tion, with its unspeakable language, but he is firm in his position that the system must fit the soils and not the reverse. In essence he takes the ancient Russian view that soil genesis provides the main taxonomic units, with the units being modified by parent material and drainage. He sees three soil zones, the tundra zone, the subpolar desert zone, and the polar desert zone, ringing the pole and a fourth one, the cold desert zone, covering Antarctica. In all these zones there are soil-forming processes at work, complete with active layers and physical transport of both crystalloids and colloids, probably even when the soil is frozen. Summer temperatures and precipitation determine the properties of the soils of the zones.

Within each zone, at least in the north, the principal genetic soil types may be expressed, though to different degrees. There may be in each zone wet and organic tundra soils in poorly drained places and, on better-drained sites, arctic brown soils (Tedrow's own discovery of 20 years ago) and even podzol soils. There may also be in each zone a vegetable carpet spread on rock (the ranker soils of Kubiëna, whose great influence Tedrow venerates) and primitive soils on young substrates or solifluction slopes. Tedrow's simple classification identifies each soil type and places it in the appropriate zone. It is a classification of reason; let us use it.

A biologist like this reviewer must hope that pedologists will follow Tedrow and let the taxonomic controversy lie. Soils cannot be classified as can Linnean species. Modern biology came about because of the almost magical discovery that living things were grouped into definite, distinct species and that these species had lineal, ancestral relationships one to another. But there is not a species of soil that is completely distinct from other species, let alone a distinct ancestral family. Thinking otherwise is the fallacy behind contrived systems for neatly ordering soils. Tedrow avoids the fallacy splendidly.

The very complex, and still unanswered, questions of soil genesis will yield not to systems of classification, but to studies of soil chemistry in different patterns of time and space. It seems that, aside from obvious correlations with temperature and pH values, we still have only hazy ideas of why sesquioxides are concentrated in some soils and silicates in others. Do plants really influence the process? Look at the beautiful color photograph of podzol soil in the Anaktuvuk Pass and ponder. Tedrow makes little attempt to discuss the chemistry of polar soil genesis, which is clearly a subject for the next generation. His book, however, will be the guide for those planning such work. He writes of red soils on Banks Island, of active soils in a polar desert, and of the correlation between biota and soils, asking sundry exciting questions to be answered by those who will follow him.

In the discussion of oriented lakes near Point Barrow, Tedrow misses the fact that it was D. A. Livingstone who first pointed out that the lake axes are aligned normal to the wind. Tedrow has been let down by his illustrator, who has drawn a map (p. 344) that is wrongly copied from the correct map of Sigafoos and that purports to show forest all over Seward Peninsula and beyond, although the accompanying text describes the tundra of the peninsula. This is a grave enough error to require the publisher to provide an erratum slip before any more copies are sold. Otherwise a reviewer looking for errors finds lean pickings. This is a fine book, well produced.

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Peculiar Structures

Stromatolites. M. R. WALTER, Ed. Elsevier, New York, 1976. xii, 790 pp., illus. $99.95. Developments in Sedimentology 20.

How did peculiar structures in some of the oldest limestones and dolomites come to be a household word to most geologists, engender a newsletter for 180 subscribers, and become the subject of this hundred-dollar compilation?

Stromatolites are layered rocks, not the familiar horizontal or inclined variety, but successive millimeter laminations arranged in wavy, crinkled, and onionlike forms (oncolites) or elaborated of hemispheroids that are linked or stacked, often with compound branching forms. They occur throughout the Phanerozoic, but are most abundant and varied in Late Precambrian and Early Paleozoic strata; in their heyday, stromatolites took a bewildering variety of shapes and sizes: branched growths the size of asparagus, domal cabbagelike masses meters across; columns half a meter in diameter and several meters or more tall made of successive hemispheroidal shells or of nested cones; reeflike masses tens of meters across. With the appearance of invertebrates this extravagant variation in form declined and, with some exceptions, only the more rudimentary planar, crinkled, and onionlike types continue to be formed today. The consensus view of how stromatolites grew is based largely on modern examples in which self-replicating mats of blue-green algae either alternate with laminations of fine lime sediment or through their own vital activities precipitate calcium carbonate.

