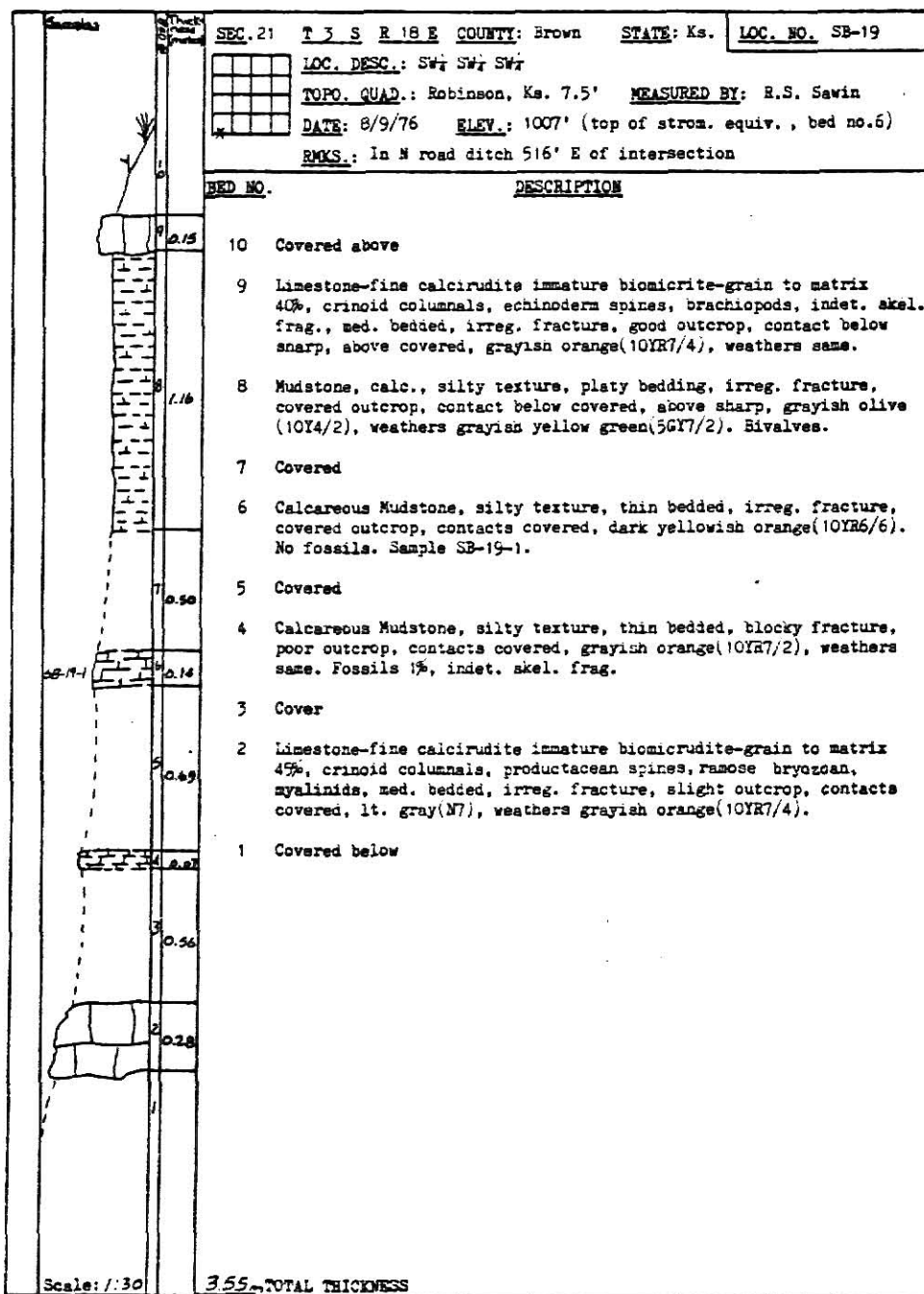


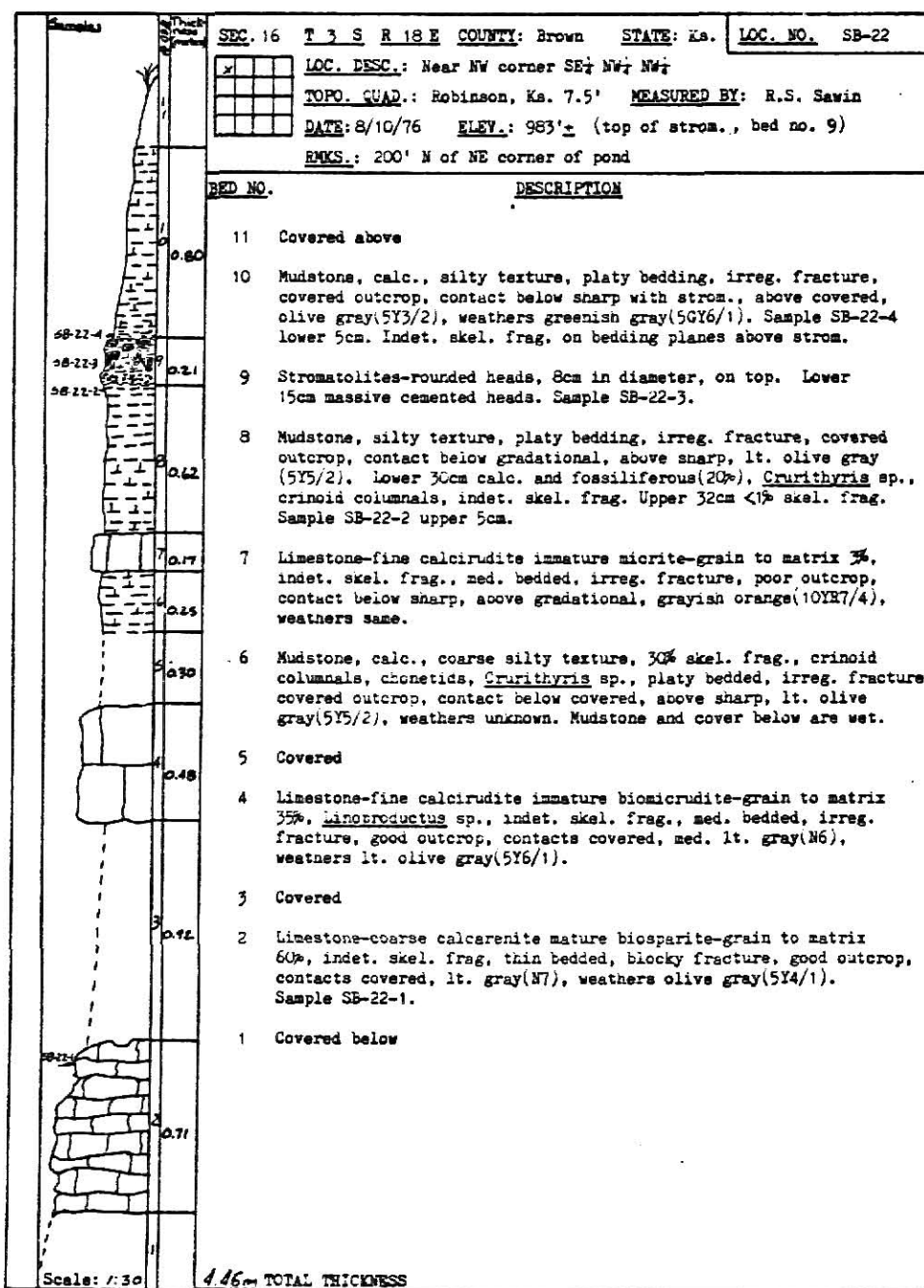
Scale: 1/30

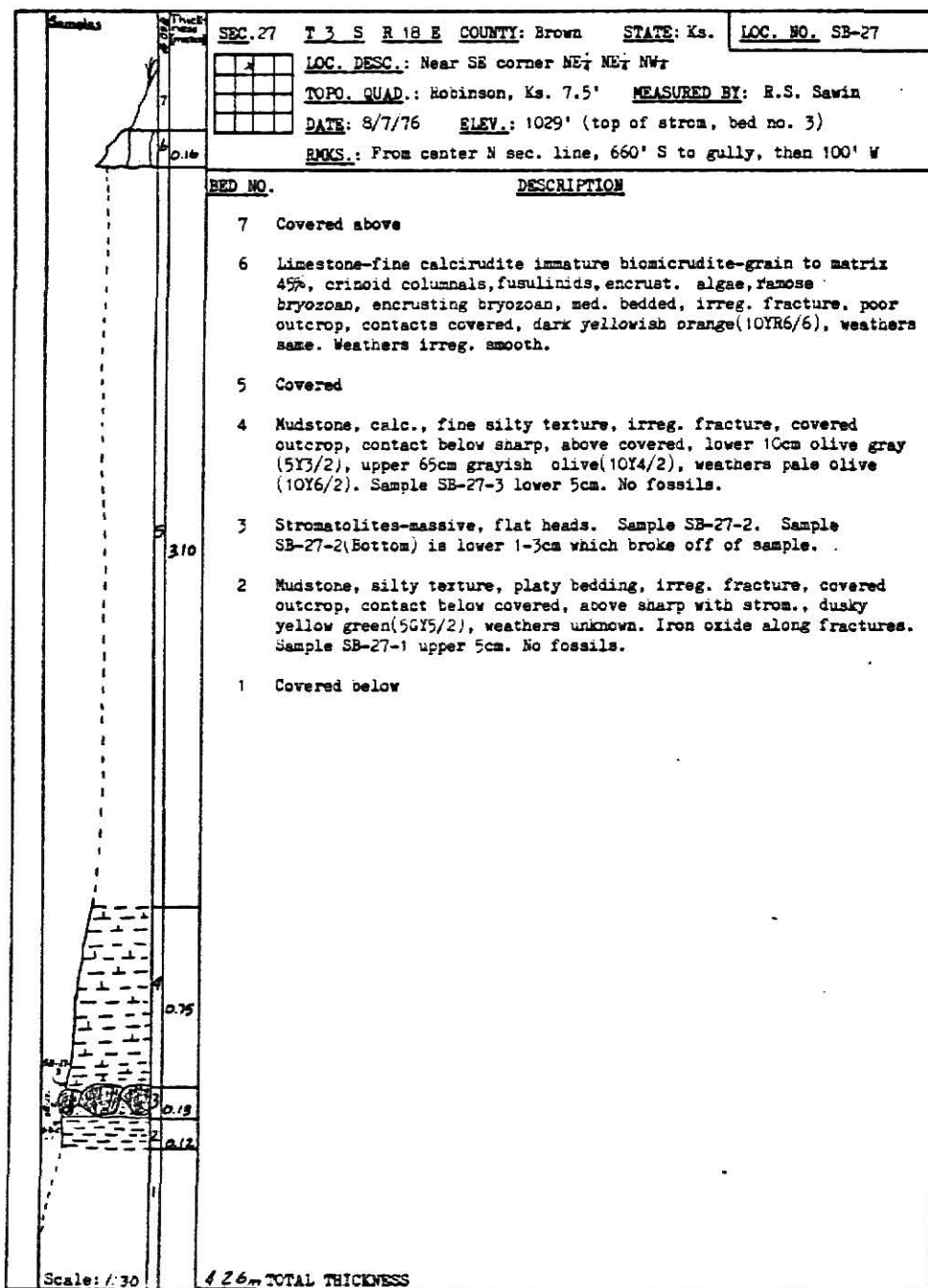
608m TOTAL THICKNESS

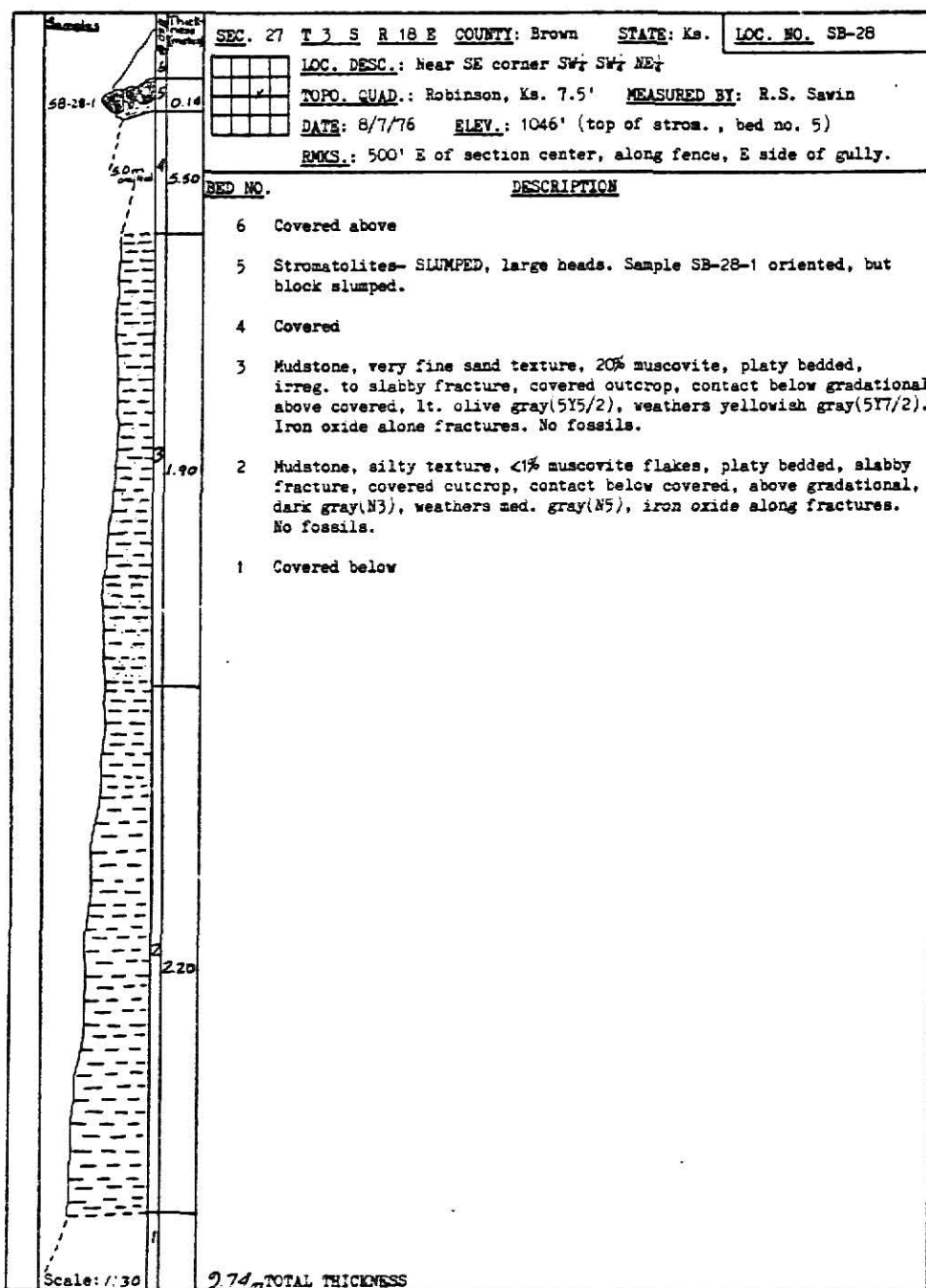
Scale: 1/30

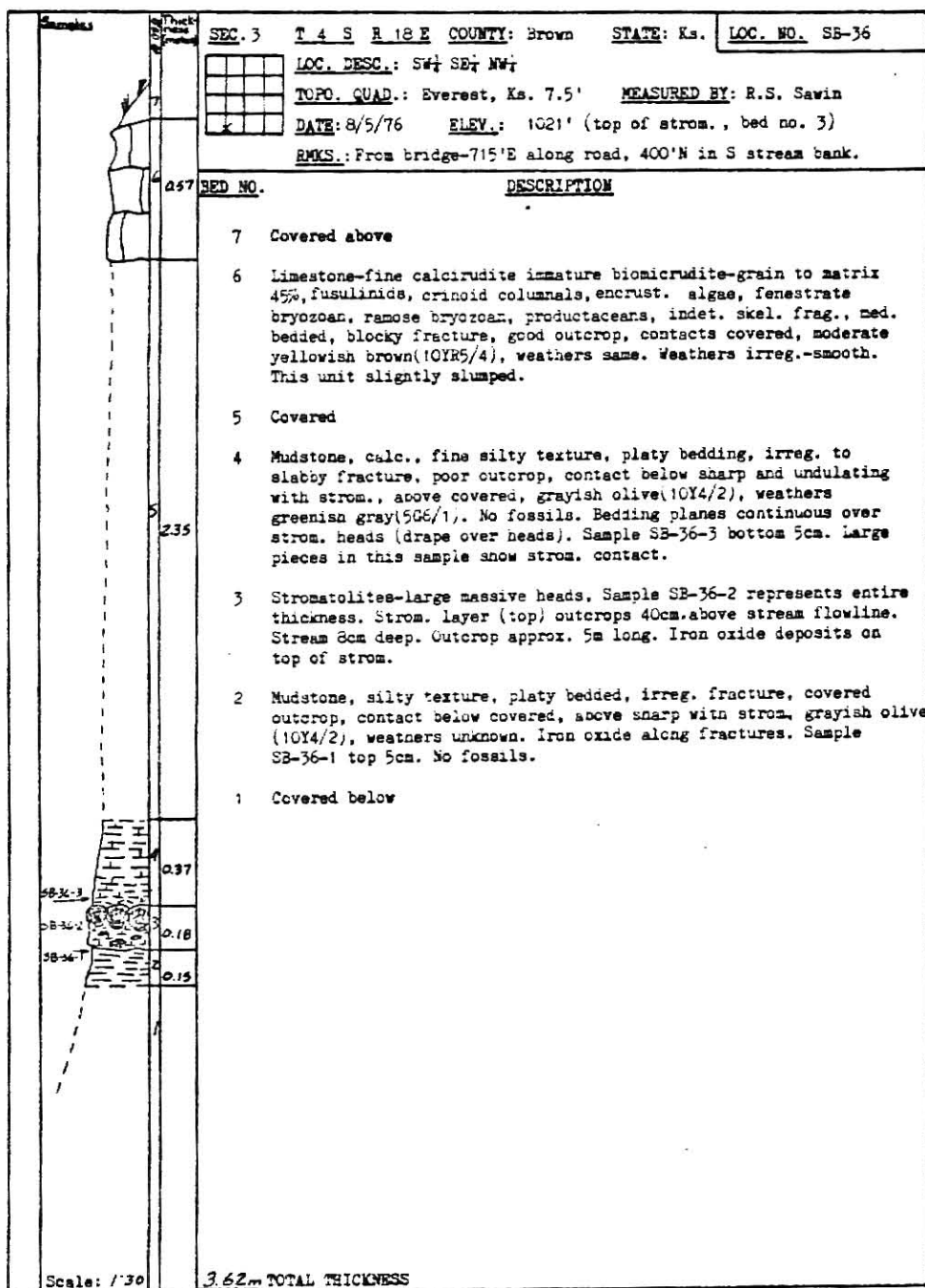
608m TOTAL THICKNESS

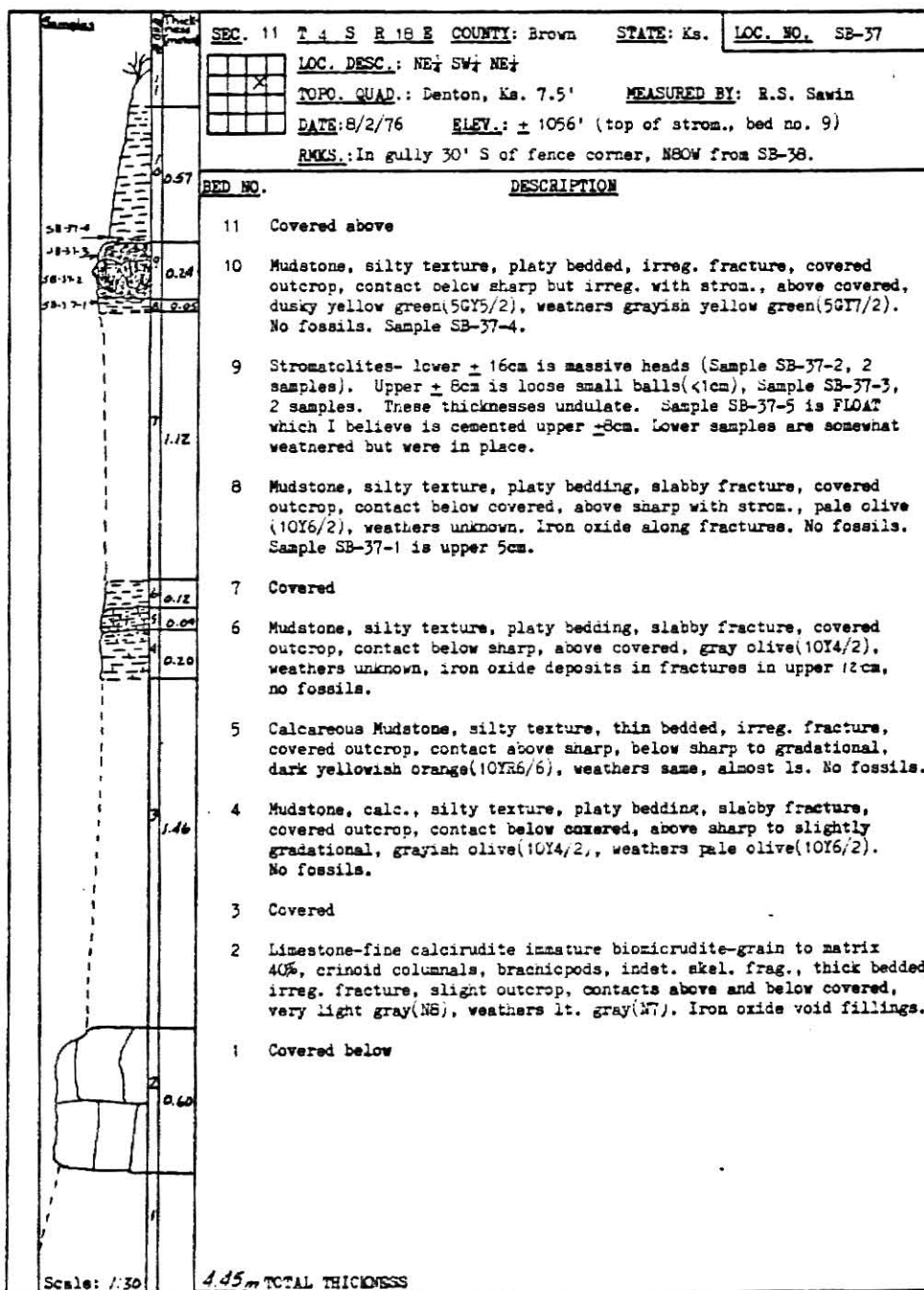


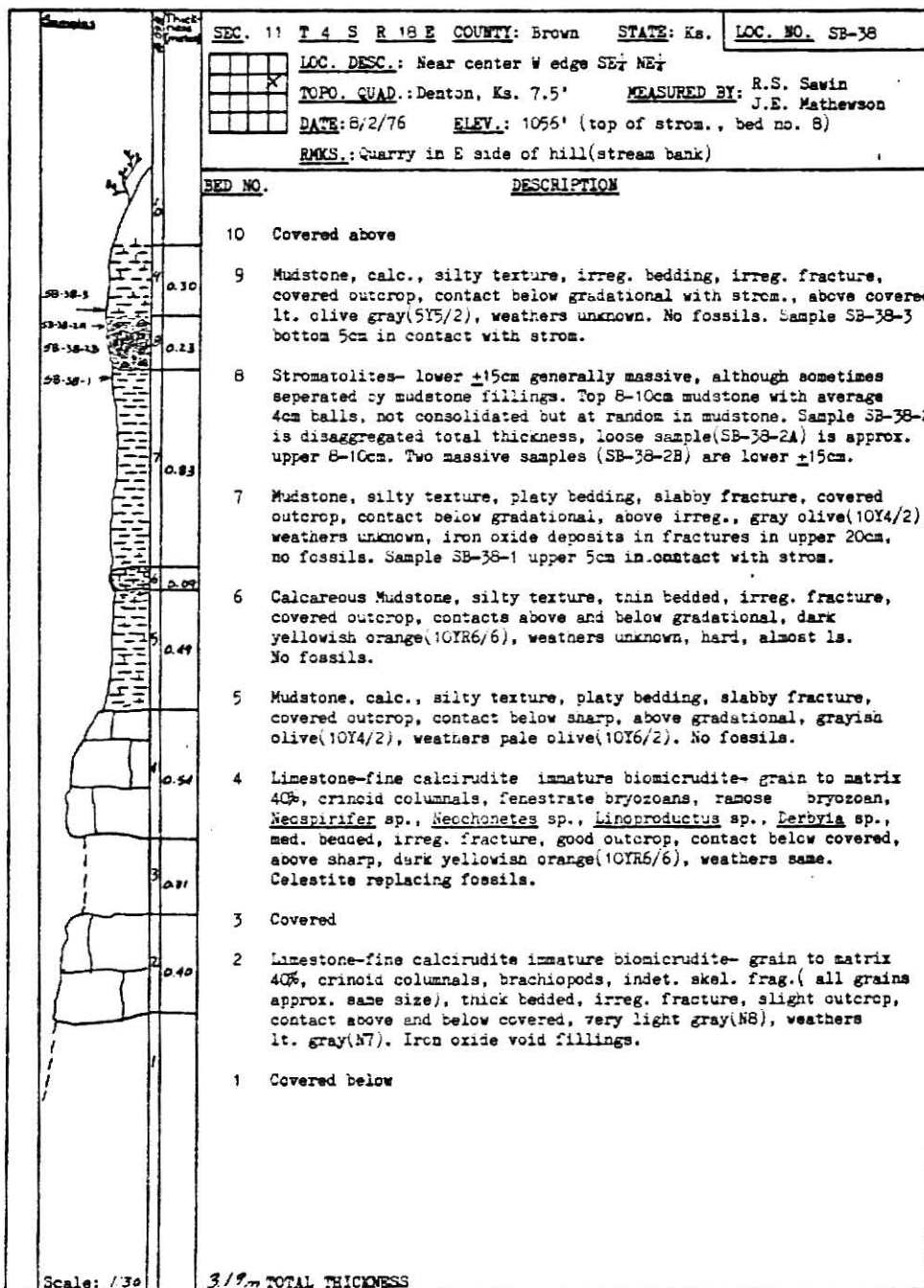


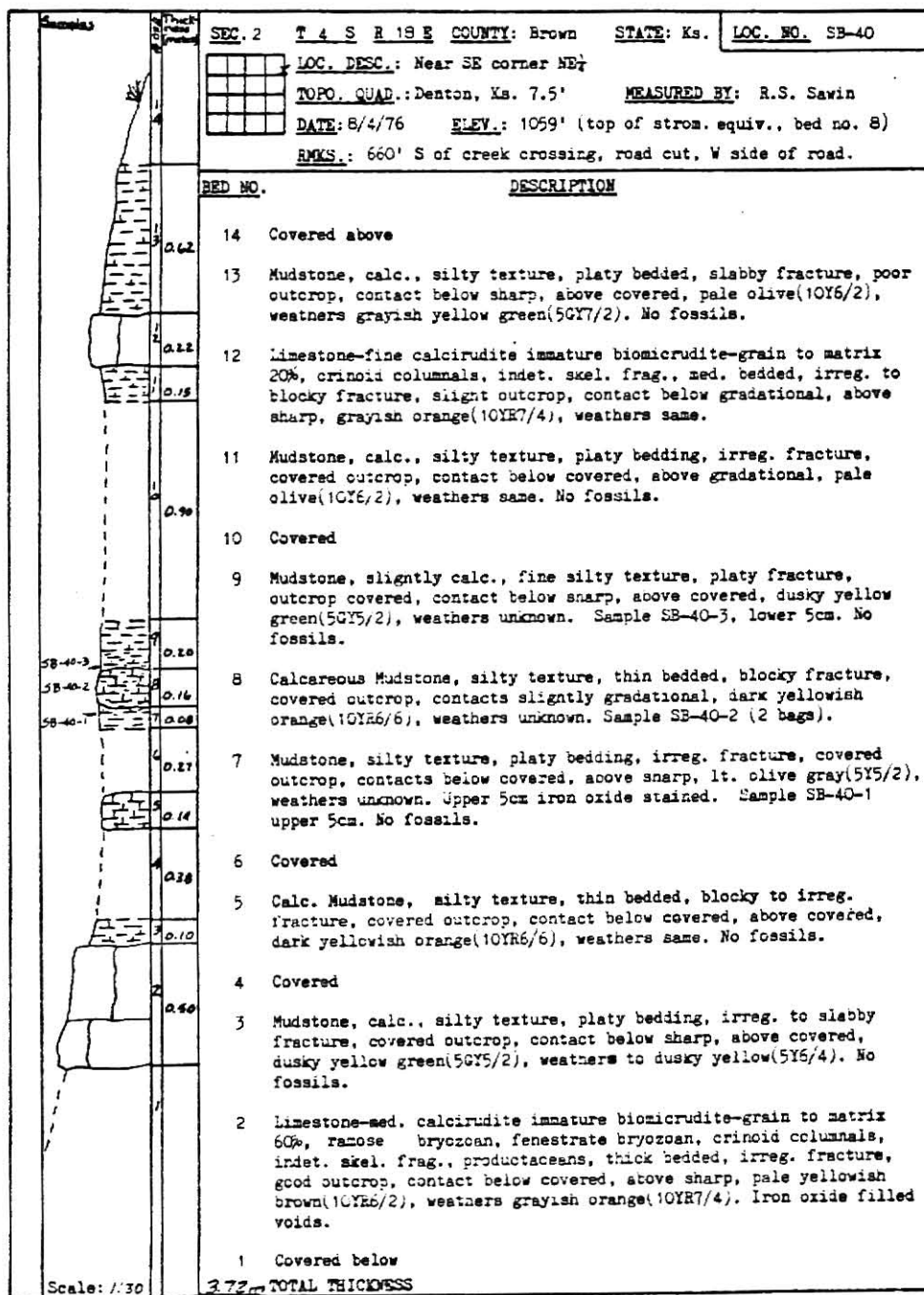


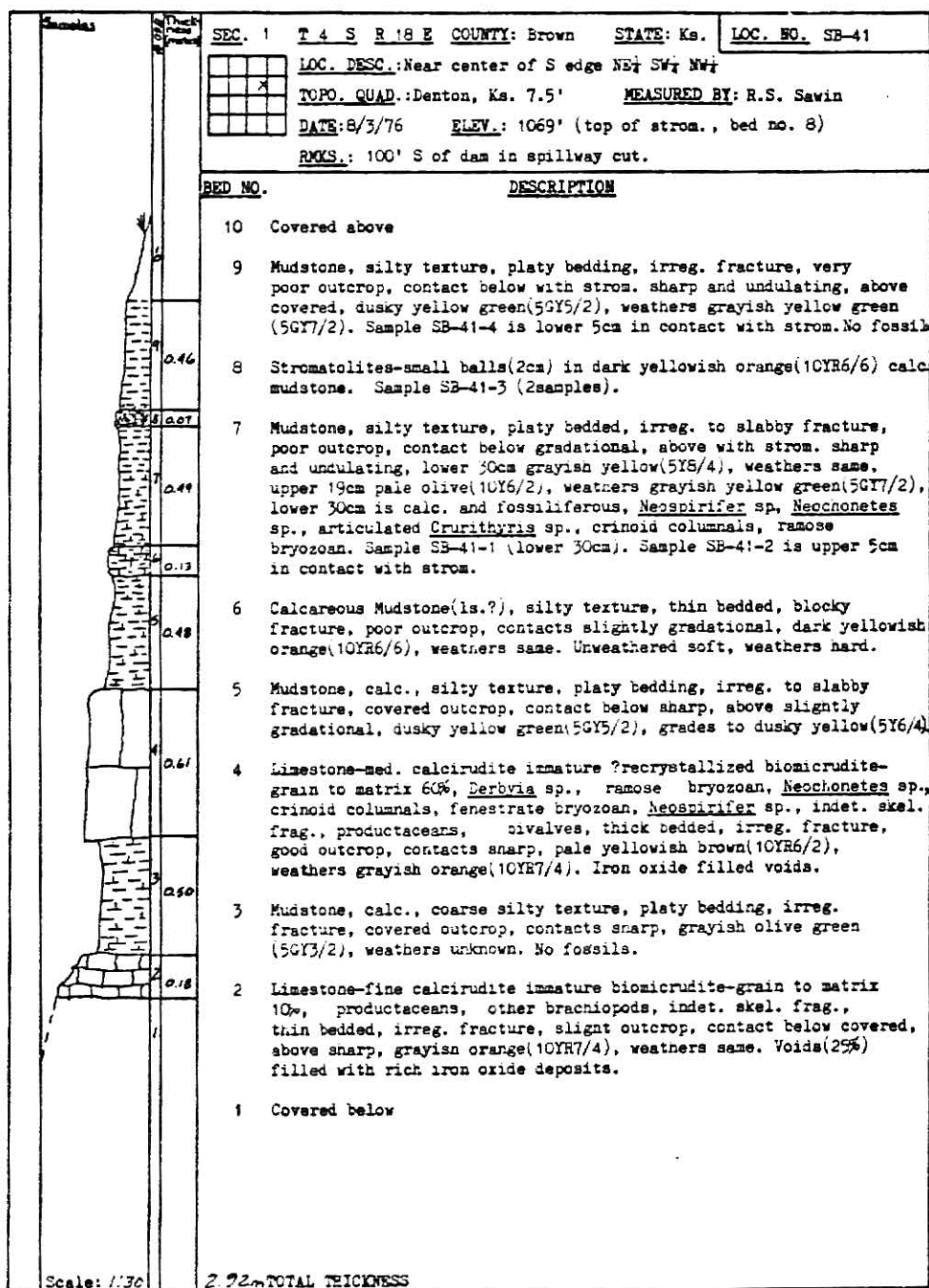


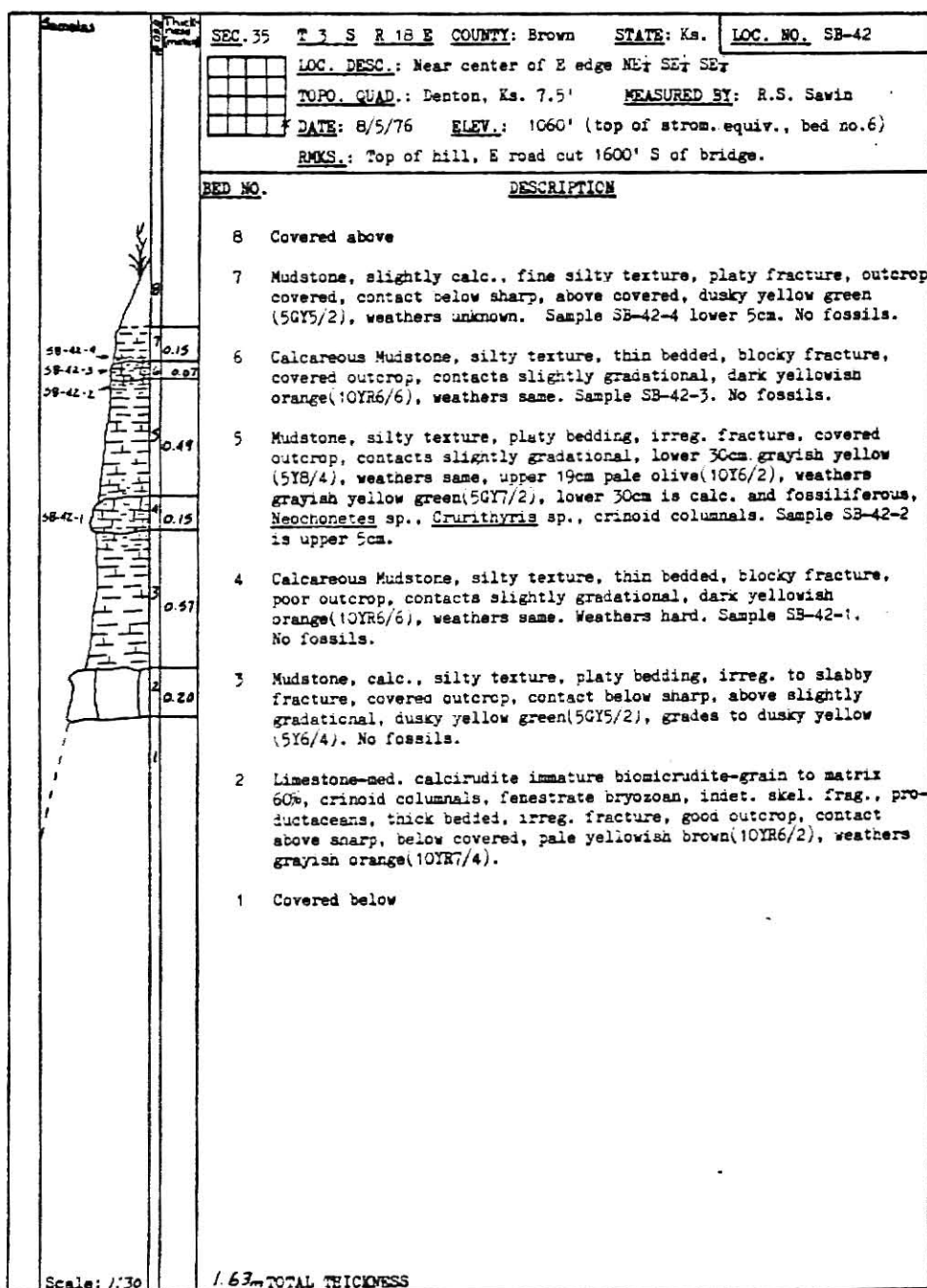


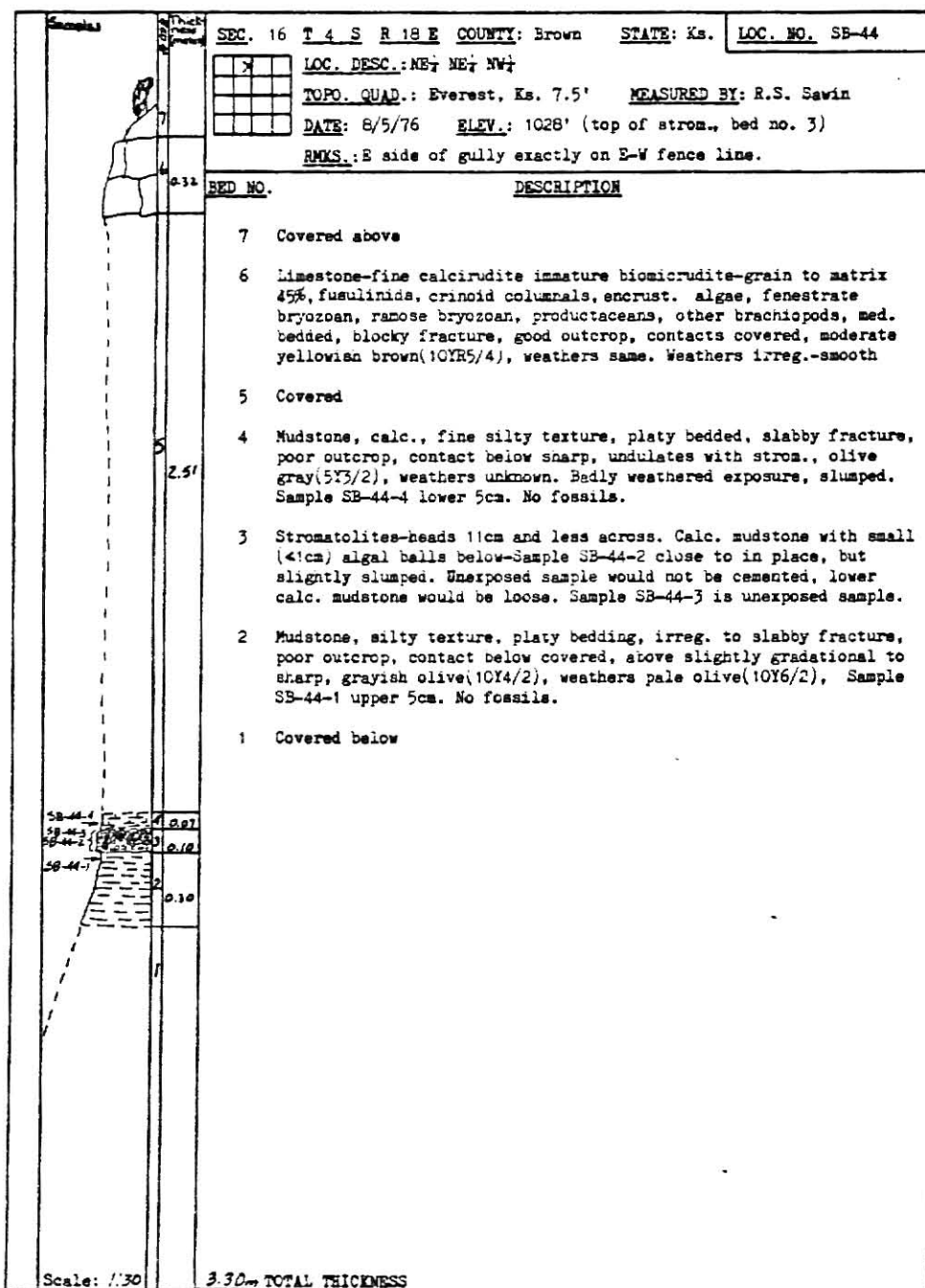




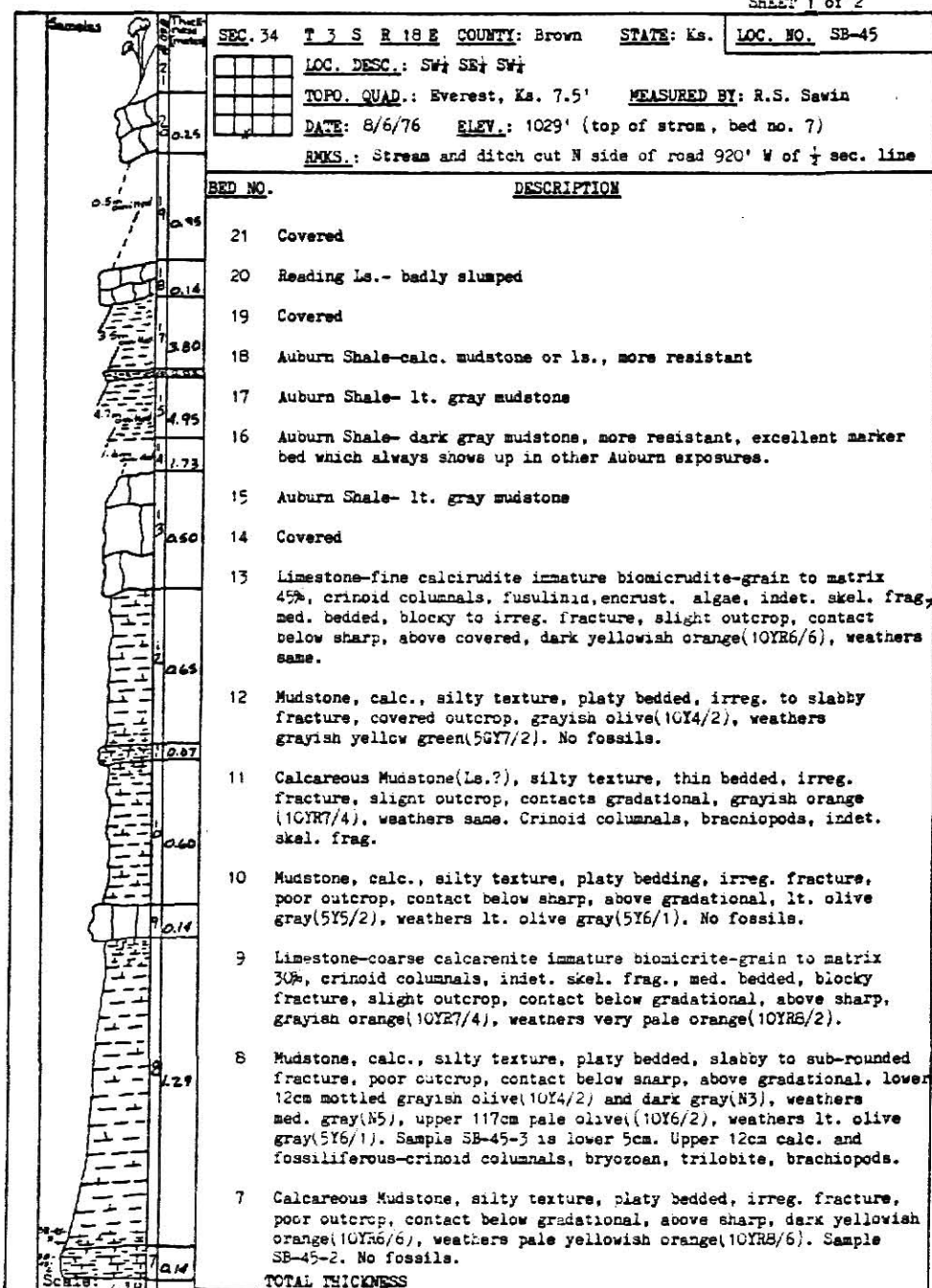








