Introduction to Microfossil Biostratigraphy

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By

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PREFACE

This is the first sequel to *Microfossils through Time: An Introduction*, which was published in 2018. It is part of a series of textbooks intended to show those making their first steps in micropaleontology the basic concepts of this science and its applications. Microfossil biostratigraphy – or microbiostratigraphy – represents the most important application of micropaleontology, which is used mostly in rock and sediment dating and correlation. The methodology itself involved in this application of micropaleontology started with the birth of biostratigraphy and biocorrelation more than 200 years ago.

Microfossil uses in biostratigraphy require specific knowledge and experience. One of the most evident difficulties I encountered during my early career as an undergraduate, then working for my degrees and finally as young specialist focused on exploration for hydrocarbons in industry was the lack of a microbiostratigraphy textbook. On a number of occasions during my career, I found myself struggling to get oriented on, for example, what groups to use for which stratigraphical intervals. Although I like to think of myself as a successful scientist who ultimately managed to find a way to successfully work with several groups of microfossils, I had to put a considerable effort into achieving this stage. Despite these efforts, it is evident to me that the absence of a coherent orientation in the field took its toll: I could have done more if well-oriented through a general textbook on microbiostratigraphy. But the problems did not stop here. Later, as an instructor in an academic environment, it was equally difficult to provide an effective orientation to the students with whom I worked and I always felt the acute absence of a textbook for a quick and detailed reference at introductory level.

The new stream of textbooks that I started with the publication of *Microfossils through Time: An Introduction* offers ample possibilities to correct this. *Introduction to Microfossil Biostratigraphy* is the first textbook of a planned trilogy in this stream that presents a new look at some of the uses of microfossils in stratigraphy, namely the concepts and methodologies developed from the time of the birth of biostratigraphy and biocorrelation to the emergence of sequence stratigraphy. The other two parts will be developed in the next few years.

I would like to know that the readers will find *Introduction to Microfossil Biostratigraphy* an informative and useful textbook and a quick reference in the everyday practice in this field of geological sciences.

—M. Dan Georgescu

Calgary, December 1, 2020

ACKNOWLEDGMENTS

I wish to thank all those who helped me during the development of this project. This includes the specialists with whom I have had helpful exchanges of ideas about biostratigraphy, biocorrelation and how they are related with the Theory of Evolution during more than three decades. All my gratitude is directed to the personnel of the University of Calgary Libraries and especially Dr. Judy Zhao for the constant and professional help; most of the documentation is due to their exemplary work. I wish to thank warmly the many students with whom I worked in the last decade who led me to the conclusion that the development of a new stream of textbooks of micropaleontology and related applications/sciences was necessary. The permanent support and encouragement from my wife, Daniela, helped me pass through the many difficult parts of the project.

INTRODUCTION

Microfossil biostratigraphy or microbiostratigraphy is the most used application of microfossils in the fundamental and applied studies. It is used practically from exploration for hydrocarbons to map production by geological surveys where sediment and rock dating with microfossils is required. This branch of stratigraphy has a long history that started early in the nineteenth century. A small number of reports prefigured the important role of microfossils in the future of biostratigraphy… but it was not the time. The nineteenth century was the time when micropaleontology was defined as a distinct branch of paleontology, most of the microfossil groups were discovered and the precise systematic positions for many of them recognized. It was also the time of the onset of another process that in the long term would prove equally important. Massive amounts of data were published and this led to the development of a scientific fundament that towards the end of the nineteenth century became immense.

The beginning of the microbiostratigraphical studies at a full scale was determined by an economic challenge. The demand for oil and natural gas is what shaped microbiostratigraphy forever. At first, it was attached mostly to foraminiferal micropaleontology and this is apparent in the first treatise on micropaleontology in the twentieth century (Glaessner 1945). The increasing demand for hydrocarbons and subsequently the development of the deep oceanic drilling technology further challenged and shaped microbiostratigraphy. Today, about half a century after the initiation of the Deep Sea Drilling Project (DSDP), more than a half of the over 40 groups of microfossils have demonstrated applications in microbiostratigraphy. A multitude of working methodologies and concepts were developed during this time period and they will prove paramount in the next decades in producing high-resolution biozonations and accurate biocorrelation. These form another component of the fundaments on which microbiostratigraphy is built. In terms of common practice, they represent the first step in assigning ages to the successions of rocks and sediments that yield a (micro)fossil content, which were intersected by a prospection or exploration well, or when we study a succession of rock outcrops and need a method to “put colors on a map”.

