The Microstratigraphy of the Roseland Quarry (Early Jurassic, Newark Supergroup, New Jersey)

Paul Eric Olsen

1975

Open File Report, Essex County Park Commission, Newark, New Jersey

Preface

This paper is the first step in presentation of information resulting from seven years of work on the Roseland Quarry. During this time I have received help from many people, especially Dr. John Ostrom, Dr. Keith Thomson, Dr. Carl Waage, Dr. John Rogers, Dr. Donald Baird, Dr. Bobb Schaeffer, Bruce Cornet, Tony Lessa, Robert Salkin, the Essex County Park Commission, and the Walter Kidde & Company Inc. I would also like to thank Stan Rachootin for reading the manuscript and supplying many helpful suggestions which substantially improved it.

INTRODUCTION

1.1 Area of Study

The Roseland Quarry is a 55 acre exposure of surficial deposits and bedrock originally excavated for fill. It is located at the northern tip of Riker Hill in the Borough of Roseland, Essex County, New Jersey (figure 1).

The numerous and well preserved dinosaur footprints found in the Roseland Quarry interest scientists and the public alike. For this reason, the owners, Walter Kidde and Company, Inc., will donate part of this area (see figure 9) to the Essex County Park Commission to be developed as an educational park.

1.2 Purpose

> "As it is not in human record but in natural history, that we are to look for the means of ascertaining what has already been, it is here proposed to examine the appearence of the earth in order to be informed of operations which have been transacted in the past. It is thus that, from priciples of natural philosophy, we may arrive at some knowlege of order and system in the oeconomy of this globe, an may form a rational opinion with regard to the course of nature, or to events which are in time to happen."
>
> James Hutton, 1785

The Roseland Quarry has been studied by this author and others for over seven years, though no scientific accounts of its geology or paleontology have been published. Nor can the quarry be understood by reference to geological phenomena of greater scale, because the study of the great body of sediments and volcanics to which the quarry bedrock belongs, the Newark Supergroup, is at present undergoing major reinterpretation. The discovery of new fossil localities and the application of new directions of inquiry have made relevant review articles obsolete. This paper surveys work done to date that may be of use to the Essex County Park Commission and interested students of geology and paleo-ecology until the many papers now in preparation are in print.

1.3 Method and Results

> "Interpretation rushes to the forefront as the obligation pressing upon the putative wise man. Laudable as the effort at explanation is in itself, it is to be condemned when it runs before a serious inquiry into the phenomenon itself. A dominant disposition to find out what is, should precede and crowd aside the question, "How came this so?" First full facts, then interpretations."
>
> T.C. Chamberlin, 1965.

This paper is divided into four major parts: Geology, Paleontology, Synthesis, Future Development. Each part consists of an introduction, a critique of the relevent nomenclature, a presentationof observations and an interpretation of the evidence. This scheme allows for easy reference, but more importantly, it permits the reader to weigh the interpretations against the original observations and, perhaps, to derive alternative theories.

Part I

GEOLOGY

2. Stratigraphy

2.1 Stratigraphic Nomenclature and Classification

> "All strtatigraphic units require distinctive names or comparable designations in order that they may be identified and differentiated from each other."
>
> J. M. Weller, 1960

> "Once we deviate from the original meanings of the terms and abandon the principle of priority, we lose our hold on the only lifeline that can save us from the slough of conflicting opinion."
>
> W.J. Arkell

A meaningfull discussion of a geologic phenomena can not begin until a suitable nomenclature is devised. That confusion arising from semantics might be avoided, a revision of the relevent terminology is presented in sections 2.2 - 2.4.

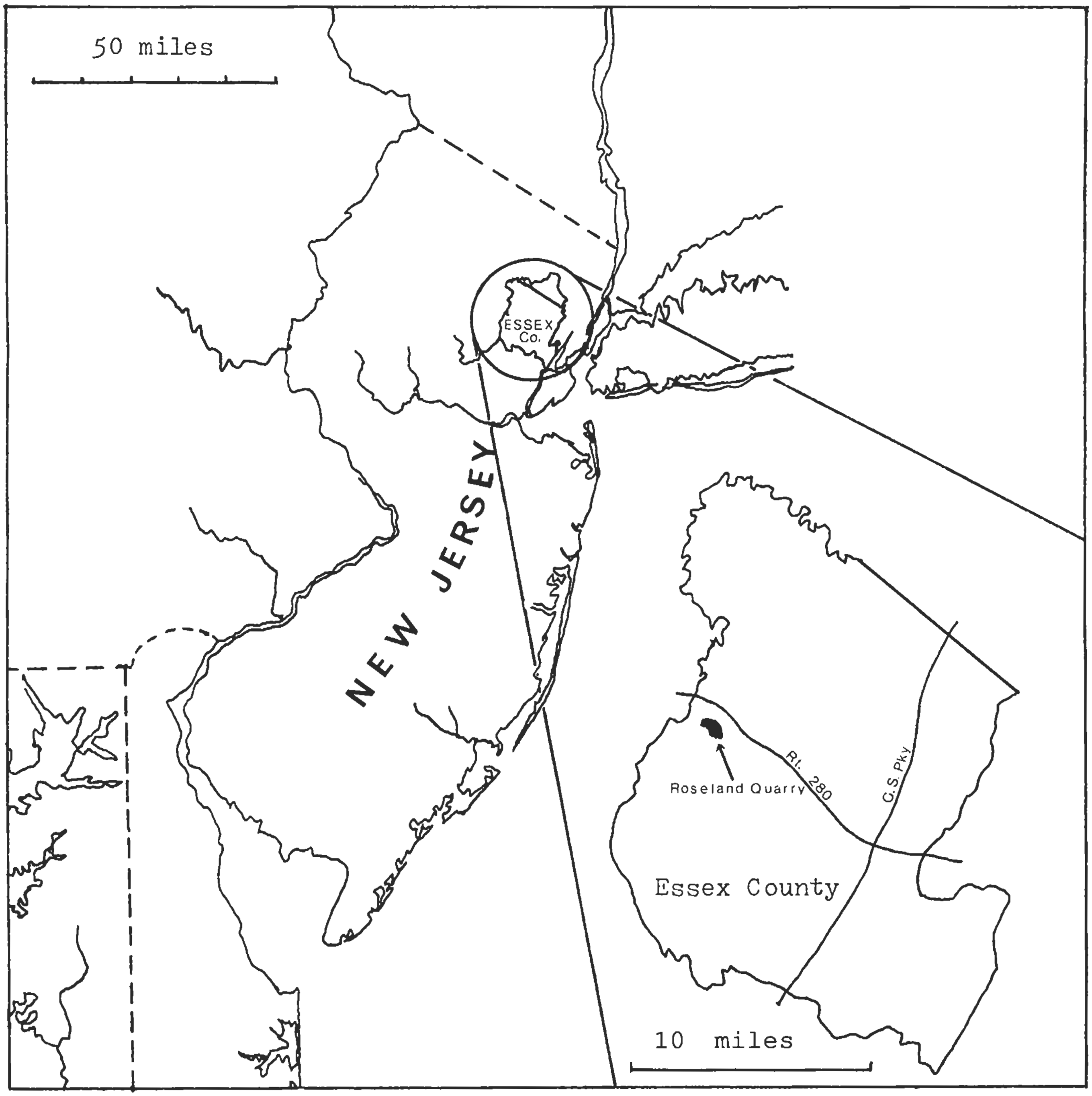
The American Commission on Stratigraphic Nomenclature was established in 1946 to develop a concise and meaninful set of terms and bring order out of 150 years of chaos. The result of this commission is the Code of Stratigraphic Nomenclature which was published in the <u>Geological Society of America Bulletin</u> (1961, v. 45, no. 5, p. 645-660) and again in Krumbine and Sloss (1963). The code distinguishes between terms which involve interpretation and those which do not. Specifically they state (1947):

> "The main source of difficulty in making a a consistent, thoroughly sound approach to classification and nomenclature of stratigraphic units as a whole is prevalent failure by geologists to exclude concepts of time from consideration of the objective data on

> which alone properly defined rock units are differentiated. Recognition of essential distinctions in the nature of time units is needed as a basis for satisfactory stratigraphic classification and terminology."

Sections 2.1 through 2.4 may seem far removed from the interpretation of the geology of the Roseland Quarry Quarry; however, the importance of a sound nomenclature cannot be over stressed. The following revision of stratigraphic terminology is essential to the understanding of the discussions and interepretations it precedes.

Figure 1. Geographic position of the Roseland Quarry.



2 STRATIGRAPHIC NOMENCLATURE

2.1 Stratigraphic Nomenclature of the Newark Supergroup.

At least 15 isolated, elongate basins[1] of sedimentary and volcanic rocks outcrop in the Piedmont physiographic province of the eastern coast of North America (see figure 2). The long axes of these basins roughly parallel the Appalachian Mountains. The rocks of these basins present a unified lithology and structure. Red beds (see section 2) are the most common sedimentary deposits and basic intrusives and theoléiitic basalts are the dominant volcanics. These unconformably overlay Precambrian and Paleozoic sedimentary, volcanic, and metamorphic rocks and are, in turn, overlain by post-Jurassic rocks of the Coastal Plain, Pleistocene deposits, or Recent alluvium and soils.

Redfield (1856) named the rocks of these basins the Newark Group (a term enjoying wide usage for over a century [Russel, 1892; Kline, 1962]). Kline (1962) restricted Newark Group to the formations of the Newark Basin because some workers have used the term in a time-stratigraphic sense. The rocks formerly considered Newark Group of the Maritime Provinces of Canada (Russel, 1892) were renamed the Fundy Group (Kline, 1962) and more recently, Thayer (1970) has labelled the rocks of the Dan River Basin the Dan River Group.

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[1]Basin is used here as a convention for a body of rock. No structural implications other than separation from surrounding rocks are intended.

The rocks of each basin are generally divided into lithologically distinct formations. Individual group names for the rocks of each basin are useful and in agreement with the Code of Stratigraphic Nomenclature (C.S.N.)[2]; however, the Newark Group cannot be composed of other groups[3]. The obvious relation of all the rocks of these basins requires an encompassing rock-stratigraphic term of appropriate rank. I propose the rank of the name Newark be raised to Supergroup[4] in order to preserve the original and familiar meaning of Redfield's designation and allow the formations of individual basins to be included in specific group names. Table I lists the suggested group names for the deposits of the basins of the Newark Supergroup (see figure 2). Most of these derive from well known basin names[5] unless there is a clear priority[6] (eg. Fundy Group of Kline), the term is preoccupied[7], or the basin geology suggests a new term of different usage (see footnotes of Table I for specific explanations).

As outlined above and in Table I, the Newark Supergroup consists of fifteen rock units of group status, four isolated and undivided formations, three tiny, undifferentiated units south of the Farmville Group, at least ten subsurface units

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[2]American Commission on Stratigraphic Nomenclature, 1961, Code of Stratigraphic Nomenclature, Am. Assoc. Petrol. Geol. Bull. v. 45, no. 5, p. 645-660, Article 9a. This paper will be referred to in this paper as the C.S.N..

[3]Ibid.

[4]Supergroup is suggested by the C.S.N., Article 9e, for a formal assemblage of related groups or formations and groups.

[5]Russel (1892) gives a list of the basin names and their histories.

[6]Ibid., Article 11. [7]Ibid., Article 11c.

The Newark Supergroup

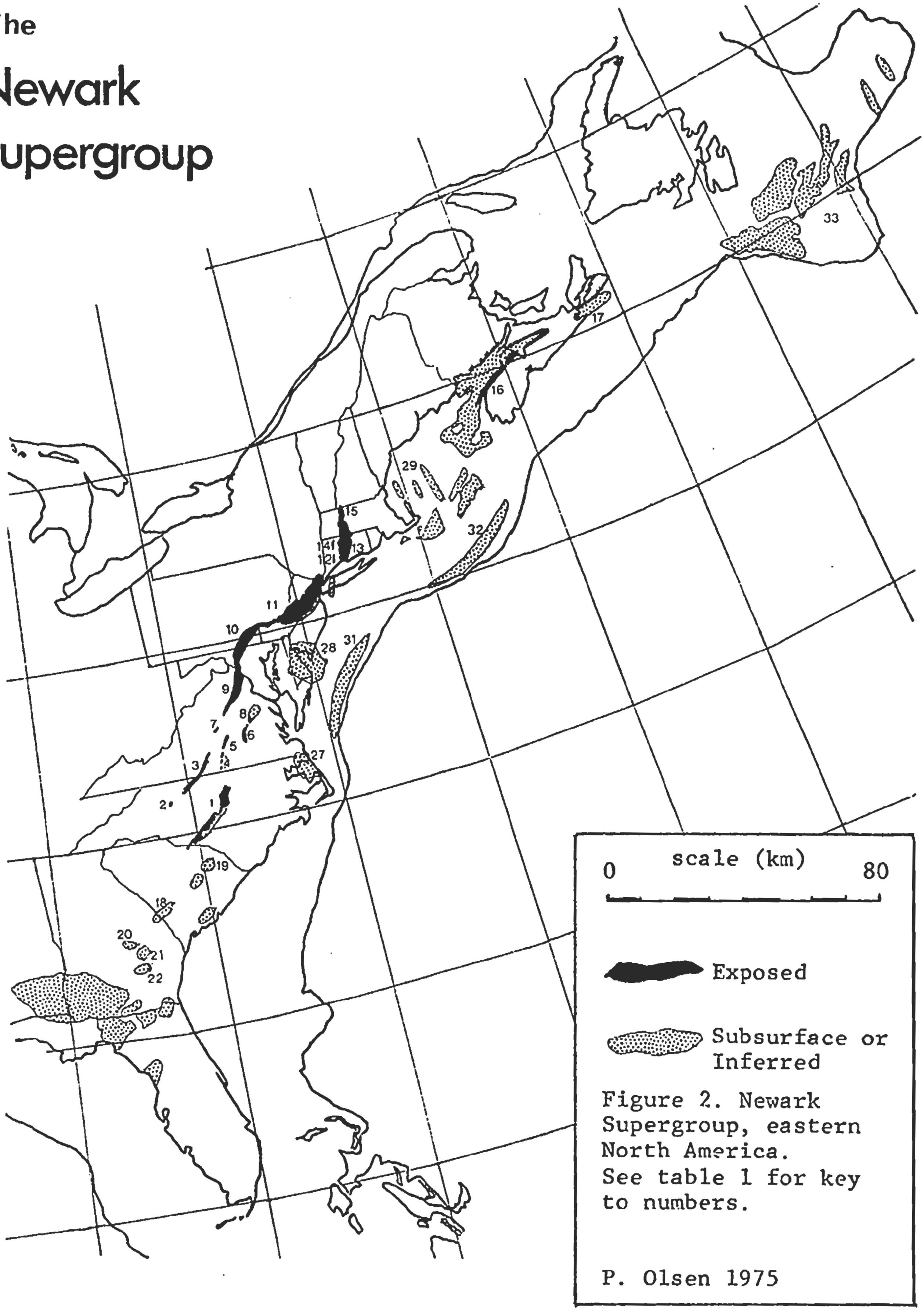

Figure 2. Newark Supergroup, eastern North America. See table 1 for key to numbers.

in the Coastal Plain, and probably the early Mesozoic red beds at the base of certain basins on the continental shelf.

Table I

Suggested and Accepted Names of the Units Included in Newark Supergroup and Key to Figure 2.

Number in Figure	Rock-Stratigraphic Term	Basin Name
Units Exposed in Peidmont		
1	Chatham Group[a]	Durham, Deep River and Wadesboro
2	Davie County Formation	Davie County[b]
3	Dan River Group[c]	Dan River and Danville
4	undifferentiated Newark[d] Supergroup	
5	Farmville Group	Farmville[e]
6	Richmond Group[f]	Richmond
7	Scottsville Group	Scottsville[g]
8	Taylorsville Group[h]	Taylorsville
9	Culpeper Group	Culpeper[i]
10	Conewago Group[j]	Gettysburg
11	Novacaesarea Group[k]	Newark
12	Southbury Group	Southbury[l]
13	Hartford Group	Hartford Basin[m]
14	Cherry Valley Formation	Cherry Valley[n]
15	Greenfield Group[o]	Deerfield
16	Fundy Group[p]	Acaidian
17	Chedabucto Formation	Chedabucto[q]

(cont.)

Units known to exist below the Coastal Plain.

18	Dunbarton Group	Dunbarton[r]
19	Florence Group	Florence[s]
20	Laurens County Diabase[t]	no basin name
21	Montgomery County Diabase[u]	no basin name
22	Appling County Basalt[v]	no basin name
23	undifferentiated Newark Supergroup[w]	no basin name
24	undifferentiated probable Newark Supergroup[x]	no basin name
25	undifferentiated probable Newark Supergroup[y]	no basin name
26	undifferentiated probable Newark Supergroup[z]	no basin name
27	undifferentiated probable Newark Supergroup[aa]	Albemarle Embayment
28	undifferentiated probable Newark Supergroup[bb]	Salisbury Embayment

Inferred Newark Supergroup deposits on Continental Shelf.

29	Probable Newark Supergroup[cc]	Gulf of Maine
30	Possible Newark Supergroup	East of Florida, Georgia, and South Carolina[dd]
31	Possible Newark Supergroup	Baltimore Trough[ee]
32	Possible Newark Supergroup	Georges Bank Trough[ff]
33	Possible Newark Supergroup	South Whale, Whale, Horeshoe, JeanneD'Arc, and Carson[gg]

Early Mesozoic Rocks probably not in Newark Supergroup.

34	Pre-Smakover Red Beds[hh]	Gulf Coast Basin

Notes:

[a]The rocks of the Durham, Deep River, and Wadesboro Basins (Kerr, 1875; Russel, 1892; Prouty, 1926) are here considered as one group because the basins are only superficially separated by a thin cover of Coastal Plain sediments. Emmons' (1857)

Chatham Group (originally series) may be used for the rocks of these basins.

[b]The rocks of the Davie County Basin (Brown, 1932) have not been divided into individual formations (Thayer, 1968,1970).

[c]Thayer, 1970. [d]Russel, 1892.

[e]Russel, 1892.

[f]Shaler and Woodworth (1897-98) divided the rocks of the Richmond Basin into the Tuckahoe Group and Chesterfield Group. To conform to the group usage in other Newark units it is suggested that all the formations in the Richmond Basin be termed the Richmond Group. It is, however, noted that the aforementioned group names were the first truely rock-stratigraphic terms applied to the rocks of the Richmond Basin (Russel, 1892).

[g]Russel, 1892. [h]Robert Weems, M.S.

[i]The Newark, Gettysburg, and Culpeper Basins (numbers 11, 10, and 9 respectively) are connected by narrow sedimentary necks (VanHouten, 1969). Three separate group names are proposed for the rocks of these basins because of the lack of homotaxality between formations (C.S.N. Article 2a). The term Culpeper Group is derived from the basin name. (Russel, 1892).

[j]The name Gettysburg cannot be used as the group name because it is used for Gettysburg Shale. The Conewago Group is proposed to include all the formations of the Gettysburg Basin. The name is taken from Big and Little Conewago Creeks along which there are numerous exposures, (C.S.N. Article 2a).

[k]The term Novacaesarea Group (Pre-Colonial name for New Jersey, suggested by Dr. Donald Baird) is proposed for the rocks of the Newark Basin (Van Houten, 1969). The term "Newark" cannot be used for a group name since it is the name of the Supergroup (C.S.N. Article 9a).

[l]Russel, 1892. [m]Cornet, 1973. [n][sic]

[o]The Hartford and Deerfield Basins seem to be connected by a narrow sedimentary neck, (Bain, 1932) for the reasons described in footnote 'i' these should have two separate group names. Deerfield cannot be used as the group name because it is preoccupied by the Deerfield Basalt. The Greenfield Group is porposed to include all the formations of the Deerfoeld Basin. Greenfield is the largest city in the Deerfield Basin.

[p]The Newark Supergroup of the Maritime Provinces of Canada poses interesting stratigraphic and nomenclatural problems. Kline (1962) includes all the Newark Supergroup outcrops in New Brunswick and Nova Scotia in his Fundy Group. Kline's Chedabucto Formation is in an isolated basin and should not be included in the Fundy Group. The rocks of Grand Manan Island, Point Lepreau, St. Martins, and Waterside, in New Brunswick seem to be connected to the Annapolis and Minas Basin rocks by continuous Newark Supergroup sediments beneath the Bay of Fundy.

[q]The Chedabucto Formation remains as a separate formation in an isolated basin (Kline, 1962).

[r]Marine and Siple, 1974, [s]Siple, 1959.