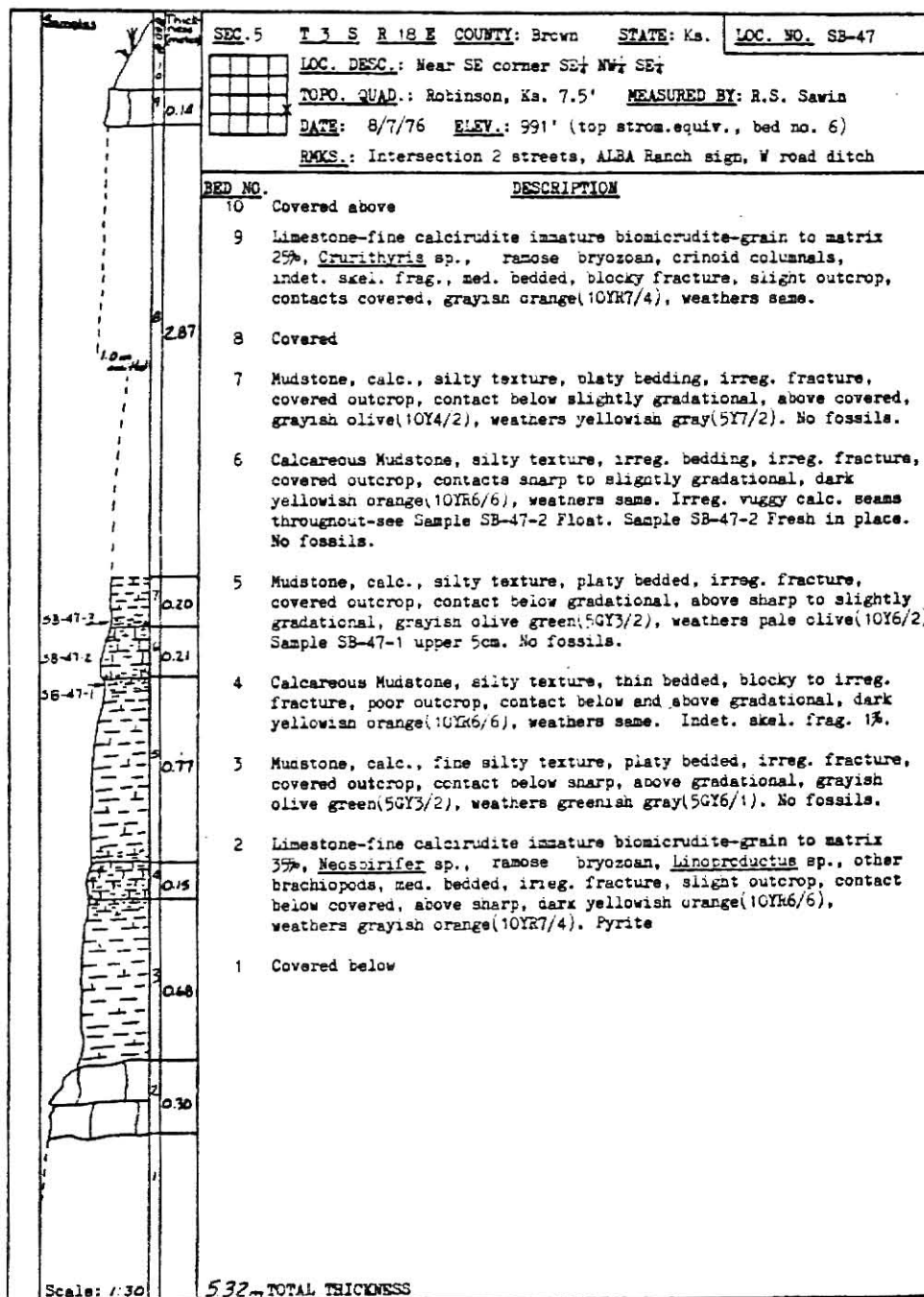
SHEET 1 of 2



SHEET 2 of 2

Samples 		SEC. T S R E COUNTY: STATE: LOC. NO. SB-45(cont.)	
LOC. DESC.: TOPO. QUAD.: DATE: ELEV.: RMKS.:		MEASURED BY:	
BED NO.		DESCRIPTION	
6		Mudstone, silty texture, platy bedding, irreg. fracture, poor outcrop, contact below gradational, above gradational, grayish green(10GY5/2), weathers lt. olive gray(5Y6/1), lower 17cm is calc. and fossiliferous- <i>Crurithyris</i> sp., indet. skel frag., grayish olive (10Y4/2). Sample SB-45-1 upper 5cm.	
