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## PROTEROZOIC STROMATOLITE ZONATION

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Dedicated to GEORGE GAYLORD SIMPSON

**ABSTRACT.** Following analysis of nomenclatural problems and methods of study, zonation of the Proterozoic strata of the USSR by means of stromatolites is briefly reviewed, and an attempt is made to extend such zonation to the Proterozoic of other parts of the world. Preliminary results are:

1. At least some of the columnar stromatolites distinguished in the upper Proterozoic of northern Eurasia occur also on other continents and over roughly the same stratigraphic ranges as defined in the USSR. The most widespread is *Conophyton*, now known from five continents and apparently restricted to rocks of Proterozoic age, although having a very long range there.

2. Even some of the forms ("species") of the distinctive columnar stromatolites have intercontinental distribution—for example, *Conophyton garganicus* Koroljuk and *Inzeria tjomusi* Krylov, identified in Europe, Asia, and Australia; and *Gruneria biwabikia* new form, found in North America and Australia.

3. Pre-upper Proterozoic (pre-Riphean) strata also contain distinctive stromatolites of intercontinental distribution not known in younger strata, such as the new groups ("genera") *Gruneria* and *Katemia* and perhaps some yet unnamed forms (for example, pl. 1, figs. 1-2).

4. The above, together with progress being made in the study of the microbiotas, offers hope that at least a gross worldwide biological subdivision of Proterozoic rocks will be practicable. The reason why this has not heretofore seemed feasible to many geologists outside the USSR is probably related both to insufficiently extensive study and to the circumstance that many of the stromatolite-containing sequences (for example, the Belt Series) seem to represent only one of the Soviet stromatolite zones.

### THE PROBLEM

Stromatolites are biogenic sedimentary structures produced by the calcium carbonate precipitating and sediment binding activities of successive mats of algae, predominantly blue-green algae. Although the word was originally coined (Kalkowski, 1908) as a purely descriptive term to cover a variety of attached<sup>1</sup> laminated structures, whether or not of biological origin, the confusion that made it useful in this sense has

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<sup>1</sup>Similar unattached growth forms or "algal balls" are called oncolites, after Pia. Stromatolites may become oncolites, but neither the latter nor other problematical structures sometimes considered useful in pre-Paleozoic biostratigraphy are considered here.

essentially disappeared, and the term has gradually taken on the genetic connotation of "algal stromatolite".

Stromatolites, in this sense, are known throughout the geologic column, from modern sediments downward into rocks believed to be older than 2.7 aeons ( $2.7 \times 10^9$  years)—the Bulawayan beds at the Huntsman Quarry, north of Bulawayo, Rhodesia. They are mostly calcareous or dolomitic, but some are siliceous; and, although much of the silica appears to be a later replacement mineral, some is evidently very early diagenetic or even primary. Stromatolites are more abundant and more varied in gross form in rocks older than about 480 m.y. (Early Ordovician and older) than in younger sediments, and they seem to be especially widespread in the younger pre-Paleozoic rocks (roughly 1.65 to 0.65 aeons).

Their occurrence throughout the Proterozoic is of special interest because of the absence from such rocks of more conventional sorts of fossils. This naturally gives rise to inquiry as to the possible utility of stromatolites in reconstructing Proterozoic history. It is agreed among those who have made such inquiry that stromatolites are useful paleoecological indicators, that they reveal the primary orientation of deformed strata containing them, and that they may, in some instances, be useful zone markers within particular sedimentary sequences. Except in the USSR, however, most students of stromatolites have concluded that they were unlikely to have an interregional stratigraphic significance.

There are good reasons for such conclusions. Modern stromatolites (for example, Logan, Rezak, and Ginsburg, 1962) appear to be the products of communities of organisms, rather than of individual algal species, and the morphology of the sedimentary structures produced by a particular community varies in response to local ecologic conditions. Because there is no satisfactory evidence that the relation was otherwise in the past, because we in fact find several or many species of fossil algae within both silicified and calcitic Proterozoic stromatolites, and because we know many stromatolitic forms that show essentially the same range of variation through long intervals of geologic time, it is eminently appropriate to be cautious in interpreting the particular morphology of any individual type of stromatolite as having geochronological significance.

Nevertheless, intensive studies over the past decade or more by a number of students of the problem at the Institute of Geology of the Academy of Sciences of the USSR have led to the conviction on the part of these geologists that *some* stromatolite morphologies do have limited ranges within Proterozoic time and can be used to define and correlate four upper Proterozoic (or Riphean) zones of broadly similar age over wide distances at least throughout the USSR (for example, Keller and others, 1960; Semikhatov, 1962; Krylov, 1963, 1967; Komar and others, 1964; Komar, Raaben, and Semikhatov, 1965; Raaben, 1964, 1969; and Nuzhnov, 1967). The conclusion of the Soviet authors, however, was based on material collected only in northeastern Eurasia (Siberia, southern Ural, parts of middle Asia); thus the possibility of

worldwide correlation of Proterozoic deposits using stromatolites remained to be investigated.<sup>2</sup> On the other hand, the vast territory within which this zonation was worked out and the hints of similarities suggested by published descriptions of Proterozoic stromatolites in North America, Africa, and Australia permitted the hope (Komar and others, 1964) that stromatolites might indeed be useful for intercontinental correlation of Proterozoic rocks.

Meanwhile, Cloud (1962, 1968, p. 37), having independently recognized the columnar stromatolite *Conophyton* as limited in time (although having a very long range within the Proterozoic), was forced by that conclusion and by his good impression of the Soviet stromatolite studies to reconsider his earlier expressed conviction (Cloud, 1942) that these structures were unlikely to be important for interregional correlation.

A test, therefore, was devised. Stromatolites were collected by Cloud wherever he observed apparently distinctive forms in the pre-Paleozoic of Australia, southern Africa, and North America. Others were loaned by several U.S. Geological Survey geologists, by K. E. Caster of the University of Cincinnati, and by A. G. Fischer of Princeton University. And arrangements were made for Semikhatov, representing the Soviet school of stromatolite geologists, to study these collections in Cloud's laboratory as unknowns. It is the results of this collaboration that are reported here.

By no means have all stromatolites been found to be stratigraphically significant, especially among the wavy-bedded, mound-shaped, and "cabbage-head" forms of generalized type whose morphology seems to be more dependent on ecological facies than that of the more stratigraphically distinctive columnar forms. Among the columnar forms, however, are several distinctive morphotypes that do seem to be found on other continents in rocks of about the same age as those containing similar forms in the USSR. This conclusion emerges from the application of the Soviet techniques of stromatolite study to samples from south and central Australia by M. R. Walter and W. V. Preis at Adelaide University (reported by M. F. Glaessner at Prague on 23 August, 1968), as well as from the present studies of stromatolites from northern Eurasia, southern Africa, Australia, and North America. The results, at any rate, are sufficiently promising to warrant reporting them at this time, in the expectation that more and more intensive research will eventually produce a usable worldwide biostratigraphic zonation of the Proterozoic. Although such a zonation cannot by any means be on the same scale of refinement as is available for the complex and rapidly evolving organisms of Phanerozoic time, it seems possible even now to define some large operational units.

Our limited goal here is to state the problem, to outline the methods, to discuss the distinctive forms and their distribution in the USSR, and

<sup>2</sup> Similarities suggested by Edgell (1964) between the pre-Paleozoic stromatolite successions of Australia and the USSR appear to depend on identification with Soviet forms that are, in fact, different in morphology and in age from their supposed Australian counterparts.

to indicate some possible extensions of the Soviet stromatolite zonation to other parts of the world. Thus, in the pages that follow, we attempt, among other things, to abstract, to condense, and to supplement and extend results that have, in large part, already been presented in numerous Soviet publications (recently summarized in English by Raaben, 1969).

#### CLASSIFICATION OF STROMATOLITES

To discuss scientifically the significance of variations in form and structure within any group of related phenomena requires a nomenclature, preferably one that can be generally agreed upon. It doesn't matter whether the classification so expressed is "natural" (that is, evolutionary) or not as long as the same words mean essentially the same thing to all discussants, although it is, of course, desirable that nomenclatural divisions reflect evolutionary sequence as closely as possible, and that they have the same form and significance in all languages.

The nomenclature and classification of stromatolites and related structures has always been a vexing problem. The question centers on the appropriateness and legality of applying biological nomenclature to what are in fact sedimentary structures of biological origin. Whereas the majority of previous workers have preferred to use a Linnean binomial nomenclature as if these objects were in fact individual organisms, others have objected on the grounds that the Code of Botanical Nomenclature specifically excludes the use of Linnean names for *associations* of organisms or their community products. A variety of proposals has been made to get around this problem, of which three will serve as illustrations: (1) the Linnean names might be retained but used only in a vernacular sense (Cloud, 1942); (2) several descriptive Latin terms might be employed (Maslov, 1960); or (3) one might use a system of symbolic letter designations and formulae derived from descriptive morphological terms (Logan, Rezak, and Ginsburg, 1964).

None of these alternatives is satisfactory. The first evades the issue. The second and third, while they have good features, are cumbersome. The third has an additional defect: it either imposes an unacceptable burden on other languages to use a purely English symbolism or would lead to a babel of symbols (including, for instance, Cyrillic and Chinese) which would soon defeat the purpose of unambiguous communication.

How, then, may the many distinctive stromatolites now known, especially the columnar forms, best receive the universal designations that are needed to facilitate discussion of them and their significance? Because they lend themselves so well to treatment as if they were in fact distinctive organisms, we believe it best to find some acceptable way to include them within the system of nomenclature that currently applies to single organisms or parts of organisms, while at the same time dealing separately with two classes of things—(1) the stromatolites themselves, and (2) the microorganisms responsible for them. The problem is similar to that involved in the nomenclatural treatment of lichens, which

are the distinctive products of associations of algae and fungi. In order to operate within the rules of botanical nomenclature, lichenologists have agreed that the fungal component, biologically considered as parasitic on the alga, will give its name to the lichen, the valid name being that first proposed, whether as fungus or lichen (for example, Hale, 1967, p. 147-157). In practice the lichens are described as lichens and not as fungi (Hale, 1967, p. 150-156, 1961, p. 106-157; Fink, 1935).

Stromatolites, similarly, are the distinctive products of consortia of a variety of algae, of algae and bacteria, and perhaps, in some instances, of monospecific communities of algae. So long as they are distinctive biological products and are subject to standardizable methods of analysis that can yield essentially similar results to different investigators, no violence need be done either to rules or to logic by treating them as if they were genera and species. Where microorganisms are found within the stromatolite, they should receive their own systematic designations. It could, of course, be understood that the name of the stromatolite would be changed to that of the dominant single-organism contributor when that became known—or the reverse. But this is hardly conducive either to taxonomic stability or to unambiguous description, and we do not care to engage in that fiction. It seems preferable, instead, to adopt independent systems of Linnean-style nomenclature for the stromatolites as well as for the true biological species that give rise to them and to urge the next revisers of the botanical code to validate this procedure (although we follow the Soviet practice of using the terms group and form instead of genus and species). Such a practice at least has the advantages of clarity, consistency, and conformity with the bulk of the descriptions to which we wish to make reference.

In arriving at systematic assignments within this system, certain characteristics of the stromatolite structure are of paramount importance, especially where the head or colony has an internal columnar or branching structure as well as the usual broadly concentric lamination. Although the gross external morphology and mode of multiplication of the individual columns or branches within such structures is usually the most conspicuous feature, the use of other features of these columns is necessary to give consistent, useful separations. Subdivision into groups ("genera") is based on a combination of characteristics—the shape of columns, the manner of branching or change in number of columns vertically and laterally, the morphology of the marginal zone, and the peculiarities of internal lamination. Discussion of the application of such criteria to the systematic analysis of stromatolites may be found in publications by Krylov (1963), Komar (1966), and Raaben (1969). In differentiating forms ("species"), interest usually focusses on the fine structure of the component laminae (Koroljuk, 1960; Semikhatov, 1962; Komar, Raaben, and Semikhatov, 1965; Komar, 1966), and, as in the case of *Conophyton*, on the structure of the axial zone. Arrangement in larger systematic subdivisions than groups may be based on larger combinations of the "generic" features. However, different students of stromatolites have different

opinions about which features are most important for classification above the group level (Koroljuk, 1963; Komar, 1966; Raaben, 1964, 1969).

The most disturbing thing about using stromatolites as time indicators is, of course, that such a use implies an evolutionary sequence of forms, whereas there appears to be no compelling theoretical reason why this should be so. On the contrary, there has been little visible morphological evolution among the blue-green algae and other organisms under whose influence stromatolites were formed—some of the microorganisms that are abundant in ancient stromatolites are morphologically indistinguishable from living forms.

It would still be empirically significant, however, for both stratigraphy and systematics if similar sequences of stromatolites occurred in rocks of similar ages in widely separated regions (Keller and others, 1960; Komar and others, 1964). Such a relation, indeed, might not unreasonably be interpreted to suggest parallelism with an invisible physiological evolution among the stromatolite-generating organisms, reflected, so far as we have evidence, only in the arrangement of the enveloping sediments. Or it might involve some deeper connection with the evolving ecology of stromatolite-supporting environments or even broader features of the developing primitive atmosphere and hydrosphere. Whatever be the connection, and it certainly deserves intensive investigation, we shall see that there has in fact apparently been a time-related change in the morphology of the Proterozoic stromatolites, and that the changes involved appear to be roughly contemporaneous in widely separated parts of the world.

#### METHODS OF ANALYSIS

Stromatolites are often so large and so firmly imbedded in the rock that it is impracticable to collect entire colonies or even large pieces of them. In the case of columnar and branching forms, however, pieces of single columns or branches, or groups of them can ordinarily be obtained for laboratory study. As regards large bioherms or biostromes it does not ordinarily matter what part is sampled, but in small bioherms, where morphological details depend more strongly on relative position (Krylov, 1967), it is desirable to have samples from both central and peripheral parts. While still in the field one must carefully study and illustrate the construction of the colony or bioherm, collect representative material, and describe visible characteristics of columns. Weathered surfaces commonly reveal such distinctive features as mode of branching, shape of columns, shape of laminae, and even the characteristics of the marginal and axial zones. Thus some stratigraphically significant stromatolite "genera" may be identified directly in the field.

Laboratory analysis of the columnar forms involves the morphological reconstruction of the exterior based on serial sections, combined with the determination from thin sections of the shape and fine structure of the component laminae and the morphology of the central and marginal zones.