[t]Marine and Siple, 1974. [u]Ibid.

[v]Ibid. [w]Ibid. [x]Ibid. [y]Ibid.

[z]Ibid. [aa]Ibid. [bb]Minard et al, 1974.

[cc]Inferred Newark Supergroup on the basis of seismic data (Ballard and Uchupi, 1974).

[dd]Inferred Newark Supergroup on the basis of seismic data (Minard et al, 1974).

[ee]Inferred on the basis of seismic data. Seems to be conformably overlain by Early Jurassic evaporites (Emery and Uchupi, 1972).

[ff]Ibid.

[gg]Amoco Ltd. and Imperial Oil Ltd., Staff (1974) describe five basins on the Grand Banks with basal red beds conformably overlain by Early Jurassic marine and non-marine clastic and evaporites. The basal beds, at least, should be included in the Newark Supergroup.

[hh]The Pre-Smakover red beds occur over a very large area which does not have the structure typical of Newark Supergroup deposites, (Marine and Siple, 1974).

2.2 Stratigraphic Nomenclature of the Novacaesarea Group.

The Novacaesarea Group consists of mainly clastic red and non-red sedimentary rocks and extrusive and intrusive volcanics preserved in the southwest trending Newark Basin, which extends from Rockland County, New York to northeastern Lancaster County, Pennsylvania (see figure 3). The Newark and Gettysburg Basins are connected by a narrow sedimentary neck. The division between the basins is arbitrarily taken to be the narrowest part of the neck. The termination of the Novacaesarea Group is defined as where the Robeson Conglomerate (McLaughlin, 1939, see page 16) pinches out in the New Oxford Formation and Gettysburg Shale. This definition is consistant with Article 6 of the Code of Stratigraphic Nomenclature (American Commission on Stratigraphic Nomenclature).

The Newark Basin is broken into at least four major fault blocks. The sedimentary and associated volcanics, in these fault blocks dip, with variation, to the northwest. Furthermore, the western beds are folded into a regular series of gentle, open anticlines and syclines (Sanders, 1963).

Precambrian and early Paleozoic rocks of the New England Upland border the Novacaesarea Group along its northeast and northwest margins. The latter overlays and is bordered by Paleozoic and minor Precambrian rocks of the Blue Ridge and Piedmont Provinces to the southest and southwest. Cretaceous and younger Coastal Plain deposits overlap part

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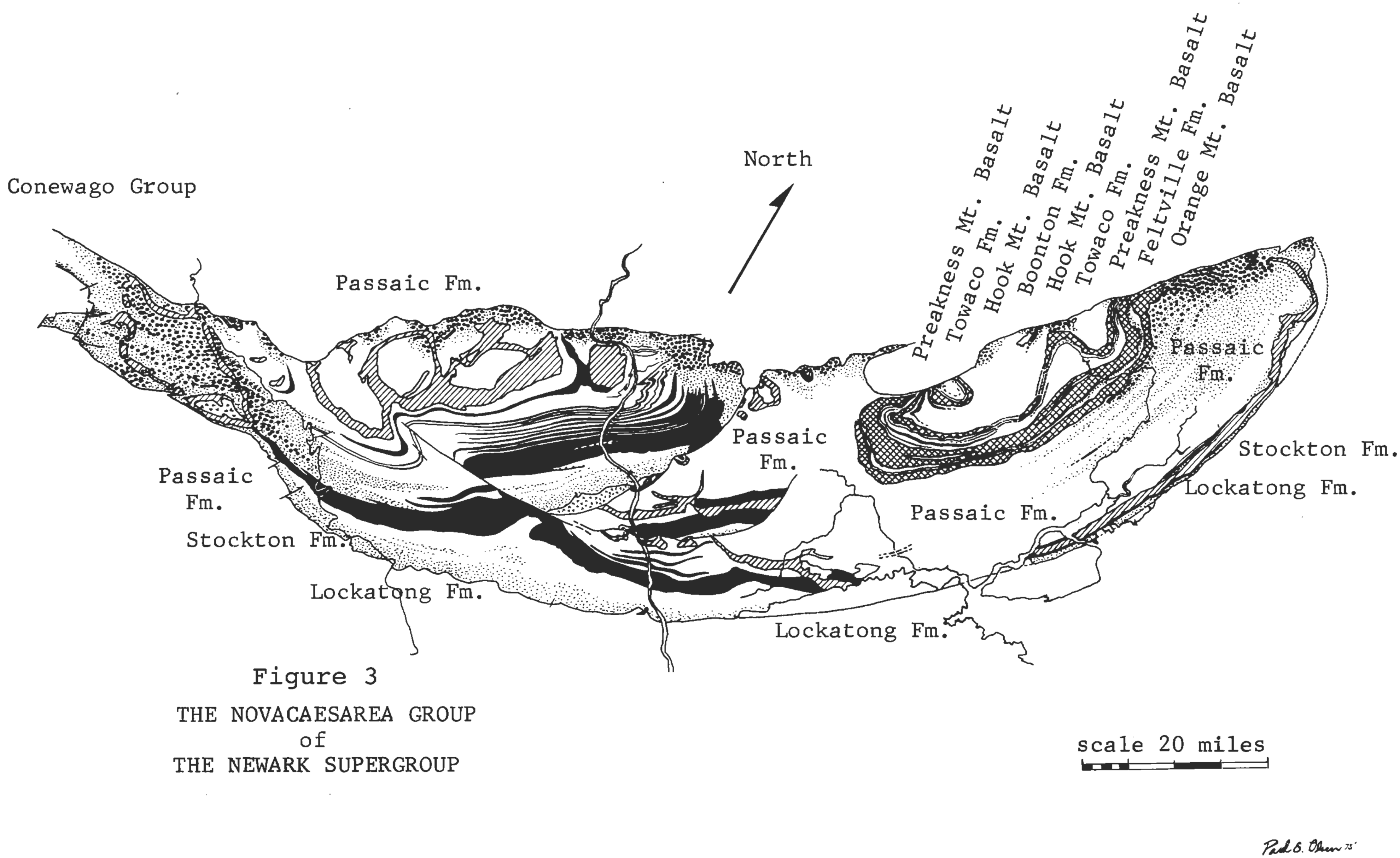

Figure 3

THE NOVACAESAREA GROUP
of
THE NEWARK SUPERGROUP

of the Novacaesarea Group along its southeast edge. The northern third of the Newark Basin is mantled by Pleistocene glacial deposits.

Although the prevailing view (Van Houten, 1969) is that the eastern edge of the Novacaesarea Group overlaps Paleozoic and Precambrian basement rocks while the western border is a high angle fault of great displacement, there is considerable evidence (Faille, 1973) the western edge south of Cushatunk Mountain may be an overlap in many places. Broad generalisations, therefore, do not hold (see section 5.3).

Kummel (1897) divides the rocks of the Newark Basin into three formations: the Stockton, Lockatong, and Brunswick. The Stockton Formation, named for characteristic exposures near Stockton, New Jersey, consists of red siltstones, sandstones and conglomerates, and well sorted buff arkose and poorly sorted conglomerate. There are minor amounts of gray and black siltstones near the top. It is about 5000 feet thick along the Delaware River in the western fault block, thining towards the eastern fault blocks, and to the northeast and southwest. The Stockton Formation rests unconformably on the basement rocks.

The Lockatong Formation is named for exposures along Lockatong Creek, north of Stockton. About 3750 feet (McLaughlin, 1945) of Lockatong Formation occurs at its type section. This formation is almost entirely composed of cyclic units of black, gray, and minor red siltstones (Van Houten, 1969). It thins and interdigitates with the overlying formation (Passaic Formation of this report) in all directions away from the type exposures. The Lockatong Formation is absent at the northern and southern extremities of the Newark Basin where Stockton interfingers with the overlying (Passaic) formation.

The beds stratigraphically above the Lockatong Formation or, where this is absent, the Stockton Formation, have been termed the Brunswick Formation by Kummel (1897) after exposures along the Raritan River near New Brunswick, New Jersey. The Brunswick Formation can be thought of as two different, major units: lower and upper Brunswick (Darton, 1889; McLaughlin, 1933, 1943, 1944, 1945; Baird and Take, 1959; and Van Houten, 1969). The lower Brunswick consists mostly of red siltstones, sandstones, conglomerates, and laterally persistent beds of Lockatong-like black and gray siltstones (Kummel, 1897; McLaughlin, 1943). The upward increasing thickness of cyclic red units marks the transition from the Lockatong to lower Brunswick Formations (Van Houten, 1969; see figure 2). The upper Brunswick Formation, on the other hand, consists of three major volcanic units termed the Watchung Basalts (Darton, 1889) and interbedded and overlying sedimentary units which have been thought of as identical to the Lower Brunswick Formation (Kummel, 1897). My recent mapping indicates that each of the Watchung Basalts and major interbedded and overlying sedimentary units are lithologically distinct from each other and the lower Brunswick Formation and can be mapped at a scale of 1 : 25,000. I propose the terms Brunswick Formation (Kummel, 1897) and

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[7]C.S.N., Article 6d.

Watchung Basalts (Darton, 1889) be dropped and their components subdivided to form seven new formations as Lehmann (1959) has for the Hartford Group and as Kline (1962) has for the Fundy Group (restricted).[8]

Table II lists the formations of the Novacaesarea Group according to Kummel (1897) and Darton (1889) and this author.

Table II

Formations of the Novacaesarea Group.

Kummel (1897, Darton (1889)	Olsen (M.S.)[9]
Brunswick Formation	Boonton Formation
third Watchung Basalt	Hook Mountain
Brunswick Formation	Towaco Formation
second Watchung Basalt	Preakness Mountain Basalt
Brunswick Formation	Feltville Formation
first Watchung Basalt	Orange Mountain Basalt
Brunswick Formation	Passaic Formation
Lockatong Formation	Lockatong Formation
Stockton Formation	Stockton Formation

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[8] Ibid., Article 14b.

[9] The terms Boonton Formation, Hook Mountain Basalt, and Towaco Formation were suggested by informal unit designations used by Baird and Take (1959) and Baird (Pers. Com.). The type section of the Passaic Formation is along Interstate Rt. 80 in Passaic, Patterson, and Clifton, New Jersey. That of the Orange Mountain Basalt is along Interstate Rt. 280 in East Orange, New Jersey. The type section of the Feltville Formation is located in the Watchung Reservation on the site of the old village of Feltville, Union County, New Jersey. The type section of the Towaco Formation is the Roseland Quarry, Roseland, New Jersey. The basalt exposures along Interstate Rt. 80 at Lincoln Park, New Jersey is the type section of the Hook Mountain Formation. The type section of the Boonton Formation is along the Rockaway River in Boonton, New Jersey.

A detailed description of these new formations is given elsewhere Olsen, M.S.). The Towaco Formation will be desribed in detail later in this report (section 3).

The northern and southern extremities of the Novacaesarea Group are major areas of conglomerate (see figure 3). The northern conglomerate area, restricted to the western two-thirds of the Novacaesarea Group, extends south from Stony Point, New York and edges out near Glen Rock, New Jersey. Large tongues of conglomerate continue as far south as Passaic, New Jersey, however. The southern conglomerate area occupies practically the entire Newark Basin west of the Schuylkill River and pinches out in the formations of the Conewago Group, in the Gettysburg Basin. Both conglomerate areas are lateral equivalents of and continous with the Passaic Formation.

The northern conglomerate area has not been well studied. Kummel (1899) and Van Houten (1969) have discussed and Savage (1968) has mapped and described the conglomerate area in New York, but the extent of the conglomerate area in New Jersey has been ignored and has been tenatively mapped by this author (see figure 3).

In contast, the southern area of conglomerate has attracted considerable attention since it was discovered and mapped by McLaughlin (1939). He named it the Robeson Conglomerate. The mapping has been elaborated by Geyer <u>et al</u>. (1958, 1963), Gray <u>et al</u>. (1958), Johnston (1966), and McLaughlin and Gerhard (1953). Glaeser (1963, 1966) did not use McLaughlin's term for the conglomerate and named the same rocks the Hammer Creek Formation. Glaeser states that the Hammer Creek Formation is lithologically distinct from the Stockton Formation, New Oxford Formation, Gettysburg Shale, and Passaic Formation (Brunswick Fm.) and, therefore, requires formational rank.

The term Robeson Conglomerate (McLaughlin, 1939) has clear priority over Hammer Creek Formation (Glaeser, 1963). It is, therefore, suggested that the term Hammer Creek Formation be discarded in favor of Robeson Conglomerate in accordance with the Code of Stratigraphic Nomenclature.[10]

The maps of Geyer _et al_. (1958, 1963), Geyer (1965), Gray (1958) and Johnston (1966) and Glaeser's (1963) type section for his Hammer Creek Formation show that the Robeson Conglomerate is identical, in terms of lithology and facies relations, to the northern conglomerate area, tongues of which are present in the type section of the Passaic Formation type section. It is clear the Robeson Conglomerate and the northern conglomerate area are simply coarse, lateral equivalents of the Passaic Formation. I propose that the northern area of conglomerate be termed the Ramapo Conglomerate. Furthermore, the Robeson and Ramapo Conglomerates should be regarded as members of the Passaic Formation. To grant these members formational rank inflates the already complex nomenclature of the Novacaesarea Group and disregards the intimate lithologic and spatial relationship between coarse and fine facies of the Passaic Formation.

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[10]C.S.N., Article 11.

2.3 Stratigraphic Nomenclature of the Towaco Formation.

The term Towaco Formation[11] (Olsen, M.S.) is applied to the predominately clastic red and non-red sedimentary rocks found below the Hook Mountain Basalt and above the Preakness Mountain Basalt. The Towaco Formation, unlike the underlying units, is exposed only in the Passaic Syncline (see figure 4). The largest exposure of the Towaco Formation is the Roseland Quarry which Olsen (M.S.) has designated as the type section. About 300 feet of the upper Towaco Formation is exposed at this locality. The total thickness of the formation near this type section is estimated at 1200 feet.

The Towaco Formation is characterized by cyclic, laterally persistant non-red units. The mean thickness of these units is 41 feet. The non-red units are separated by red units with a mean thickness of 54 feet. Unlike most Novacaesarea formations, the Towaco formation is only one-half red. It is possible to map these units as McLaughlin (1933, 1943, 1944. 1945, 1946a.b, 1959) has for the Passaic Formation in the Hunterdon Plateau and south (see figures 3,4). Poor exposure is a limiting factor to mapping north of the Wisconsin terminal moraine (see figure 4) and mapping must be based on three or four good exposures and well records. Exposures of the Towaco Formation are common south of Chatham and I have mapped this area in detail (Olsen, M.S.: see figure 6).

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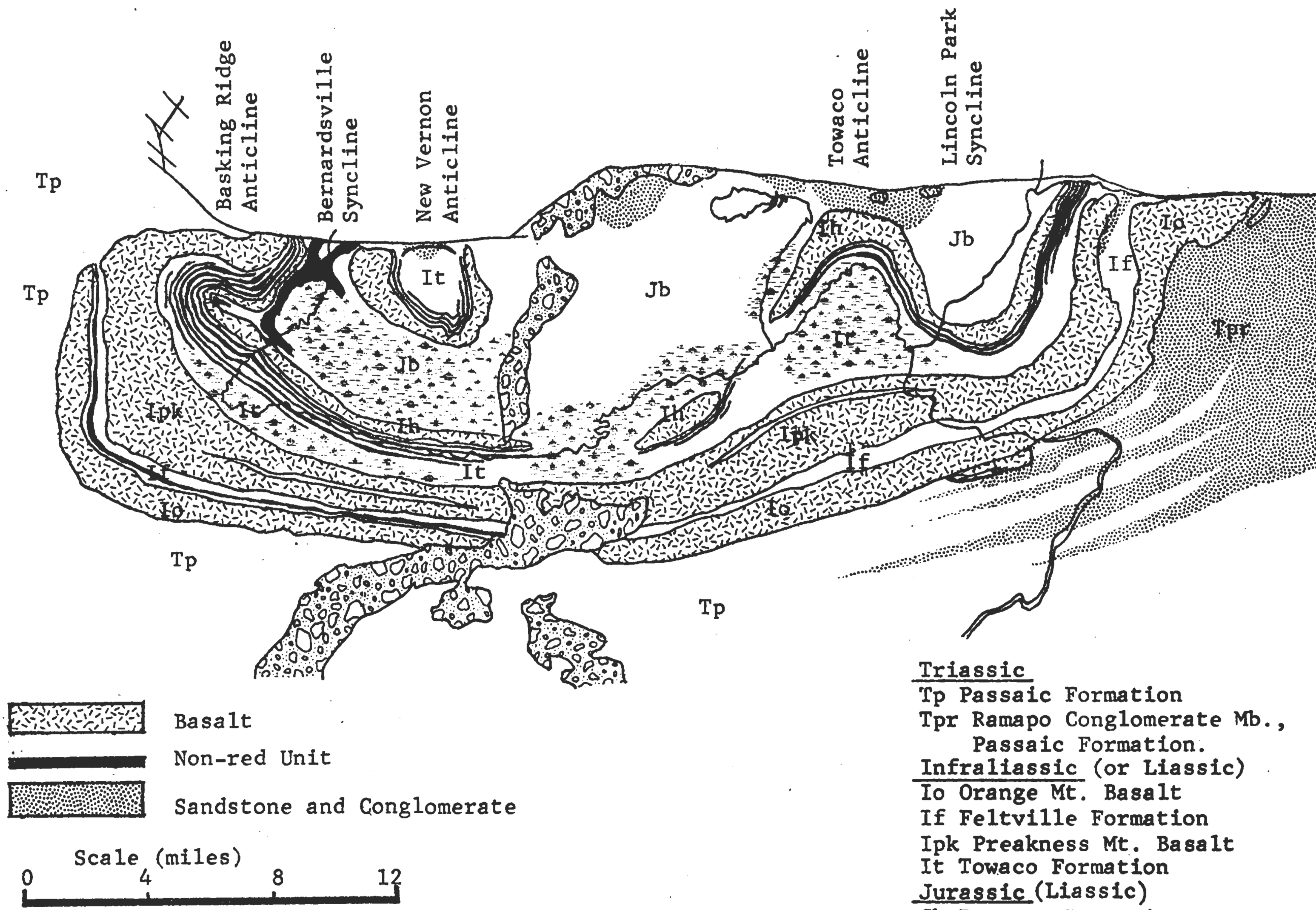
[11] The name 'Towaco' is taken from Towaco Mountain near Lincoln Park, New Jersey. The term Roseland would be prefered but is preoccupied by the Roseland Anorthosite in Virginia.