5		Limestone(calc. mudstone?)-fine calcirudite immature micrudite-grain to matrix 1%, crinoid columnals, indet. skel. frag., med. bedded, irreg. to blocky fracture, slight outcrop, contact below and above gradational, lt. gray(N7), weathers grayish orange(10YR7/4). In a slumped exposure this unit shows typical characteristics usually observed at this stratigraphic horizon. This unit is unusually hard and faded in color.	
4		Mudstone, calc., silty texture, platy bedding, irreg. fracture, covered outcrop, contact below sharp, above gradational, dusky yellow green(5GY5/2), weathers grayish yellow green(5GY7/2), lower 7cm dark gray(N3), weathers unknown. Lower 7cm non-calc. No fossils.	
3		Limestone-fine calcirudite immature biomicrudite-grain to matrix 40%, crinoid columnals, fenestrate bryozoan, productaceans, bivalves, <i>Linoproductus</i> sp., <i>Straparollus</i> sp., thin bedded, irreg. fracture, good outcrop, contact below transitional, above sharp, lt. gray(N7), weathers dark yellowish orange(10YR6/6).	
2		Mudstone, slightly calc., coarse silty texture, platy bedding, irreg. fracture, covered outcrop, contact below covered, above sharp, grayish olive(10Y4/2), weathers unknown. No fossils.	
1		Covered below	
Scale: 1/30		17.6m TOTAL THICKNESS	