The external morphology is reconstructed by means of a method long used in vertebrate paleontology and originally applied to stromatolites by Krylov (1959, 1963). First one cuts an oriented succession of slabs (fig. 1A), preferably parallel to the axes of columns and so placed as to give a number of sections through an individual column. The profiles shown on the slab surfaces are then drawn in sequence directly on a transparent base (fig. 1B). Each profile is marked at one edge to indicate its relation to a base line or lines drawn straight across a suitable external surface of the stromatolite-containing rock. The profiles are next drawn one on top of another in a topographic perspective chosen to illustrate gross external morphology (fig. 1C). Registration is achieved by drawing the successive superposed profiles in relation to a line or lines, tilted 45° so as to produce the desired perspective—each surface drawn being offset along this line by half the thickness between surfaces. Finally the indicated morphology is sketched in according to the outlines on each slab to suggest a solid form that reflects the shape of the stromatolitic column or columns studied (fig. 1D).

Such reconstructions, in combination with detailed examination of the slab surfaces and of thin sections, show the morphology of the external surface and marginal zone, as well as the growth pattern of related columns.

The nature of the marginal zone, whether smooth because of marginally enveloping or evenly terminating laminae, or ragged because of

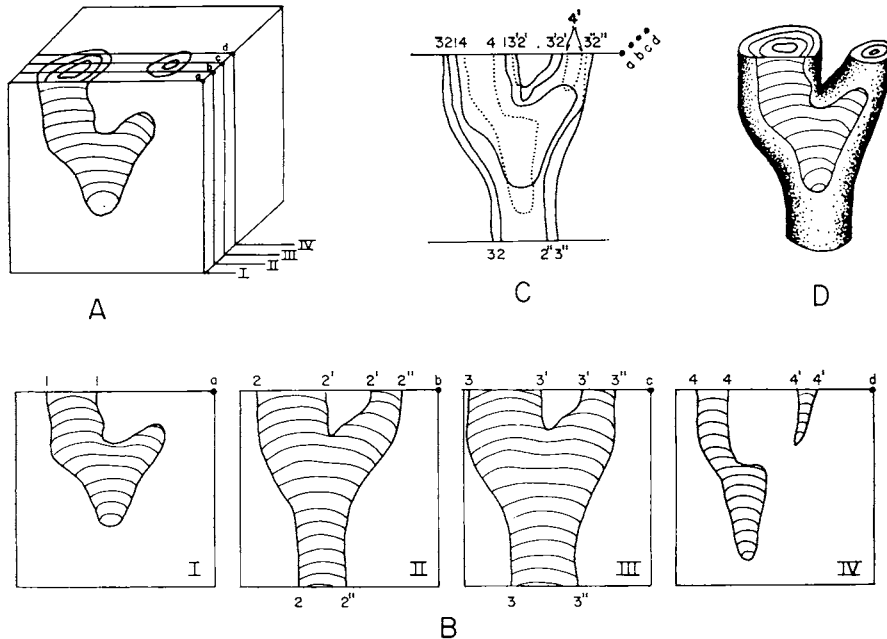


Fig. 1. Reconstructing the surface morphology of a columnar stromatolite from serial profiles.

projecting laminae, or otherwise irregular, is observed in slabs and especially in thin sections, as is the shape of the laminae and the structure of the central part of the columns. Successive laminae within a given stromatolite may be essentially uniform in convexity and similar in construction, or they may differ in shape from one to another, or they may develop a narrow axial zone with disturbed lamination (as in *Conophyton*).

The microstructure of individual laminae is best observed microscopically in thin sections at magnifications of 5 to 100 times, but, in some instances, much can also be seen with the naked eye or by hand lens on weathered, broken, or sawn and wetted or acid-etched surfaces. In analyzing microstructure, the geometry and orientation of primary components are the most distinctive characteristics, but size of such components is also important. In *Conophyton*, for instance, statistical analysis of dimensions of laminae has supplemented the discrimination of "species", each of which shows a distinctive range in width of laminae, and forms so characterized seem to be essentially constant throughout a large area (Komar, Raaben, and Semikhatov, 1965). The results are illustrated in figure 2.

Presentation of the data in a manner that permits unequivocal recognition of the form specified requires at least a photograph of a profile showing the characteristics of branching, external morphology, marginal and central zones, and description of the main distinctive features. Where practicable, the above should be supplemented by a three-dimensional drawing of the external form and growth pattern and especially by photographs of thin sections showing characteristics of the fine lamination and other features of the central and marginal zones of columns.

#### CHARACTERISTICS AND ZONATION OF THE DISTINCTIVE FORMS

Taking into consideration the above mentioned features of morphology and microstructure of stromatolites, and using the described methods of study, more than 30 groups, containing about 100 forms, are now described in Soviet publications.

Many of these taxa are too generalized and too continuous in time to be stratigraphically useful. For instance, the non-distinctively layered stromatolite *Stratifera* (apparently equivalent to *Weedia* of Walcott, 1914) is known not only throughout the Proterozoic but also in the Phanerozoic and even in Recent deposits. A similar very great stratigraphic range is known for several other nodular and layered stromatolites with non-distinctive lamination and structure. Among the columnar types, however, are several groups whose known stratigraphical ranges, although long in comparison with metazoan and metaphyte index fossils, do seem to approach terminal limits.

Many distinctive groups of columnar stromatolites in the upper Proterozoic of the USSR are widely distributed in space and succeed or overlap one another in time. They can be used to define four different stratigraphic complexes, comprising forms distinctive of the Lower, Mid-

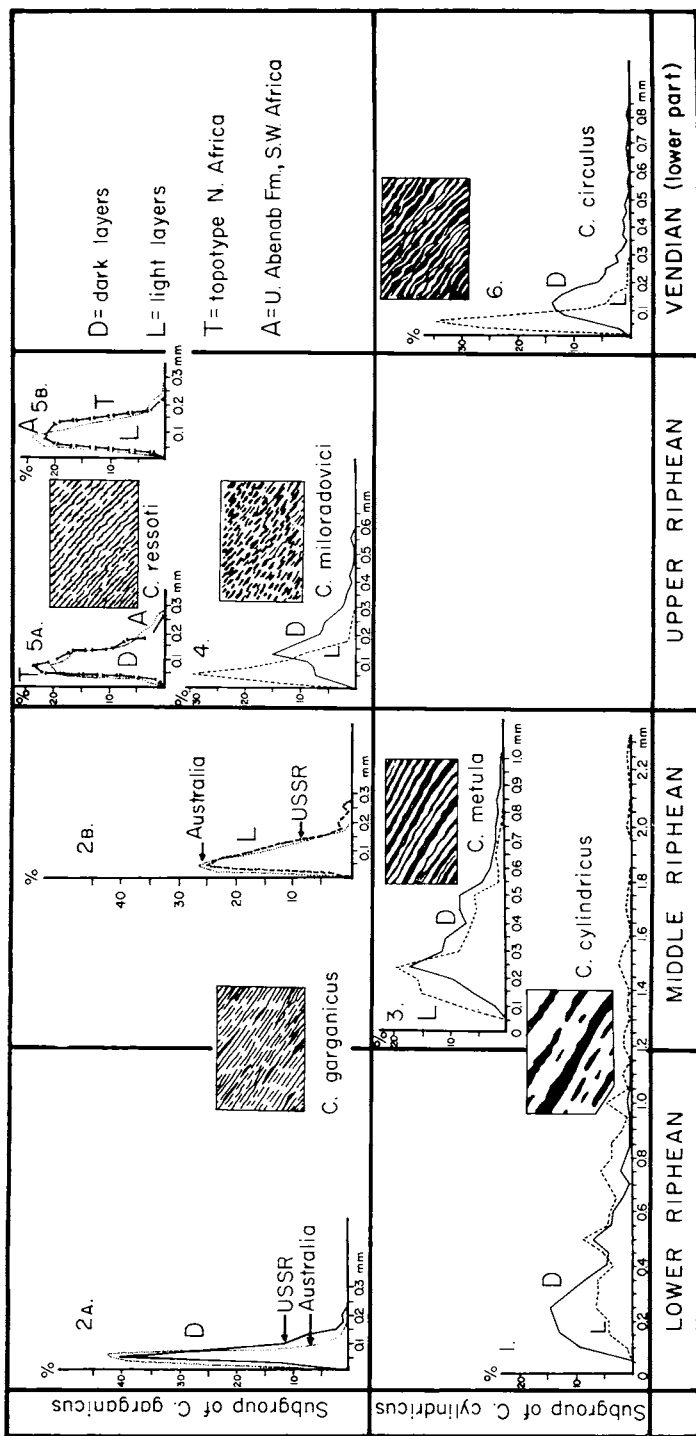


Fig. 2. Changes with time in configuration and thickness of lamination of *Conophyton*. Explanation: Solid lines and short dashed lines represent hundreds of measurements from many samples and several localities. Dotted lines represent hundreds of measurements in several samples from one locality. Lines of 1's in 5A and B represent measurements in two toptype samples from the Sahara supplied to Semikhatov by Prof. N. N. MENCHIKOFF.

"Genus"	Shape and ornamentation of column	Type of branching	Shape of growth-laminae
LINELLA	Tuberous Subcylindrical Smooth or pustulose	Complex Irregular With many stubby branches	Flat to strongly convex
BOXONIA	Subcylindrical Very smooth	Bifid or trifid Non-expanding Parallel	Strongly to moderately convex
JURUSANIA	Subcylindrical Ragged	Mostly bifid May be joined	Moderately convex
MINJARIA	Subcylindrical Smooth	Usually bifid Slightly ex- panding With subparal- lel axes	Variably convex
GYMNOSOLEN	Subcylindrical Swollen below branches Smooth	Complex Expanding With subparal- lel axes	Moderately to strongly convex
INZERIA	Irregularly subcylindrical Surface uneven- ly annular	Daughter col- umns often starting in niche in par- ent column	Relatively flat, to domal or rarely subconical
TUNGUSSIA	Tuberous Irregularly subcylindrical Smooth	Complex Many inclined columns	Variably convex
BAICALIA	Tuberous Irregularly subcylindrical Pustulose	Several expand- ing branches for each division	Variably convex
ANABARIA	Subcylindrical Smooth	Expanding Radiate Multibranching	Moderately convex
KUSSIELLA	Subcylindrical Surface annular	Usually bifid Non-expanding Parallel	Moderately convex
COLONNELLA	Subcylindrical Smooth	Non-branching	Strongly con- vex to domal
CONOPHYTON	Subcylindrical Connected or discrete	Non-branching	Conical, with axial inter- ruption

Fig. 3. Characteristics and ranges of stratigraphically significant columnar stromatolites in the USSR. (Vertical dashed line in Vendian interval indicates position of

Marginal zone	Central zone	Stratigraphic range					Sketch of axial profile
		PROTEROZOIC					
		pre-Riphean	Riphean			Vend.	
		L	M	U			
Discontinuously enveloping Edges even or lumpy	Nondistinctive						
Markedly enveloping Edges smooth	Nondistinctive						
Non-enveloping or with thin selvage of non-layered carbonate Edges ragged or smooth	Nondistinctive						
Enveloping Edges smooth	Nondistinctive						
Enveloping Edges smooth	Nondistinctive						
Covered by interrupted selvage of non-layered carbonate Edges uneven	Nondistinctive						
Mostly non-enveloping Edges even	Nondistinctive						
Non-enveloping Edges lumpy	Nondistinctive						
Mostly non-enveloping Edges even	Nondistinctive						
Non-enveloping Edges uneven	Nondistinctive						
Non-enveloping Edges even	Nondistinctive						
Non-enveloping or (in younger forms) with irregular thick selvage	With a sharply defined axial zone						

tillites, where Cloud would place the Proterozoic—Paleozoic boundary on biogeological grounds).

dle, and Upper Riphean and the Vendian. The composition of each complex is more or less the same throughout the USSR, and very similar stromatolites are found not only in different types of carbonate rock, but also, at some places, as separate calcareous masses within siliceous detrital rocks. Such empirical facts argue strongly for the stratigraphical significance of stromatolites, at least within the upper Proterozoic. This conclusion (Keller and others, 1960) is strongly supported by near-concordant isotopic ages on associated glauconite and on related magmatic and igneous rocks (Garris and others, 1964; Komar and others, 1964; Komar, Raaben, and Semikhatov, 1965).

The observed fourfold subdivision of the Upper Proterozoic of the USSR (Keller and others, 1960; Komar and others, 1964; Semikhatov, 1965; Keller and Semikhatov, 1968), indicated in figures 3 and 4, is now followed by many geologists in the USSR. Cloud dissents from this only to the extent that he prefers to locate the Proterozoic-Paleozoic boundary at the upper tillite zone in the middle of the Vendian, below the Ediacarian fauna (for example, Glaessner and Wade, 1966), and above the youngest *Conophyton*, as indicated by a vertical dashed line in figure 3. In such an arrangement only the lower Vendian, containing *Conophyton*, would be included with the Proterozoic—as a part of the Riphean System.

The stromatolites that appear to be most useful for the indicated zonation are *Baicalia*, *Boxonia*, *Colonnella*, *Conophyton*, *Gymnosolen*, *Inzeria*, *Jurusania*, *Kussiella*, *Linella*, *Minjaria*, *Tungussia*, and, with less confidence, *Anabaria*. Their characteristic features and ranges in the USSR are summarized in figure 3.

It will be noted that all groups, even of the stratigraphically useful columnar stromatolites, have large vertical ranges. At the same time, however, the forms recognized within at least some of these groups have narrower limits in time. A good example of the use of stromatolite forms is found in *Conophyton*. Although that group is known throughout most of the Proterozoic (a range of about  $2 \times 10^9$  yrs), its forms are considered to be useful in subdividing the upper Proterozoic (Komar, Raaben, and Semikhatov, 1965). In addition, many forms of columnar stromatolites are now being used in subdividing the upper Proterozoic (Komar, Raaben, and Semikhatov, 1965; present fig. 3) in the USSR and in correlating between Siberia and the Urals (Semikhatov and Komar, 1965; Komar and Semikhatov, 1968). For details on the stromatolite associations and zonation in the upper Proterozoic of the USSR, the reader should refer to Krylov, 1963; Komar and others, 1964; Komar and Semikhatov, 1968; and Raaben, 1969.