Figure 4. The Passaic Syncline. (adapted from Olsen, M.S.; and N.J.G.S. Geologic Overlay Sheet 27)



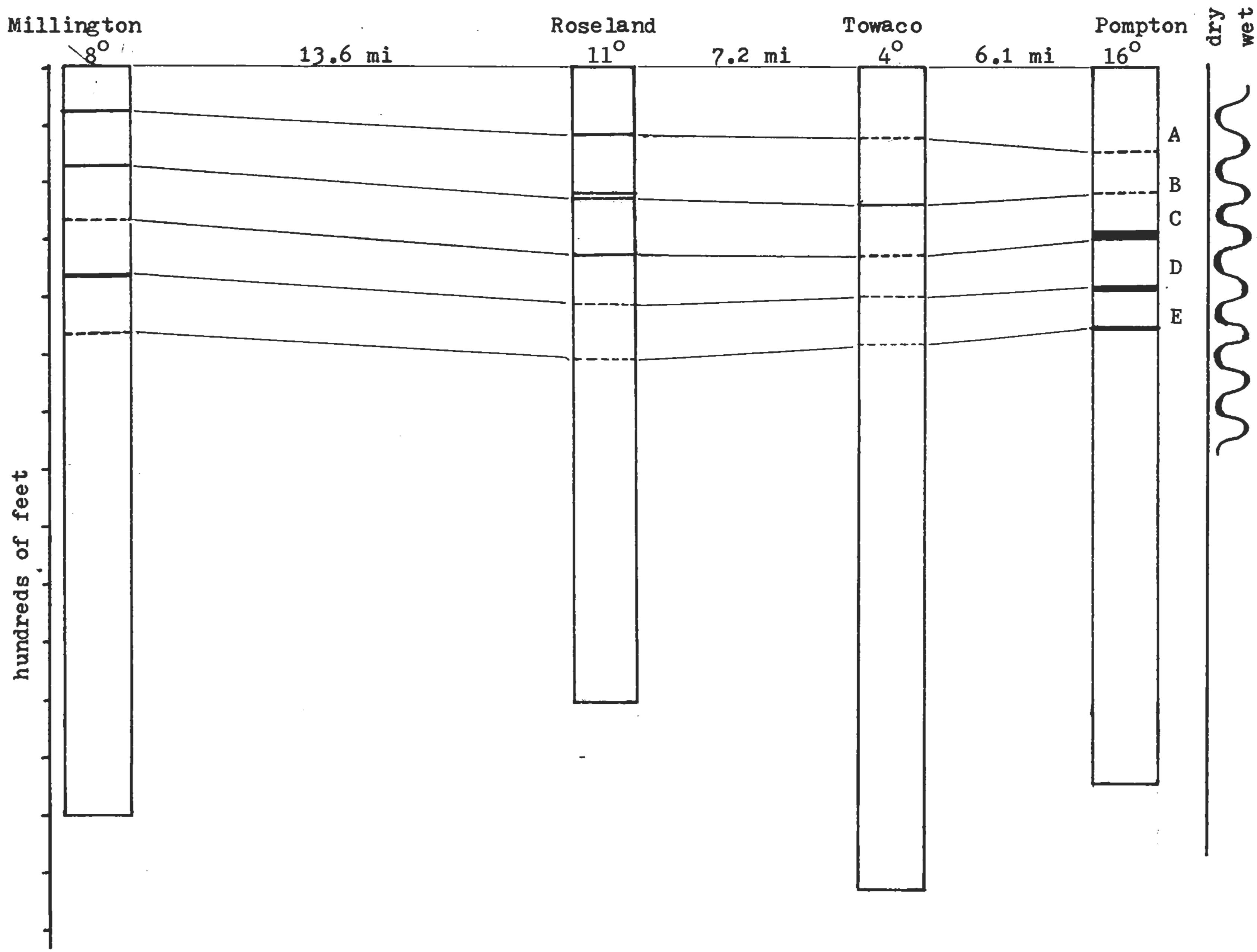
Two non-red units are exposed in the Roseland Quarry (see section 3); the upper unit and the overlying red beds being termed member A, and the lower unit and the red beds in superposition termed member B. A third non-red unit is known from a well just to the east of the Roseland Quarry (Olsen, M.S.) and this and its red beds are termed member C. Similarly, there are members D,E and F exposed elswhere in stratigraphically lower positions.

Members A and B are very well exposed and have been traced throughout the Passaic Syncline. Members C, D., and E are well exposed in gorges near Pompton. Member B is well exposed at Tom's Point, about six miles to the south (see figure 5). South of Chatham, members A, B, D, and F are exposed in numerous places. Members A and B are especially well exposed near Millington and member A is again very well exposed at Bernardsville. Figure 6 is a possible correlation along strike of these members in the upper half of the Towaco Formation. Since the mean thickness of the units (non-red plus red portions) is 95 feet, 12 non-red units may be present in the Towaco Formation. Unfortunately, the Lower Towaco Formation is nowhere well exposed and mapping must proceed after analysis of the well data.

The thickness of the Towaco Formation and its subdivisions vary little along strike (see figure 5). Near Bernardsville, however, the Towaco Formation thins from 1300 feet at Millington to 100 feet. This area has been mapped in detail (see figure 6).

There are only two exposures of major conglomerate beds

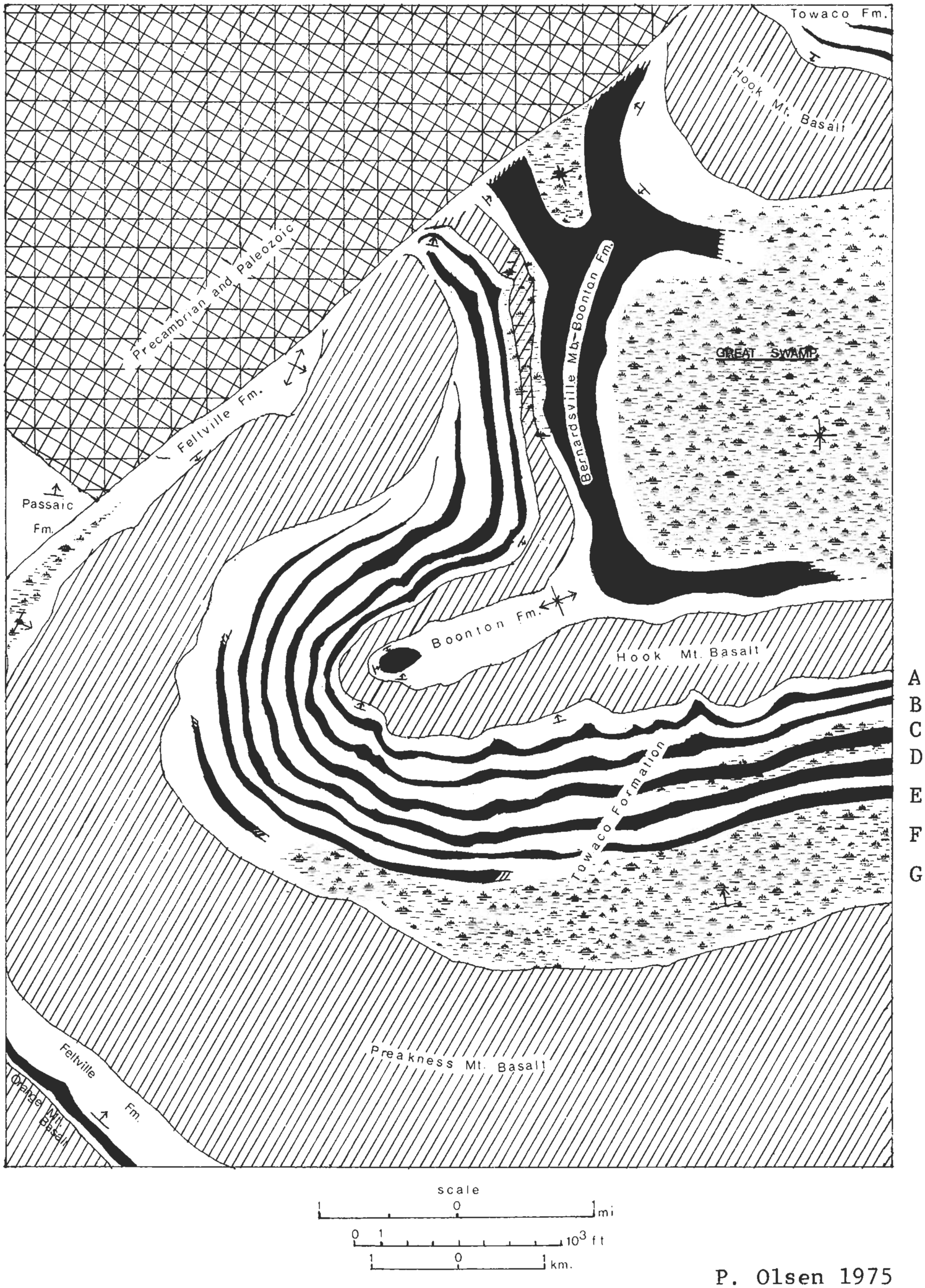
Figure 5 . Correlation of cycles along strike.



in the Towaco Formation. The thickest is the well known Pompton Limestone Conglomerate which forms the upper part of member D (Rogers, H.D., 1836; Redfield, 1853). The other, at New Vernon, is exposed as several units of basalt conglomerate and gneiss conglomerate, about 1000 feet east of the Newark Basin edge.

There is a thin tuff unit at the contact between the Hook Mountain Basalt and the Towaco Formation. It is about 3-10 feet thick and occurs at all exposures of the uppermost Towaco Formation except at Pompton, where it is replaced by a green phyllite conglomerate which seems to contain some volcanic clasts.

Figure 6. Preliminary Bedrock Geology. Bernardsville Quadrangle



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3. STRATIGRAPHY OF THE ROSELAND QUARRY.

3.1 Areal Geology of Riker Hill.

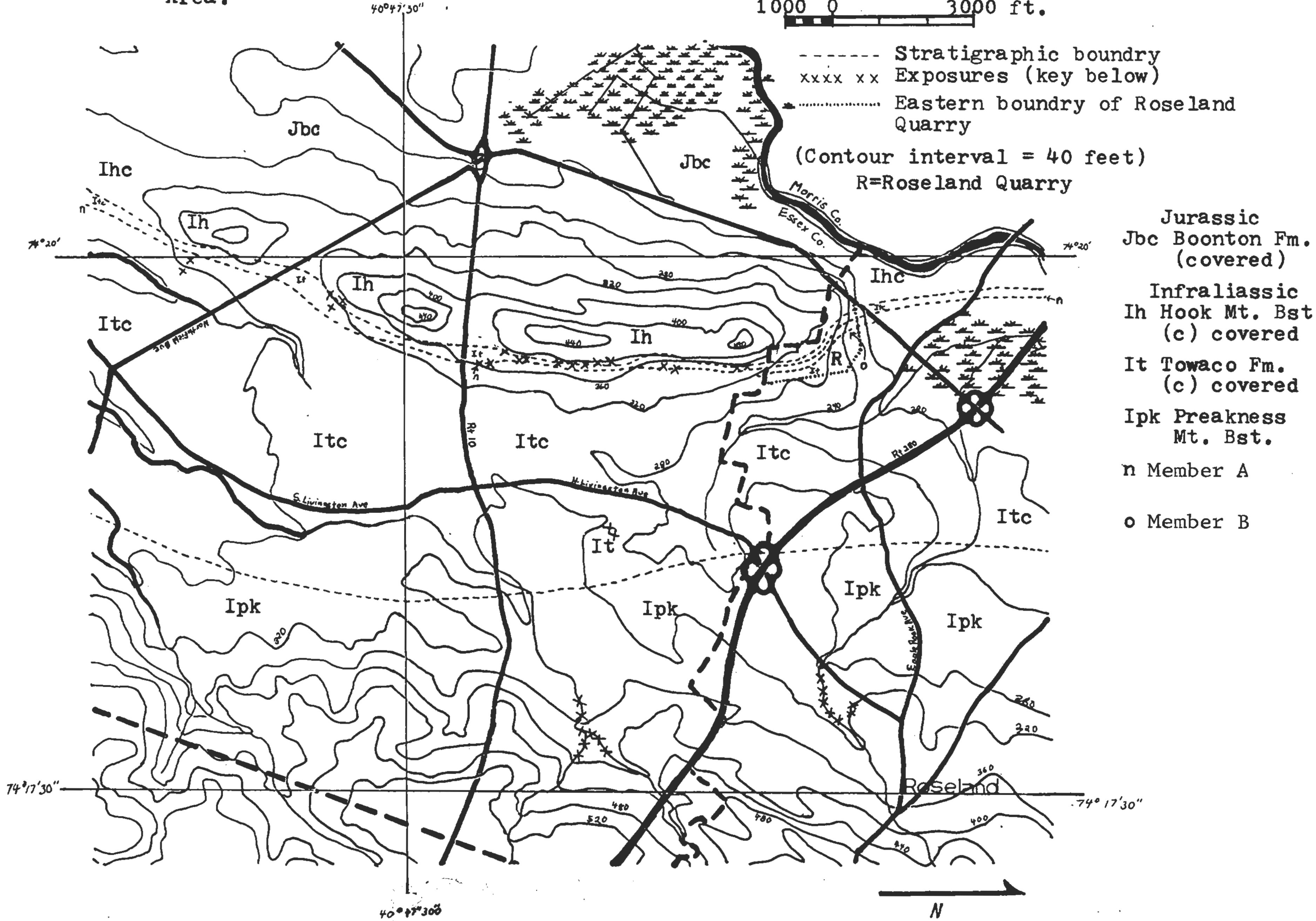
Riker Hill is an isolated segment of the Third Watchung Mountain (see figure 1). The bedrock (see figure 7) consists of Boonton Formation, Hook Mountain Basalt, and Towaco Formation. Unfortunately, the entire area is thickly mantled by Pleistocene glacial deposits and exposures are rare.

The Roseland Quarry occupies the northern-most tip of Riker Hill and is the largest single exposure of the Towaco Formation. While exposures of Hook Mountain Basalt are relatively common along the crest of Riker Hill, outcrops of the Towaco Formation are limited to temporary exposures on the east slope. There is, however, one outcrop of lower Towaco Formation at the Harrison School in Livingston (see figure 7). The only other known exposures of bedrock near Riker Hill occur on the west slope of the Second Watchung Mountain. Here, there are several good exposures of upper Preakness Mountain Basalt. The contact between the Towaco Formation and Preakness Mountain Basalt is nowhere exposed in the Riker Hill area.

Riker Hill is isolated on three sides by the flood plain of the Passaic River (see figure 7). In these areas the Hook Mountain Basalt and underlying Towaco Formation slope beneath the flood plain deposits. There are no exposures of the Boonton Formation in this area.

The Towaco Formation seems to be about 1200 feet thick at Roseland. The contact between the Towaco Formation and the Hook Mountain Basalt has been mapped over Riker Hill from

Figure 7. Areal Geology of Riker Hill and Surrounding Area.



several good exposures and well records. The thin tuff is present at the contact at every exposure. Unit A (see section 2,4) has been encountered in several foundation excavations and wells and has been mapped. There are no known exposures of the non-red portion of unit A outside of the Roseland Quarry which are accessible at present. There are a few exposures of the red portion of unit B at the southern tip of Riker Hill but other than the exposure at Harrison School, there are no known exposures of units below B anywhere nearby.

Mapping in the Riker Hill area will be aided by examining the well record data. Most of the water in Livingston is obtained from artesian wells within the Towaco Formation. The non-red portions of the Towaco are much more fractured and slicken-slided than the red beds and these are major aquifers; the well for the Environmental Sciences Center of the Essex County Park Commission was placed into the non-red portion of unit A. The data needed for mapping of the non-red units should be readily available from the well drillers.

3.2 Descriptive Stratigraphy of the Roseland Quarry

One third of the area of the Roseland Quarry is exposed bedrock, The rest of the quarry exposes Pleistocene and Recent sediments. These will not be discussed here. Figure 9a is the topographic base map of the quarry and figure 9b is the geologic map. The maps of the Roseland Quarry are divided into square sections, 500 feet on the side, to facilitate

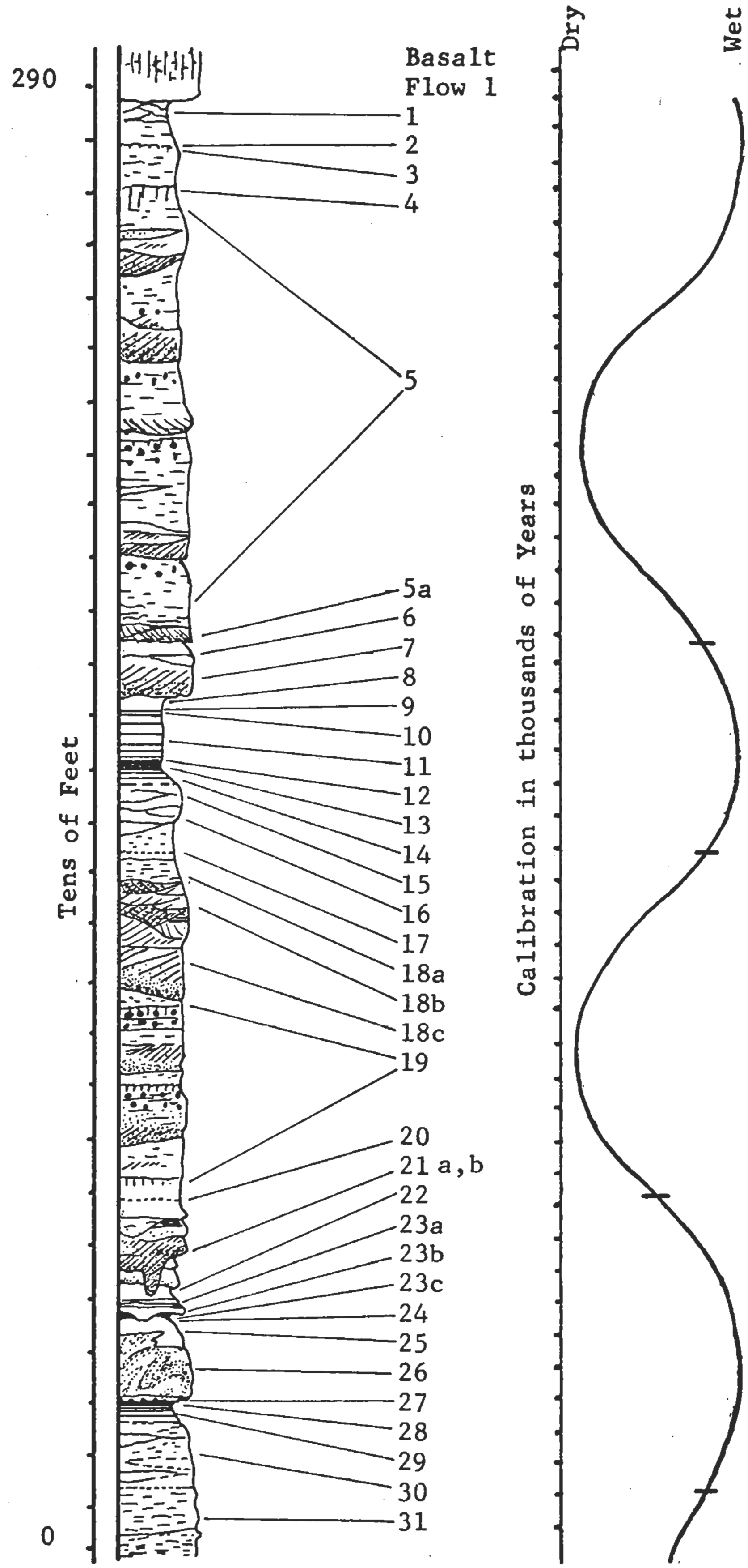


Figure 8. Key diagram for Roseland Quarry Section.

P. Olsen 1975

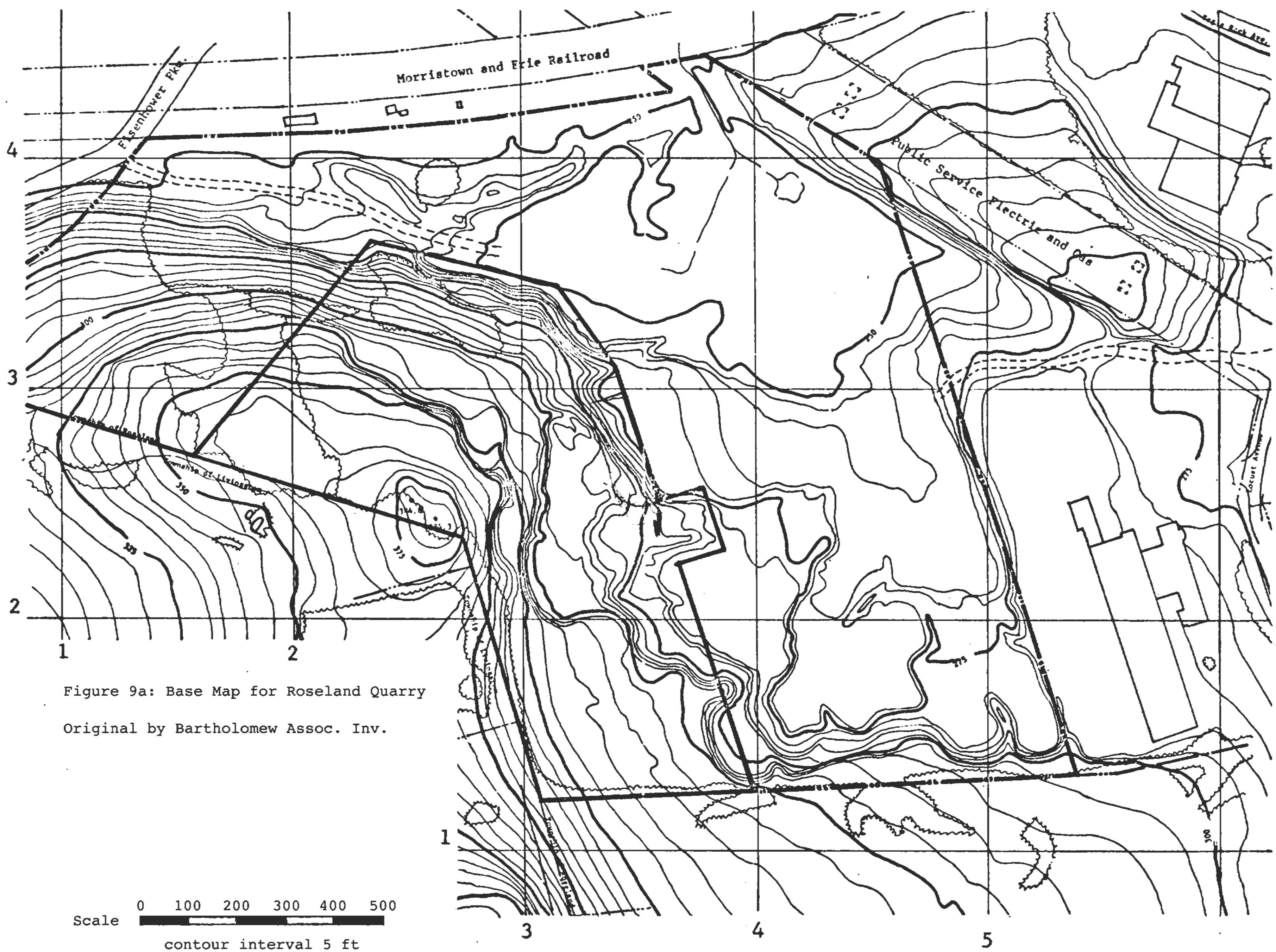


Figure 9a: Base Map for Roseland Quarry

Original by Bartholomew Assoc. Inv.