The interest in stromatolites can be traced to a unique combination of extraordinary longevity (3 billion years), ubiquitous occurrence in shallow-water carbonate sediments, including those of modern shallow seas, association with metallic ores, and successive controversies about the relative roles of organisms and environment in producing variations in form and internal structure. Most of the expansion of interest has come in the last 15 years; just ten years ago there were fewer than two dozen participants from North America and Western Europe at a workshop on stromatolites (see R. N. Ginsburg, *Science* **157**, 339 [1967]) and probably no more than 30 stromatolite researchers worldwide. The present volume has 42 authors, and the worldwide community of stromatophiles probably numbers well over a hundred.

According to the editor, Malcolm Walter, the compilation aims to provide a comprehensive coverage of stromatolites for specialists and nonspecialists, with reviews of tried and tested work balanced by reports of new methods and research.

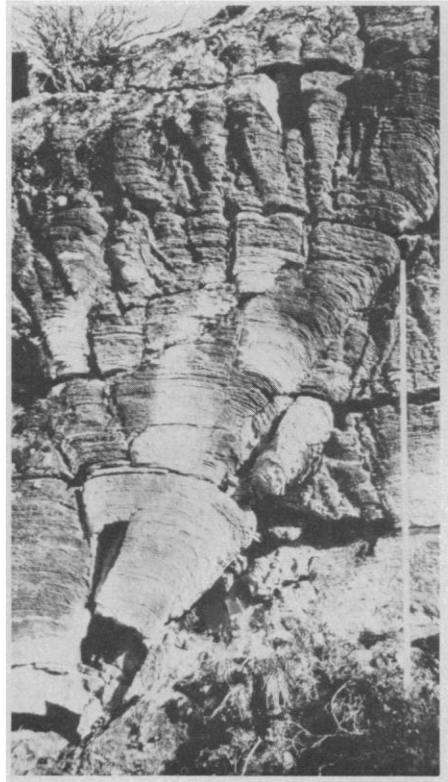
As a report of the state of knowledge, the book is on the whole well done, no small accomplishment considering the multiple authorship and the rapidly expanding field. Some of the contributions are succinct status reports. The subjects they cover include classification (Krylov), microstructure of Precambrian stromatolites (Bertrand-Sarfati), taxonomy of modern blue-green algae (Golubic), environmental range of microorganisms (Brock), microorganisms in fossil examples (Awramik, Margulis, and Barghoorn), distribution and morphogenesis of the stunning growths in Shark Bay (Hoffman, Playford, and Cockbain), and mineral deposits associated with stromatolites (Mendelsohn). Assessing the state of knowledge pertaining to microstructure, biostratigraphy, and environmental range demands much more effort on the part of the reader, for the contributions are not summarized or evaluated. Missing also is any résumé of the history of studies of stromatolites that would make clear the progress recorded in this volume. As the editor indicates, the compilation is a hybrid—partly state of knowledge, partly source book.

Some of the items of lore one finds are: how to reconstruct the form of stromatolites with serial sections; that there are 12 different schemes for classifying columnar forms; how to avoid confusing stromatolites made in soils, caves, and hot springs with those produced by microorganisms; the distinctive microstructures of modern algal mats; the astonishing antiquity, a billion years, of the modern mat-forming community of blue-green algae; the variety of metallic ores, copper, lead-zinc, and even gold, associated with stromatolitic deposits; and that some stromatolites grew in depths of 45 meters.

Summaries of individual examples of modern and ancient occurrences are a valuable part of the compilation. All the much-cited Recent marine examples are presented—Shark Bay, Andros Island, the Trucial Coast—as well as nonmarine examples from Green Lake, Great Salt Lake, the Florida Everglades, and Andros Island. Six of the nine examples of ancient stromatolites are from the Precambrian, with the remaining three from the Cambrian, Devonian, and Eocene. Many of these case histories are succinct summaries; among the longer ones that offer previously undescribed examples is one that documents deep-water stromatolites from the Devonian (Playford *et al.*).