#### DISTRIBUTION OF SELECTED STROMATOLITES FROM NORTH AMERICA, AUSTRALIA, AND SOUTHERN AFRICA

A yet very inadequate sampling of stromatolites of known stratigraphic position in sequences of known or approximately bracketed age outside the USSR indicates that, to a degree at least, the zonation of

Taxon	Approximate age in aeons (years x 10 <sup>9</sup> )					
	> 2.6	2.6 - 1.65	1.65 - 1.35	1.35 - 0.95	0.95 - 0.68	0.68 - 0.57
Boxonia aff. B. gracilis Koroljuk						⑭ N.A. Johnnie Fm.
Linella aff. L. ukka Krylov						⑭ N.A. Johnnie Fm.
Inzeria tjomusi Krylov				← ?? — ⑫ A. Dook Ck. Fm. — ? →	⑬ A. Hinde Dol. 0.6-0.7	
Inzeria cf. I. tjomusi Krylov					⑪ A. Bitter Springs Fm. 0.8?	
Jurusania alicia n.f.					⑪ A. Bitter Springs Fm. 0.8?	
Anabaria juvenis n.f.					⑪ A. Bitter Springs Fm. 0.8?	
Baicalia aff. B. rara Semikhatov					⑨ S.A. L. Abenab Fm. < 1.2	
Tungussia f. indet.				⑧ N.A. Mescal Ls. 1.2-1.4		
Eucapsiphora paradisa n.f.		⑥ A. Paradise Cr. Fm. 1.6				
Conophyton resotii Menchikoff					⑩ S.A. U. Abenab > 0.6	
C. f. indet.				← ?? — ⑫ A. Dook Ck. Fm. — ? →		
C. cylindricus Maslov				⑦ N.A. Belt Ser. 1.1-1.6 Mescal Ls. 1.2-1.4		
C. gargonius Koroljuk			⑤ A. Amelia Dol. 1.6			
Kussiella f. indet.		④ A. Elgee Siltst. > 1.8				
Gruneria biwabikia n.f.		③ N.A. Biwabik & Gunflint 1.9 A. Mt. Jape Volc. 2.2 ±				
Katernia africana n.f.		② S.A. Dolomite Ser. 2 N.A. ? Nash Fm. 1.7-1.9				
Group B form indet.	① S.A. Bulawayo Dol. > 2.7					

Fig. 4. Distribution of selected stromatolites from North America (NA), Australia (A), and southern Africa (SA).

the Upper Proterozoic indicated in figure 3 can be carried by means of stromatolites to other continents and supplemented by new occurrences. Figure 4 summarizes the distribution of stromatolites described in this paper. Some other occurrences, particularly of such distinctive and widespread forms as *Conophyton*, could be added from published records (for example, Komar, Raaben, and Semikhatov, 1965), but here we prefer to restrict ourselves mainly to what we have in hand and thus are reasonably sure of. We also restrict our systematic treatment to forms known (or likely) from more than one continent and believed to be potentially significant for intercontinental correlation.

Records indicated by circled numbers in figure 4 are discussed below, roughly in order of inferred age from older to younger:

1. Macgregor's 1941 report of stromatolites in the Bulawayo Dolomite of Rhodesia, about which Cloud (1968, p. 11) earlier expressed reservation, has now been fully substantiated. Although description or close systematic identification must await the availability of better material, specimens in hand (pl. 1, fig. 1) are clearly analogous with other structures of known algal origin (microfossils have now also been described from these rocks by Oberlies and Prashnowsky, 1968). An age of  $>2.7$  aeons is suggested for these rocks by the work of Holmes (1954), but it must be kept in mind that the rocks dated are 300 km or so east of the stromatolitic rocks.

2. A variety of stromatolites is known from the approximately 2 aeon old Dolomite Series of the northern Cape Province, South Africa, as a result of the work of Young (for example, 1932, 1934). One of the more distinctive of these (*Katernia africana* f.n., pl. 3, figs. 4-5) seems to be close to a form from the Nash Formation in Wyoming (Knight and Keefer, 1966; Knight, 1969), giving Sr-Rb whole rock ages of 1.65 to 1.9 aeons (Houston, Hills, and Gast, 1966). The Dolomite Series (Transvaal System) is dated by its relation to the overlying well-dated Bushveld Complex (Nicolaysen, 1962, p. 580, 582). Other distinctive forms are also known from the Dolomite Series (for example, pl. 1, fig. 2), but, as this is not a systematic treatise, we have restricted our description of new material to that known from more than one continent.

3. The distinctive branching colonies of *Gruneria biwabikia* n.f. (pl. 3, figs. 1-3) are found in the Biwabik and Gunflint iron formations of northeastern Minnesota and southern Ontario and are also associated with the Mt. Jope Volcanics of the Fortescue Group in the Marble Bar area of western Australia. Compston and Arriens (1968, p. 566) date the Fortescue Group as at about 2.2 aeons. The age of the Gunflint is considered to be about 1.9 aeons (Hurley and others, 1962) and that of the Biwabik about the same (Goldich, 1968, p. 721).

4. The "genus" *Kussiella* (pl. 7, fig. 4) occurs in the Elgee Siltstone, Kimberly Group, on Margaret River in Western Australia. An age  $>1.8$  aeons is indicated for the Kimberley Group by an isochron on the intrusive Hart Dolerite (Compston and Arriens, 1968, p. 569). This implies

a downward time extension for the range of *Kussiella*, which in the USSR is known only in the Riphean, and predominantly in the lower Riphean.

5. *Conophyton garganicus* Koroljuk (pl. 1, figs. 3-4; pl. 2, fig. 1) occurs in the Amelia Dolomite, in the McArthur Basin, Northern Territory, Australia. The Amelia gives a model lead age of 1.56 aeons (Compston and Arriens, 1968, p. 572). In northern Eurasia *C. garganicus* is considered to be a typical lower Middle Riphean form (1.6 to 0.95 aeons).

6. A variety of stromatolites, including authentic *Conophyton*, is known from the Paradise Creek Formation of northwest Queensland (Robertson, 1960). Here we note especially the distinctive new form *Eucapsiphora paradisa* (pl. 4, figs. 1-3) and a problematical form with affinities to *Conophyton* (pl. 7, figs. 5-6). Bracketing radiometric dates implying an age of 1.6 aeons for these rocks are discussed by Licari, Cloud, and Smith (1969). Stromatolites very similar to *Eucapsiphora paradisa* are found in the Yatulian beds of Karelia in the USSR, the Yatulian being considered to span a time range of 1.65 to 1.8 aeons (Tougarinov and Voitkevich, 1966).

7. The typically lower Middle Riphean stromatolite *Conophyton cylindricus* Maslov (pl. 2, figs. 3-5) is known in North America from the Siyeh Limestone and from an undesignated part of the Missoula Group in the Belt Series, Glacier National Park, Montana, as well as from the algal member of the Mescal Limestone, Apache Group, in southern Arizona. The Belt Series seems to be mainly older than 1.1 aeons (Gulbrandsen, Goldich, and Thomas, 1963; Obradovich and Peterman, 1968), and it postdates an episode of regional metamorphism at around 1.6 aeons (Giletti, 1966). The Apache Group has an age of about 1.2 to 1.4 aeons (Shride, 1967, p. 76-77; Livingston and Damon, 1968).

8. The Middle Riphean to Vendian stromatolite *Tungussia* Semikhatov is found in the Mescal Limestone of the Apache Group in southern Arizona (pl. 5, fig. 1). As noted under item 7 above, the Mescal also contains the lower Middle Riphean form *Conophyton cylindricus*. These occurrences are in good agreement with radiometric data indicating an age of 1.2 to 1.4 aeons.

9. *Baicalia* aff. *B. rara* Semikhatov (pl. 4, figs. 4-5) is found in the lower Abenab Formation of the Otavi Facies in the Tsumeb District, South West Africa. The Otavi is now generally correlated with the Katanga Series of the Congo, and the Abenab is the middle of three main divisions within it. The age of the Abenab itself is not at all certain, because of thermal overprint on dated materials. However, Clifford (1967, p. 9, 18-22, 93) seems to place it in the range of 0.6 to <1.3 aeons, and Cahen and Snelling (1966, p. 155) give an age of approximately 1.2 aeons for the beginning of Katangan sedimentation in South West Africa. Supposedly syngenetic galena from the lower part of the Katanga Series in the Congo gives a model age of 1.145 aeons (Cahen and Snelling, 1966, p. 105), so those numbers are consistent. Finally, *Baicalia* is a mainly Middle Riphean form, and *B. rara* is characteristic of approximately 1

aeon old rocks in Siberia. Thus an age of around an aeon seems likely for the lower Abenab and our *B. aff. B. rara*.

10. *Conophyton ressoi* Menchikoff (pl. 2, figs. 2, 6) was collected from the upper Abenab Formation, 1000 m or more above the occurrence of *Baicalia aff. B. rara*, noted above. This form has also been reported in the upper pre-Paleozoic rocks of the Anti-Atlas area in northern Africa (Menchikoff, 1946), just below the upper Riphean stromatolite *Jurusania* (Keller and Semikhatov, 1968, p. 65). An upper Riphean age (0.95-0.65 aeons) for *C. ressoi* is also supported by its similarities to the post-Middle Riphean conophytons of northern Eurasia.

11. Among a variety of stromatolites observed in the Bitter Springs Formation of central Australia in the field, three are noted here, all belonging to known Russian genera. These are *Inzeria cf. I. tjomusi* Krylov, *Jurusania alicia* n.f. (pl. 5, figs. 4-5), and *Anabaria juvenis* n.f. (pl. 5, figs. 2-3). In the USSR *Inzeria* is characteristic of the Upper Riphean (especially its lower part) and *Jurusania* of the Upper Riphean and Vendian, whereas *Anabaria* is from the Middle Riphean of northern Siberia. The Bitter Springs Formation is not precisely dated, but Dunn, Plumb, and Roberts (1966) consider it likely to be about 0.8 to 0.9 aeons. This is consistent with the apparent time ranges of *Inzeria* and *Jurusania* in the USSR and suggests an upward time extension for *Anabaria* in Australia. It also supports M. R. Walter's assignment (reported by M. F. Glaessner at Prague on 23 August 1968) of an Upper Riphean age to the Bitter Springs stromatolites.<sup>3</sup> It is not known which, if any of the foregoing or associated stromatolites may be associated with the diverse and well-preserved Bitter Springs microbiota described by Schopf (1968).

12. An unidentified species of *Conophyton* (pl. 1, fig. 4), as well as *Inzeria tjomusi* Krylov (see 13, below), occurs in the Dook Creek Dolomite, Mt. Rigg Group, in the Beswick area of Northern Territory, Australia. Radiometric data on glauconites imply an age greater than 1.2 aeons (Compston and Arriens, 1968, p. 572; Dunn, Plumb, and Roberts, 1966, p. 597). Field similarity between the Dook Creek and Hinde dolomites (see 13, below), however, and the occurrence in both of the upper Riphean stromatolite *Inzeria* suggest that these two dolomites may be nearly contemporaneous<sup>4</sup> and that the apparent radiometric age of the

<sup>3</sup> The conclusions herein expressed are supported and in part amplified in an important paper by M. F. Glaessner, W. V. Preiss, and M. R. Walter that appeared while this work was in press (Precambrian columnar stromatolites in Australia: Morphological and stratigraphic analysis; *Science*, 30 May 1969, v. 164, p. 1056-1058). Glaessner, Preiss, and Walter add the names of *Linella*, *Boxonia*, *Tungussia*, and *Minjaria* to the list of stromatolites known from the Bitter Springs Formation, and they record other wide ranging stromatolites from the Umberatana and Burra Groups of the Adelaide geosyncline (including *Patomia* and *Katavia*) and from the Pertatataka Formation of the Amadeus basin. They also assign a specimen that strongly resembles our *Jurusania alicia* (pl. 5, fig. 5) to "*Cryptozoon*" *australicum* Howchin, although we are unable to confirm this assignment from Howchin's original description and illustrations (*Royal Soc. South Australia Trans.*, 1914, v. 38, p. 6-7, pls. 1-2).

<sup>4</sup> A similar conclusion is reported by Brown, Campbell, and Crook (1968), but, whereas the stromatolites imply that the true age may be close to the 0.6 to 0.7 aeons indicated for the Hinde Dolomite (see 13, below), Brown, Campbell, and Crook suggest that both the Hinde and the Dook Creek are older than 1.4 aeons.

Dook Creek may be biased from reworking of older glauconitic parent materials (or the glauconite itself?).

13. *Inzeria tjomusi* Krylov (pl. 6, figs. 1-3) is well represented in the Hinde Dolomite, Tolmer Group on the east slope of Mt. Hinde, about 100 km south of Darwin, Northern Territory, Australia, and also in strikingly similar strata in the Dook Creek Dolomite north of Beswick, some 260 km to the southeast. The radiometric age of the Tolmer Group (and Hinde Dolomite) is indicated to be in the range of 0.6 to 0.7 aeons by Dunn, Plumb, and Roberts (1966), which is consistent with the range of *Inzeria* in the USSR (0.95 to 0.65 aeons). As discussed under item 12 (above), this suggests the need for reexamination of the much greater age implied for the Dook Creek Dolomite by a literal interpretation of the glauconite data. Alternately, if a large difference in age should be substantiated, this would support the idea that the distinctive morphology of the associated stromatolites was, in fact, a response to the similar environmental conditions under which these deposits were accumulated.

14. The columnar stromatolite *Boxonia*, with its strikingly distinctive enveloping marginal zone, is known from the middle part of the Johnnie Formation of very old Paleozoic or very young Proterozoic age in the southern Nopah Range of California (pl. 6, figs. 3-4). Not far away, in lower Johnnie rocks at the south end of the Ibex Hills, *Linella* aff. *L. ukka* Krylov was found (pl. 7, figs. 1-3). No radiometric age control is available for the Johnnie Formation, but the association in it of the upper Riphean to Lower Cambrian stromatolite *Boxonia*, and of typical Vendian *Linella*, implies an age in the range of 570 to 675 m.y.

#### SYSTEMATIC DESCRIPTIONS

The descriptions below treat 12 groups of columnar stromatolites that are known (or probable) on two or more continents. Three of these—*Eucapsiphora*, *Gruneria*, and *Katernia*—are here described for the first time. The other nine have previously been described in Soviet publications. Our goal not being primarily taxonomic, we have kept description to a minimum and have named new groups and forms sparingly. The types are at the University of California, Santa Barbara. The order of treatment is alphabetical.