Samples 		SEC. 5 T 3 S R 18 E COUNTY: Brown STATE: Ks. LOC. NO. SB-46 LOC. DESC.: Near SE corner SW 1/4 NE 1/4 SE 1/4 TOPO. QUAD.: Robinson, Ks. 7.5' MEASURED BY: R.S. Sawin DATE: 8/7/76 ELEV.: 985' (top of strom., bed no. 7) RMKS.: Between road and house in N ditch	
BED NO.	DESCRIPTION		
8	Covered above		
7	Stromatolites- very poor exposure, probably slumped. Disaggregated sample SB-46-3. Sample SB-46-1 is float. Maximum float thickness measured is 5cm (Sample SB-46-4).		
6	Mudstone, calc., silty texture, platy bedded, irreg. fracture, covered outcrop, contact below covered, above gradational with strom., grayish olive green (5GY3/2), weathers unknown. Sample SB-46-2. No fossils.		
5	Covered		
4	Calcareous Mudstone, silty texture, thin bedded, blocky fracture, covered outcrop, contacts covered, dark yellowish orange (10YR5/6), weathers same. No fossils.		
3	Covered		
2	Limestone-fine calcirudite immature bioalcrudite-grain to matrix 35%, ramosse bryozoan, <u>Linoproductus</u> sp., brachiopods, indet. skel. frag., med. bedded, irreg. fracture, slight outcrop, contacts covered, dark yellowish orange (10YR5/6), weathers same.		
1	Covered below		
Scale: 1:30 1.48m TOTAL THICKNESS			



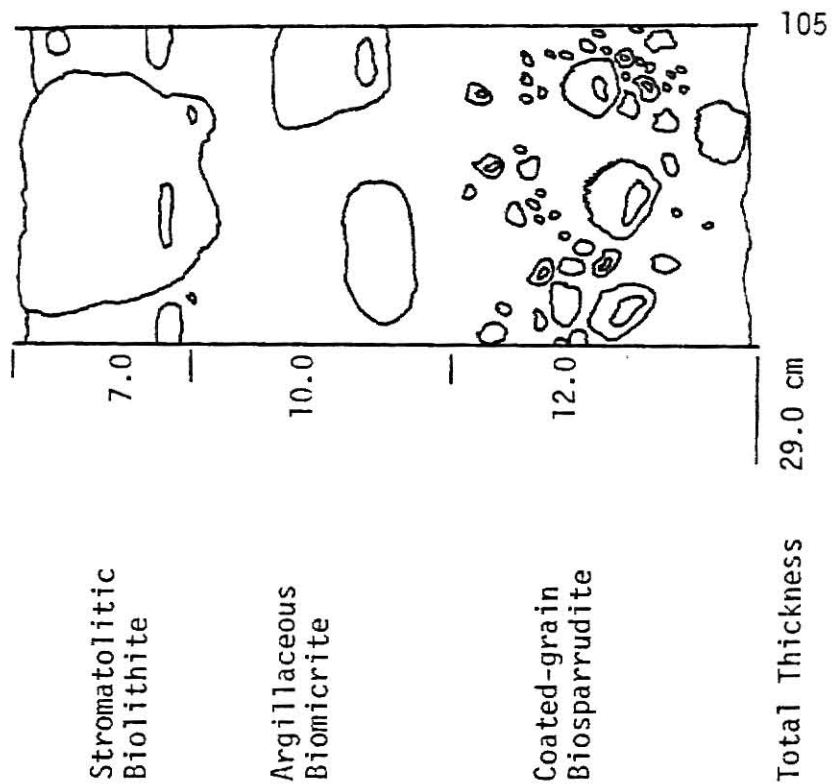
APPENDIX III

Vertical Slabs of the Stromatolite Biostrome

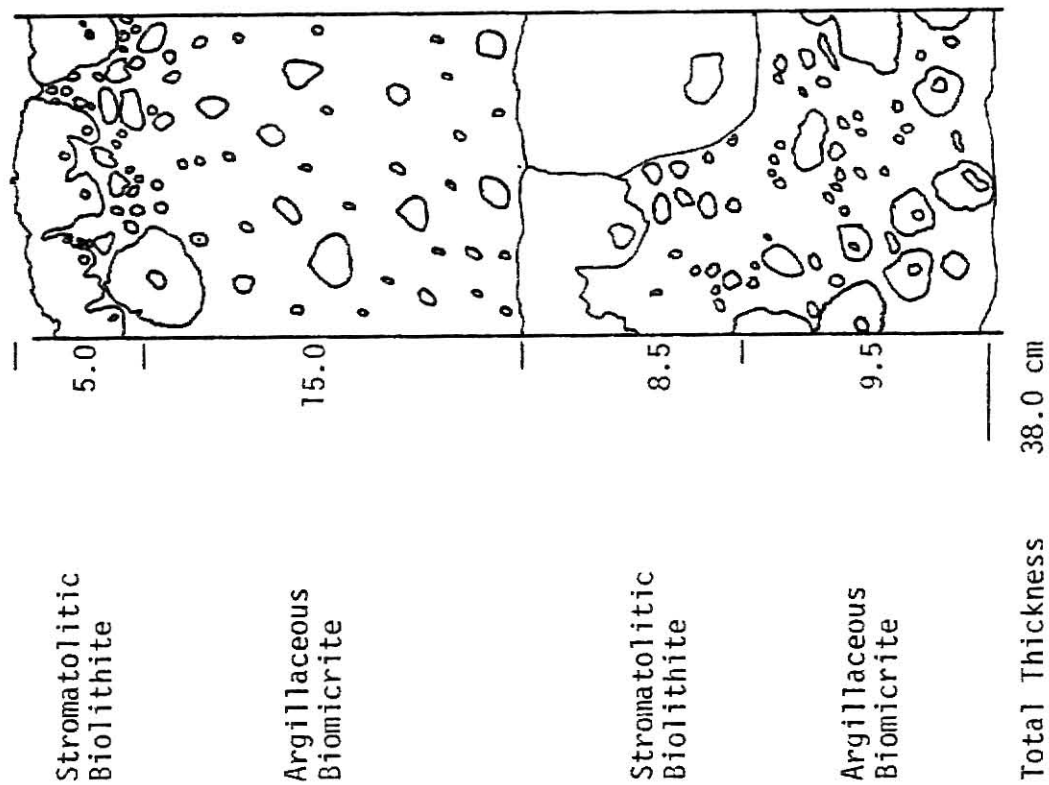
Semi-diagrammatic sketches traced from vertical slabs. Refer to Appendix II for locations.

Scale 1 : 3

LOCALITY SB-5

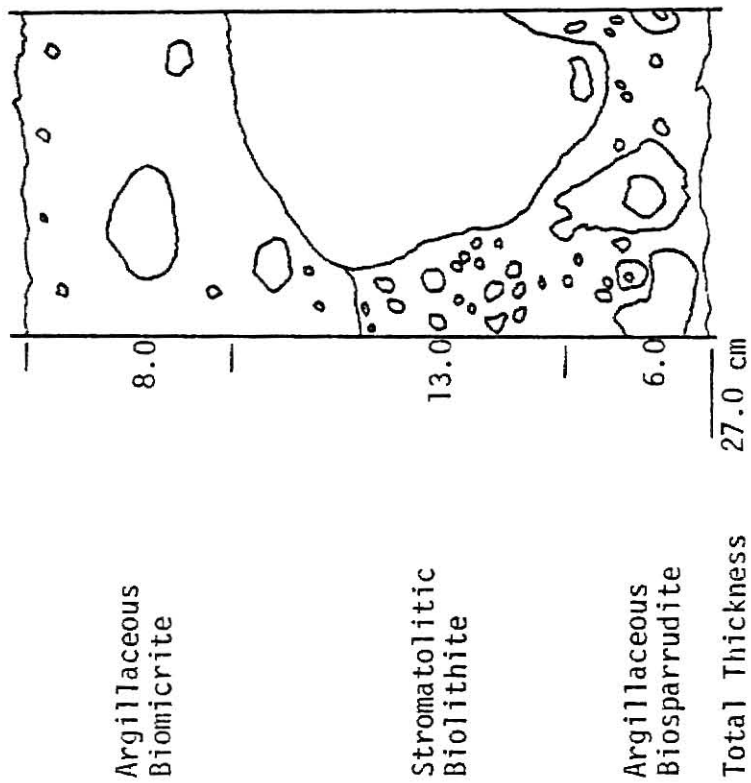


LOCALITY SB-1

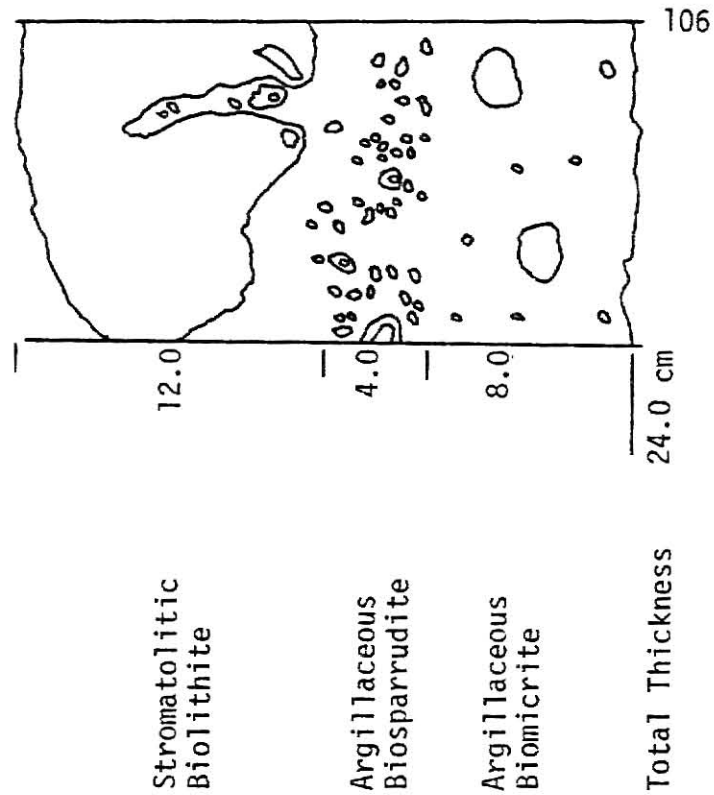


Scale 1 : 3

LOCALITY SB-6

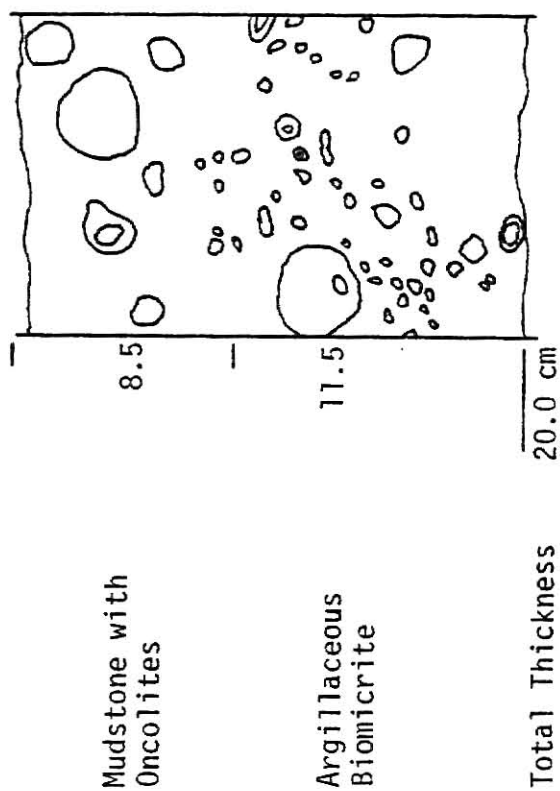
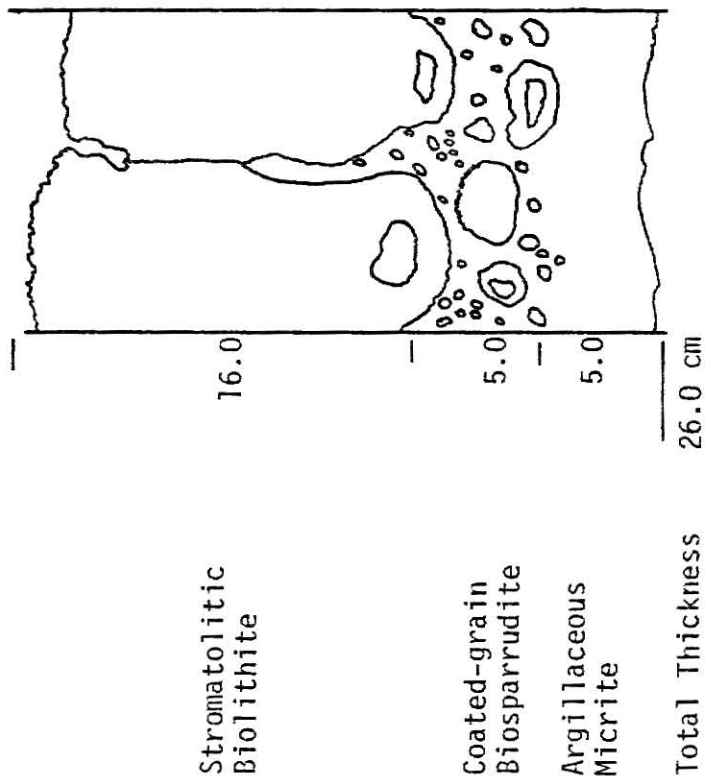