Paul E. Olsen, 1975

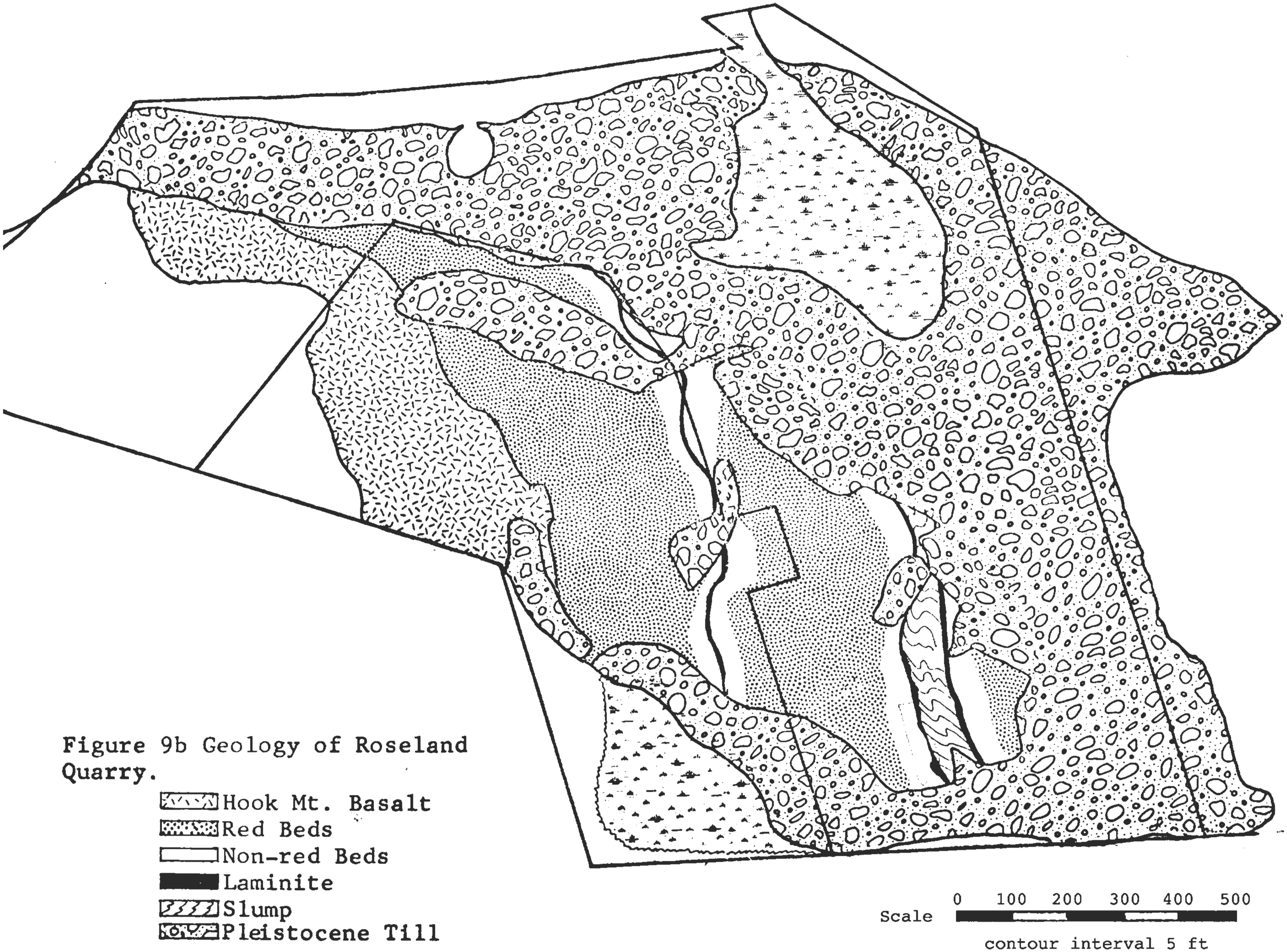


Figure 9b Geology of Roseland Quarry.

reference in the text or tables to certain areas. Each section will be referred to by its coordinate position on the maps (eg., map section 3.2).

The Roseland Quarry exposes about 300 stratigraphic feet of the Upper Towaco Formation and 100 feet of the Hook Mountain Basalt. Figure 8 is a diagram and key to the Roseland Quarry section which is described in Table III The section has been divided into beds of distinctive lithologic character each of which has been given an informal unit number. Certain units have been subdivided after the initial mapping and given letters (eg. 23a, 23b, 23c). The order of the unit numbers is not meant to suggest a temporal or spacial sequence but merely as a convenience. Table III is included in section 4.7 to facilitate reference from the purely descriptive to the interpretive.

4 ENVIRONMENTAL RECONSTRUCTION

4.1 Introduction to Environmental Interpretation

Observations on modern sedimentary processes, cautiously applied, provide the basis for interpretting ancient environments. Such interpretations are both analogical and historical and are subject to certain limitations. Diagenesis, diastrophism, and poor exposure introduce problems not easily overcome. The present is the key to the past but the uniqueness of every environment, past or present, must always be remembered.

The following sections (4.2-4.3) will suggest the environment of deposition of the various rock units described in sections 3.1 and 3.2, beginning with the major characteristics of certain suites of sediments in the Towaco Formation (sections 4.2-4.6) and continuing with the individual units in the Roseland Quarry (section 4.6a). The sediments in the Roseland Quarry are viewed in the context of changes affecting all of Towaco sedimentation.

4.2 Sedimentary Cycles in the Towaco Formation

> "Those who accept rhythm in nature will find it even where it is rather indistinct, and they will arrive at proper conclusions. Those who do not want to, will not find it even where it is obvious."
>
> (Yu. A. Zhenchuzhnikov, 1958)

A sedimentary cycle can be defined as a series of lithologic elements repeated through a succession (Duff, Hallam, and Walton, 1967). These are very common and have been described in rocks of all ages. Obvious cycles of several types comprise most of the Towaco Formation, as in all sedimentary deposits of the Newark Supergroup (Van Houten, 1969).

The scale of cycles present in the Towaco Formation varies from the varve couplet (section 4.5) which results from annual changes in sedimentation, to fining-upwards cycles, to lacustrine-fluvial cycles of 21,000 years' duration.

Duff, Hallam, and Walton (1967) recommend that a modal cycle (one that best fits the observed sequence) be defined for each cyclical sequence. For the cycles in the Towaco Formation, only those units which are present at all exposures are included in the modal cycle.

4.3 Lacustrine-Fluvial Cycles - The Towaco Cycle and Red Beds

"Essentially all deposition is cyclic or rhythmic."
(Twenhofel, 1939, p.502)

The Towaco Formation consists of alternating red and non-red beds. Each non-red unit and the red beds above them have been referred to as lettered units of the Towaco Formation (eg., A, B, C, etc.). Each of these units is composed of a suite of sedimentary units which is characteristic of all the units. The sequence is a sedimentary cycle and may be called a "Towaco Cycle" (or cyclothem). The Towaco Cycle is characterized by the alternation of red and non-red beds. Basic to the interpretation of the cycle, therefore, is some understanding of red beds.

The term "red beds" applies to a variety of sedimentary rocks ranging from reddish-brown through maroon and purple. Red beds may be of any age and possess many different types of primary and sedimentary structures. The coloring agent in Newark Supergroup rocks and red beds is red ferric oxide (hematite:Fe_2O_3) present as pore fillings, coatings on grains, or dispersed in a clay matrix (Krynine, 1950; Van Houten, 1972).

The origin of hematite-colored red beds has been debated for many years and attempts have been made to assign specific climatic significance to the red color. Russel (1889) proposed one of the first modern views:

> "The red rocks of the Newark System and the Rocky Mountain Red Beds were formed from the debris of lands that have been long exposed to the action of warm, moist atmosphere."[10]

Barrel (1909), on the other hand, believed that red beds formed in arid and semi-arid climates. He cited as evidence the Great Valley of California and other modern examples and noted the association of some red beds with evaporites.

These opposing views have been long debated. Krynine (1949, 1950) advocated Russel's theory and received wide support. Crucial to his argument is the distribution of recent red soils. Krynine believed that red beds inherited their color directly from eroded and redeposited residual soils. Because modern red soils are produced in areas with warm, humid climates, he assumed that red beds indicate the same sort of climate.

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[10] Russel (1889, p. 46).

Conversely, Shotton (1956), Jackson (1962), McKee (1964) and Walker (1967, 1969) have supported Barrel and demonstrated that red beds do form in deserts and semi-arid regions today.

Berner (1970,1971) has shown that hematite requires no special conditions to form from limonite (mostly goethite, FeO(OH)). Limonite is the chief, yellow-brown pigment in most recent sedimentary deposits, regardless of climate. He concludes that red beds may have been originally yellow or brown.

> "Thus, it appears that red beds are not good paleoclimatic indicators. However, the red color does indicate that ferric oxides, whether originally yellow or red, have withstood reduction to ferrous minerals during diagenesis because of a lack of metabolizable matter in the sediments."[11]

Most of the iron in non-red beds of the Towaco Formation is in the form of pyrite[12] FeS_2. Pyrite forms from the reaction of dissolved H_2S with finely grained ferric oxides, especially goethite. Berner (1972) points out that the two major sources of sulfide are bacterial sulfate and organic sulfur compounds with the former being more important. The source of dissolved sulfate is primarily organic matter decaying in an aerobic environment (Berner, 1972). If the sulfate is not reduced, it accumulates and is unchanged. Aquatic, anaerobic bacteria utilize organic material to reduce sulfate to H_2S. Thus, the two factors limiting pyrite formation are the quantity of organic matter and the permanence of unoxygenated water.

[11] Berner (1971, p. 198).

[12] Ferroan dolomite, siderite, and free goethite are present in small quantities. This discussion includes pyrites dimer marcasite.

Red beds of the Towaco Formation, then, are colored by authigenic hematite derived from goethite which escaped reduction to pyrite during diagenesis. The non-red beds however, have been subject to H_2S before hematite could form. Walker (1967) observes that limonite converts to hematite in ground waters of low temperatures in Recent and Pleistocene sediments in California. This probably takes many thousands of years (Van Houten, 1973). During this period the detrital goethite could be reduced.

The genesis of red and non-red beds in the Towaco Formation might be expected to have been influenced by:

1) quantity of detrital goethite
2) quantity of available organic matter
3) availability of dissolved sulfate
4) porosity of sediments
5) permanence of interstitial water
6) quantity of dissolved O_2
7) rate of change from goethite to hematite

The relative importance of these factors to an understanding of the alternation of red and non-red beds in the Towaco Formation is dependent on an analysis of the entire sedimentary sequence.

The study of vertical and areal changes in sedimentary structures provides more information about the ancient depositional environment than the study of red beds in isolation. The vertical units in the modal Towaco Cycles are diagrammed in figure 10. Towaco cycles are composed of two other major cycle types, both of which have been identified in many sedimentary sequences. The varved and laminated siltstones (described below, 4.5) are the most laterally persistent of all the parts of a Towaco cycle. Fining-upwards cycles, although always present, are much more local (see section 4.4) The lateral changes in the major divisions of Towaco Cycles are interpretted in figure 11.

Towaco Cycles bear a very close resemblance to at least two other cyclic deposits. Van Houten (1952, 1964, 1965, 1969) described cycles from the Lockatong Formation (Novacaesarea Group). The sequence of sedimentary structures is the same as in the Towaco Cycle, though the scale is different (see figure 10). A similar sequence is again seen in the Caithness Flagstones (Devonian of Scotland) described by Crampton et al (1914), (see figure 10). These papers contain different explanations for the origin of the cycles: Van Houten(1962) suggests that the Lockatong cycles result from climatic changes varying within the 21,000 year precession cycle, while Crampton et al. believe that the Caithness Flagstone cycles were controlled tectonically. Both agree that the efficient cause of the cycles is the transgression and regression of a large lake. I will present evidence that the Towaco Cycles owe their origin to the waxing and waning of large lakes and I will suggest that periodicity relates to the precession cycle.

4.4 Fluvial Deposition- The Fining-Upwards Cycle

The vertical sequence of beds and the lateral variation of much of the Towaco Formation is typical of fluvial depositional environments. Fining-upwards cycles have been described both from the fossil deposits (including the Middle Old Red Sandstone of Britain; Allen, 1964a, 1965, 1970), the Middle Passaic Formation of New Jersey (Van Houten, 1969), and Recent sediments including those of the Bramaputra River (Coleman, 1969) and streams in Utah (Picard and High, 1973).

Reineck and Singh (1973) have grouped alluvial deposits into three major groups:

1. Channel deposits; formed mainly from activity of river channels, including channel lag, point bar, channel bar, and channel fill deposits.
2. Bank deposits; formed on the river banks and produced during flood periods. These include levee and crevasse splay deposits.
3. Flood basin deposits; fine-grained sediments formed when the river surges over levees onto the flood bain. They include marsh deposits.

Fining-upwards cycles form the bulk of the Towaco Formation. The modal fining-upwards cycle is described in figure 12. The lower, massive parts of the modal cycle (see figure 12) are interpretted as channel deposits, usually point bar. The middle portion of the cycle, dominated by beds of siltstone with climbing ripples in drift, is probably a bank deposit. The upper beds of fine-grained siltstones contain reptile footprints, root

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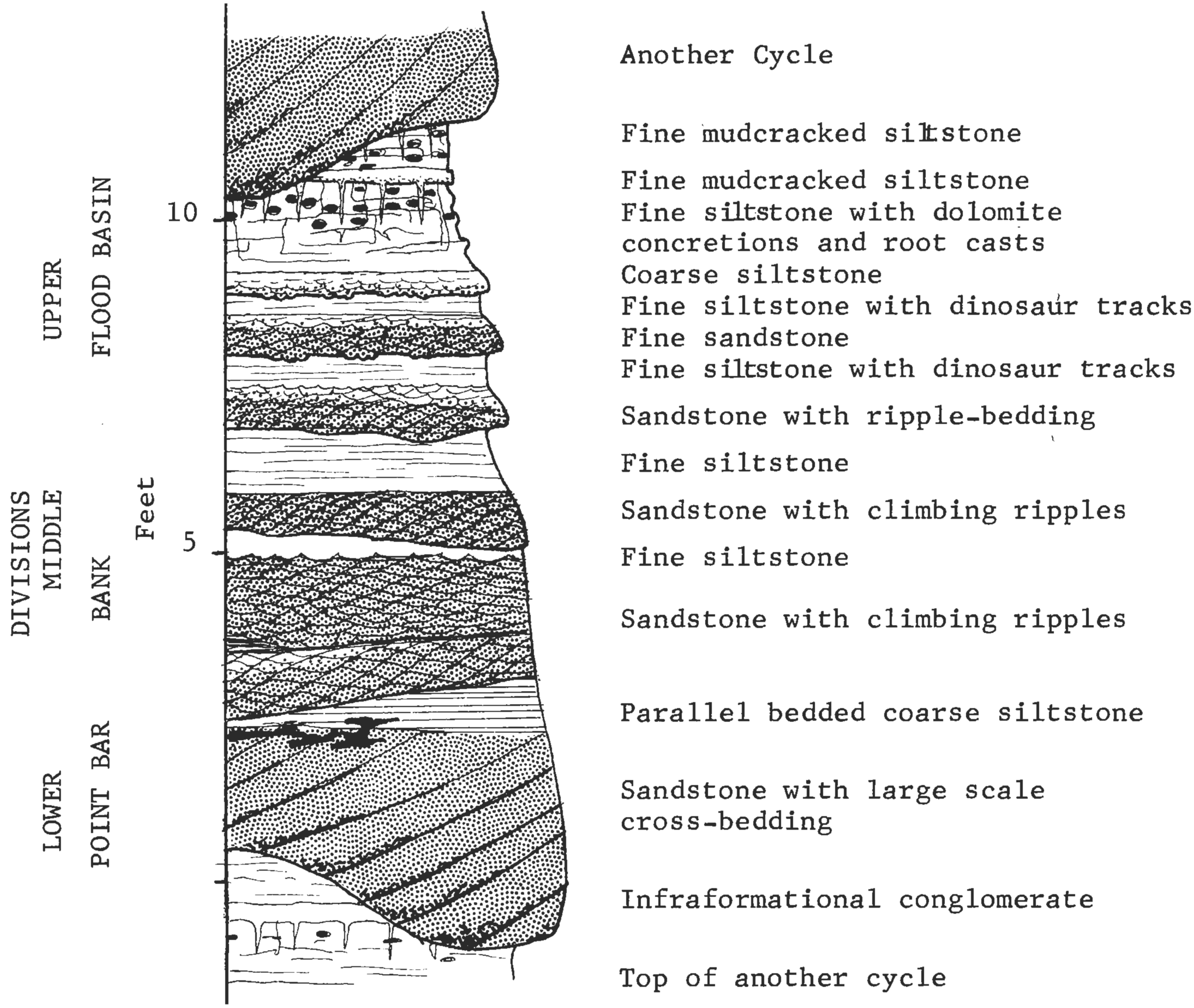

Figure 12. The modal fining-upwards cycle for the Towaco Formation.

horizons, and carbonate concretions, indicating flood basin deposits.

The migrating channel cuts into older beds in the direction of migration, redepositing the sediments as channel (lateral accretion) deposits. Bank, and then flood basin sediments, follow in vertical sequence as the channel migrates further away from a given section. Because the channel erodes several feet of sediment as it migrates, no upward coarsening persists; none are preserved, producing at each section a strongly assymetrical, fining-upward cycle.

4.5 Varved Laminites - The Deep Water Lake Environment

The lower third of every fluvial-lacustrine cycle in the Towaco Formation has a bed of very well bedded and laminated calcareous, clayey siltstone whose laminae are traceable over a very large area. Most of this sediment is composed of couplets of laminae: one of silt, and the other of carbonate (usually $CaCO_3$) or sapropel. The couplet thickness is 0,4 mm. thick. This distinctive sediment is termed a laminite (Davies and Ludlam, 1973). These laminites are important not only for environmental reconstruction, but also because they usually contain a well preserved fish fauna.

Davies and Ludlam (1973) point out that deposition of laminites is typical of large, chemically stratified bodies of water (an anoxic bottom layer of water is present, only subject to rare mixing). The absence of any evidence of subaerial exposure, the subordinate role of current bedding, the complete absence of any marine invertebrates, and the numerous fossil fish indicate lacustrine deposition for the Towaco laminites. The articulated condition of the fish (a <u>lethal-pantostrat</u> biofacies, Shafer, 1963), the absence of bioturbation, and the lack of trails on bedding plains suggest deposition in a meromictic lake (stratified).