#### **Group *Anabaria* Komar 1966**

##### ***Anabaria juvenis* new form**

Figure 5; plate 5, figures 2 and 3

*Group characteristics:* Bushy colonies consisting of straight or slightly curved columns 5 to 20 mm in diameter, with complicated branching. Before branching columns thicken, then split into thinner columns or finger-like branches which fan out from the locus of branching. Complication and frequency of branching increases upward. Surfaces even, non-enveloping as a rule. Horizontal profile of columns rounded, irregular, and lobate at zones of branching. Internal layering moderately and uniformly convex. Such features indicate assignment to *Anabaria*, as diag-

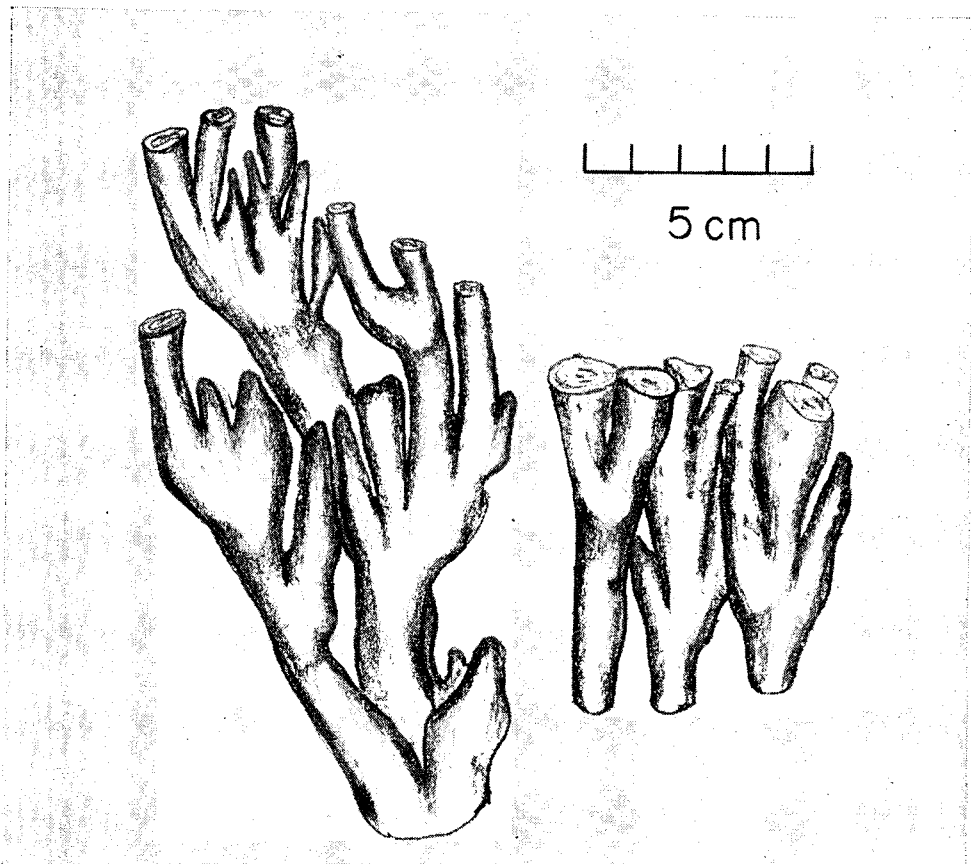


Fig. 5. *Anabaria juvenis* new form, Bitter Springs Formation, central Australia (loc. 4 of 3/7/65).

nosed from the Middle Riphean of Siberia (Komar, 1966, p. 84-86, figs. 20-21).

*Form characteristics:* Microstructure characterized by continuous or interrupted very thin dark layers that represent concentrations of many ovoid spots (of possible algal origin) from less than 0.05 to 0.1 mm in diameter, the dark lines being separated by thicker, lighter colored bands with lesser concentrations of the dark spots but often with very thin concentrations within them. This structure is reminiscent of that of *A. divergens* Komar (Komar, 1966, p. 86, pl. X, figs. 1-2) but differs from it in the thickness of dark layers and size of the spots composing them. The columns of *A. juvenis* are also relatively thin and delicate, as implied by the name.

*Type:* Specimen illustrated in plate 5, figure 3.

*Occurrence of Group:* Middle Riphean of USSR; Bitter Springs Formation of central Australia.

**Group *Baicalia* Krylov 1963**  
***Baicalia* aff. *B. rara* Semikhatov**  
Figure 6; plate 4, figures 4 and 5

*Group characteristics:* Colonies consisting of tuberous and irregularly subcylindrical columns varying in diameter up to 17 cm. On branching, they split into two thinner columns usually narrowing sharply at the base. Horizontal profile subcircular. Surface uneven, frequently ragged, non-enveloping. Internal laminations gently convex to flattened.

*Form characteristics:* Microstructure of many ovoid spots of dark aphanitic calcareous matter 0.06 to 0.1 mm (or rarely 0.15 mm) in diameter, in a fine-grained, light-hued matrix, producing a grumose appearance. Although irregular in distribution these spots tend to be concentrated in particular alternating layers, which results in a laminated structure.

Among known *Baicalia* only *B. rara* has a grumose structure such as described above. Its clots, however, are larger and more regularly stratified (Semikhatov, 1962, p. 201, pl. 2, figs. 5-6). Thus our South African specimens could just as well have been described as a separate form.

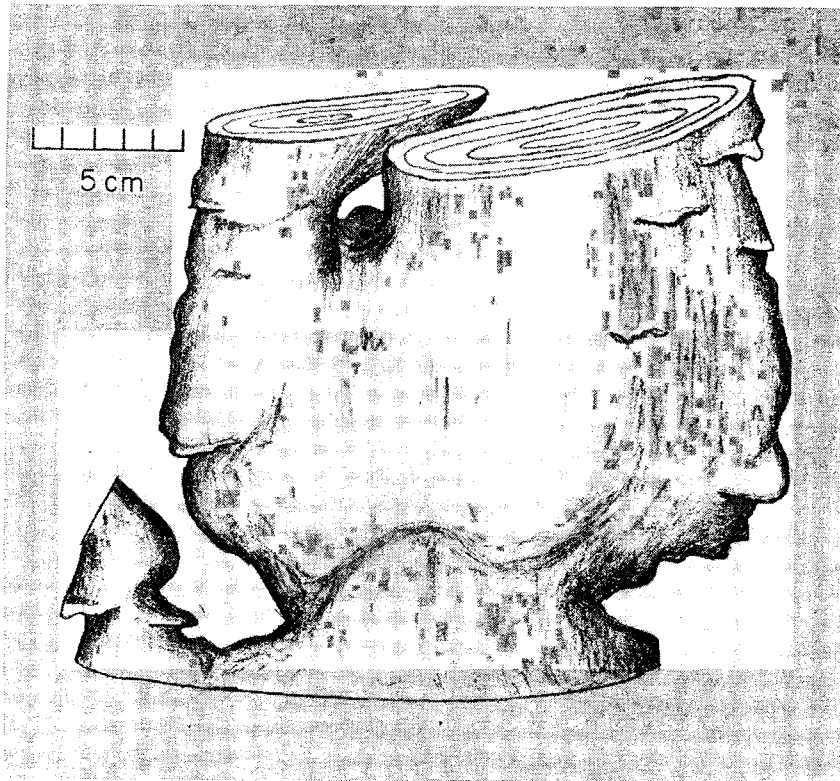


Fig. 6. *Baicalia* aff. *B. rara* Semikhatov, lower Abenab Formation, Tsumeb area, South West Africa (loc. 1 of 28/8/65).

Because recrystallization has obscured the details, however, we prefer the designation *B. aff. B. rara*.

*Occurrence of Group*: Middle and lower Upper Riphean of USSR; lower Abenab Formation of northern South West Africa.

**Group *Boxonia* Koroljuk 1960**

***Boxonia* aff. *B. gracilis* Koroljuk**

Figure 7; plate 6, figures 3 and 4

*Group characteristics*: Colonies consisting of erect, subcylindrical to club-shaped columns that periodically branch into 2 to 3 new subparallel columns without increasing in diameter or with only a slight thickening before branching. Horizontal profile subcircular, rarely subangular. Surface smooth, with multilayer enveloping producing a wall-like boundary.

*Form characteristics*: Internal laminae rather evenly convex, closely spaced, 0.1 to 0.5 mm thick, and consisting of very thin, somewhat wavy plates of aphanitic, tan-colored, partially silicified carbonate. In their peripheral parts these layers envelop the columns, whereas in the central part they tend to fade out into irregular but sizable areas of nearly clear finely recrystallized carbonate. Parts of the latter display a clotted or grumose microstructure, with dark areas in the central parts of many of the subglobular clots. The characteristics observed are closest to those of *B. gracilis* Koroljuk, which has similar layering and microstructure.

*Occurrence of Group*: Uppermost Riphean, Vendian, and lower Cambrian of USSR; Johnnie Formation of eastern California.

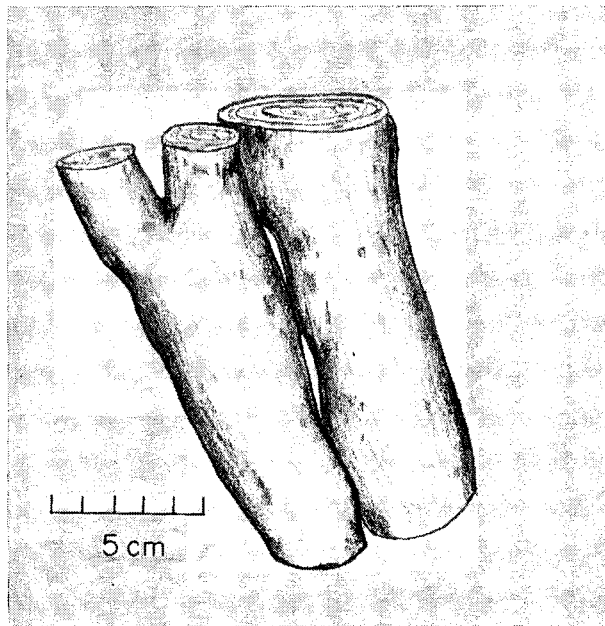


Fig. 7. *Boxonia* aff. *B. gracilis* Koroljuk, Johnnie Formation, Southern Nopah Range, California.

**Group *Conophyton* Maslov 1937**

*Conophyton* is characterized by strikingly conical internal laminae whose apices define, or are interrupted by, a distinctive axial zone (pl. 1, figs. 3-5). The subcylindrical columns, often broad and high but ranging widely in size, display a conspicuously and regularly concentric structure in horizontal section (pl. 2, figs. 5-6). The horizontal profile is subcircular, ranging to ovate, sphenoidal, or irregular where crowded (pl. 2, fig. 5). The internal laminae are commonly continuous from one column to another (for example pl. 1, fig. 3), in which case vertical profiles through a colony show downward as well as upward apicing of the laminae. The axial zone, however, invariably apexes toward the original upper surface of the containing stratum (obliquely upward in peripheral parts of the colony) except where rotated out of growth-position by contemporaneous deformation and sliding.

A number of distinctive forms of *Conophyton* have been differentiated (for example, Komar, Raaben, and Semikhatov, 1965) on the basis of systematic variations in the configurations and thicknesses of the distinctively alternating light and dark laminae, as well as on variations in the characteristics of the axial and marginal zones. Three of those forms, important in intercontinental correlation, are described below, and a fourth form is described but not named.

*Occurrence:* *Conophyton* is the most distinctive and longest ranging pre-Paleozoic "fossil" yet known, extending from fairly well down in the Proterozoic on upward into the Vendian, but apparently not above the Vendian tillites. It is widely distributed in rocks of this age from Europe, Asia, Africa, Australia, and North America.

***Conophyton cylindricus* Maslov**

Plate 2, figures 3 to 5

Colonies consisting of subvertical or oblique columns from 10 to 70 cm in diameter with conical laminae interrupted by a wide axial zone. Columns may be isolated or connected by common layers. Horizontal profile normally subcircular, becoming irregular where crowded (pl. 2, fig. 5). The apical angle of the conical internal laminae may vary along the column. The dark finer grained laminae show as wide, continuous, or interrupted ribbons that vary widely in thickness (pl. 2, figs. 3-4). They commonly show sharp lower boundaries and irregular upper ones (pl. 2, fig. 4). The light-colored sparry layers that alternate with the dark ones are continuous, thicker, and more variable in thickness. The thickness of the lighter layers of the samples from the Mescal Limestone of Arizona is 2.5 to 0.3 mm (mean range of 0.5 to 1.5) as compared with a range of 0.05 to 0.9 mm (mean range of 0.1-0.7) for samples from the Belt Series. For the same pair of samples the thickness of the dark layers is 0.2 to 1.15 mm (mean range of 0.1 to 0.7) and 0.05 to 0.75 mm (mean range of 0.1 to 0.35) respectively. In respect both to gross morphology and microstructure, these conophytions are both similar to *C. cylindricus* from the lower and middle Riphean of Siberia and the Urals (Komar,

Raaben, and Semikhatov, 1965, p. 30-34, pl. I-II), which shows wide variation in the thickness of the internal lamination (fig. 3, curve 1).

The above described *Conophyton* from the Belt Series was named *C. inclinatum* by Rezak (1957) in recognition of its unusual field orientation. However, Cloud has observed that at least some of the *Conophyton* masses from the same locality have been displaced from their growth orientation by submarine sliding (the mass of pl. 2, fig. 5, for instance). Since, in other respects, the growth form and microstructure falls within the range of that of *C. cylindricus*, *C. inclinatum* appears to be a synonym of that form.

*Occurrence of Form:* Lower Middle Riphean of the USSR; Siyeh Limestone and Missoula Group of Belt Series, Montana; Mescal Limestone, Apache Group, Arizona.

***Conophyton garganicus* Koroljuk**

Plate 1, figures 3 and 4; plate 2, figure 1

Includes colonies having subvertical columns up to 40 cm in diameter and 2 m high and made up of steeply conical laminae with sharp apexes and narrow straight axial zones rarely more than 1 cm in diameter (pl. 1, figs. 3-4). Axial zone alternately pinched and expanded. Contiguous columns commonly connected by layers that are continuous from one column to another, especially in the lower parts of bioherms. Horizontal profile of columns subcircular to oval. Dark members of internal lamination generally in the range of 0.03 to 0.08 mm thick (fig. 3, curve 2A), straight, and consisting of distinctly outlined plates of varying length. The longer of these plates are of relatively constant thickness, whereas the shorter ones lens out. In the axial zone the dark layers thicken and become deformed. The light layers are mostly thicker than the dark ones, averaging 0.03 to 0.13 mm (fig. 3, curve 2B). They are also more continuous and more sparry than the dark ones.