LOCALITY SB-7



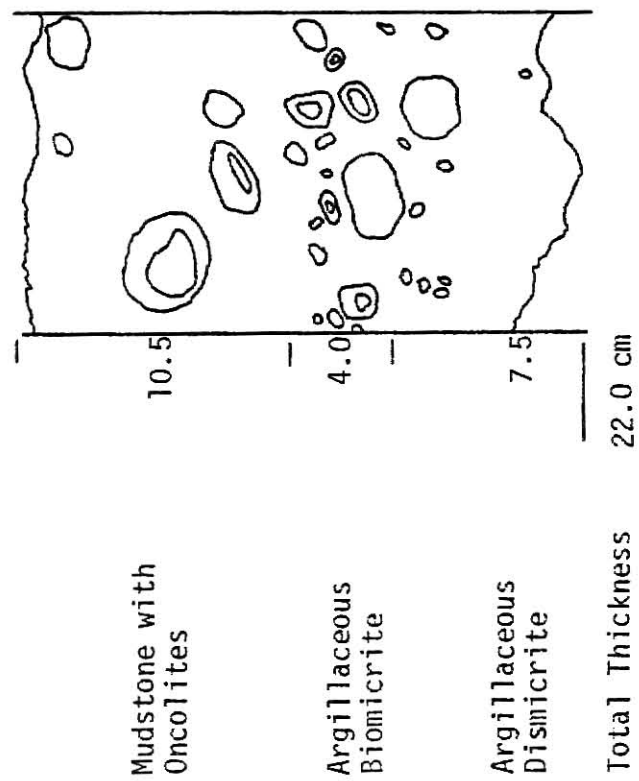
Scale 1 : 3

LOCALITY SB-9

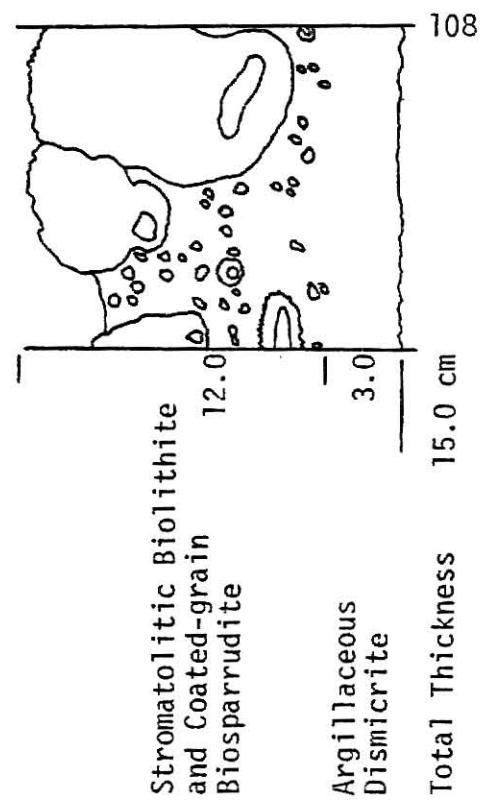


Scale 1 : 3

LOCALITY SB-10



LOCALITY SB-11

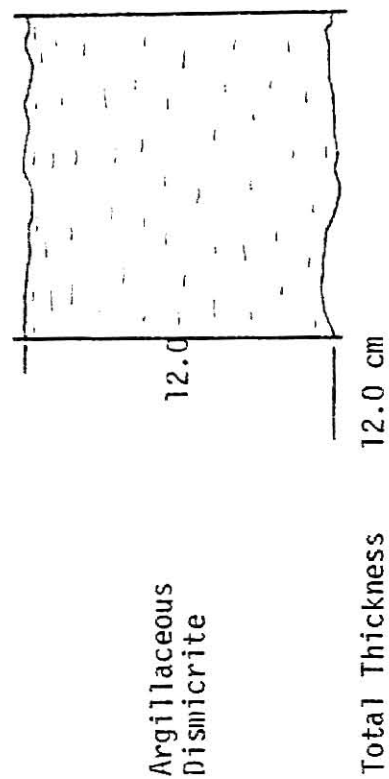
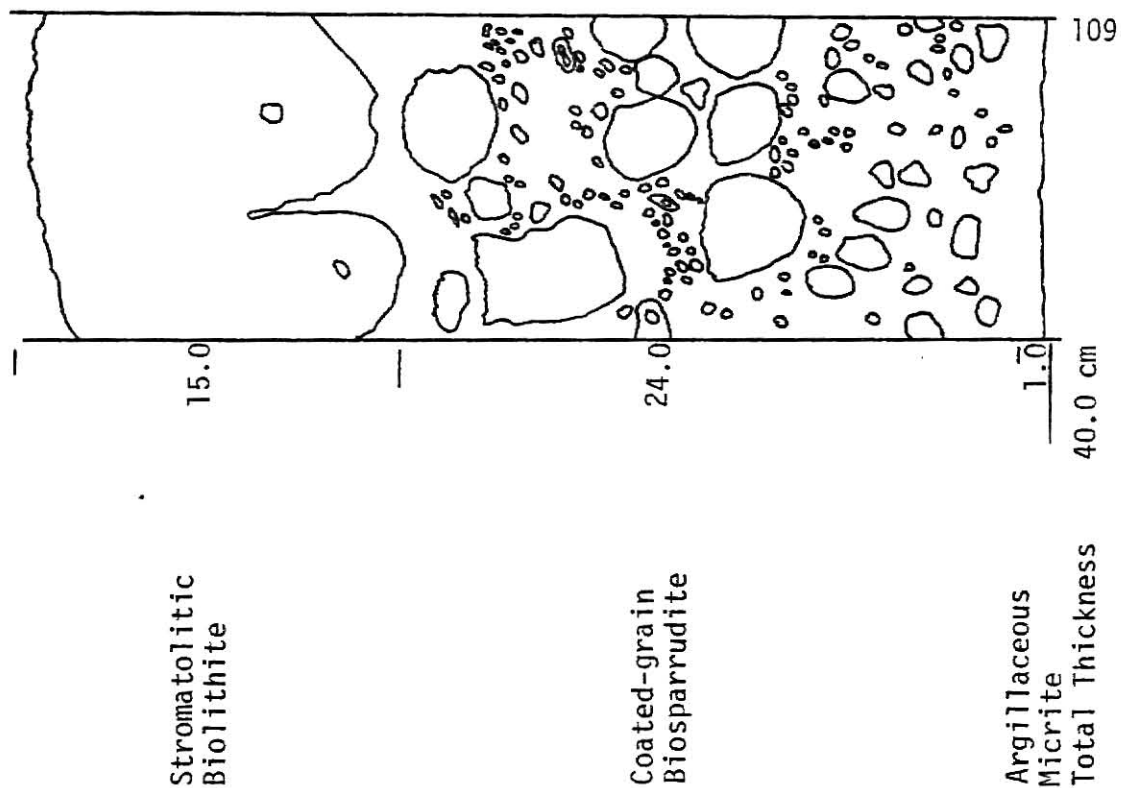


108

Scale 1 : 3

LOCALITY SB-16

LOCALITY SB-18

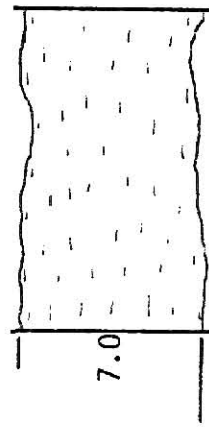


Scale 1 : 3

LOCALITY SB-19

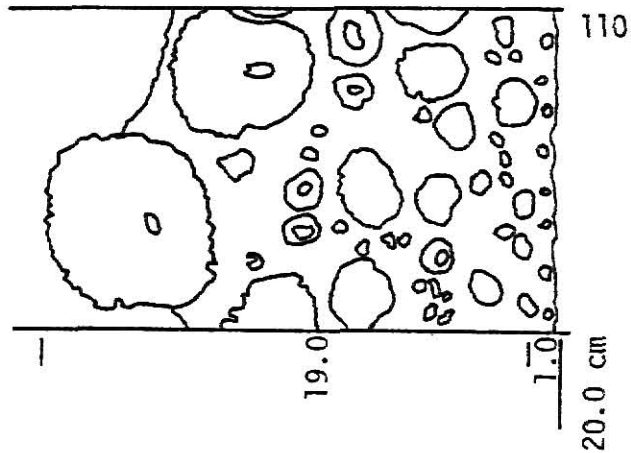
LOCALITY SB-22

Argillaceous
Dismicrite



Total Thickness

Coated-grain
Biosparrudite

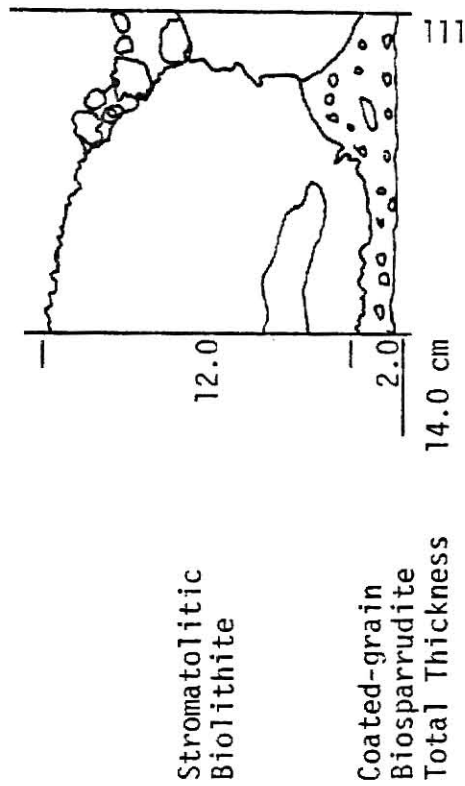
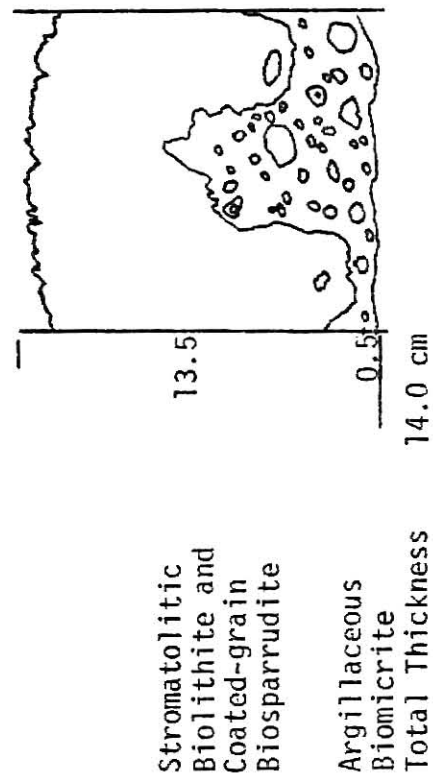