The Towaco laminites are very similar to modern laminites of Green Lake, New York (Ludlam, 1969), the Adriatic Sea (Sicbold, 1958; Van Straaten, 1970), the Black Sea (Ross et al, 1970), and the Dead Sea (Neev and Emery, 1967). Similar fossil deposits include the Middle Devonian Elk Point Basin beds of Canada (Davies and Ludlam, 1973) and the Achanarras Limestone of the Caithness Flagstones of Scotland (Crampton et al 1914), the Triassic Lockatong Formation of New Jersey (Van Houten, 1962), the Jurassic Todilto Limestone of New Mexico (Anderson and Kirkland, 1960) the Eocene Green River Formation of Wyoming (Bradley, 1929; Surdam and Wolfbouer, 1975), the Oligocene Florissant Lake beds of Colorodao (Anderson, 1964), and the Miocene Monterey Formation of California (Bramlette, 1916; Anderson, 1964). These include both lacustrine and marine examples. Davies and Ludlam state:

> "...laminited sediments are a natural product of rythmic sediment accumulation by settling in any stratified body of water subject to cyclic changes. These laminations will be preserved only where the effect of bioturbation and physical disturbance is small compared with the sedimentation rate."
> (Moore and Scruton, 1965).[13]

The area of the laminite unit is a minimum size of the lake during its highest level. In the Towaco Formation, the laminite units are traceable over all of the Passaic syncline demonstrating a minimum area of 920 $km.^2$ (360 $mi.^2$). The actual area was probably much larger.[14]

The smallest scale cyclic units in the Towaco Formation are the couplets of laminites, which might plausibly result from annual variation in sedimentation. Such is the case in Recent deposits which have been dated (Ludlam, 1973). If it be accepted that each couplet represents one year's deposition, the term varve may be applied (De Geer, 1912). These varved laminites are the only cyclic sediments of the Towaco Formation whose rate of deposition is known. The presence of varved sediments associated with other sediments allow the sequence to be calibrated (Anderson, 1964).

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[13]Davies and Ludlam, 1973, p. 3539.

[14]The area of laminites in underlying formations indicate a minimum area of 2760 $km.^2$ (1080 $mi.^2$) for the Feltville Formation and 14,400 $km.^2$ (5600 $mi.^2$) for the Lockatong Formation and Passaic Formation.

4.6 Lacustrine Turbidites

Turbidity currents are intrusions of dense sediment-laden water which flow beneath less dense water along the basin floor. The characteristic sediment these currents deposit has the same fundamental structure, a turbidite, whether deposited in fresh or marine waters. Generally, grain size decreases upwards and there forms a defined sequence of sedimentary structures (see figure 13). Turbidites usually occur in large numbers and are a type of cyclic deposit. The Bouma Cycle (Bouma, 1962, 1964; Bouma and Brouwer, 1964) is a type of turbidite for which a modal cycle has been defined (see figure 13). Numerous variants from the modal cycle can be explained by a proximal-distal turbidite model (Walker, 1965, 1967; Dzulynski and Walton, 1965; Allen, 1969). The Bouma Cycle is a proximal turbidite (see figure 13).

Turbidity currents play major roles in lacustrine accumulation; for instance, they account for as much as half the accumulation in Green Lake,[15] New York (Ludlam, 1974). Houbolt and Jonker (1968) show similar results for Lake Geneva. Indeed, turbidity currents may be the sole source of coarse sediments in large bodies of water.

Two modes of origin are known for turbidity currents in lakes. Houbolt and Jonker (1968) have found turbidity currents produced when the cool sediment-rich waters of the Rhone River underflow the relatively warm waters of Lake Geneva. The stream of the Rhone retains its identity and flows towards the deepest part of the lake along a submarine channel with levees to a depth of

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[15] This lake is meromictic and deposits varved calcareous siltstones resembling the varved laminites of the Towaco Formation.

about 300 meters, where it dissipates at the channel fan. They recognise five types of sediments deposited partly or entirely by turbidity currents: channel deposits, levee deposits, channel fan sediments, fan margin beds, and central plain deposits. Submarine analogues to crevasse splay sediment may also occur on the delta. These types of sediments also occur in marine turbidities.

Another origin of turbidity currents in lakes has been described by Ludlam (1973) from Green Lake, New York. These turbidity flows begin as slumps along the basin margin. The slump slides down the basin slope, liquifies as it mixes with water, and becomes a turbidity current. The internal structure of turbidites so formed resemble distal marine turbidities and those deposited on the channel fan margin of Lake Geneva.

These two modes of turbidite formation may correspond to the two postulated turbidite types of geosynclines: longitudinal and transverse (Duff, Hallam, and Walton, 1967). Each type should be recognizable by paleocurrent analysis. The constituents of the turbidite sediments may also differ as the sediments of the sources need not be the same.

Cyclic units resembling turbidites are found in association with the laminite units in the Towaco Formation. Slumps and proximal-distal turbidites are present and will be discussed in specific in sections 4.7A, 4.7B.

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[16] Von Engeln (1931), Courel (1951), and Ludlam (1967) describe similar occurences of other lakes.

4.7A Interpretation of the Microstratigraphy of the Roseland Quarry.

The discussion, heretofore, has considered general inferences from Towaco Formation sedimentation. This section presents a detailed interpretation of the stratigraphic section exposed in the Roseland Quarry, from the lowest exposed unit and proceeds up the section. The interpretation is carried out with reference to basin wide environmental events.

The even numbered pages carry the purely descriptive stratigraphic section of the Roseland Quarry (Table 3). The odd numbered pages contain the environmental interpretation of the units described on the left.

TABLE IV. Roseland Quarry section. Refer to section 3.2.

Unit	Thickness	Area Exposed	Description
31	+14	(4,1)	Red siltstone much like parts of unit 19. Small scale climbing straight and cuspidate ripples-in drift, very few fine siltstone parting plains. Lateral exposure very poor base of unit not exposed. This is the upper part of member C of the Towaco Formation.
30	13.3	(4,1)	Transition from unit 31 to 30 marked by color change from red to red-orange to gray. Base of unit 30 has same sediemntary structures as unit31. Upper half has lenticular beds of coarse siltstones and fine sandstone separated by fine siltstones. Each coarse unit is dominated by small scale trough cross-bedding and ripple bedding and fining upward of grain size in less than a foot. Possible reptile footprints present as well as common carbonised plant remains.These are the basal beds of member B of the Towaco Formation.
29	2.0	(4.1)	This is distinctly finer than preceeding units and is characterised by dissapear-ance upward of current bedding and the appearance of fine, laterally continous black laminae. The upper few inches are very well bedded and have very numerous black laminae.

Unit 31.

Interpretation is difficult because of poor exposure. The red color indicates only that the detritial goethite was not reduced during diagenesis. The climbing straight and cuspidate ripples-in-drift indicate more or less continous deposition by moderate currents within the lower flow regime. The structure and upward fining nature suggests the upper part of a point bar sequence or a levee deposit (see section 4.40. A fluvial environment is indicated.

Unit 30.

The transition from red to grey sediments indicates that goethite was reduced to pyrite before it could age to hematite. The sedimentary structures suggest that unit 30 represents flood basin and crevasse splay beds and, hence, an environment similar to unit 31 is envisioned. Since goethite takes considerable time to age to hematite and is suseptible to reduction during that time, the color of unit 30 could be influenced by interstitial waters of superposed sediments.

Unit 29. Plate II

These beds represent the transition from flood basin to lacustrine sedimentation. This type of lithology may be typical of new shallow lakes that are not stratified. The black laminae near the top of the unit may represent the first sediments deposited in a meromictic lake.

Unit	Thickness	Area Exposed	Description
28	1.5	(4,1)	Black and brown laminated siltstone much like unit 23c (both laminites). Charaterized by couplets of black sapropel-rich and calcium carbonate laminae. Transition between units 29 and 28 (2cm.) black, platy siltstone. Lower contact smooth, planer and slowly gradational. Upper contact deeply irregular. Upper part of unit has thin (5mm.) black graded beds between laminite couplets. Unit is very badly weathered. This is the base of the laminite of member B. Couplets .4mm. thick.
27	1.0	(4.1)	Contact between units 27 and 28 is sharp but irregular, on a scale of 18-25 cm. Lower surface formed by numerous, large, spiral flute casts. This is a gray, dense siltstone resembling unit 23b. Internal structure graded and unit is laterally discontinous over 100 feet of exposure (see Plate II).
26	6.7+	(4,1) (4,2)	Grey contorted siltstone. Jumbled mixture of several lithologies, none of which are laterally continous. Contacts beween 26 and 27, and 28 are sharp and very irregular. Most of this unit consists of parallel bedded siltstones thrown into large discontinous folds, hooks, and roll up structures (see Plate III). Intermixed with masses of slurried grey silstone with numerous black silstone (?laminite) blebs. Weathers with spheroidal exfoliation.

Unit 28. Plate II

Varve counts indicate that the preserved part of of this unit was deposited during a minimum of 1125 years in a lake of at least 920 km.^{2} (360 mi.^{2}). The platy black transition beds between units 29 and 28 record the full development of a meromictic lake through about 50 years.[17] Alternately, they could record the lateral passage of the lake chemocline as water depth increased. In any case, the beds of unit 28 were probably deposited in the sulfide (H_2S) enriched hypolimnion of a meromictic lake.

Unit 27. Plate II

There is little deformation of unit 28 at the contact so erosional implacement is suggested for this unit. The internal structure and sequence of beds are very suggestive of a Bouma Cycle (see section 4.6, 4.7B, figure 14). This unit is believed to be a proximal turbidite deposited in the meromictic lake. The flute structures and large grain size (graded) indicates deposition by initally high velocity currents of the upper flow regime.

Unit 26. Plate III

Two interpretations of unit 26 are possible, The unit could have been originally deposited horizontally, but liquified by a dewatering process or seismic shock that resulted in décollement - like structures. This does not explain, however, why the presumably less competent beds of unit 28 did not participate. A suggestion more in keeping with the large scale of this unit is deposition by

Unit	Thickness	Area Exposed	Description
25	8.5	(4,1) (4,2)	Gray poorly bedded siltstone identical to finer siltstones of unit 26. Coarse slump structures present locally. Lower contact slurried. Small black siltstone blebs present throughout.
24	.5	(4.1)	Black indistinctly bedded siltstone with uncommon plant fragments. Upper surface wavy.
23c	1.0	(4,1)	Same lithology as unit 28. Large numbers of fossil fish present on bedding planes with plant stems and leaves (rare). Upper part of unit with several thin (5mm.) black graded siltstones. Sapropel rich silt-carbonate couplets .4 mm. thick. Unit parallels upper surface of 24 and has an irregular upper surface which cross-cuts laminae. Unit laterally discontinous.

slumping. This unit was probably deposited on a subaqueous slope, freed by oversteepening, and transported to the site as a semi-liquified mass (see section 4.7B, figure 13).

Unit 25.

This unit was probably deposited with unit 26 and is the result of differential settling of the slumped mass (see section 4.6A).

Unit 24.

It seems likely that this unit was the last part of the slump of units 26 and 25 to settle out. It should be noted that there is no indication of subaerial exposure in units 26-24.

Unit 23c.

Unit 23c is charaterised by a letal-pantostrat biofacies with numerous Semionotus sp. Deposition was in a large meromictic lake with a lake chemistry similar to that which deposited unit 28. There is nothing to suggest that this does not represent the same lake as that unit, as well. Both units 28 and 23c are correlative with the single laminite unit present at other exposures of the basal part of member B of the Towaco Formation (see section 4.7B).

The thin graded beds are interpreted as distal turbidites as are those in the upper part of unit 28. Varve counts indicate deposition over minimum of 750 years.

Unit	Thickness	Exposed	Description
23b.	.6	(4.1)	Gray very hard siltstone. Base plainer bedded with some load casts. Lower part of unit massive with microcross-bedding. Middle unit .3-.7 cm. beds of rippled and small scale load casted siltstones, Upper unit parallel bedded with numerous fossil fish with some three dimensionality. Unit terminates abruptly against part of unit 23c at this units most southern exposure. Sediment distinctly graded.
23a	1.0	(4.1)	Gray-brown-black siltstone intraformational conglomerate. Clasts resemble unit 23c or 28. Minor grey and Black thin siltstone lenses. Carbonised plant fragments infrequent.

Unit 23b

Articulated fossil fish, as are found in this unit, are very rarely found outside of laminite units. It is likely, therefore, that this unit was deposited during the life of the lake. The internal structure of this unit is very suggestive of a Bouma Cycle: a proximal turbidite (see section 4.7B).

Unit 23a

This is probably a small proximal turbidite derived from newly exposed laminite units. This unit overlaps both 23c and 23b and may indicate the waning of the lake.

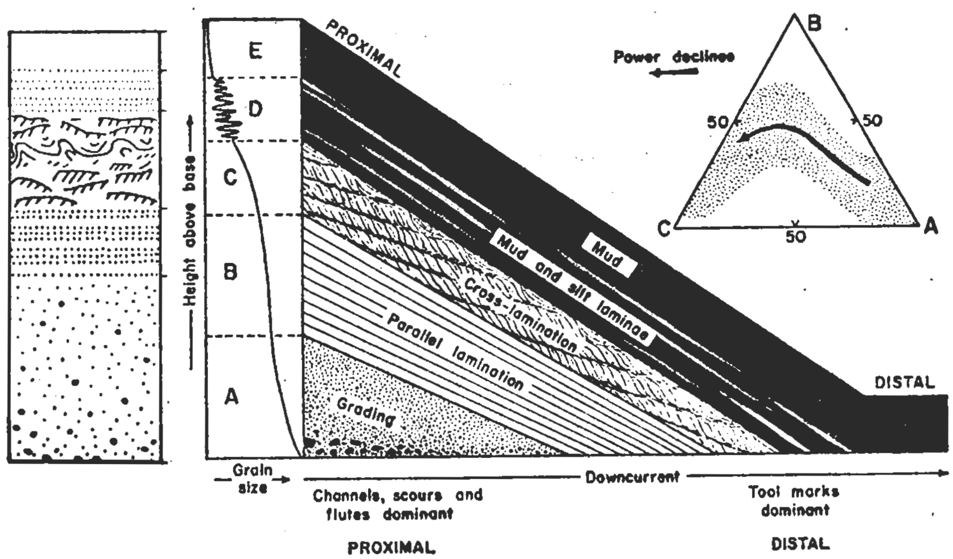


Figure 13. The Bouma cycle and Allen's 1969 interpretation of its lateral relations. From Allan, 1969).

4.7B Turbidities of Units 28-23c and Their Relation to Slumps

Beds closely resembling turbidities (see section 4.6) occur in association with laminites in the Towaco Formation. The graded black beds of units 28 and 23c correspond to distal, and units 27 and 23b resemble proximal turbidites. These and the slump units (26, 25, 24) can be related by a single proximal-distal turbidite model (see figure 14). Of course a slump is not <u>sine qua non</u> for a turbidite; perhaps both river and slump generative mechanisms may have been operative during the deposition of the Towaco Formation.

The facies relationships of these units are complex. Figure 15 is an interpretation of the lateral relationships of units 31-20. Note the down-cutting nature of most of the coarse units, especially those purported to be turbidites.

The thickness of a turbidite increases exponentially with proximity to the source (Allen, 1969). The thickness of the turbidites and slump beds of member B in the Roseland Quarry increases exponentially with its position in relation to the laminites in the section 28, 27, 25, 24, and 23c, 23b (see figure 16). This is interpretted as the result of a turbidite and slump source approaching at a constant rate.

This moving source may have been the migrating lobes of a submarine channel fan derived from a major entering river. Houbolt and Jonker (1968) found that the natural levees of the submarine channel of the Rhone River stood 12 meters above the channel floor.

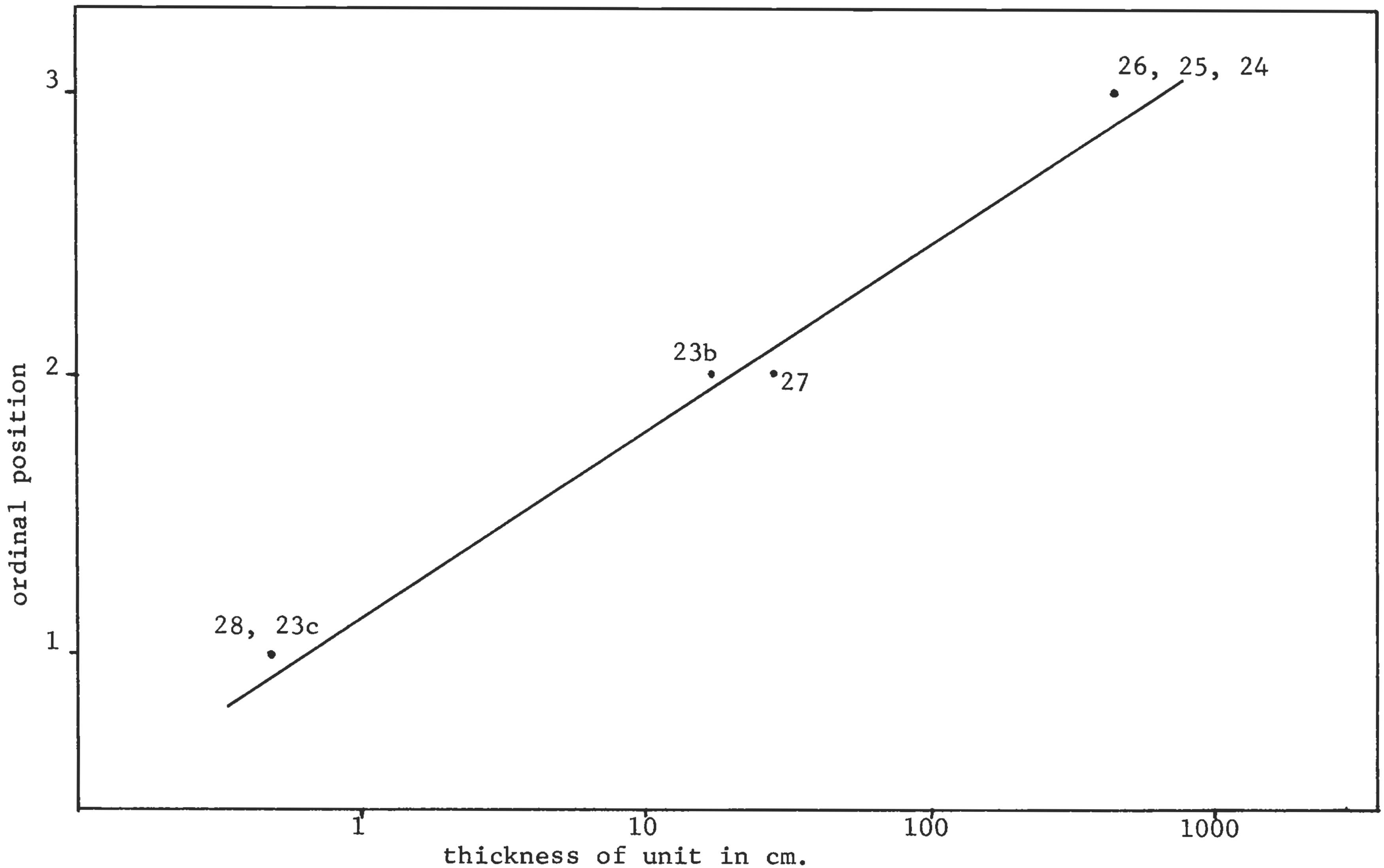
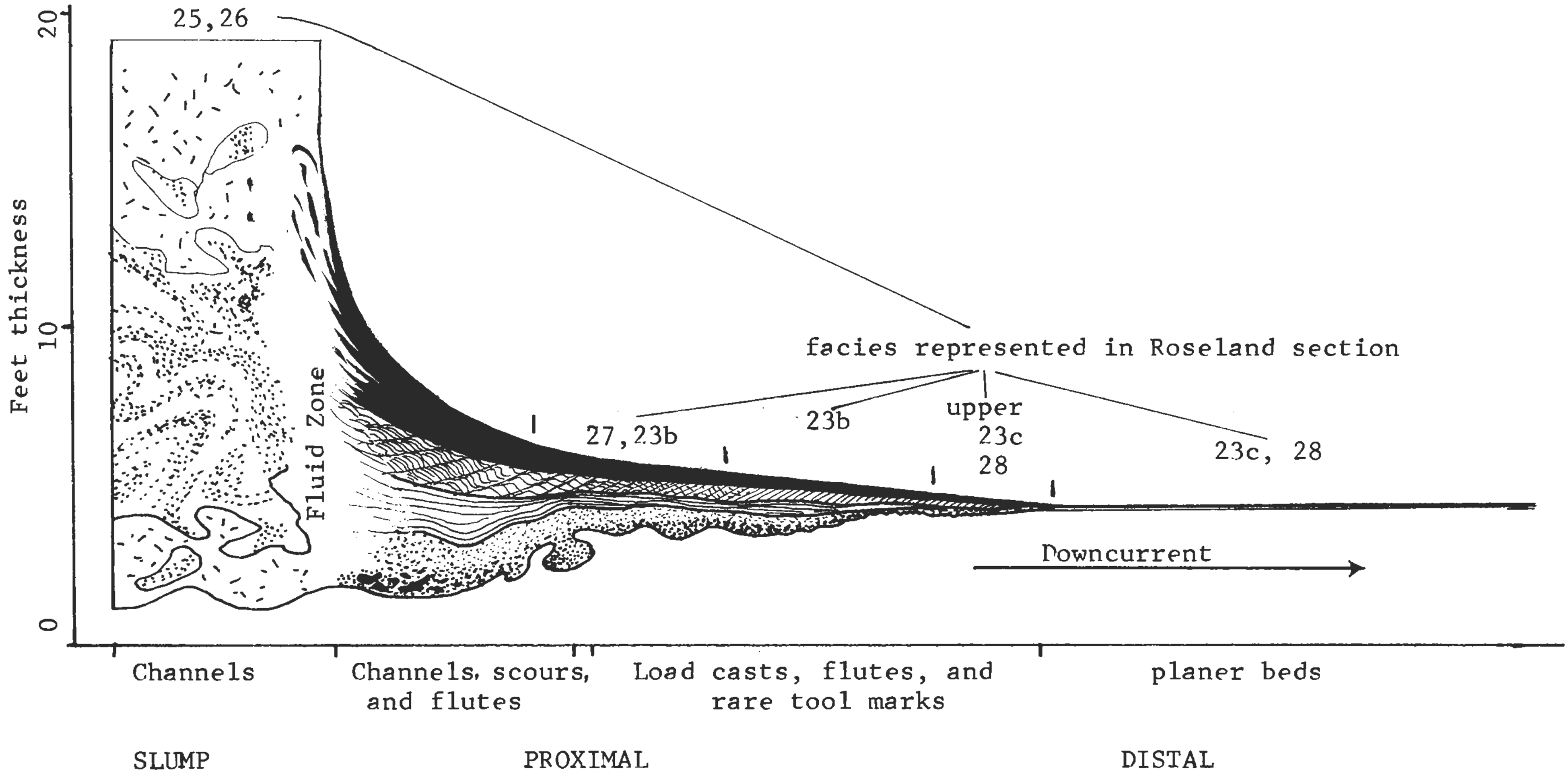


Figure 16. Relationship between ordinal position and thickness of turbidites and slumps in Roseland Quarry. (line fitted by eye)

Figure 14. Facies relations between slump and proximal and distal turbidites, downcurrent.