The Australian forms are similar in all distinctive characteristics to *C. garganicus* from the Riphean of Siberia (Komar, Raaben, and Semikhatov, 1965, p. 42-46; pl. IV, figs. 3-4; pl. VII, figs. 1-3). The only difference is that the dark layers of the Siberian specimens average a little thicker (fig. 3, curve 2A), but the range in thickness overlaps.

*Occurrence of Form:* Middle and (especially) Lower Riphean of European and Asian USSR; Amelia Dolomite, Northern Territory, Australia.

***Conophyton ressoti* Menchikov**

Plate 2, figures 2, 6

Colonies consist of subvertical columns up to 35 cm in diameter, consisting of steeply conical laminae which converge on an axial zone that varies in width from 1.5 to 3.5 cm. Horizontal profile subcircular to oval. Marginal zone of columns characterized by fading out of the internal conical laminae into an amorphous or irregularly laminated mantle of variable thickness up to 2 to 2.5 cm. Dark internal laminae sinuous, mostly interrupted, 0.03 to 0.13 mm thick (fig. 3, curve 5A), commonly

clotted or grumose. Lighter granular laminae continuous, roughly similar in thickness to dark (fig. 3, curve 5B). Boundaries of laminae uneven to indistinct. Dark laminae thicken toward axial zone and become deformed, whereas light layers retain their shape. Enveloping mantle of light finely crystalline calcitic or dolomitic matter in which are found bands and lenses similar to dark layers.

Our South West African material is similar to topotype material from the upper pre-Paleozoic of the Sahara obtained from N. N. Menchikoff, differing only in size of columns and the more pronounced clotted structure of the dark layers. It also resembles *C. gargaricus* (pl. 1, figs. 3-4; pl. 2, fig. 1) as concerns the thickness and shape of the dark laminae but differs in the wavy and clotted structure of the dark layers and in the mantled structure of the marginal zone. The latter characteristics recall *C. miloradovici*, but the dark layers of *C. resotti* are thinner and less extended.

*Occurrence of Form:* Upper Proterozoic of Anti-Atlas, northern Africa; upper Abenab Formation of northern South West Africa; upper Riphean of northern Eurasia(?).

#### ***Conophyton* form indeterminate**

Plate 1, figure 5

Colonies are made up of subcylindrical columns, of which the specimen collected attains a diameter of 25 cm. Conical internal laminae converging on a broad and curiously contorted axial zone 1 to 5 cm wide, across which they tend to thicken and become interrupted. Fine structure obscured by dolomitic recrystallization. Dook Creek Dolomite, Mt. Rigg Group, Northern Territory, Australia.

#### **Group *Eucapsiphora*, new group**

*Eucapsiphora* (bearing "*Eucapsis*") comprises colonies of narrow, straight or curved, finger-like, subcylindrical columns that pinch and swell in diameter (1 to 2.5 cm) and thicken conspicuously before branching into two or three thinner new columns (fig. 8). Daughter columns subparallel to somewhat divergent, some terminating upward as others thicken to branch again. Groups of columns often connected at their bases (or terminated above) by common layers which occur at different levels within the colony. Horizontal profile of columns subcircular. Internal laminae of columns moderately to weakly convex or nearly flat, fading into a generally smooth marginal zone that shows local overhangs and discontinuous enveloping. Growth habit of the colony encrusting (pl. 4, fig. 3), growing around high places and pinnacles on the antecedent surface and even beneath overhangs. Shape and dimensions of colony affected by that of surface encrusted but tending to form of pinnacles 1 to 2 m wide and 2 to 2.5 m high.

Among other known stromatolites, that most similar to *Eucapsiphora* is *Gymnosolen* Steinmann (Raaben, 1964; Komar, 1966; Krylov, 1967). *Gymnosolen*, however, has a markedly and consistently enveloping mar-

ginal zone, whereas *Eucapsiphora* shows only local enveloping and commonly ragged peripheral projections and overhangs. The columns of *Eucapsiphora* also are much more variable in diameter than those of *Gymnosolen* and much less strikingly parallel to one another.

*Type: Eucapsiphora paradisa* new form.

*Occurrence:* The genotype of *Eucapsiphora* is from the Paradise Creek Formation of northwestern Queensland, having an age bracketed by dated granitic intrusions as being about 1.6 aeons. Bioherms of *Eucapsiphora* at this locality (pl. 4, fig. 3) contain remains of a microscopic blue-green alga which is strikingly similar in its cubical colonial structure to the living genus *Eucapsis*. This occurrence is described in detail by Licari, Cloud, and Smith (1969). Similar stromatolites have been described and illustrated by Krylov (1966, p. 100, fig. 1B) from the Yatulian of Karelia, in the USSR.

***Eucapsiphora paradisa* new form**

Figure 8; plate 4, figures 1 to 3

Growth form and dimensions as above. Details of microstructure obscured by silicification in specimens at hand, but laminae show as uneven to sinuous ribbons 0.15 to 0.3 mm thick that tend to blur at the boundaries between dark and light layers and also in the marginal zone.

*Type:* Specimen illustrated in plate 4, figure 2.

*Occurrence:* As for the Group *Eucapsiphora*.

**Group *Gruneria*, new group**

The term *Gruneria* (for Dr. John Gruner) is here applied to commonly large domal colonies of branching and interconnected columns which vary in vertical profile from boss-like to wedge-shaped to elongate and which have dimensions that commonly range from 0.5 to 1.5 cm across and 2 to 4 cm high. Horizontal profile of columns subcircular to elongate. Columns characteristically widen upward before branching, and daughter columns diverge from the locus of branching. Marginal zone non-enveloping, the lateral surface being characteristically ragged from numerous small projections and overhangs of the internal laminae or ill-defined because of laminae crossing over to the next column. At places, however, the laminae overhang so conspicuously as to make smooth peripheral surfaces that verge on an enveloping structure. The laminae are extended, thin, and vary in convexity from flattened to strongly convex or even parabolic where they approach the margins. As all known specimens are dominantly cherty, it seems that the microorganisms responsible for these structures may well have been depositing a primary silica gel. Alternatively silicification could have been very early diagenetic.

Of previously described stromatolites, that most similar to *Gruneria* is *Parmites* Raaben (1964, p. 103), but the columns of *Parmites* radiate into a branching bush-like structure and display a contrasting structure in the marginal zone.

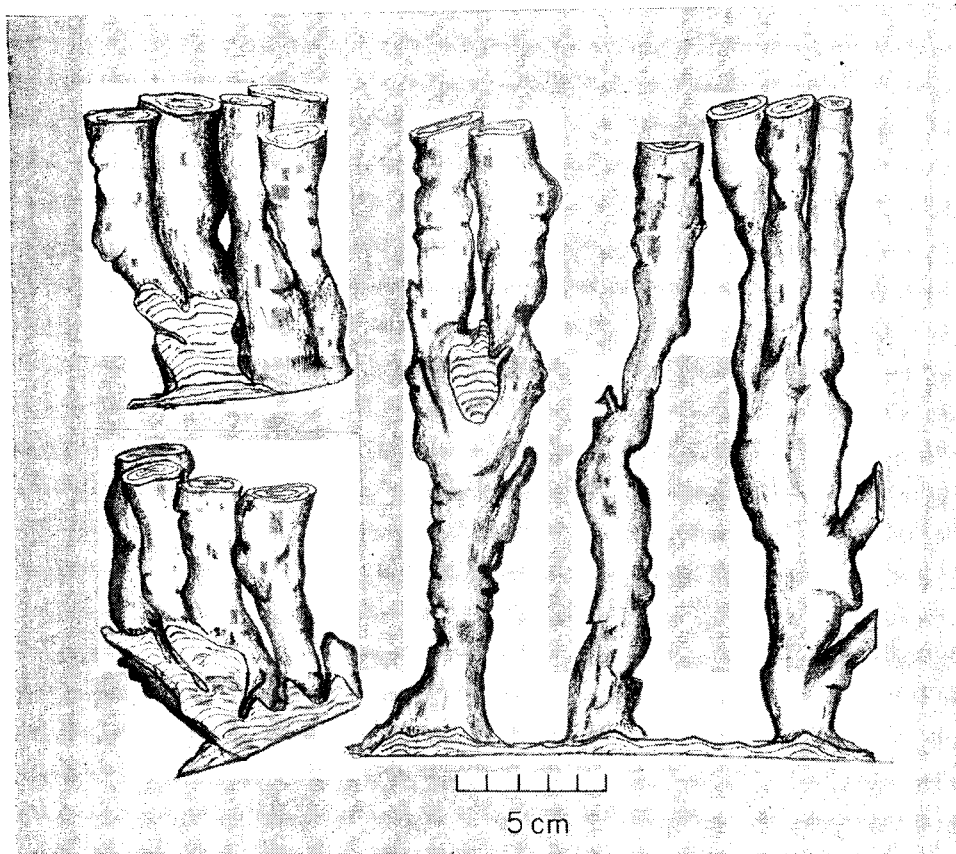


Fig. 8. *Eucapsiphora paradisa* new form., Paradise Creek Formation, Northwest Queensland (loc. 3 of 20/7/65).

*Type:* *Gruneria biwabikia* new form.

*Occurrence:* The genotype of *Gruneria* is characteristic of the algal zone of the upper cherty member of the Biwabik Iron Formation, where it is known throughout the Mesabi Range in northeastern Minnesota. It also occurs in algal chert of the laterally equivalent Gunflint Iron Formation of southern Ontario, where it carries a rich microflora described by Barghoorn and Tyler (1965) and by Cloud (1965). These rocks are believed to be around 1.9 aeons old (Goldich, 1968). Apparently the same form (pl. 3, fig. 2) is found in the Mount Jope Volcanics (Fortescue Group) of Western Australia, in siliceous rocks there dated as about 2.2 aeons old (Compston and Arriens, 1968, p. 566).

***Gruneria biwabikia* new form**

Plate 3, figures 1 to 3 (also Cloud, 1965, figs. 1-2)

Growth form and dimensions as above. Internal lamination mostly very continuous but of variable thickness. The dark layers, which owe

their color to the concentrations in them of organic matter (or hematite replacing organic matter), are even to slightly undulating sheets only 0.01 to 0.02 mm thick. Although their thickness is ordinarily constant, these dark layers show local sublenticular swellings, and some layers or parts of layers (especially upper surfaces) are darker than others due to greater concentration of organic matter (in the Gunflint) or hematite (in the Biwabik). Occasionally a single layer will divide into two, or two will come together to form one. The intervening light layers range in thickness from 0.02 to 0.1 mm, occasionally thinning to disappearance so that adjacent dark layers flow together and thicken. Both dark and light layers are siliceous (except locally), and the dark layers contain a rich microbiota at localities in southern Ontario and northeastern Minnesota.

*Type:* Specimen illustrated in plate 3, figure 3.

*Occurrence:* As for the Group *Gruneria*.

**Group *Inzeria* Krylov 1963**

***Inzeria tjomusi* Krylov**

Figures 9 to 11; plate 6, figures 1 and 2

*Group characteristics:* Colonies comprising irregularly subcylindrical and subparallel columns of a wide range in diameter (for example, figs. 10-11) and with many irregular surface protuberances and depressions. Mode of branching distinctive. New columns characteristically bud off

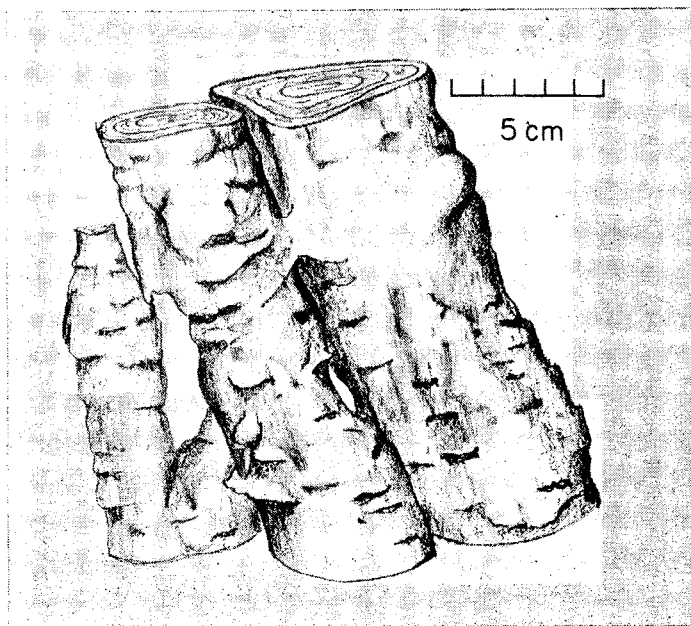


Fig. 9. *Inzeria tjomusi* Krylov, Dook Creek Formation, Northern Territory, Australia (loc. 1 of 29/7/65).

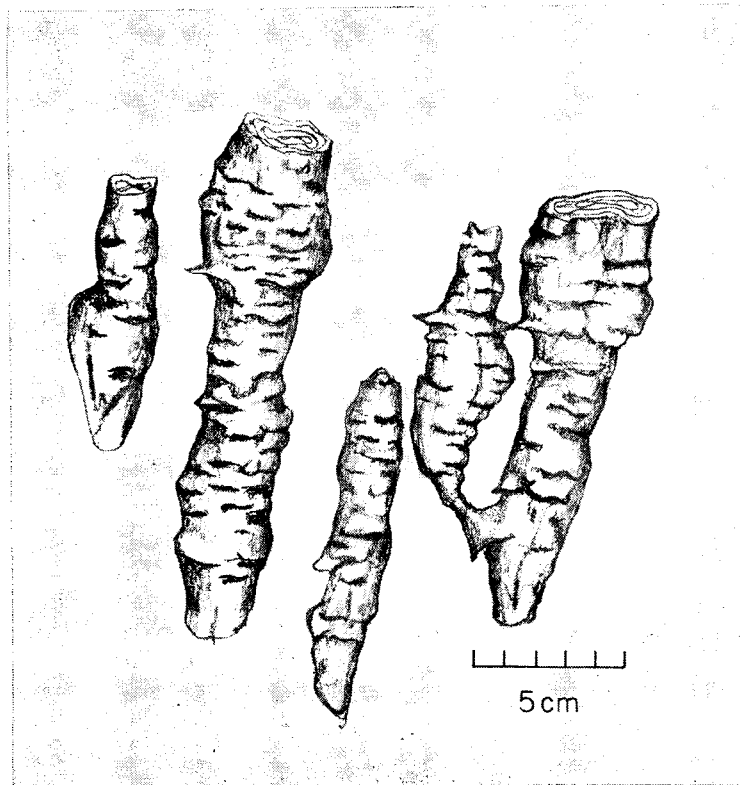


Fig. 10. *Inzeria tjomusi* Krylov, lower exposures of Hinde Dolomite, east slope, Mt. Hinde, Northern Territory, Australia (loc. 1 of 2/8/65).

from the parent column, often arising from niche-like indentations (fig. 11; pl. 6, fig. 1). Occasionally, however, a column will divide into two of about the same diameter. Horizontal profile rounded to ovate or more elongate. Lateral surfaces uneven, gently undulating to ragged, in the latter case displaying a crude annulation. Marginal zone characteristically non-enveloping but commonly covered with a discontinuous film (up to 2 to 2.5 mm thick) of non-laminated calcitic material having granularity and color contrasting with both the laminated part of the column and the surrounding rock. Laminae varying from moderately convex, to domal, to subconical.