The birth of biostratigraphy at the beginning of the nineteenth century reverberated across the subdisciplines of geology: correlation over longer distances became possible, the concept of facies could be defined and, overall, the use of the data from the fossil record got new valences. Above all, the concepts and fossil record patterns noted in the course of different biostratigraphical studies became major sources of data in the study of life evolution on Earth. In this context it is not surprising that the development of a completely fossil-based biostratigraphical methodology preceded by one year the release of the Theory of Evolution in 1859. All these data show beyond doubt that biostratigraphy was born as a component of natural sciences and all its developments are part of natural sciences. These fundamental aspects are kept unaltered in the textbook. Such a mention appears necessary in the introductive part for a variety of mathematical methods were used in the interpretation of biostratigraphical data in the last decades. Moreover, there are articles in which the mathematical interpretations are presented as the next step in the development of biostratigraphy. I find it hard to agree with this perspective and the term parabiocorrelations is herein proposed to accommodate the mathematical methods that are closer to mathematics rather than the natural sciences. This separation is considered most useful in providing a correct guidance to those who begin the study of biostratigraphy and microbiostratigraphy.

A new perspective on microbiostratigraphy that comes with a wide synthesis of data from the vast array of microfossil groups with biostratigraphical uses is expected to emerge in conjunction with conceptual novelties. Three directions of further development are prefigured herein: microfossil orthostratigraphy, integrated biozonations and calibrated biozonations. Not all of them are complete novelties; some were partially developed in the past, but not at a large scale. Furthermore, the suitability of each of them was not assessed for the whole array of microfossil groups. However, each of them has the potential to be developed in an independent work at the size of the present one, and they represent distinct directions of development for the future.

The numerical (absolute) ages throughout this textbook are calibrated to the framework of the Geological Time Scale 2004 (Gradstein et al. 2004). I found this framework compatible not only with the present textbook but also with the sequels that will follow and have it as a fundament.

Most of the illustrated microfossils in this work were used in the past, especially in works on the biozonations of certain stratigraphical intervals. They are included herein under the auspices of fair dealing or fair practice. For each of them I have provided a complete citation of the origin and copyright owner in the respective caption, together with a complete citation in the list of references. Besides the scientific content each of these illustrations carries, I also regard them as a form of acknowledgement for the high-quality work of the respective scientists who brought them into the public domain in the first place. In case the authors and/or publishers of the original work would like them removed, then I will do it so in the second edition of this work.

SECTION A –

HISTORICAL DEVELOPMENT AND BASIC CONCEPTS

CHAPTER 1

TOWARDS MICROFOSSIL BIOSTRATIGRAPHY – A HISTORICAL ACCOUNT

There is not one simple definition for biostratigraphy. It is widely accepted amongst scientists that biostratigraphy consists of a series of methodologies derived from the study of the fossil record. These include, but are not restricted to, the recognition of patterns determined by evolutionary changes, colonization and abandonment of certain ecological niches, distribution patterns related to sea level changes, different paleoecological factors, and climatic fluctuations. The obtained results are primarily used to recognize a succession of events in the fossil record that can be further used in fundamental and/or applied studies. In this context, the biostratigraphical studies should be regarded in general as synthesis studies, which are based on data provided by different subdisciplines of geology.

Biostratigraphy is a branch of stratigraphy and differs from the other components of stratigraphy (e.g., lithostratigraphy, magnetostratigraphy, physical event stratigraphy, cyclostratigraphy and pedostratigraphy) by the fact that the markers used in the study of the succession of events in the Earth's history are those recognized in the fossil record. The bioevents recognized in the succession of strata can be further used for correlation; the type of correlation in which the markers are provided only by the fossil record is termed biocorrelation. High-resolution modern stratigraphical frameworks in general use data from several branches of stratigraphy, with biostratigraphy representing only a part of them.