Argillaceous
Biomicroite
Total Thickness

Scale 1 : 3

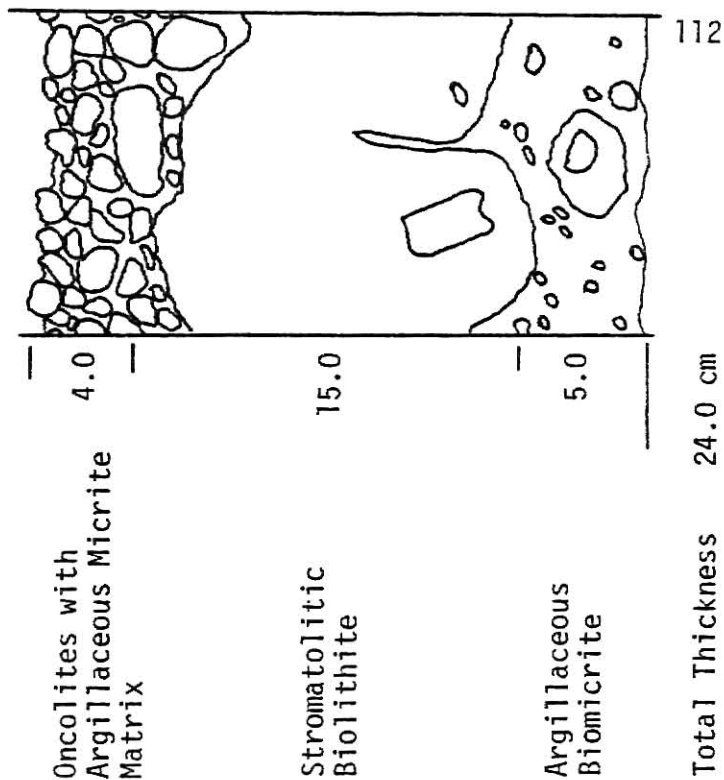
LOCALITY SB-27

LOCALITY SB-28

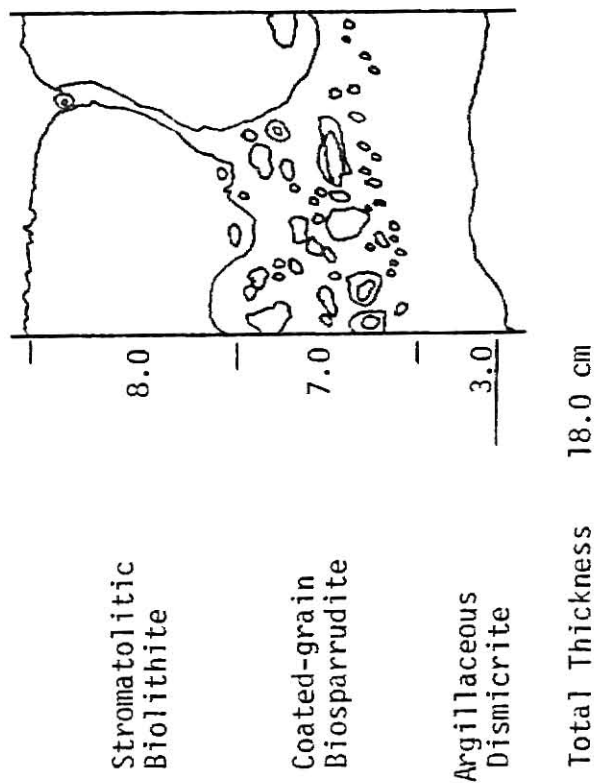


Scale 1 : 3

LOCALITY SB-37

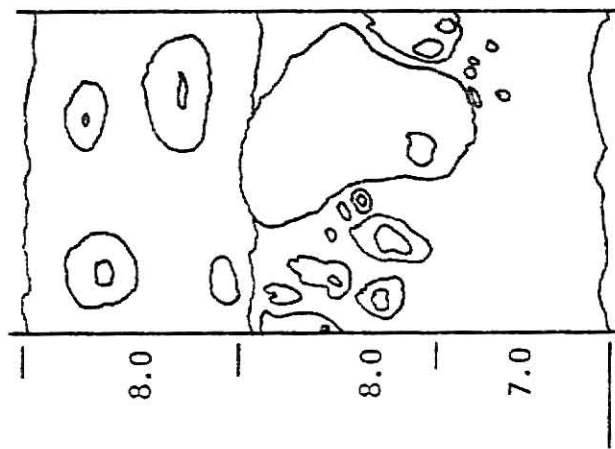


LOCALITY SB-36



Scale 1 : 3

LOCALITY SB-40

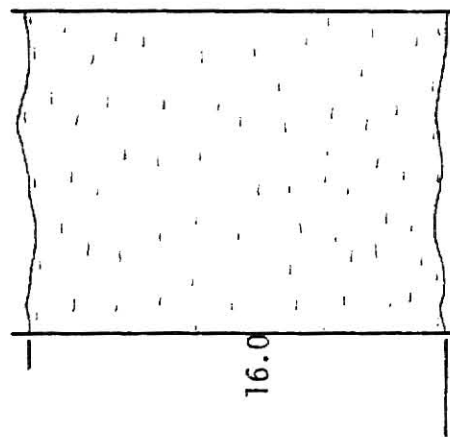


Argillaceous
Biomicrite

Stromatolitic
Biolithite with
Argillaceous
Micrite Matrix

Argillaceous
Dismicrite

Total Thickness



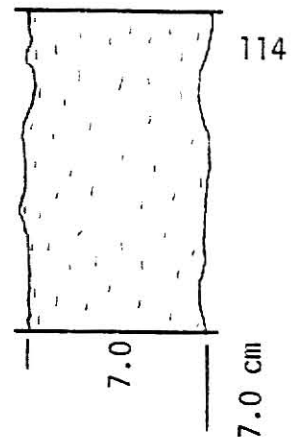
Argillaceous
Dismicrite

Total Thickness

113

Scale 1 : 3

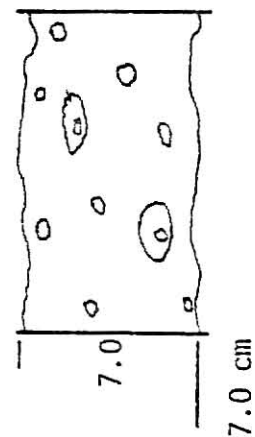
LOCALITY SB-42



Argillaceous
Dismicrite

Total Thickness

LOCALITY SB-41



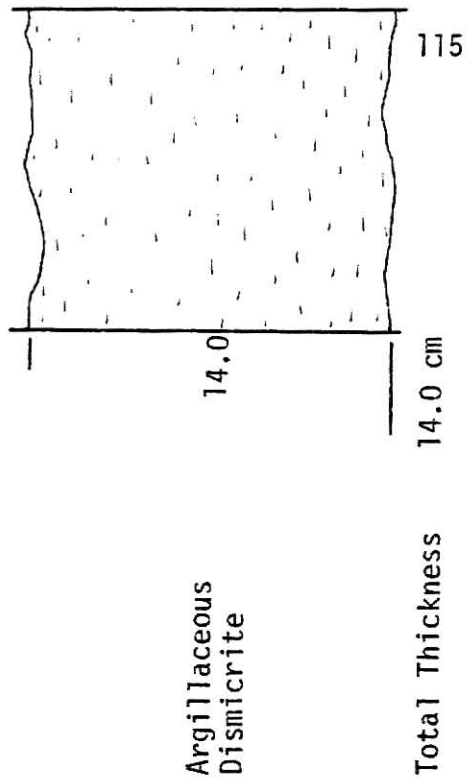
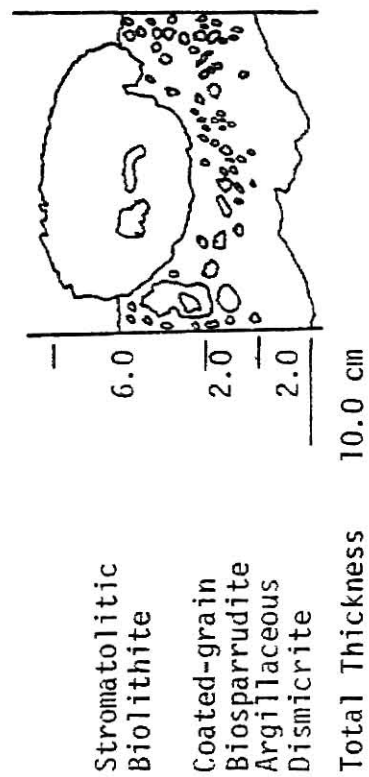
Argillaceous
Biomicrite

Total Thickness

Scale 1 : 3

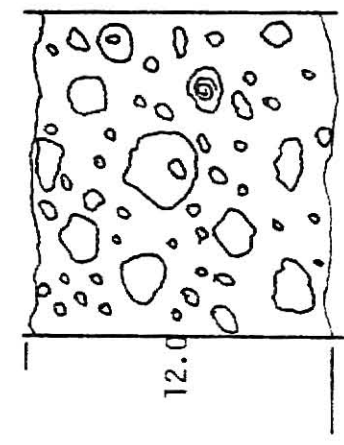
LOCALITY SB-44

LOCALITY SB-45



Scale 1 : 3

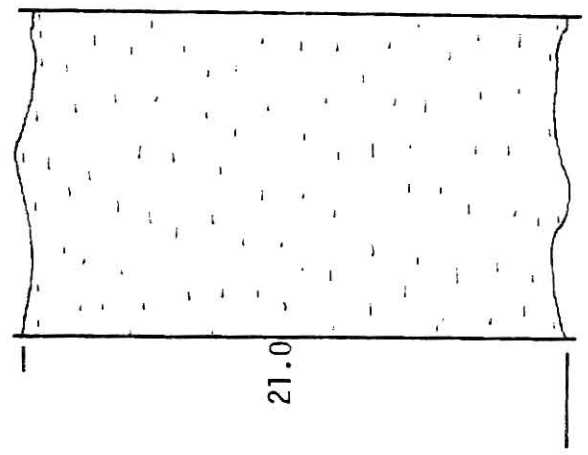
LOCALITY SB-47



Argillaceous
Biomicrite

12.0 cm

Total Thickness



Argillaceous
Dismicrite

21.0

21.0 cm

Total Thickness

116

APPENDIX IV

X-ray Diffraction Data: Quartz, Calcite, and Dolomite
Ni-filtered Cu K α Radiation

Sample Number	Mineral	2 θ (degrees)	Angstrom Units	Percent Quartz: Calcite: Dolomite*
A-1	Quartz	26.55	3.354	10
	Calcite	29.35	3.041	50
	Dolomite	30.64	2.915	40
H-1	Quartz	26.50	3.361	10
	Calcite	29.20	3.056	50
	Dolomite	30.50	2.928	40
H-2	Quartz	26.60	3.348	20
	Calcite	29.44	3.031	70
	Dolomite	30.69	2.911	10
H-3	Quartz	26.56	3.353	20
	Calcite	29.38	3.037	80
	Dolomite	-	-	0

*Based on peak heights

APPENDIX V

Oncolite Measurements

Locality SB-15, Sections D to H

Spherical Oncolites
(diameter in cm)

1.3
 1.5
 1.3
 1.2
 1.3
 1.0
 1.1
 1.2
 1.5
 1.2
 1.5
 2.0
 1.5
 1.5
 2.0
 2.3
 3.2
 2.7
 2.0
 2.0
 1.7
 2.0
 4.2
 1.7
 3.0
 1.5
 2.3
 4.0
 3.5
 2.7
 3.0

 $\bar{x} = 2.0$
Stabilized Oncolites That Form
Stromatolites (diameter in cm)

1.2
 2.2
 2.0
 2.0
 1.5
 2.2
 1.7
 2.8
 3.5
 3.7
 2.5
 4.0
 3.0
 3.8
 3.3
 2.7
 3.0
 3.7
 3.5
 4.0
 4.0
 3.2
 3.2
 2.4
 2.7
 3.5
 3.7
 3.5
 2.7
 3.0
 7.0
 6.5

 $\bar{x} = 3.2$

Measurements from vertical slabs

Stabilized Oncolites (digitate growth) - cut intersects nucleus, maximum diameter measured.

Section D

30
30
 $\bar{x} = 30.0 \text{ mm}$

Section E

70
 65
 33
 35
40
 $\bar{x} = 48.6 \text{ mm}$

Section F

31
 38
 28
 17
 33
 36
 13
 30
 25
 19
40
 $\bar{x} = 28.2 \text{ mm}$

Section G

22
 20
 19
 22
 32
 28
 25
 16
 19
 22
 35
25
 $\bar{x} = 23.8 \text{ mm}$

Section H

16
 12
 15
 11
 17
 18
 12
 16
 14
 14
 13
 15
 20
12
 $\bar{x} = 14.6$

Measurements from vertical slabs

APPENDIX VI

Biotic Components of the Stromatolite Biostrome
Locality SB-15, Sections A to H

This appendix contains data from acetate peel analysis of 4 cm by 6 cm area. See figure 11 for position of samples. Taxa were recorded as coated or uncoated.

CG = Coated Grain

NC = Not Coated Grain

ad = argillaceous dismicrite

cb = coated-grain biosparrodite

sb = stromatolitic biolithite

Biotic Components - Stromatolite Biostrome, Locality SB-15

Acetate Peel Analysis

Biotic Components	A-1(ad)		B-1(ad)		C-1(ad)		D-1(ad)	
	CG	NC	CG	NC	CG	NC	CG	NC
Mollusca								
Bivalve, fragment		3		4		2	1	1
Bivalve, whole								
Planispiral gastropod								
High spired gastropod								
Unidentifiable gastropod								
Brachiopoda								
Impunctate, fragment		1		3	1	1		
Impunctate, whole								
Pseudopunctate, fragment								
Punctate, fragment								
Bryozoa								
Ramosa								
Unidentifiable								
Echinodermata								
Crinoid								
Echinoid								
Unidentifiable								
Anthropoda								
Trilobite								
Ostracode								
Vertebrata								
Debris		2						
Total Coated Grains	-		-		1		1	
Total Uncoated Grains		6		7		3		1
Total All Grains		6		7		4		2

Biotic Components - Stromatolite Biostrome, Locality SB-15

Acetate Peel Analysis

Biotic Components	D-2(cb)		D-3(ad)		E-1(ad)		E-2(cb)	
	CG	NC	CG	NC	CG	NC	CG	NC
Mollusca								
Bivalve, fragment	31	4		1		4	59	7
Bivalve, whole								
Planispiral gastropod								
High spired gastropod								
Unidentifiable gastropod	1						4	3
Brachiopoda								
Impunctate, fragment	20	5				1	39	2
Impunctate, whole								
Pseudopunctate, fragment								
Punctate, fragment								
Bryozoa								
Ramose	3						8	
Unidentifiable								
Echinodermata								
Crinoid	1						2	
Echinoid							2	
Unidentifiable	2						8	1
Anthropoda								
Trilobite	5						10	2
Ostracode								
Vertebrata								
Debris	3	4		6		1	4	14
Total Coated Grains	66		-		-		136	
Total Uncoated Grains		13		7		6		29
Total All Grains	79		7		6		165	