*Form characteristics:* Wavy internal laminae consist of fine calcitic particles and dark interstitial matter. They include very thin (0.02 to 0.1 mm) and discontinuous darker layers separated along uneven boundaries by irregularly alternating thicker (0.3 to 0.5, or up to 1.3 mm) and lighter layers that include a higher proportion of granular carbonate (especially their lower parts) and less of the dark material and somewhat less thick lensing layers of still more granular carbonate that commonly show crinkly microlaminations. In our Australian specimens the dark material

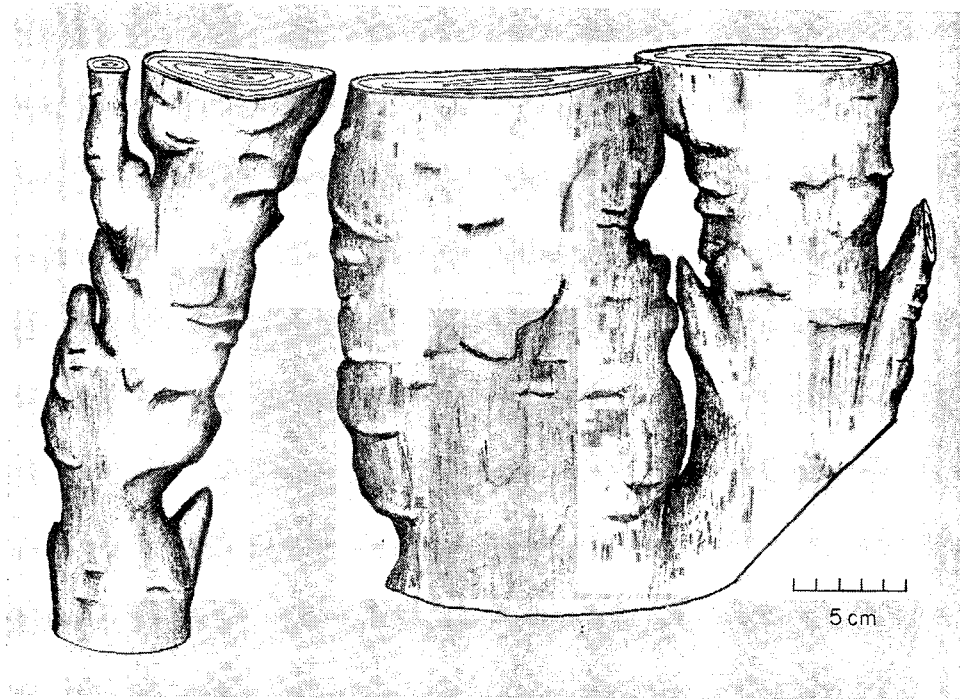


Fig. 11. *Inzeria tjomusi* Krylov, 25 m  $\pm$  above basal exposure of Hinde Dolomite, Eastern slope Mt. Hinde, Northern Territory, Australia (loc. 2 of 2/8/65).

is locally concentrated along microstylolites that have a tendency to converge on the dark layers.

*Occurrence:* *Inzeria tjomusi* from the Hinde Dolomite south of Darwin, Northern Territory, Australia (for example, fig. 11) are essentially identical to the holotype from the Katau Suite in the Urals (Krylov, 1963, p. 72-75, pl. 13). Available specimens from the Dook Creek Dolomite (also Northern Territory, Australia) do not show the niche-like hollows and niche branches, but then these are commonly absent from topotype material as well. The microstructure of the Dook Creek *Inzeria* is also poorly preserved, so their assignment to *I. tjomusi* is somewhat conditional. It is of interest that the columns of *Inzeria* in both the Hinde and Dook Creek dolomites are strikingly elongated and tapered in horizontal profile. The orientation in the Hinde Dolomite at Mt. Hinde averages close to N 10° E, with the blunt end north, indicating (along with abundant edgewise flat-pebble conglomerate) strong currents, which, in the interpretation of Hoffman (1967), would have been from the south.

*Inzeria* with the distinctive niche branching are known from the Bitter Springs Formation in central Australia. Their microstructure, however, is too poorly preserved to warrant a firmer designation than

*I. cf. I. tjomusi*. The Group *Inzeria* is widely distributed in the USSR in rocks of Upper Riphean age (950 to 675 m.y. ago).

**Group *Jurusania* Krylov 1963**

***Jurusania alicia* new form**

Figure 12; plate 5, figures 4 to 5

*Group characteristics:* Colonies of subcylindrical columns 1 to 5 cm in diameter which branch upward into subparallel columns of initially lesser diameter and which may be joined to adjacent columns by connecting layers. Horizontal profile subcircular to irregular. Lateral surfaces mostly ragged, with large projections and indentations. Marginal zone non-enveloping, but commonly with thin selvage of non-layered carbonate.

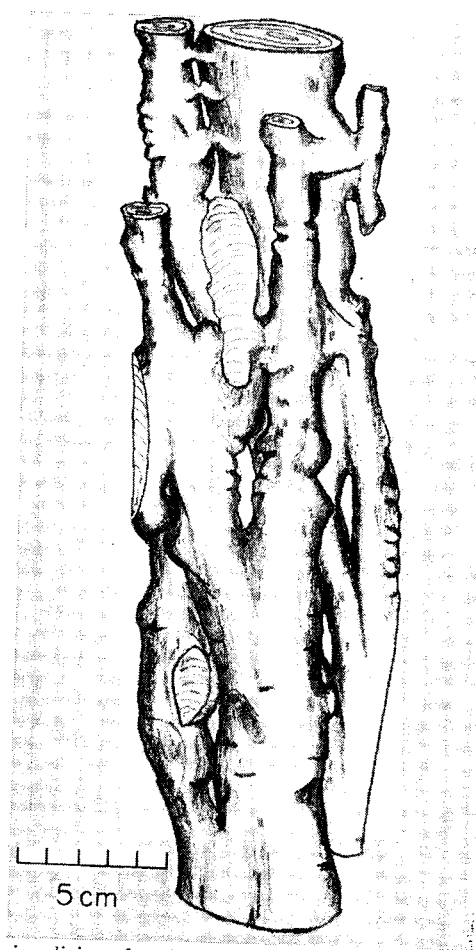


Fig. 12. *Jurusania alicia* n.f., Bitter Springs Formation, central Australia (loc. 6 of 3/7/65).

*Form characteristics:* Internal laminae moderately convex to flattened, irregular, roughly 0.2 to 0.6 mm thick but obscurely bounded except where they terminate in the thin dark stylolitic boundaries that are common in these samples. Lower part of layers commonly lighter and more conspicuously granular than upper. *J. alicia* differs from the similar Upper Riphean *J. cylindrica* of the Urals and Siberia in lacking the peculiar marginally enveloping non-layered selvage of that species, in the clotted structure of its laminae, and in the much greater frequency with which individual columns are joined by common laminae.

*Occurrence:* *J. alicia* is as yet known only from the Bitter Springs Formation of central Australia.

**Group *Katernia*, new group**

*Katernia* (luxuriantly branching) includes domal stromatolites that consist of large numbers of interconnected small bushlike growths of which the individual columns are only 2 to 7 mm in diameter, no more than 2.5 to 3 cm high between points of branching, and interconnected by numbers of common laminae. Before branching, the columns widen and then split into 2 or 3 new thinner columns which diverge from the locus of branching at small angles, or they may arise from a broad common base. Lateral surfaces ragged on a fine scale and non-enveloping.

These small multi-branching columns, with their connecting layers and intercolumnar matter, make up individual stromatolitic domes that show a concentric internal layering, attain amplitudes of 2.5 to 3 m, and, with the nonbiogenic rock between, make up extensive stromatolitic dolomites and limestones in the Dolomite Series of northern Cape Province, South Africa—especially near Schmidt's Drift and Boetsap, where they have been described and illustrated in much greater detail by Young (1932, 1934) and Young and Mendelssohn (1948), and where they frequently show truncated and desiccation-cracked surfaces, interdomal and edge-wise flat-pebble conglomerates, and other indications of extensive tidal-flat deposition.

Among described stromatolites *Katernia* most closely resembles the new Group *Gruneria* (pl. 3, figs. 1-3), of roughly similar age. Their similarities lie in abundance of connecting layers and domal form of colonies, but the individual columns of *Katernia* are much smaller and better defined, their mode of branching is more regular, and the interconnecting lamination is more prevalent and more persistent.

*Type:* *Katernia africana* new form.

*Occurrence:* Dolomite Series, South Africa, in rocks about 2 aeons old (Nicolaysen, 1962). Also, probably, in the Nash Formation of the Medicine Bow Mts., Wyoming (Knight, 1969), about 1.7 to 1.9 aeons old (Houston, Hills, and Gast, 1966).

***Katernia africana* new form**

Plate 3, figures 4 and 5 (also illustrations in Young, 1932, 1934; Young and Mendelssohn, 1948)

Growth form and dimensions as above. Internal laminae indistinct, commonly discontinuous, variable in form and convexity, 0.15 to 0.45

mm thick. Locally they contain dark rounded clots up to 0.1 to 0.15 mm in diameter. Connecting laminae most common in lower and upper parts of adjoining columns. Ordinarily of gentle convexity, they may at places dip up very steeply to adjoining columns, especially toward the margins of their enclosing domal masses.

*Type:* Specimen illustrated on plate 3, figure 5.

*Occurrence:* As for Group Katernia.

**Group *Kussiella* Krylov 1963**

***Kussiella* form indeterminate**

Figure 13; plate 7, figure 4

Colonies of elongate subcylindrical columns 2 to 3 cm in diameter, with non-enveloping marginal zone and with finely annulate lateral surfaces produced by projecting edges of internal laminae. Branching takes place by division of the parent column into two subparallel daughter columns of smaller diameter, above which the daughter column gradually thickens to the next locus of branching. Occasionally small daughter columns bud off laterally (fig. 13, left and center) but not from niches as in *Inzeria*. Internal laminae moderately convex. Microstructure not well enough preserved for confident assignment of the species, which however appears to differ from known representatives of the Group described from the Lower Riphean of the USSR.

*Occurrence of Group:* Mainly Lower Riphean, but extending through Middle and into Upper Riphean of USSR. Elgee Siltstone, Western Australia, age greater than 1.8 aeons (Compston and Arriens, 1968, p. 569).

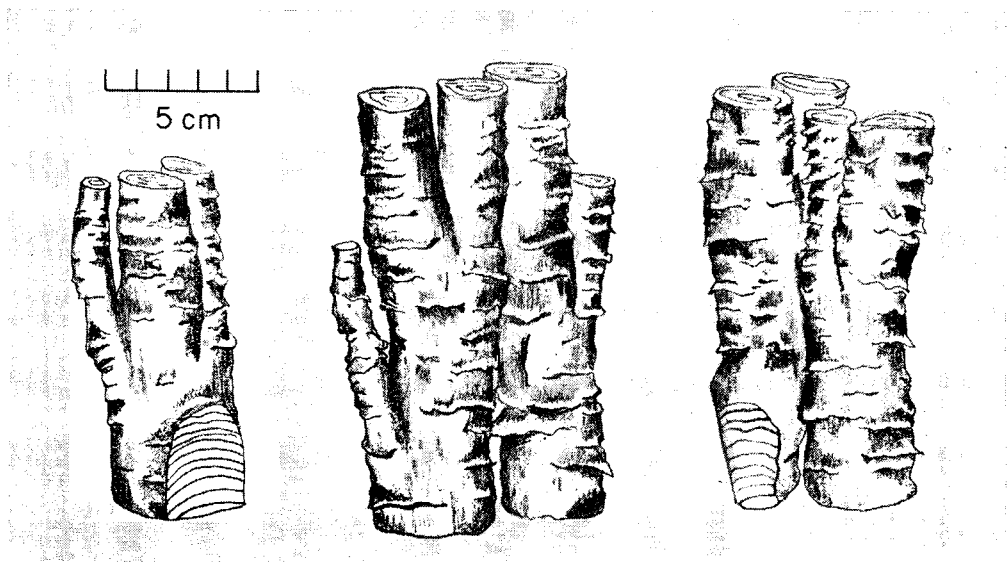


Fig. 13. *Kussiella* f.? Elgee Siltstone, Southern Kimberley District, Western Australia (loc. 1 of 9/7/65).

## Explanation of plates 1 through 7

## PLATE 1

Stromatolites from Bulawayo Dolomite, Dolomite Series, Amelia Dolomite, and Dook Creek Formation.

Fig. 1. Stromatolite group and form indeterminate. Bulawayo Dolomite, Cloud's locality 1 of 22/9/65, Huntsman Quarry, about 63 km north-northeast of Bulawayo, Rhodesia. Sawn and etched vertical surface.

Fig. 2. Stromatolite new form. Dolomite Series, Cloud's locality 1 of 9/9/65, north boundary of Farm Adams, about 8 km north of Lime Acres, Northern Cape Province, South Africa. Sawn and etched vertical surface.

Figs. 3-4. *Conophyton garganicus* Koroljuk. Cloud's locality 2 of 29/7/65. Amelia Dolomite, about 4.2 km southeast of McArthur River Camp of Carpentaria Exploration Co. Proprietary Ltd., McArthur River area, Northern Territory, Australia. Polished vertical surfaces showing multiconical structure, axial zone, and (at right of fig. 3) laminae that connect across from cylinder illustrated to adjacent on its right (see also Pl. 2, fig. 1).