The fossil record covers most of the Earth's history, i.e. 4.6 billion years. The oldest fossil debris are stromatolite structures from the Isua Formation of Greenland (EU, Denmark), for which an age of circa 3.7 billion years is calculated (Nutman et al. 2016). Both macrofossils and microfossils are frequently used for the characterization of different rocks of the Neoproterozoic age, but the data from the fossil record can be effectively used in biostratigraphy only above the boundary between the eonothems Proterozoic and Phanerozoic. That biostratigraphy is one of the most useful and accurate methods used in stratigraphy is demonstrated by the in-use geological time scale, which presents the highest number of subdivisions within the Phanerozoic Eonothem that encompasses a time interval of circa 542 million years. In contrast, only a small number of biostratigraphical units are defined within the Archaean and Proterozoic Eonothems that together encompass a time interval of circa 3.5 billion years (Fig. 1). Despite the considerable efforts that were made in the last half century towards the development of magnetostratigraphy, cyclostratigraphy and chemostratigraphy especially, the Phanerozoic subdivisions are mostly defined with the aid of biostratigraphical markers.

Biostratigraphy is closely related to paleontology, and high-resolution biostratigraphical studies depend on the use of accurate classification frameworks and variability assessments of all of the encountered taxa. The connection between biostratigraphy and paleontology is so close that it is possible to describe biostratigraphy as a paleontology-related science or the paleontology-derived branch of stratigraphy. Other branches of geology with which biostratigraphy is closely related are paleobiogeography and paleoecology, which study, respectively, the fossil distribution in space and time as part of bioprovinces and the relationships between ancient organisms and surrounding organic and inorganic environments.

Biostratigraphy has two methodological components through which it advances, and the two also represent the goals for every study in this branch of stratigraphy: biozonation and biocorrelation. Biozonation represents the subdivision of a succession of layers and bodies of rocks into biostratigraphical units based on data from the fossil record. Biocorrelation represents that component of biostratigraphical correlation that uses the bioevent equivalence from two or more sections (e.g., outcrops, wells, etc.) in recognizing coeval features in the rock and fossil record. The term biozonation occurs frequently in literature in the shortened form of "zonation"; this term has a broader meaning and is used across the different branches of stratigraphy.

One definition that I found useful in practical teaching, especially in courses for non-major students, is that biostratigraphy represents the study of the fossil distribution in space and time. Such a definition allows a direct follow-up discussion on the relationships between biostratigraphy on the one side and paleobiogeography and paleoecology on the other. Despite its ambiguity, which is evident for a specialist, such a simple definition has its advantages as it points out to the beginner in the study of this field the basic procedure in this branch of geology: to recognize the position in space and time of the fossils. Surprisingly or not, this brings us to the earliest reports of fossils, which came long before the birth of biostratigraphy.

1.1 Precursor studies; or before the birth of biostratigraphy

Biostratigraphy is probably the traditional branch of geology with the most abrupt beginning. So abrupt was its birth, even today many scientists and historians of science do not acknowledge any significant development before the contributions of Sir William Smith in the early nineteenth century, which are almost unanimously accepted as representing the birth of biostratigraphy.