The distinctive and variable microstructure of stromatolites is a principal theme of the volume, mentioned, described, or illustrated in most contributions. The numerous summaries, descriptions, and photomicrographs are most welcome, but what is lacking is a summary and guide for nonspecialist readers. The extensive treatment of microstructure does serve to emphasize the danger of generalizing about the relative roles of microorganisms and environment in the formation of stromatolites. Even among modern examples there are some in which microorganisms clearly control microstructure and some in which the nature and the rhythm of sediment deposition are the primary control. In many modern examples one sees that microorganisms and their physical environment are so closely coupled as to defy separation; in fossil examples with a diagenetic overprint it is much more difficult, perhaps impossible, to assess the roles of these two factors. What can be done is demonstrated by an analysis of the microstructure of Mid-Proterozoic stromatolites in Montana (Horodyski); the occurrence of detrital quartz and feldspar is used to interpret some laminae as trapped particulate sediment and their absence in other laminae is inferred to mean that those were precipitated.

The most controversial aspect of stromatolites—their biostratigraphy—is con-



(Left) Outcrop view of the laterally linked columnar stromatolite *Omachtenia* from the pre-Riphean Pethei Group (about 1.8 billion years old), Great Slave Lake, Northwest Territories, Canada. On bedding surfaces, the columns are strongly elongate parallel to paleocurrents and normal to the shelf edge. Scale 1.5 m long. (Right) Outcrop view of alternations of linked, domal (*Omachtenia*), and planar stromatolites from the pre-Riphean Rocknest Formation (about 2 billion years old), Coronation Gulf, Northwest Territories, Canada. The change from domal and columnar forms to flat laminations is interpreted to reflect decreasing wave action from lower to higher tidal flats. [From *Stromatolites*, courtesy Paul Hoffman]

"Club-shaped, cylindrical, and conical subtidal stromatolites 180 m offshore, 2.8 km southwest of Flagpole Landing [Hamelin Pool, Shark Bay, Western Australia], photographed at low tide in November 1974, in water about 1 m deep. Note the living coliform mat on the crowns of the stromatolites and the sparse 'beard' *Acetabularia* on the sides." [From *Stromatolites*, courtesy P. E. Playford and A. E. Cockbain] sidered in several contributions. One of these (Semikhatov) gives a valuable historical perspective of stromatolite biostratigraphy in the Soviet Union, where it originated. The consensus is that "more work needs to be done"; the appearance of increasing inconsistencies with the zonation of a decade ago has cast doubt on its reliability.

The volume has a useful glossary, a list of available translations of works in Russian, a comprehensive bibliography of over 2000 references, with an index largely by geologic age, and a subject index of 18 pages.

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On the Uses of Rigorous Proof

Proofs and Refutations. The Logic of Mathematical Discovery. IMRE LAKATOS. John Worrall and Elie Zahar, Eds. Cambridge University Press, New York, 1976. xii, 174 pp., illus. Cloth, $19.50; paper, $4.95.

Every beginning student is taught that, in mathematics, results are *proved*. The idea is old as Euclid. Genuine mathematics is done by beginning with immediately self-evident principles (axioms) and using these principles in chains of unimpeachable reasoning (proofs). The 20th century has seen a variety of attempts to elaborate this familiar theme. Philosophers of quite different persuasions have tried to uncover the foundations of finished mathematical theories, with the aim of showing that the theorems of those theories can be rigorously proved. Questions about mathematical discovery and about the evolution of mathematical concepts have been bypassed in favor of issues concerning mathematical truth and mathematical evidence.