Fig. 5. *Conophyton* form indeterminate. Dook Creek Dolomite, Mt. Rigg Group, about 13 km north of Beswick Homestead, Katherine Quadrangle, Northern Territory, Australia. Polished vertical surface showing multiconical structure and axial zone.

## PLATE 2

*Conophyton* from various localities.

Fig. 1. *Conophyton garganicus* Koroljuk. Amelia Dolomite, Australia. Same locality as plate 1, figures 3 and 4. Longitudinal thin section away from axial zone (C181a).

Figs. 2, 6. *Conophyton ressolii* Menchikoff. Upper Abenab Formation, Cloud's locality 2 of 28/8/65, Nosib Farm, about 32 km south-southeast of Tsumeb on old main road to Grootfontein, South West Africa. Longitudinal thin section away from axial zone (C188d) and weathered horizontal cross-section.

Fig. 3. *Conophyton cylindricus* Maslov. A silicified specimen from algal member of Mescal Limestone, Apache Group, locality X-107 of A. F. Shride (USGS), crest of ridge between Gentry and Ellison Creeks, sec. 27, T N N, R 15 E, eastern Gila County, Arizona. Longitudinal thin section away from axial zone (C177) showing structure of laminae.

Figs. 4-5. *Conophyton cylindricus* Maslov. Upper Siyeh Limestone, Belt Series, Glacier National Park, Montana. Figure 5 is a thin section from the specimen illustrated by Rezak, 1957, plate 23, figure 5, from USGS locality D-74. Figure 5 is a photograph of the outcrop along Going-to-the-Sun Highway west of Logan Pass, looking horizontally at the truncated, now vertically oriented, original upper surface of the slid biohermal mass.

## PLATE 3

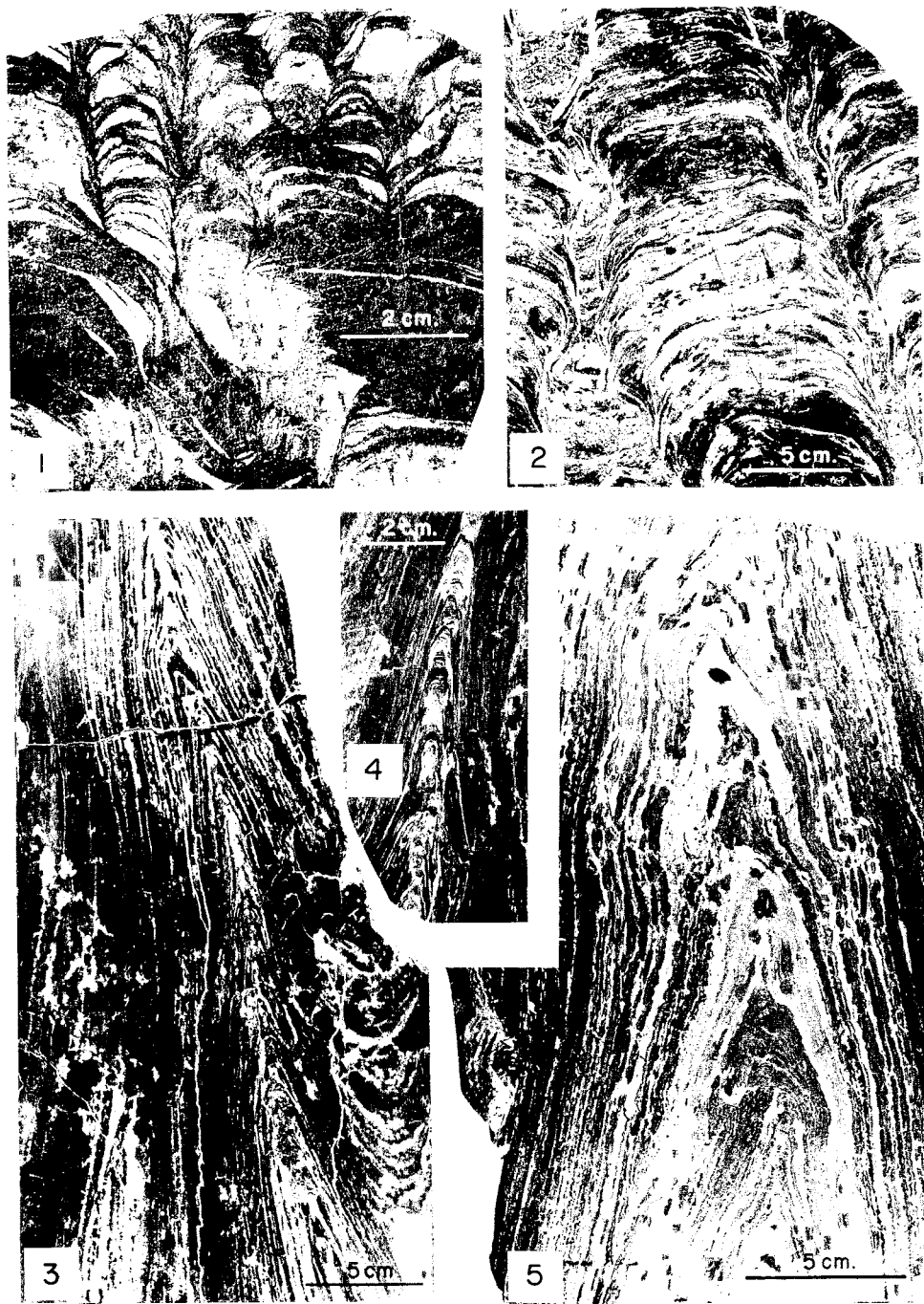
*Gruneria* and *Katernia*

Figs. 1, 3. *Gruneria biwabikia* new form. Biwabik Iron Formation, Cloud's locality 3 of 5/10/63, old Corsica Mine, east of Gilbert, St. Louis County, Minnesota. Longitudinal thin section C12(4) and polished vertical surface of holotype showing ragged edges and laterally linked columns.

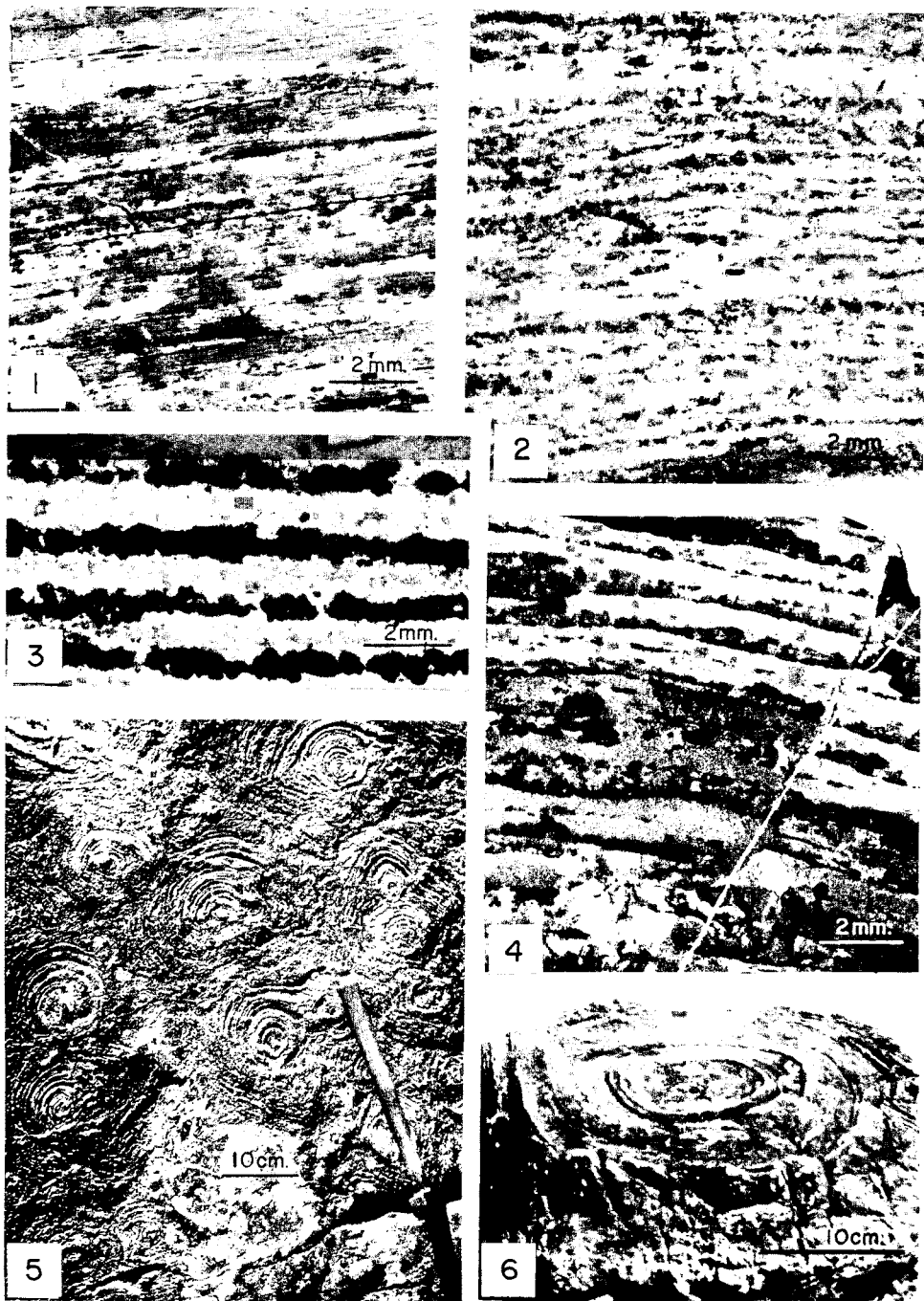
Fig. 2. *Gruneria biwabikia* new form. Mt. Jope Volcanics, Fortescue Group, Marble Bar Quadrangle, Western Australia. Longitudinal thin section C220. Specimen the gift of Keith McKay, Geological Survey of Western Australia, his locality R2422.

Figs. 4 and 5. *Katernia africana* new form. Dolomite Series, about 7 km northwest of Schmidts Drift, Northern Cape Province, South Africa. Longitudinal thin section C192a and sawn and etched vertical surface of holotype from Cloud's locality 4 of 6/9/65, showing striking bifid branching and rough edges of the numerous small bushy colonies, source of the group name.

Explanation continued on page 1056.



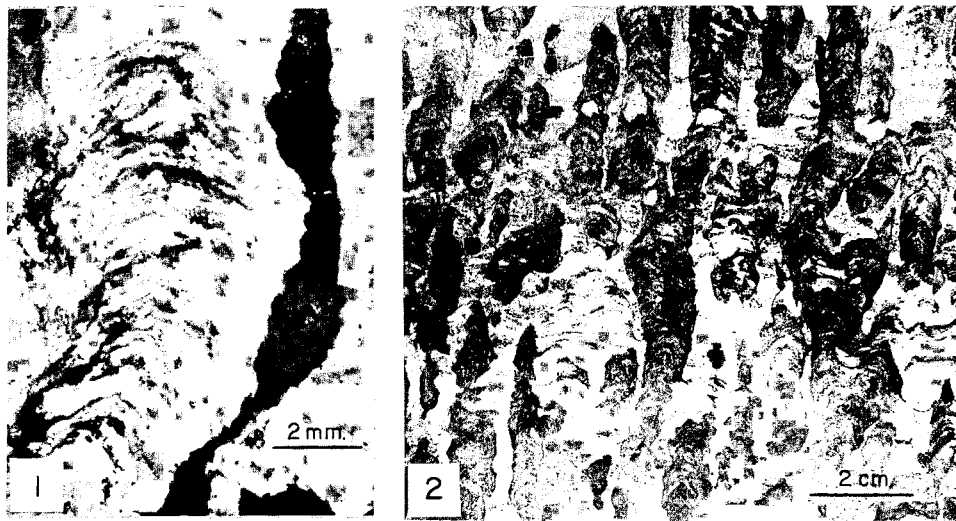
Stromatolites from Bulawayo Dolomite, Dolomite Series, Amelia Dolomite, and Dook Creek Formation.



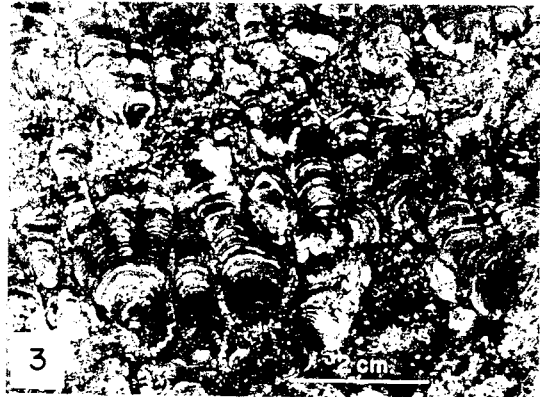
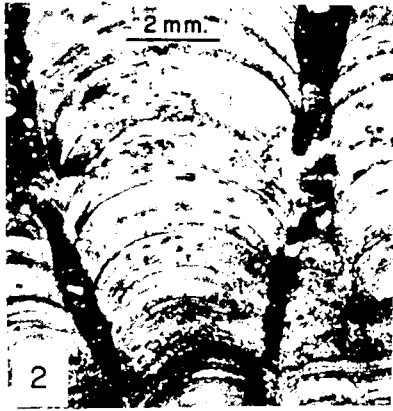
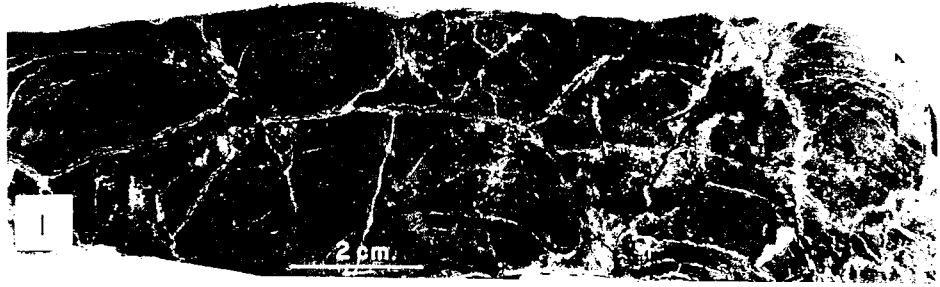
*Conophyton* from various localities.