The slope of a similar channel may have been sufficient to form the Roseland slumps.

According to this model, the black graded siltstones of units 28 and 23c are distal turbidites of the channel fan margin, units 27 and 23c are deposits of the channel fan, and the slump was derived from the steep slopes of the channel.

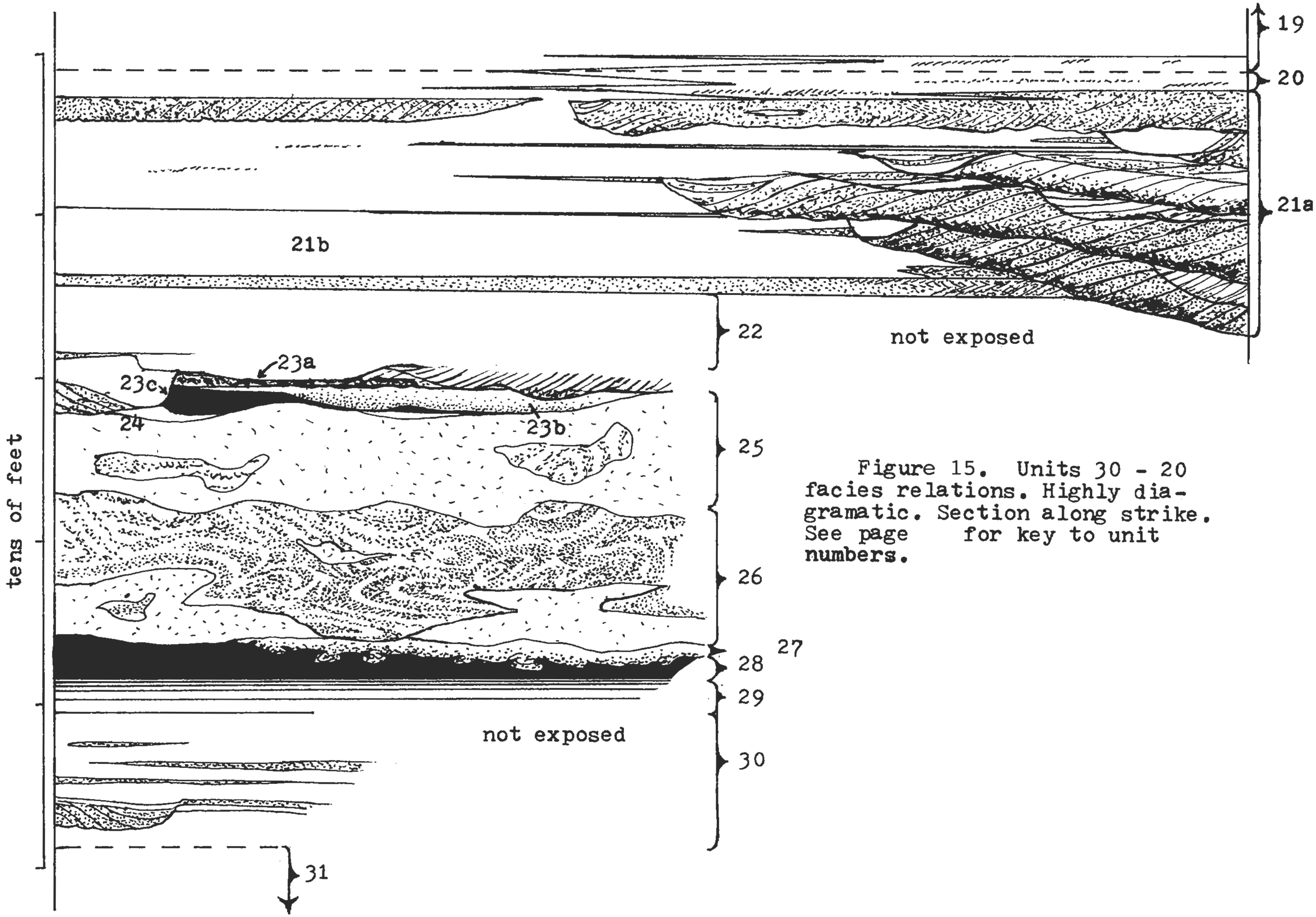


Figure 15. Units 30 - 20 facies relations. Highly diagramatic. Section along strike. See page for key to unit numbers.

Unit	Thickness	Exposed	Description
22	3.7	(4,1) (4,2)	Grey fine siltstone and claystone with good bedding. Thin stringers of coarser siltstone with ripple bedding. Lower contact sharp but irregular.
21b	+3	(4.1)	Southern stratigraphic equivalent of 21a. Grey well bedded siltstones with small scale ripple bedding, scour marks, very common. Dinosaur footprints very common (<u>Anchisauripus</u> sp.) One exposed bedding plain (see Plate VII) has over 170 footprints on an area of 120 $ft.^2$. These beds alternate with thicker beds of fine siltstone resembling unit 22.
21a	10 ± 1	(4.2)	Massive sandstone with large scale cross-bedding (longitudinal). Intraformational conglomerate at base containing blebs of units 23c and 22. Upper part of unit with ripple bedding and rare small lenses of very fine siltstone with plant remains. Fine beds palyniferous.

4.7C Units 22-18a.

Unit 22.

The small grain size and lack of proofs of exposure suggests suaqueous deposition in quiet water. As varves do not occur, it is probable that unit 22 was deposited in much shallower water than the laminates.

Units 21a, 21b, and 20.

Unit 21a is a fining-upwards cycle of the type described in section 4.4. Its lateral equivalent, unit 21b, is part of the same cycle. Unit 20 differs from 21a and 21b only in color and occupies the middle and upper parts of the cycle. Figure 15 interprets the lateral relationships of these units. These unit are especially interesting since they represent the reestablishment of fluvial deposition on the shores of a receeding lake.

The massive, large scale cross-bedded unit is believed to represent the base of the cycle: a point bar deposit. The fine siltstone lense near the top of the unit is probably a starved channel fill, possibly a former chute. The coarser beds of unit 21b are crevasse splay and natural levee beds of the channels of unit 21a. The lack of mudcracks and the subordinate role of current bedding in the fine beds of unit 21b (resembling unit 22) suggest deposition in quiet lacustrine water was the rule, with subaerial exposure the rare exception. These unit were deposited on the fluctuating shores of the waning lake.

Unit	Thickness	Area Exposed	Description
20	3	(4,1) (4,2)	Northern beds with climbing ripples grading upwards into fine ripple bedded siltstone. Southern exposures consist of alternating layers of fine red siltstones and coarse gray siltstone and minor sandstone. Color change from gray to red upward.
19	55	(3,1) (3,2) (3,3) (4,1) (4,2)	Red massive fine sandstones, siltstones, fine siltstones and minor claystones in three upward fining cycles. Large scale cross-bedding in coarse units and ripple bedding in fine units. Base of some massive units downcutting with longitudinal grooves (see plate VIII). Middle and upper parts of upward fining cycles with numerous root zones and dolomitic concretions.(see plate IX). Dinosaur footprints present in finer beds. Plant impressions present locally. Common mud cracks in upper parts of cycles.
18c	+5	(3,2) (3,3)	Red massive sandstone with intraformational siltstone conglomerate at base. Small and scale cross-bedding common, Large casts of of tree limbs and reptile?bones at base.
18b	4	(3,2)	Red siltstones and claystone alternating with brown and red sandstone and coarse siltstone. Small scale cross-bedding common in fine units and upward-fining common in thin sandstones. Mean sandstone bed thickness less than .5 foot. Reptile footprints exceedingly common. Rare bone fragments, impressions of plants (mostly conifers) ripple marks, and rare mud cracks.
18a	1.5	(3,2)	Red claystone and siltstone with ripple bedding and rare mud cracks. Numerous reptile footprints. Plant fragments as impressions present.

Unit 20 illustrates the relationship between sediment porosity and red bed formation. The northern exposures of the unit are natural levee deposits grading upward into flood plain beds (upper part of fining upward cycle). The southern exposures are the finer beds of the flood basin, alternating with the coarser beds of crevasse splay.

The sandy beds were undoubtably more porous shortly after deposition than the fine siltstones. The color distribuntion of unit 20 can be explained by assuming that reduction of the non-red beds occured as the detritial goethite was exposed to the "pool" of sulfide rich interstitial waters of the hypolimnion of the previously existing meromictic lake[17]. Units 22, 21a, 21b, and 20 are transitional between lacustrine and fluvial deposits. The frequency of submergence of unit 20 after its deposition was sufficiently great to reduce the goethite in the permeable, coarse sediments but insufficient to reduce all of the goethite in the silts and clays of the fine beds. Enough goethite remained in these beds to age to hematite and color them red.

Units 19, 18a, and 18b. Plates VIII, IX, X

Unit 19 is a series of three upward fining cycles of the type described in section 4.4. This is a very heterogeneous unit which should be subdivided after further mapping. Units

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[17]Berner (1971) notes that amounts of H_2S are not the limiting factor in pyrite production. There is always an excess of sulfide. The sulfide concentration increases through the life of a meromictic lake with closed circulation. This may remain after the destruction of the lake as a "pool" of available sulfides in ground water.

18c, 18b, and 18a form an upward fining cycle of the same type. The lower division of the cycles consists of massive cross bedded sandstone with a basal intraformational conglomerate: a point bar deposit. In the middle division beds of fine siltstone alternate with coarser beds in a typical bank deposit. In unit 19 the upper divison is a flood basin unit with abundant evidence of desiccation. Evidence of desiccation is not present in unit 18a.

Reptile footprints are very common in the upper two divisions of the fining-upwards cycles, especially in unit 18b. Footprints of the highest quality are found in the middle division, with very shallow footprints in the upper division. The finest footprints (natural casts, see plate X) occur in beds where crevasse splay deposits alternate with flood basin sediments.

The crevasse splay beds of the middle division of upward fining cycles show a series of cyclic sedimentary structures. These cycles resemble modern crevasse splay of the Brahmaputra River described by Coleman (1969), A sandy sequence with ripple bedding a few centimeters to a few decimeters thick is topped by a fine siltstone layer. (see figure 12). Reptile footprints may occur as sole marks on the lower surface or as impressions on the upper surface.

Unit 18c is a typical lower division of a fining-upwards cycle. The lowest portion contains an intraformational conglomerate and large siltstone casts of tree limbs and a possible large reptile jaw (Dr, Donald Baird, Pers. Com.). Unit 18b has very well developed crevasse splay and natural

Unit	Thickness	Area Exposed	Description
17	7.2	(3,2)	Red grading up into grey-green fine siltstone. Rare mudcracks, ripple-bedding, reptile footprints rare plant fragments preserved as impressions and carbonized compressions.

17.7

levees. The finest dinosaur footprints in the Roseland Quarry come from this unit. Reptile teeth have been found in the lower parts of the crevasse splay beds as well. On the whole, the fauna of units 18c-18a is more diverse and plentiful than preceeding upward fining cycles.

Unit 17.

This is the uppermost part of the previously described upward fining cycle. The sedimentary structures of these beds indicate that the environment of deposition was still fluvial (flood basin). The color change in relation to the preservation of plants in this unit deserves special notice.

Plant remains, in the form of fragmented debris, twigs, leaves, and branches, are common in most Roseland sedimentary units. These occur as impressions along bedding plains, and siltstone casts in red beds and as carbonized compressions in non-red beds. The occurrence of carbonized plant remains surrounded by green halos can be explained by the following hypothesis.

In most red beds in the Roseland Quarry, the organic matter of plant remains must have been removed by rotting and leaching after deposition. This took place in an aerobic environment so that sulfur containing organics were oxidized to sulfates and washed out of the sediments. Shortly after the deposition of unit 17, however, the meromictic lake of member A (see section 4.7D) began to develop and sulfide containing waters of the hypolimnion began to saturate the sediments. The enclosed plant remains of unit

17 added sufficient sulfide locally, that when added to the hypolimnic sulfides, the concentration was sufficient to reduce the zone directly around the plants but insufficient to stop goethite aging in the bulk of the sediments at the same horizon. Shortly thereafter, the hypolimnic waters became sufficiently sulfide rich to reduce the units above 17.

4.7D Summary of Units 31-17.

Member B of the Towaco Formation is represented by units 30-17 in the Roseland Quarry. Briefly restated, these beds record the formation and destruction of a deep meromictic lake covering a minimum of 920 km^2 (360 $mi.^2$). Fluvial conditions followed lacustrine. Deposition of a varved laminite, turbidites and slumps occured during highest the highest lake levels, while meandering streams and rivers produced upward fining cycles during the fluvial stage.

4.7E Member A of the Towaco Formation: Units 17-5.

The upper part of unit 17 is the base of another Towaco cycle (member A). The exposures of member A in the Roseland Quarry are more typical of Towaco cycles than member B. The main differences between units 30-17 and and units 17-5 are the lack of slump beds in the laminite unit of member A and the absence of another Towaco cycle above member A.

Unit	Thickness	Area Exposed	Description
16	6.3	(3,2)	Gray fine sandstones and siltstones in fining upwards sequence. Irregular calcium carbonate nodules which weather out to form limonitic cavites. Unit ripple bedded with rare small mud cracks. ripple marks, and common dinosaur footprints. Common large carbonized plant stems and tree branches.
15	2	(3,2)	Green-gray friable fine siltstone. Very poorly exposed.
14	1	(3,2)	Very soft gray clayey siltstone. Black laminae in upper part. Gradational with unit 13. Extremely poor exposure.
13	.8	(3,2)	Black laminite. Black sapropel-rich and white calcium carbonate couplets .42 mm. thick. Upper part of unit has several 5 mm. thick graded black siltstone layers. Grades into unit 12. Very poorly exposed.

4.7E Units 16 - 5 - Member A

Units 16-14.

These units record much the same sequence of environments of deposition as units 30 and 29. Unit 16 is a small fining upwards cycle, the internal structure of which, resembles the natural levees of the Bramaputra River (Coleman, 1969) rather than a fully developed meandering channel cycle. There are numerous calcium carbonate nodules which could be result of a rapidly fluctuating water table. The middle portion of these beds contain numerous dinosaur footprints (see plate XI).

Units 15 and 14 are interpreted as transitional lacustrine sediments resembling unit 29. Apparently, units 16-14 are the shore deposits of a transgressing lake.

Unit 13.

The varved laminite of member A (unit 13) is very similar to units 28 and 23c and deposition in a meromictic lake seems likely. The black graded beds appearing near the top of the unit are interpreted as distal turbidites. The recumbent folds in the upper part of this unit must have been formed when the beds were still plastic and may have something to due with the diagenesis of the overlying units.

The varves of unit 13 are very obvious and thin, Varve counts indicate deposition at the rate of .42 mm./ yr. This lake, like that of member B must have covered a minimum of 920 $km.^2$ (360 $mi.^2$).

Unit	Thickness	Area Exposed	Description
12	1.2	(3,2)	Black, completely slickensided clayey siltstone with numerous flint nodules. Poor exposure.
11	1.5+	(3,2) (3,3)	Grey fine clastics. Some graded bedding. Rare impressions of gypsum crystals on bedding planes.
10	.2	(3,2) (3,3)	Very dark grey massive clay claystone with black laminae. Lower contact smooth and non-gradational. Conchoidal fracture with no parting planes. Good plant fragments including *Brachyphyllum* twigs and cones, *Semionotus* scales, and insects.
9	.2	(3,2) (3,3)	Grey massive claystone with dark laminae similar to unit 10. *Semionotus* scales absent. Lower contact sharp but without parting planes.

Unit	Thickness	Area Exposed	Description
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10	.2	(3,2) (3,3)	Very dark grey massive clay claystone with black laminae. Lower contact smooth and non-gradational. Conchoidal fracture with no parting planes. Good plant fragments including _Brachyphyllum_ twigs and cones, _Semionotus_ scales, and insects.
9	.2	(3,2) (3,3)	Grey massive claystone with dark laminae similar to unit 10. _Semionotus_ scales absent. Lower contact sharp but without parting planes.

Unit 12.

The meromictic lake seems to have still been in existence during the deposition of unit 12. A similar grain size and remnant varves indicate a similar rate of deposition to unit 13. Deposition of units 12 and 13, therefore, took a a minimum of 1380 years: an indication of the minimum life of the stratified lake.

An origin for the flint nodules is difficult to find. They may be replacing limestone, but since no limestone is present, this is uncertain. The nodules must have been present before dewatering of the beds since the deformation of this unit has not effected stratification present in the flint. It seems probable that deformation of the unit is partially the result of differential compaction during dewatering and a small thrust fault through the unit.

Unit 11.

The lack of recent exposure precludes a detailed interpretation. What information is known is consistant with deposition by suspension and tubidity currents in a shrinking lake. Occasional gypsum crystals are evidence of increasing solute concentration in the late stages of the lake.

Units 10 and 9.

These are interpreted as a shallow water lake deposit. The lack of current bedding and parting plains indicates a very protected environment.

Unit	Thickness	Exposed	Description
8	3.6	(3,3)	Gray-light green, fine siltstone, massive, indistinctly bedded, with sedimentary dikes. Carbonized plant remains common. Minor siltstone layers with possible reptile footprints.
7	+5	(3,1) (3,2) (3,3)	Massive gray sandstone and coarse siltstone grading upward into brown siltstones. Lower part massive with large scale cross-bedding, current lineation, rib and furrow structures, ripple marks and a minor intraformational conglomerate at base. Upper contact gradational and lower contact sharp and cross cutting against unit 8. Carbonized plant remains common.
6	?6	(3,2) (formerly)	Gray-buff-lavender-brown siltstone, nowhere exposed: known from quarried blocks.
5a	3	(3,2)	Buff siltstone in a maroon matrix: an intraformational conglomerate.
5	93	(3,2) (3,3) (2,2) (2,3) (1,3)	5 successive fining-upwards cycles of red cross-bedded sandstones grading up into red siltstones. Lower massive portions have large scale cross-bedding, climbing ripples, graded beds, intraformational conglomerates, and current lineation. Upper divisions charaterised by small scale cross-bedding, alternating beds of persistant 1-10 cm. beds of coarse siltstones with samall scale cross-bedding. Three middle fining-upwards cycles with

Unit 8.

The lithology of unit 8 is indicative of the same kind of depositional environment that produced units 22 and 21b: transitional fluvio-lacustrine beds deposited in the quiet shallows along the margins of the shrinking lake.

Units 7 and 6.

These units comprise a fining-upwards cycle nearly identical to units 21a and 20. Fluvial deposition by meandering rivers and streams near the shore of the dwindling lake is probable. The transition from red to grey in unit appears to be very similar to unit 20 but poor exposure precludes a finer interpretation.