Biotic Components - Stromatolite Biostrome, Locality SB-15

Acetate Peel Analysis

Biotic Components	F-1(ad)		F-2(cb)		F-3(sb)		G-1(cb)	
	CG	NC	CG	NC	CG	NC	CG	NC
Mollusca								
Bivalve, fragment	5	6	47	12	9	3	55	23
Bivalve, whole			3	2				
Planispiral gastropod			1			1		
High spired gastropod						1		1
Unidentifiable gastropod			2	7	3	3	1	3
Brachiopoda								
Impunctate, fragment	12	8	20	7	6	2	32	15
Impunctate, whole			1	1				
Pseudopunctate, fragment			3				7	
Punctate, fragment							1	
Bryozoa								
Ramose			2				3	1
Unidentifiable	2	2	6		4			
Echinodermata								
Crinoid				1	1		1	
Echinoid			2	1			1	
Unidentifiable			4	1	5			
Anthropoda								
Trilobite	4	4	17	3	2		19	4
Ostracode				1		1		
Vertebrata								
Debris			13	27	4	16	10	19
Total Coated Grains	23		121		34		130	
Total Uncoated Grains		20		63		27		66
Total All Grains	43		184		61		196	

Biotic Components - Stromatolite Biostrome, Locality SB-15

Acetate Peel Analysis

Biotic Components	G-2(sb)		H-1(cb)		H-2(sb)	
	CG	NC	CG	NC	CG	NC
Mollusca						
Bivalve, fragment	9	2	22	2	24	5
Bivalve, whole		1	1	5		
Planispiral gastropod			1	2		
High spired gastropod				1		
Unidentifiable gastropod	3	3		6		2
Brachiopoda						
Impunctate, fragment	7	3	7	3	2	
Impunctate, whole				1		
Pseudopunctate, fragment	1	2	6	1	2	1
Punctate, fragment	1					
Bryozoa						
Ramosa			1	2	2	1
Unidentifiable						
Echinodermata						
Crinoid	4		1	2	1	
Echinoid	2	1				
Unidentifiable						
Anthropoda						
Trilobite	3	1	2	1		
Ostracode		1	1	1		
Vertebrata						
Debris	4	31	4	23	3	13
Total Coated Grains	34		46		34	
Total Uncoated Grains		45		50		22
Total All Grains	79		96		56	

Biotic Components - Stromatolite Biostrome, Locality SB-15

Acetate Peel Analysis

Biotic Components	TOTAL Sections A-H	
	CG	NC
Mollusca		
Bivalve, fragment	262	79
Bivalve, whole	4	8
Planispiral gastropod	2	3
High spired gastropod		3
Unidentifiable gastropod	14	27
Brachiopoda		
Impunctate, fragment	146	51
Impunctate, whole	1	2
Pseudopunctate, fragment	19	4
Punctate, fragment	2	
Bryozoa		
Ramose	19	4
Unidentifiable	12	2
Echinodermata		
Crinoid	11	3
Echinoid	7	2
Unidentifiable	19	2
Anthropoda		
Trilobite	62	15
Ostracode	1	4
Vertebrata		
Debris	45	156
Total Coated Grains	626	
Total Uncoated Grains		365
Total All Grains	991	

Biotic Components of Underlying and Overlying Mudstones at Locality SB-15

See Appendix II for position of samples. Samples weighed approximately 700 grams before disaggregation.

PS = palaeoslide

Locality SB-15

Sample

- A-1: Crurithyris, productacean (PS #14), chonetid, ?Derbyia fragment, bivalve, bellerophontid (PS #20, 21), high-spired gastropod (PS #17), trubiniform gastropod (PS #23, 24), planispiral gastropod, Bairdia (PS #6), healdiacean, crinoid columnals, echinoid spine, vertebrates (bone, teeth, scales), coated-grains, ramose bryozoan, fenestrate bryozoan
- A-2: Lingulid, discoid, Septimyalina, unidentifiable bivalve A, unidentifiable bivalve B, Bairdia, healdiacean, geisid, fenestrate bryozoan, vertebrates (bone, teeth, scales) coated-grains
- B-1: Crurithyris, chonetid (two genera), productacean (strophalosiacean brachiopod), Punctospirifer, turbiniform gastropod, planispiral gastropod, ?Glabrocingulum, healdiacean, trilobite, crinoid columnal, crinoid plate, echinoid plate and spine, ramose bryozoan (two types), fenestrate bryozoan, fusulinid, encrusting foram on chonetids
- B-2: Crurithyris, turbiniform gastropod, ?Glabrocingulum, bivalve, Bairdia, healdiacean, fenestrate bryozoan, ramose bryozoan, vertebrates (bone, teeth, scales - Cladodus (PS #37), acanthodid scales (PS #38, 39), coelacanth? tooth (PS #40), coated-grains
- B-3: Unidentifiable bivalve A, geisid, healdiacean, vertebrates (bone, teeth, scales), coated-grains
- B-4: Lingula, unidentifiable bivalve A, unidentifiable bivalve C, healdiacean, geisid, vertebrates (bone, teeth, scales)
- B-5: myalinid, unidentifiable bivalve D, unidentifiable bivalve E, geisid, vertebrates (bone, teeth, scales)
- B-6: productacean spines, large bivalve, taxodont bivalve dentition (PS #44), high spired gastropod (PS #18), medium spired gastropod (PS #33), ?Glabrocingulum (PS #36), planispiral gastropod, healdiacean (PS #8,9), vertebrate skeletal debris
- B-7: productacean spine, 3 unidentifiable bivalves, bellerophontid, medium spired gastropod, high spired gastropod, healdiacean ostracode, crinoid columnal, vertebrates (scales, bone, teeth)
- C-1: Crurithyris, chonetid, productacean spine, planispiral gastropod (PS #1), turbiniform gastropod (PS #24), ?Trepostira (PS #26) high spired gastropod B (PS #29), healdiacean, echinoid spine, crinoid columnal, fenestrate bryozoan, ramose bryozoan, vertebrates (bone, teeth, scales), coated-grains (some desiccated)

Locality SB-15

Sample

- C-2: healdiacean, ramose bryozoan, vertebrate (bone, teeth, scales), coated-grains
- D-1: Crurithyris, productacean, planispiral gastropod, high spired gastropod A, low spired gastropod A, healdiacean, geisinid, crinoid columnal, ramose bryozoan, hindeodellid conodonts (PS #2), vertebrate (teeth, bone, scales), coated-grains (some desiccated)
- D-2: crinoid columnal, vertebrates (bone, teeth, scales), coated-grains
- E-1: Crurithyris, productacean, unidentifiable bivalve A, low spired gastropod B, ?Trepostira, healdiacean, crinoid columnal, fenestrate, bryozoan, vertebrates (bone, teeth, scales)
- E-2: Crurithyris, productacean spine, permophorid bivalve, unidentifiable bivalve A, turbiniform gastropod, trilobite, geisinid, vertebrates (bone, teeth, scales), coated-grains
- F-1: Crurithyris, chonetid, productacean, permophorid, high spired gastropod A, planispiral gastropod, turbiniform gastropod, Bairdia, healdiacean, crinoid columnal, fenestrate bryozoan, hindeodellid conodont, vertebrates (bone, teeth, scales), coated-grains (some desiccated)
- F-2: unidentifiable bivalve A, healdiacean, geisinid, ramose bryozoan, vertebrates (teeth, bone, scales)
- G-1: chonetid, small productacean (PS #15), strophalosiacean brachiopod, ?Dielasma, Derbyia, myalinid, ?Worthenia, Bairdia, hollinellid, healdiacean, trilobite, crinoid columnals and spine, echnoid spine and plate, ramose bryozoan (2 types), fenestrate bryozoan, fusulinid, encrusting foram
- G-2: Crurithyris, chonetid, ?Worthenia, medium spired gastropod (PS #25) bellerophonitid, healdiacean, geisinid, crinoid columnal, ramose bryozoan, fenestrate bryozoan, vertebrates (bone, teeth, scales), coated-grains
- G-3: discinid, unidentifiable bivalve A, unidentifiable bivalve B, healdiacean, geisinid, vertebrates (bone, teeth, scales)
- G-4: Lingula discinid, unidentifiable bivalve A, unidentifiable bivalve B, myalinid, healdiacean, geisinid, vertebrates (teeth, bone, scales)

Locality SB-15

Sample

- G-5: myalinid, unidentifiable bivalve B, geisinid (PS #10), vertebrates (scales, bone, teeth)
- G-6: productacean spine, unidentifiable bivalve B, planispiral gastropod, healdiacean, vertebrate skeletal debris
- G-7: productacean, small bivalve, medium spired gastropod, healdiacean, crinoid columnals, echinoid spine, ramose bryozoan, hindeodellid conodont (PS #5), vertebrates (bone, teeth)
- H-1: Crurithyris, productacean spine, ?Phestia, turbiniform gastropod, bellerophontid, geisinid, vertebrates (bone, teeth, scales, xenacanth tooth), coated-grains
- H-2: Unidentifiable bivalve A, unidentifiable bivalve B, healdiacean, geisinid, vertebrates (bone, teeth, scales)
- I-1: Crurithyris, vertebrates (bone, teeth, scales), coated-grains
- I-2: Crurithyris, lingulid?, unidentifiable bivalve A, geisinid, ramose bryozoan, vertebrates (bone, teeth, scales)
- I/2-1: Crurithyris, productacean, ?Trepostira (PS #27), high spired gastropod A, Bairdia, healdiacean, crinoid columnal, ramose bryozoan, fenestrate bryozoan, vertebrates (bone, teeth, scales) coated-grains
- I/2-2: Crurithyris, schizodont bivalve A, schizodont bivalve B, ?Glabrocingulum (PS #32), geisinid, crinoid columnals, ramose bryozoan, vertebrates (bones, teeth, scales, xenacanth tooth = PS #41), coated-grains
- J-1: chonetid, Crurithyris, productacean, Derbyia, ?Glabrocingulum, hollinellid (PS #12, 13), Bairdia, trilobite, crinoid columnals and spines, echinoid spines and plate, ramose bryozoan, fenestrate bryozoan, encrusting bryozoan (a crinoid columnal), Fistulipora, vertebrate teeth
- J-2: Crurithyris, productacean, ?Aviculopecten, turbiniform gastropod, geisinid, vertebrates (bone, teeth, scales)

Locality SB-15

Sample

- J-3: Lingula, discinid, unidentifiable bivalve A, Septimyalina, unidentifiable bivalve B, geisinid (PS #11), vertebrates (bone, teeth, scales)
- J-4: Lingula, discinid, unidentifiable bivalve A, unidentifiable bivalve C, healdiacean, geisinid, vertebrates (bone, teeth, scales)
- J-5: Lingula, myalinid, unidentifiable bivalve B, geisinid, vertebrates (bone, scales, teeth)
- J-6: Phestia, ?Nuculopsis, large bivalve, medium spired gastropod (PS #49), turbiniform gastropod (PS #47) (2 types), high spired gastropod A, bellerophontid, healdiacean ostracode, vertebrate skeletal debris
- J-7: productacean spine, 3 unidentifiable bivalves, medium spired gastropod, healdiacean (PS #7), crinoid columnal, vertebrates (bone, scales)
- K-1 Crurithyris, chonetid, productacean, turbiniform gastropod, healdiacean, crinoid columnal, ramose bryozoan, fenestrate bryozoan, vertebrates (bone, teeth, scales, vertebra), coated-grains
- K-2: vertebrates (teeth), coated-grains

PALAEOENVIRONMENTAL INTERPRETATION OF A
VIRGILIAN (PENNSYLVANIAN) STROMATOLITE
BIOSTROME IN NORTHEASTERN KANSAS

by

ROBERT SCOTT SAWIN

B. S., Kansas State University, 1972

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Geology

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1977

ABSTRACT

A palaeoenvironmental investigation of a stromatolite occurrence in the Soldier Creek Shale Member of the Bern Limestone was undertaken to 1) describe the stromatolites and their biostromal relationships, 2) determine their position according to sea level, 3) examine the palaeogeographical relationships within the study area, and 4) compare this occurrence with the Holocene example at Shark Bay, Western Australia.

Cryptalgal structures in the Soldier Creek Shale occur in three forms: oncolites, stromatolites, and coalescing stromatolites that form a biostrome. The digitate internal structure has a laminoid fabric of calcium carbonate.

Stromatolites probably developed in low intertidal or shallow subtidal environments. Their position corresponds to the wave "break" zone caused by a steepening gradient associated with argillaceous dismicrite "highs".

Distribution of vertebrate (lungfish, amphibians, sharks, fish) skeletal debris and southward thinning of the Soldier Creek Shale suggest a northern source of sediment and vertebrate skeletal debris.

Soldier Creek stromatolites resemble forms developing in bight areas in Hamelin Pool, Shark Bay, Western Australia. Characteristics common to both are: 1) low intertidal or shallow subtidal position, 2) development in the wave "break" zone which coincides with gradient changes, 3) digitate internal structure and crenulated surface textures, and 4) shoreward transport of sediment and seaward progradation.