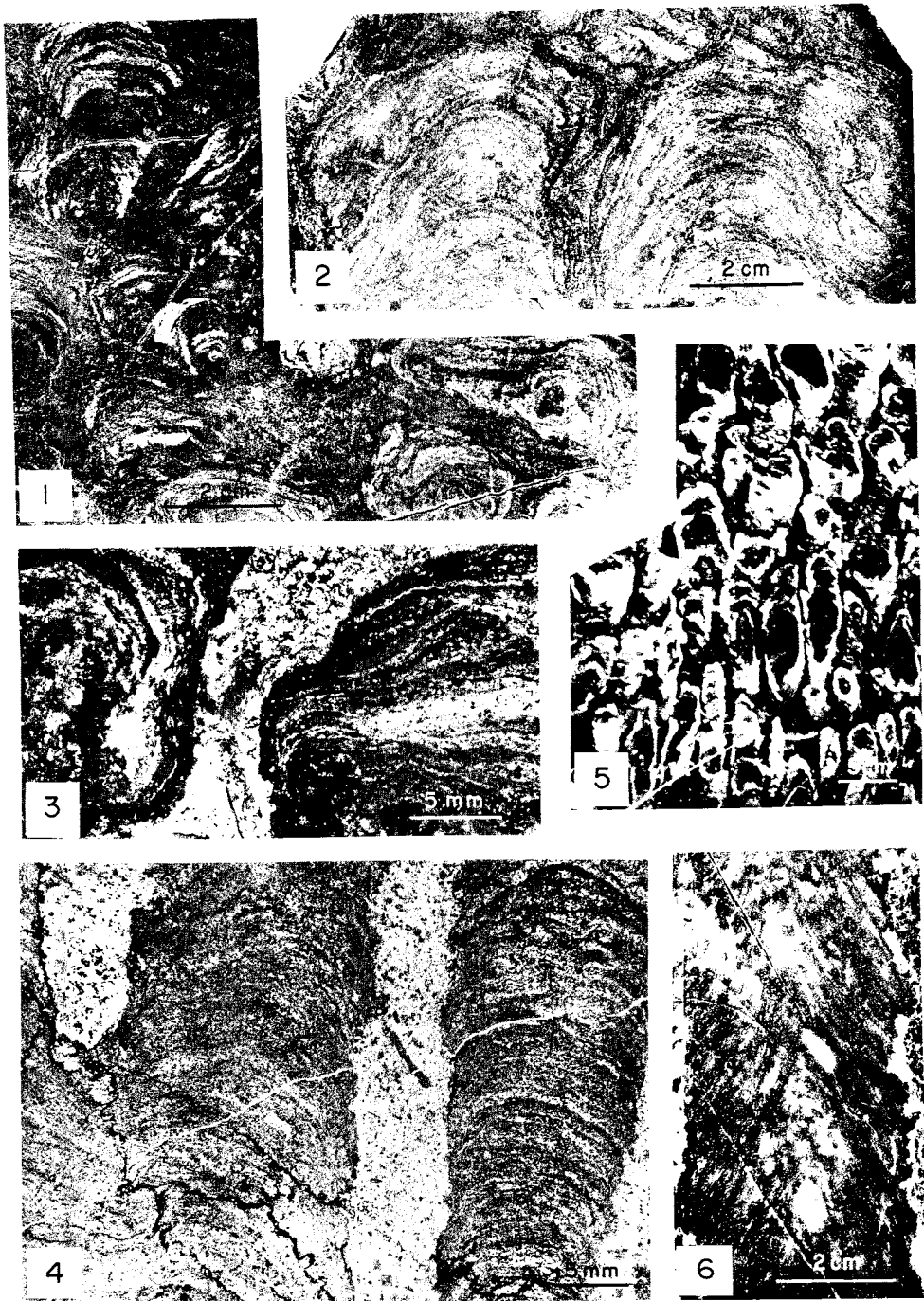
*Gruneria and Katernia*



*Eucapsiphora* and *Baicalia*







*Linella, Kussiella, and aff. Gonophyton*

## PLATE 4

*Eucapsiphora* and *Baicalia*

Figs. 1 to 3. *Eucapsiphora paradisa* new form. Paradise Creek Formation, Cloud's locality 3 of 20/7/65, south side of Paradise Creek, about 113 km north of Mt. Isa and downstream from Lady Annie Mine, Northwest Queensland, Australia. Longitudinal thin section C210a, polished surface of holotype showing complex interlinked branches and rough margins, and side view of outcrop showing growth around pinacles of older dolomite on irregular growth-surface.

Figs. 4 and 5. *Baicalia* aff. *B. rara* Semikhatov. Lower Abenab Formation, Cloud's locality 1 of 28/8/65, about 25 km southeast of Tsumeb and 50 m west of main road to Grootfontein, South West Africa. Longitudinal thin section C213b (showing grumose fine structure) and polished surface (showing tuberous irregular columns).

## PLATE 5

*Tungussia*, *Anabaria*, and *Jurusania*

Fig. 1. *Tungussia* form indeterminate. Base of algal member of Mescal Limestone, Apache Group, locality X-93 of A. F. Shride (USGS), about 11 km east of Rock House and at west edge of Navajo County, sec. 23, T 7 N, R 15 E, Arizona. Polished surface showing completely branching included columns.

Figs. 2 and 3. *Anabaria juvenis* new form. Bitter Springs Formation, Cloud's locality 4 of 3/7/65, about 38 km east of Alice Springs, Northern Territory, Australia. Longitudinal thin section C182c and polished surface of holotype showing smooth marginal zone and multiple branching.

Figs. 4 and 5. *Jurusania alicia* new form. Bitter Springs Formation, Cloud's locality 6 of 3/7/65, about 38 km east of Alice Springs, Northern Territory, Australia. Longitudinal thin section C191a and sawn vertical surface of holotype, showing ragged edges and joined branches.

## PLATE 6

*Inzeria* and *Boxonia*

Figs. 1 and 2. *Inzeria tjomusi* Krylov. Hinde Dolomite, Tolmer Group, Cloud's localities 1 (fig. 2) and 2 (fig. 1) of 2/8/65, east slope Mt. Hinde, about 107 km south of Darwin, Burnside Quadrangle, Northern Territory, Australia. Figure 1, sawn and etched vertical surface showing distinctive niche-branches; figure 2, vertical thin section C199a.

Figs. 3 and 4. *Boxonia* aff. *B. gracilis* Koroljuk. About 120 m below the top of the Johnnie Formation, about 1 km east of Gunsight Mine, SW 1/4 sec. 10, T 20 N, R 8 E, southern Nopah Range, Tecopa Quadrangle, California (Keith Kettner, USGS, collector). Sawn vertical surface and vertical thin section C176a, showing enveloping laminae of marginal zone and smooth external surface.

## PLATE 7

*Linella*, *Kussiella*, and aff. *Conophyton*

Figs. 1 to 3. *Linella* aff. *L. ukka* Krylov. Top of lower member, Johnnie Formation, Cloud's locality 2 of 24/11/66, south end of Ibex Hills, Shostone Quadrangle, California. Vertical sawn and etched surfaces (figs. 1-2) and vertical thin section C189c (fig. 3), showing tuberous form and incomplete enveloping of laminae in marginal zone.

Fig. 4. *Kussiella* form indeterminate. Elgee Siltstone, Kimberley Group, Cloud's locality 1 of 9/7/65, on left bank of Margaret River, about 42 km north of Louisa Downs Station Headquarters, southern Kimberley Division, Western Australia. Vertical thin section C184, showing characteristics of marginal zone and branching (upper left).

Figs. 5 to 6. Aff. *Conophyton*, group and form indeterminate. Paradise Creek Formation, Cloud's locality 2 of 20/7/65, south side of Paradise Creek, about 113 km north of Mt. Isa and downstream from Lady Annie Mine, Northwest Queensland, Australia. Oblique view of outcrop and vertical polished surface of unusual discrete cylinders with conical structure reminiscent of *Conophyton*, but with apical angle much less acute than usual and without a well-defined axial zone. (Although genuine *Conophyton* was also seen at this locality [Robertson, 1960, pl. 23], none was collected.)

**Group *Linella* Krylov 1967*****Linella* aff. *L. ukka* Krylov**

Figure 14; plate 7, figures 1 to 3

*Group characteristics:* Colonies consisting of irregular, short, curved, tuberos and crudely subcylindrical warty columns 3 to 10 cm in diameter. Branching complex (for example, fig. 14), especially where warty protuberances and new columns diverge upward and sideways. Profile normal to length of columns, subcircular to rounded, irregular. Lateral surfaces lumpy, incompletely enveloping.

*Form characteristics:* Lamination highly variable, commonly asymmetrical, consisting of mostly darker layers of amorphous carbonate and mostly lighter layers of more granular carbonate. Amorphous layers continuous, 0.1 to 1.5 mm thick, their boundaries usually well-defined but uneven—especially the upper boundary, because the tendency of the upper part of some of the amorphous layers to break down into small rounded clots that grade into the more granular structure of the lighter layers. The lighter more granular layers are also more persistent. They range in thickness from tenths of millimeters to 2 or 3 mm. The amorphous layers may thus be widely separated or degenerate to an irregular clotted zone.

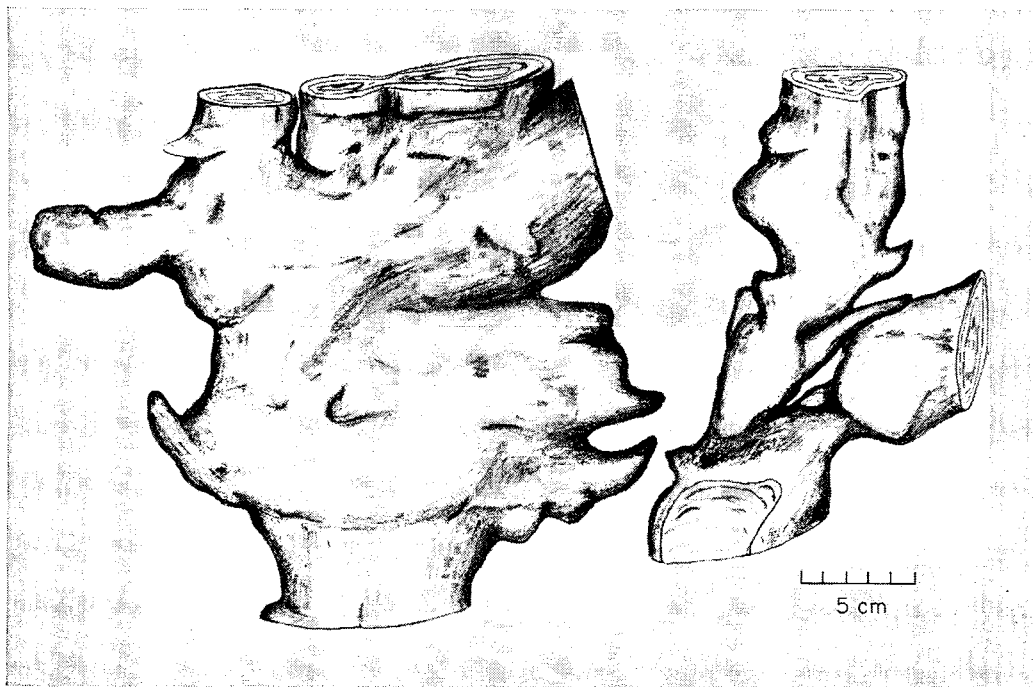


Fig. 14. *Linella* aff. *L. ukka* Krylov, Johnnie Formation, South IbeX Hills, California (loc. 2 of 24/11/66).

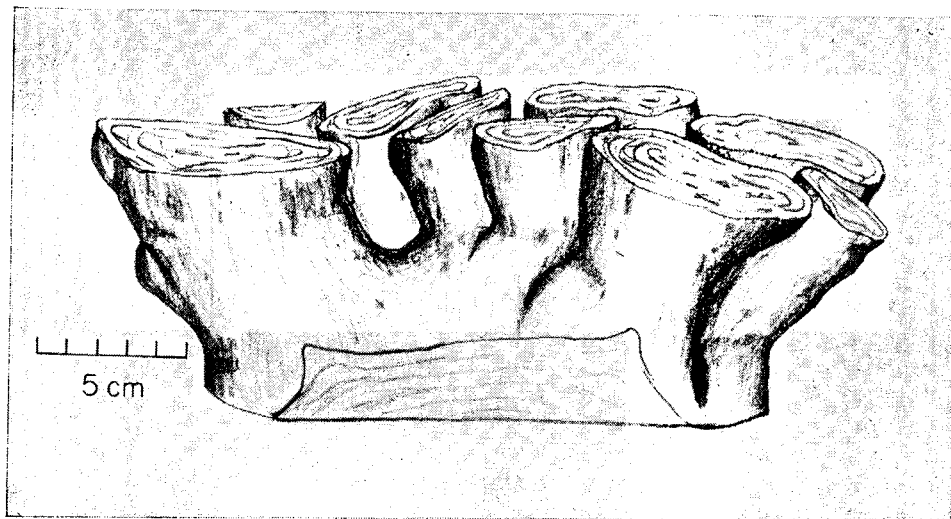


Fig. 15. *Tungussia* f.? Mescal Limestone, Southern Arizona.

*Distribution:* The characteristics described above are those of *Linella* from the Johnnie Formation of late pre-Paleozoic or early Paleozoic age in eastern California. They are close to those of *L. ukka* (Krylov, 1967, p. 39-41, pl. 4, figs. 1-3), but the latter has dark clots dispersed throughout the dark layers instead of only in the upper part. *L. ukka* is a characteristic Vendian stromatolite in the USSR, implying a similar age range for the Johnnie.

#### Group *Tungussia* Semikhatov 1962

##### *Tungussia* form indeterminate

Figure 15; plate 5, figure 1

Colonies of tuberous, irregularly subcylindrical, and subconical columns with complicated branching in whorls of 5 to 10 daughter columns that radiate out from a basal area or thick parent column (fig. 15). Daughter columns narrow at base, but thickening upward, developing separate swellings and tubercles and eventually giving rise to its own whorl of sideways and upwards radiating daughter columns. Lateral surfaces non-enveloping, smooth or slightly irregular. Microstructure poorly preserved.

*Occurrence:* The poor preservation of microstructure in the dolomitized *Tungussia* from the Mescal Limestone of southern Arizona does not permit assignment as to form. The Arizona specimens, however, are similar in characteristics observed to middle Upper Riphean and Vendian *Tungussia* of Siberia and the Urals, among them particularly to *T. confusa* Semikhatov (1962, p. 207-208, pl. VII, fig. 3; pl. VIII, figs. 4-5).

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