Units 5a and 5.

The fining-upwards cycles of this unit indicate deposition under conditions, more or less, similar to those responsible for unit 19. Unit 5a is the base of the lowest fining-upwards cycle. It contains debris of units 8 and 6 indicating active erosion of those units. The upper division of the lowest cycle contains fine red siltstones with rare coprolites containing fish scales (Semionotus sp.) and worm burrows (see plate XII).

The upper divisions of the middle three fining-upwards cycles of unit 5 contain indications of rather severe desiccation. These beds are singularly devoid of good reptile footprints. The highest fining-upwards cycle, on the other hand, has numerous casts and impressions of

Unit	Thickness	Area Exposed	Description
4	6	(2,2) (2,3)	Deep red, hard siltstone grading into above and below. Well bedded with small scale ripple bedding, mud cracks common. Possible reptile footprints.
3	4	(2,2) (2,3)	Dark lavender and maroon siltstone with the small orange crystals (badly weatherd) common along vertical planes. Small scale cross-bedding common.
2	1-2	(2,2) (2,3)	Light gray and lavender tuffaceous silstone, locally laminated with small scale cross-bedding. Same crystals as unit 3.
1	3	(2.2) (2,3)	Light brown or buff, badly weathered, poorly bedded tuff with light shards. Spheroidal exfoliation locally. Contact with basalt sharp and irregular on a small scale.
Hook Mountain Basalt			
flow 1	50	(2,2) (2,3) (1,3)	Theoleiitic basalt. Massive at base, columnar jointed in middle, vesicular at the top.
flow 2	10+	(2,2) (2,3) (1,3)	Highly vesicular and pillowed. Lower contact very irregular.

of conifers and articulates, twigs and branches. It may be important to note that beds, at the same stratigraphic position, 2 miles to the north, contain a bed of red and gree mottled siltstone with numerous carbonized plant fragments, fish scales and coprolites.

4.7E Summary of units 17-5.

The sequence of depositional environments of units 17-5 and 30-18a, as interpreted here, have much in common. A large deep meromictic lake developed, waxed, waned, and and finally was replaced by a fluvial environment. There is some indication of desiccation in the middle of unit 19 and a return to moister conditions near the top of unit 5 (see figure 8).

4.7F The End of Towaco Deposition.

Units 4-1 incorporate increasing amounts of tuffaceous material upward. There is also an increase in the degree thermal metamorphism due to the effects of the Hook Mountain Basalt. Units 4, 3, and 2 are water deposited in a fluvial environment, while unit 1 may be an air born tuff. Similar units have been described interbedded in the Orange Mountain Basalt, and Hampden Basalt by Van Houten (1969) and Sanders (1963).

5. THE LARGER PICTURE:DISCUSSION.

5.1 Depositional Environment.

A conclusion from the interpretation of the Roseland Quarry section, applicable to all of Towaco sedimentation, is that members A and B of the Towaco Formation record two episodes of meromictic lake development and demise. Exposures of Towaco members C, D, E, and F are, more or less, similar to members A and B and probably reflect the same series of depositional environments. Specific environmental reconstruction of other units must be based on the detailed study of their lithology and facies relations.

The non-red portions of Towaco cycles and the adjoining fluvial, upward fining cycles contain a rich and varied fish and reptile fauna and a diverse flora (Olsen, M.S., Cornet, M.S.). This speaks for a relatively hospitable climate during the deposition of these beds. On the other hand, certain upward fining cycles in the middle portions of the red units of Towaco cycles may have been deposited under more arid conditions. A model of calibration of the Towaco Formation is presented in section 5.3 which suggests climatic control of the Towaco cycles. This model involves climatic fluctuations through all of Towaco deposition, so climatic generalities are, at this point, premature.

5.2 More on Red Beds.

<u>The significance of color for environmental</u> interpretation

in the Towaco Formation rests with the relation between the rate of goethite aging and the availability of sulfide rich waters. The major source of water rich in sulfides is the hypolimnion of meromictic lakes, rich in sulfate reducing bacteria. The effects of hypolimnic water in resepect to sediment color seems to have been three-fold:

1. reduction of benthic sediments.

2. post-depositional reductionof underlying beds in which the goethite did not age to hematite before establishment of the meromictic lake.

3. development of a "pool" of sulfide rich water which persisted after the destruction of the meromictic lake, resulting in the reduction of fluvial deposits formed after the lake was gone until this "pool" had dissipated. Rate of reduction dependent on amount of time the beds were exposed to sulfide rich waters and the porosity of the sediments.

As long as the water table of sulfide rich waters was below the zone of goethite aging in the sediments, the fluvial beds could age to red beds. The results of 2 and 3 (above) could be termed "shadow" effects since the hypolimnic waters affect the color of beds deposited before and after the lakes existence. The interpretation of the environmental significance of red and non-red beds must, therefore, proceed with caution. On the whole, non-red beds are indicative of lacustrine deposition in the Towaco Formation.

5.3 Rates of Deposition.

The sequence of beds within a Towaco cycle closely resemble a Lockatong cycle (see figure 10). The mean thickness of Lockatong cycles is 15 feet (Van Houten, 1969) while that of a Towaco cycle is 95 feet. Van Houten (1969) has related the

Lockatong cycle to the precession cycle of 21,000 years. What is the relationship of a Towaco cycle to a Lockatong cycle and what relationship, if any, is there to the precession cycle?

Both Lockatong and Towaco cycles result from the same cyclic phenomena: waxings and waningsof large lakes. A calibration of the duration of a Towaco lacustrine fluvial cycle depends on inferring the rates of sedimentation, which is a notoriusly speculative process. Van Houten (1969) found that by extrapolating the rates of deposition over the entire Lockatong cycle the total duration of the cycle was a mean of 21,000 yrs. This was reasonable because the grain size of the cycles is very fine. Towaco cycle sediments vary from very fine to very coarse and it would be illogical to extrapolate varve sedimentation rates over the whole cycle.

Anderson (1964) defines seven orders of stratification on the basis of varve calibration (see figure 16). Cyclic units of the Towaco Formation can be related to several of his orders of stratification. First order cycles are present as varves in the laminites. If the assumption is made that the fining upward fluvial cycles correspond to his 4th order cycles (1000-3000+ yrs: low energy bedding and high energy scour bedding), it is possible to attempt to calibrate the Towaco cycles.

A calculation of the duration of Towaco cycles rests on the following assumptions:

1. extrapolation of varve counts to other fine grained beds is valid

2. the deposition of the slump beds of units 26-24 involved an insignificant amount of time.

3. fining-upward cycles correspond to a mean duration of 2000 years.

The following is used to calculate the duration of a Towaco Formation (all data from Table III).

Table V

	thickness	years
Member B. - number of varves / cm. = 25		
thickness of laminites (units 28+23c)	75 cm.	1875
thickness of other fines	186 cm.	4650
6 upward fining cycles		12000
total duration of member B		18525
Member A. - number of varves / cm. = 23		
thickness of laminites	60 cm.	1380
thickness of other fines	360 cm.	8280
7 upward fining cycles		14000
toatal duration of member A		23660
Mean duration Towaco cycle at Roseland		21095 yrs.

It is realized that this is an exercise in extrapolation and that the significance of the results is limited by the assumptions (which are tenous). Nevertheless, this may be used as a working hypothesis: the duration of a Towaco cycle may have been in the order of 21,000 years.

Van Houten (1969) ascribes the 21,000 yr. periodicity of the Lockatong Formation to climatic control based on the precession cycle. Since both the mode of origin and the relative duration of the two cycle types seem to be the same, it is tempting to infer climatic control of Towaco cycles. Assuming this to be true, the lacustrine portion of a Towaco cycle developed in a moist climate, while the fluvial part was deposited during a more arid climate. It is interesting to note (see figure 8, section 4.6F) the evidence of most severe desiccation occurs near the middle of the red bed sequences in the Roseland Quarry, exactly where they would be expected by this model.

If the Towaco cycles are based on the precession cycle, the mean sedimentation rate for the Towaco Formation is about 1.4 mm./yr. and the whole formation was deposited in about 250,000 yrs. This is an order of magnitude faster than Van Houten's estimate of Lockatong sedimentation rates (.215 mm./yr.) but within the rates of flysch and Mollasse sedimentation (Fisher, 1969).

5.4 Basin Rates of Subsidence and Rifting of the North Atlantic

Some implications of the mode of Towaco cycle deposition include basin and plate tectonics. The inferred rates of deposition suggest an increased rate of basin subsidence compared to that during Lockatong deposition.

All known volcanics of the Newark Supergroup seem to have been implaced or extruded during a relatively short period of volcanism (De Boer, 1968; Faille, 1973). All of the sedimentary units interbedded between lava flows which have been dated by contained palynomorphs and faunules are of lower Liassic age, confirming a restricted period of vulcanism.

If it is assumed that the deposition of the Towaco Formation was in equilibrium with basin subsidence, the implied rate is more than six times Van Houten's estimate for the Lockatong Formation (1.4 mm./yr. compared to .215mm./yr). Cycles similar in morphology and scale to Towaco cycles occur in the Feltville Formation of the Novacaesarea Group, the upper half of the Culpeper Group (between lava flows, Olsen, pers. obs.), and the Shuttle Meadow Formation and East Berlin Formation. Similar rates of basin subsidence and deposition are inferred for these units and the Towaco Formation.

Faille (1973) provides evidence that the Newark and Gettysburg Basins may have been simple downwarps during deposition of the Newark Supergroup. Sanders, on the other hand, supplies equally good evidence that the Newark and Hartford Basins were deposited in down-faulted grabens. It must be pointed out that all of Faille's argument is based on the morphology of the lower half of the Novacaesarea Group and the Conewago Group both of which are Upper Triassic in age. Sanders' evidence is based on the beds of the Upper Novacaesarea Group (Passaic syncline) and the upper Hartford Group, both of which are lower Jurassic! Both researchers may be correct in their respective areas.

Basin subsidence during the deposition of the lower Novacaesarea Group seems to have been much less than that of the upper part of the Novacaesarea Group, upper Hartford Group, and upper Culpeper Group. The low rate of subsidence of the lower Newark Supergroup is associated with a downwarp basin morphology, the complete lack of contemporaneous volcanics, and an Upper Triassic age. Contrarywise, the upper Newark Supergroup, with its high rate of basin subsidence, is associated with graben structures, extrusive and intrusive volcanics, and a Lower Jurassic age. I suggest that many Newark Basins originated as downwarps during the late, Middle Triassic or early, Late Triassic and it was not until the Early Jurassic that graben structures were superimposed.

It may be very significant that the earliest known Mesozoic marine beds of the continental shelves of eastern North America and West Africa are Early Jurassic limestones, evaporites, and clastics overlapping red beds of Newark Supergroup lithology (Amoco Ltd. and Imperial Oil Ltd., 1974). The earliest known marine beds of the Atlantic are, therefore, contemporaneous with the upper Newark Supergroup of the Eastern Piedmont. It is therefore probable, that the basins of the rift zone between the North American and African plates did not open to marine waters until the Early Jurassic.

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Plate I. View from (4,1) to the northwest. Note contact between Hook Mountain Basalt and Towaco Formation.

Plate II. Units 30-26. Looking north. Note black surface streak of unit 28, the laminite of member B.

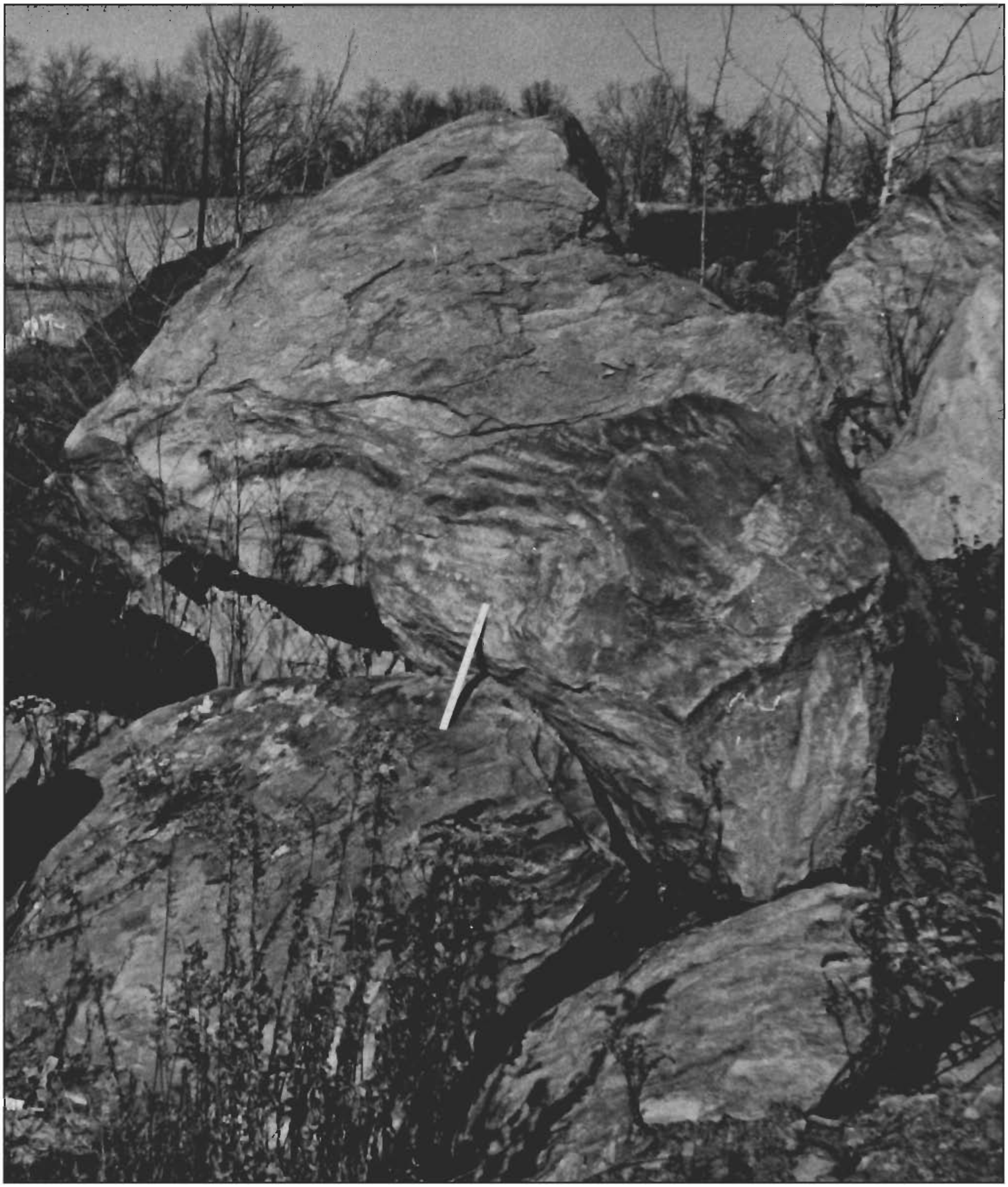

Plate III. Hook structures from unit 26. Ruler = 1 ft.
photo by P. Olsen

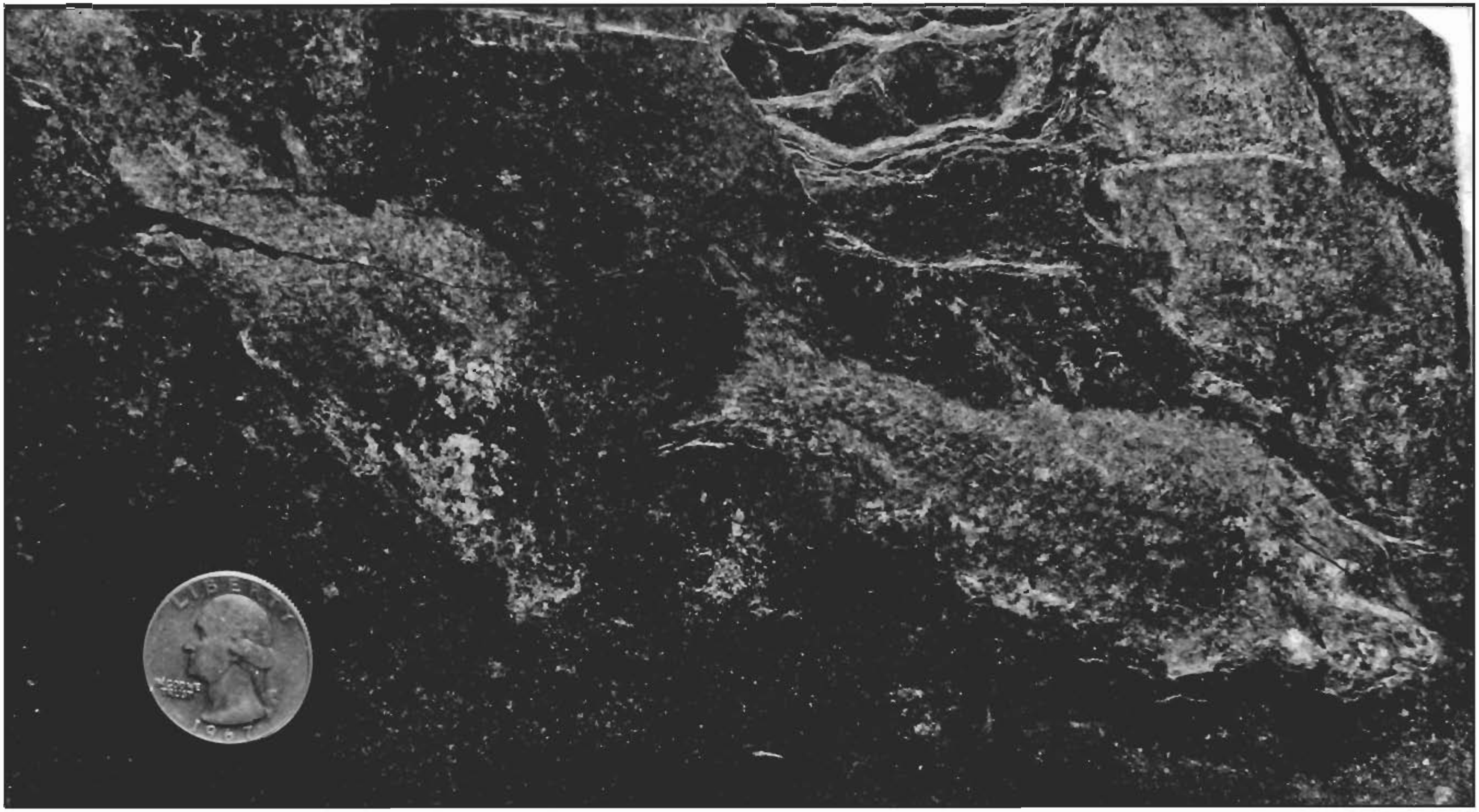

Plate IV. Semionotus sp from unit 23c. Note traces of coelomic cavity.

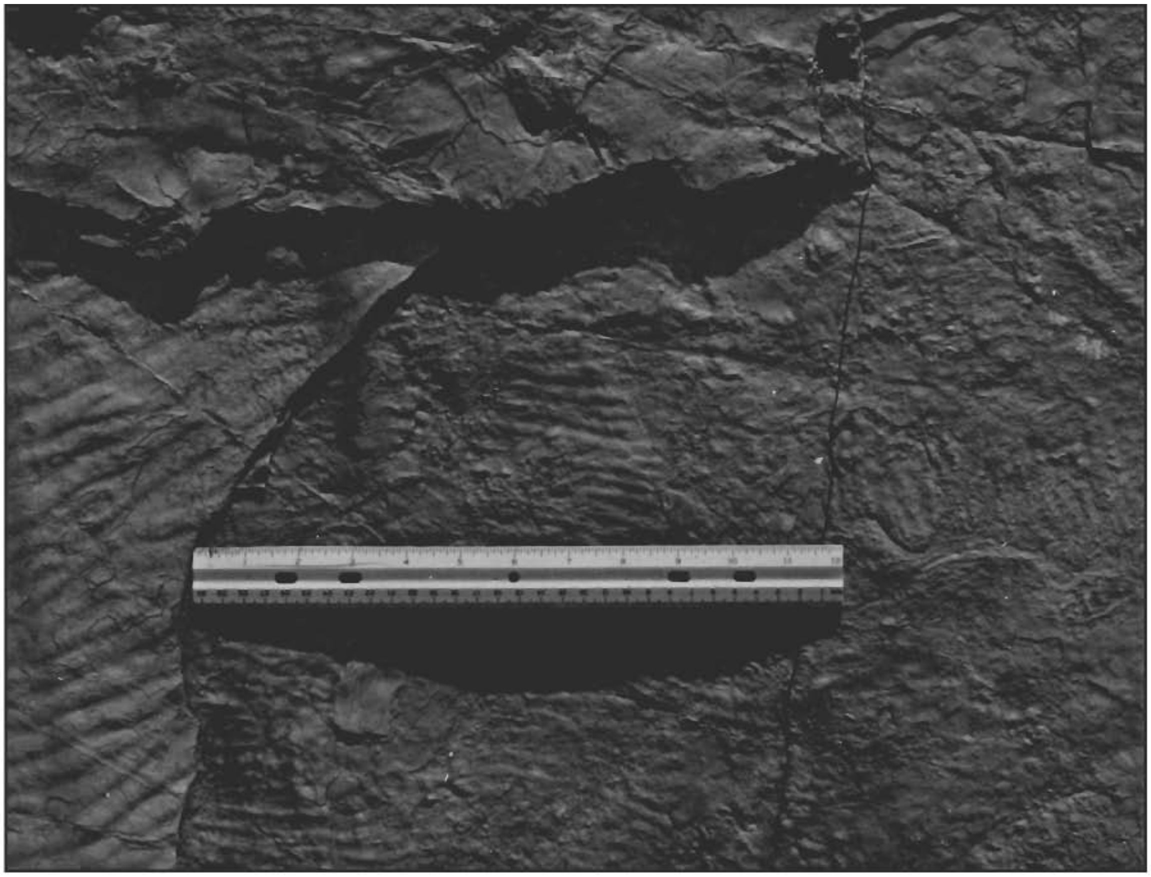

Plate V. Upper surface of unit 23b (above).