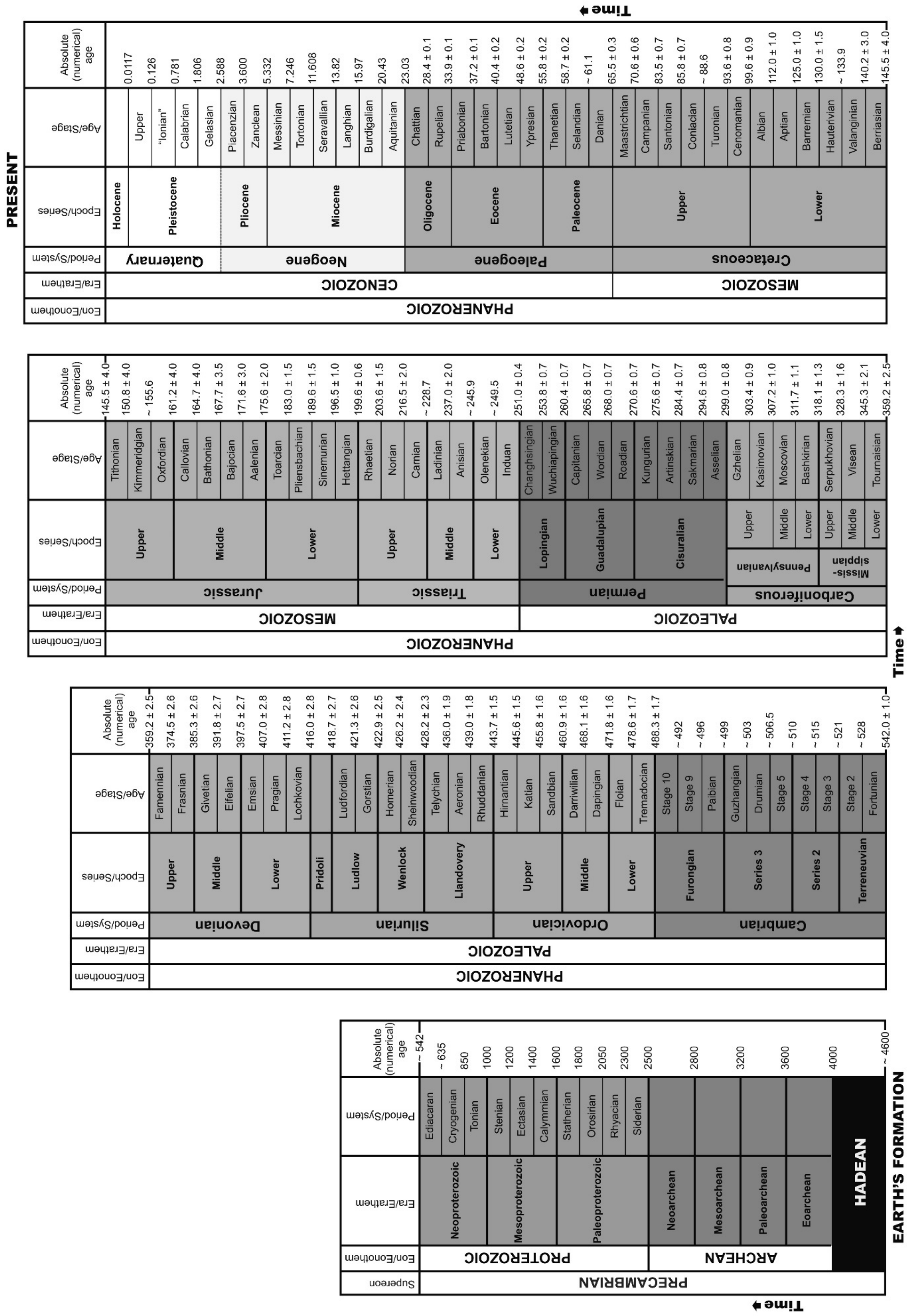

Fig. 1. Geological time scale (after Gradstein et al. 2004, with modifications); previously illustrated by Georgescu (2018, p. 7).

Throughout Antiquity, fossils were considered vestiges of ancient life forms, just as we consider them today. The explanations for their occurrences in the modern continental areas were basically related to the concept of the diminishing of the sea, which was widely accepted in Ancient Greece. The correct interpretation of the nature of fossils has led some historians of science to call Xenophanes of Colophon (~570 – ~475 B.C.), who reported the first fossils from Malta, Sicily and the Adriatic Sea, the earliest known paleontologist (Pease 1942). A different perspective was given by Lucius Apuleius (~125 – ~180 A.D.), who considered that the fossilized fishes in the mountains of Gaetulia of northern Africa (modern Algeria) represented occurrences resulting from the flooding event which was known in Greek mythology as the Deucalion's Flood. These early writings show beyond doubt that the Antiquity scholars of the Greek Rationalism period were concerned with the causes that led to the occurrences of fossils of plants and animals in zones actually situated far away from their original environments. This was a time when science itself was at its beginning and occurrences of fossils were associated with a process or event rather than a rock type. At that time there was no knowledge of the vastness of geological time and the birth of modern geology was circa two millennia in the future.