Imre Lakatos's collection of essays is designed to challenge both the aims of 20th-century philosophy of mathematics and the Euclidean picture of mathematics that lies behind them. His central thesis is that the role of proofs in mathematics is misunderstood, and he suggests that this crucial misunderstanding will affect the quality both of mathematical research and of mathematical education. The mistake is to regard proofs as instruments of justification. Instead we should see them as tools of discovery, to be employed in the development of mathematical concepts and the refinement of mathematical conjectures.

This approach to mathematical proofs is elaborated and defended in the title essay (a very slightly revised version of an article published in four parts in the *British Journal for the Philosophy of Science* in 1963–64), which occupies 105 of the 154 pages of text. Lakatos had planned to amplify his suggestions, but he died in 1974, at the age of 51, and it has been left to two of his former students, John Worrall and Elie Zahar, to complete the book he envisaged. They have added one short chapter and two appendixes, all deriving from Lakatos's doctoral dissertation. These shorter pieces illuminate and extend some of the main ideas of the title essay, but they do not (and could not) tie up all the loose ends.

Lakatos proposes that a proof is "a thought-experiment . . . which suggests a decomposition of the original conjecture into subconjectures or lemmas" (p. 9). The creative mathematician begins with a conjecture and tries both to prove it and to refute it. By uncovering counterexamples he refines his proof-ideas, and by using the more refined proof-ideas he unearths new counterexamples. This process, in which proofs and refutations interact, leads from an initial conjecture, couched in vague terminology, to a body of precisely formulated results. The process is vividly illustrated in the title essay. Lakatos imagines a student discussion of Euler's conjecture about the relation between the numbers of edges, vertices, and faces of polyhedra. His imaginary students adopt, defend, and criticize the positions taken by historical figures. Their discussion formulates explicitly Lakatos's method of proofs and refutations and uses it to improve the original conjecture into sophisticated theorems.

What does the example show? I think that Lakatos has demonstrated that there are important issues about mathematical discovery that should not be neglected. The process of mathematical discovery cannot be dismissed (as it so often has been) as a series of "happy guesses." Yet we might feel that Lakatos's picture is complementary to, rather than inconsistent with, the classical Euclidean view. Perhaps the method of proofs and refutations enables mathematicians to discover mathematical truths, but they then have the duty of proving those truths by constructing rigorous derivations from uncontroversial axioms. So, while Lakatos has insightfully investigated mathematical discovery, we might suppose that issues about mathematical justification are still important and are unaffected by his suggestions. Furthermore, there are reasons for skepticism about the general applicability of his method. Conjectures about polyhedra are testable in obvious ways—we can construct or draw polyhedra. Are there analogous ways in which we can test conjectures about topological spaces or continuous functions?

Lakatos endeavors to forestall these objections in chapter 2 and appendix 1, respectively. The theme of chapter 2 is that completely rigorous mathematical proofs can be obtained only if the theorems of finished parts of mathematics are recast as "arithmetico-set theoretical tautologies" (p. 125). Thus Lakatos seems to conclude that a particular development of the Euclidean picture of mathematics is true, but rather uninteresting. (Interestingly enough, Lakatos appears to hold that logic is immune to question, a position that is reinforced by several editorial footnotes.) He offers no account of how mathematical claims could be justified during the process of developing a mathematical theory.

Appendix 1 sketches the history of the development of the concept of uniform convergence. Lakatos attempts to rebut the criticism that the method of proofs and refutations is inapplicable in areas of abstract mathematics by arguing that, in this case too, the method plays a vital role. He provides an accurate account of Cauchy's attempts to prove that the sum of a convergent series of continuous functions is continuous, and he proposes that the concept of uniform convergence was forged in an attempt to refine the proof against known counterexamples from the theory of Fourier series. Unfortunately, the rational reconstruction of the history is much less convincing here than in the case of the Euler conjecture. There are two related reasons for the difference. Lakatos has tried to detach the problem of convergence from the cluster of issues addressed in early-19th-century analysis, and the development of ideas on these other issues is relevant to the elaboration of concepts of convergence. Moreover, because Lakatos has not provided an account of how mathematical principles can