<u>Semionotus</u> sp. from unit 23b (below)

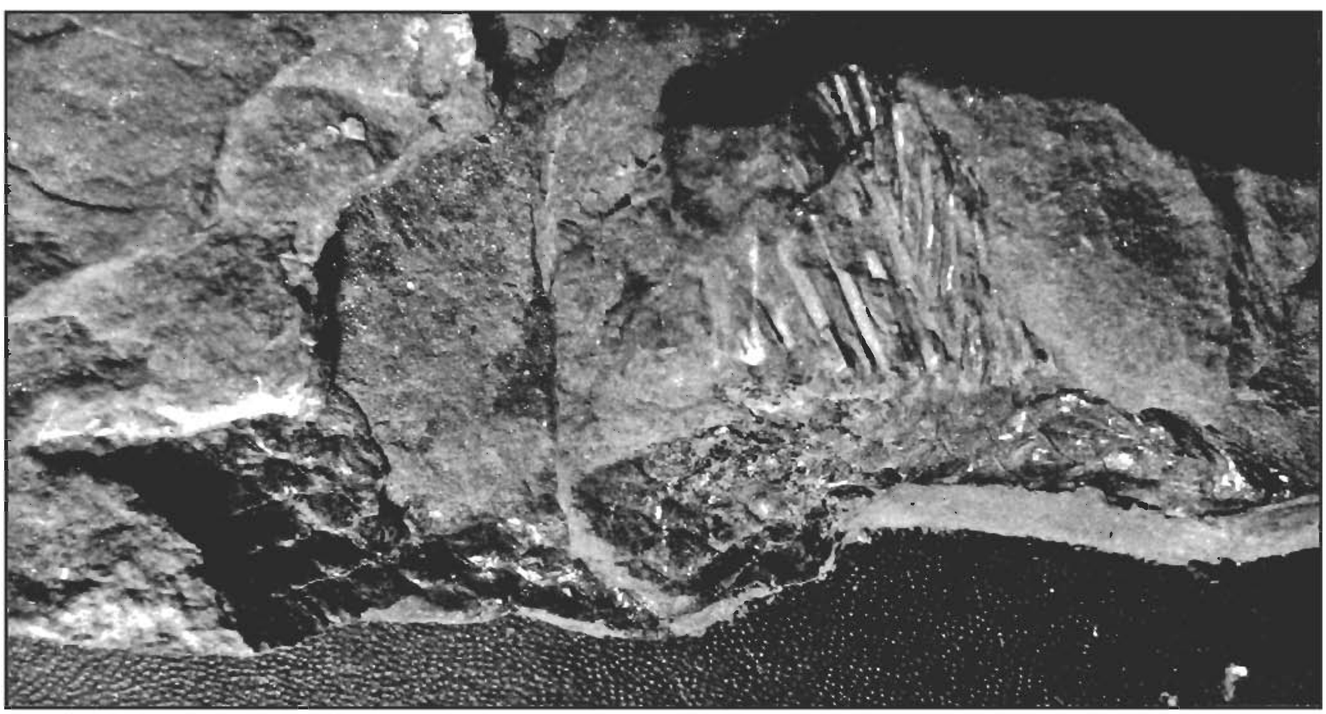

Plate VI. Longitudinal cross-bedding in unit 21a.

Plate VIII. Longitudinal grooves in base of channel of unit 19.

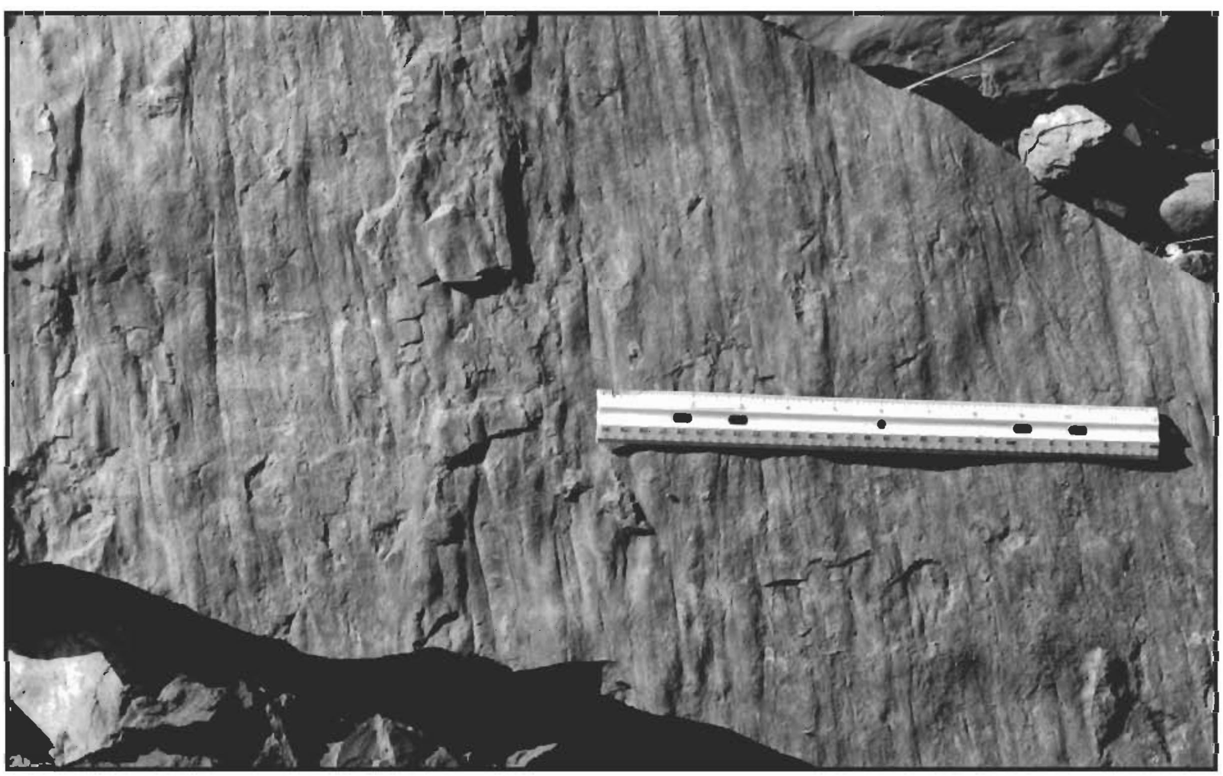

Plate VII. Lower bedding surface of crevasse splay bed unit 21b. Note very numerous Anchisauripus footprints.

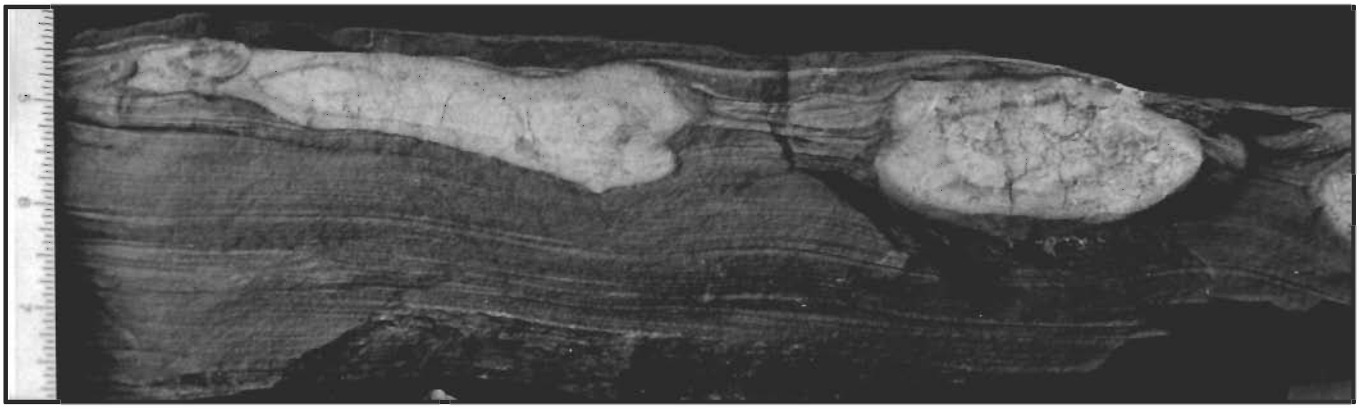

Plate IX. Dolomitic concretions in laminated red siltstone. Unit 19, second fining-upwards cycle (above). Scale in inches.

Dolomitic concretions and root casts. same unit as above (below). Scale in cm.

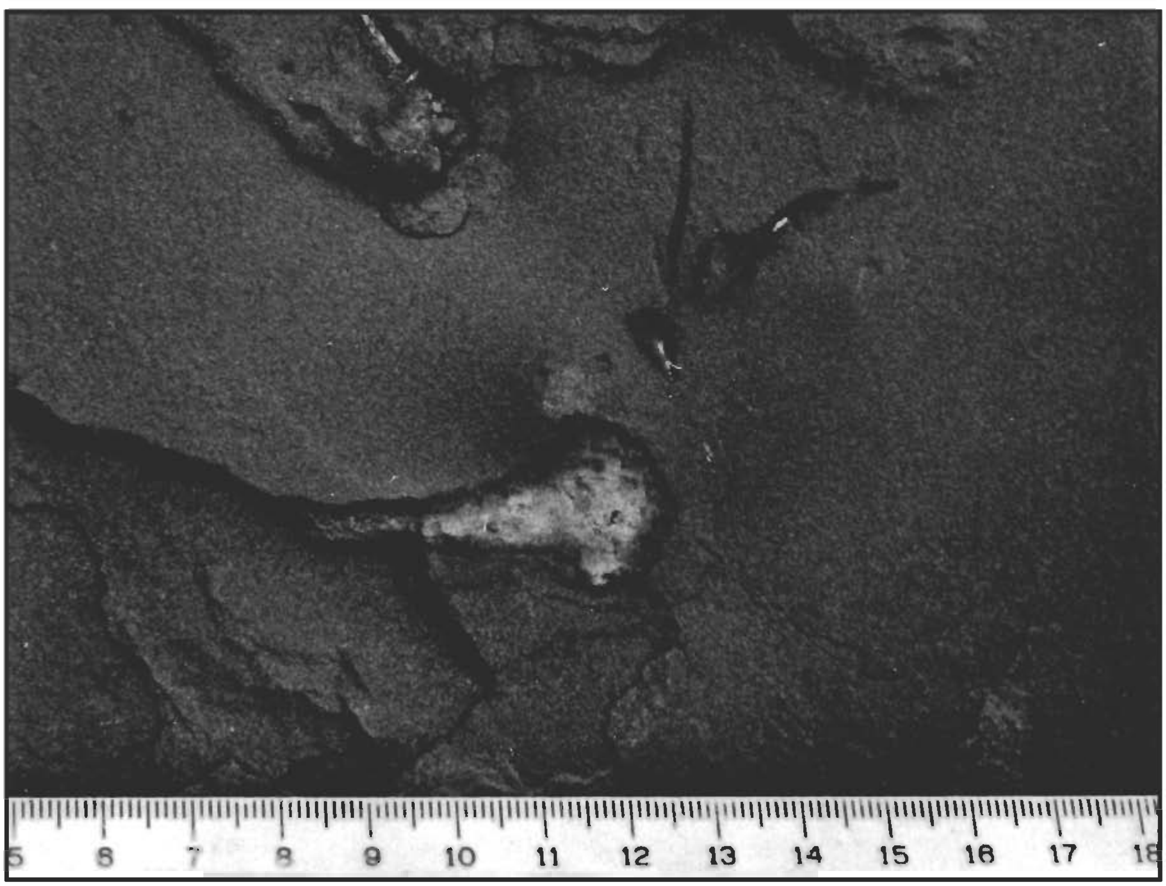

Plate X. Anomoepus crassus. Natural casts on lower surface of sandy crevasse splay. From unit 18b. Pes about 10 cm. in length.

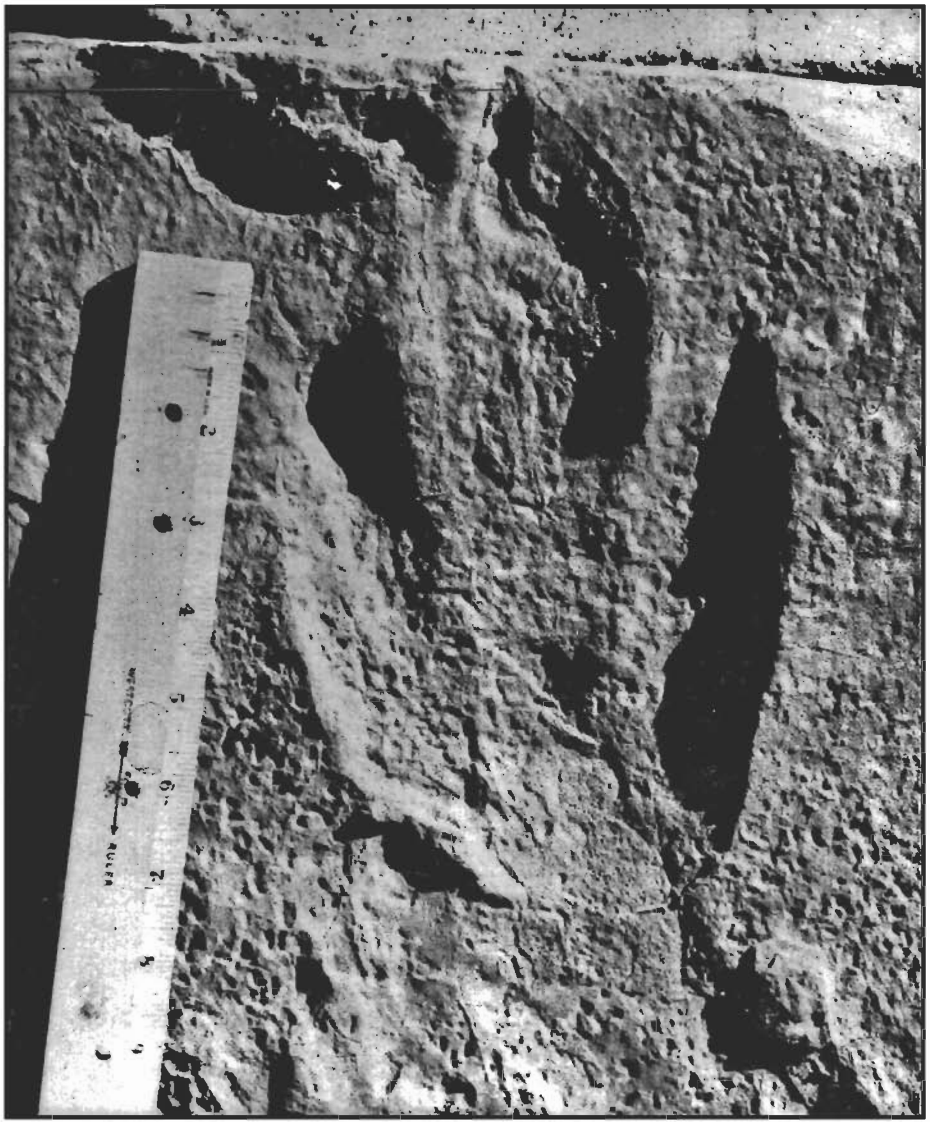

Plate XI. *Anchisauripus* sp. on rain marked surface of unit 16.

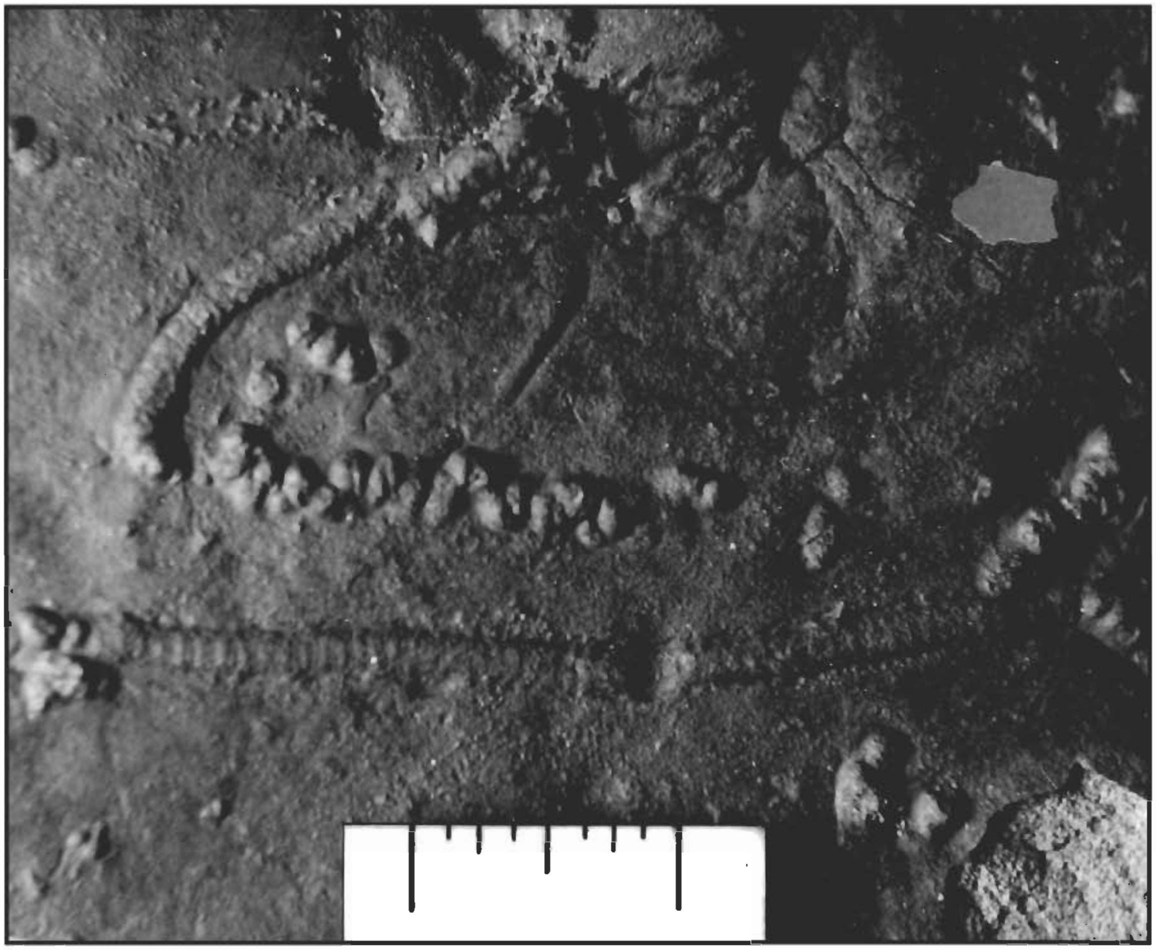

Plate XII. Worm burrows in lower surface of crevasse splay of unit 5. (above)

Impression of Brachyphylum sp. from unit 5, uppermost cycle (below).