Despite the lack of accurate knowledge, progress continued, but at a slow pace. Towards the end of Antiquity, Isidore of Seville (~560 – 636) noted in *Etymologies* that humans witnessed not one, but three flood events of which the biblical flood was only the first one. It was the first time that flooding events were interpreted as recurrent causes for the inland occurrences of fossils. Six years before the death of Isidore of Seville, the year 630 is considered that in which Europe collapsed into the Dark Ages. Nevertheless, the idea of recurrent transgressions of the sea over continental regions persisted and reoccurred in a manuscript written in 1025 and preserved in the Sultan Fatih Library in Istanbul. The manuscript was written by the famous scholar Al-Biruni, who is also known by the Latinized name of Alberonius (Prostov 1942).

The slow pace of development continued in the Renaissance times, and the true nature of fossils as vestiges of ancient life forms survived the Dark Ages (Albertus Magnus fide Lang 1931, Ristoro d'Arezzo fide Narducci 1859, Jean Sire de Joinville fide Wedgwood 1906, Leonardo da Vinci fide MacCurdy 1955, Alessandri ab Alessandro 1565). Then everything started to change with the formulation of the principles of layer formation (Steno 1669). The principle of layer superposition, according to which in a succession of undisturbed layers the oldest one is situated at the base of the successions and younger layers gradually occupy a higher position in the succession, opened the door towards the birth of stratigraphy. The relative ages of the layers with respect to each other within a succession could be recognized, but the correlation of the layers that occurred in distant sections and between which there was no continuity was still a problem that awaited a solution. Steno's principle of layer superposition marked a revolution in the methodology of making field observations on the stratigraphical successions of layers. Afterwards, scientists started making detailed notes on the mineralogical and lithological characteristics of the layers occurring in different successions, resulting in an increase in the accuracy of the data to be used in lithological correlation. This type of correlation is the oldest methodology through which the stratigraphical position of the layers could be compared, and remained the only one for nearly two hundred years after the publication of Steno's main scientific work, known mostly by its shortened name of *Prodromus* (Steno 1669).

The development led to the highly accurate description of stratigraphical successions and the use of lithological correlation. Gradual improvements in both directions are obvious in works published in the circa 150 years after Steno (e.g., Plot 1677, Morton 1712, Woodward 1728, Martin 1809, Watson 1811, etc.). One common feature that occurred in all these studies is that fossils were still considered vestiges of ancient life forms and not shapes and forms that occur accidentally within different layers of rocks. In parallel, fossil classifications and works of a monographic character were developed more frequently towards the end of the eighteenth century. In addition, the original environment of the fossils became a topic of actuality and two categories of fossils were recognized according to their provenance, namely littoral and pelagic fossils, with the two categories including fossilized organic debris that originally lived in shallow and deep waters respectively (Woodward 1728). One cannot pass without noting that the recognition of these two categories of fossils is an excellent *avant la lettre* example of the use of the principle of actualism that would become well-established amongst geologists towards the end of the eighteenth century. Another step forward realized during this period is represented by the use of fossils in the description of certain strata. One such example is the use of the gastropod *Cyrena* in the description of one layer from a succession reported from Languedoc in France (de Sauvages 1752). The fossil descriptions and occurrences within one stratigraphical succession were so accurate that based on the original reports it was possible to recognize the reworked fossils and their source in a subsequent review nearly 250 years later (Sissingh 2012).

The eighteenth century was a period in which the general perspective on the Earth's history changed. The many works dealing with these general changes and life history on Earth led to new and interesting discoveries and interpretations, without one of which biostratigraphy could not have started: this is the concept of species extinction. The idea of the extinction of species occurs for the first time in the middle part of the century in the work of a mathematician and philosopher who is also known for studying for the first time the hereditary propagation of characters in the case of humans with polydactyly (de Mapertuis 1751, Glass 1947). According to his perspective, the life changes on Earth happened through two antagonistic processes: spontaneous generation and extinction. The essay "Thoughts on the Interpretation of Nature", meanwhile, discussed how species history stretched over a long period of time (Diderot 1751). Subsequent authors interpreted these works as either trying to adapt philosophical ideas to the new developments in science or as representing true proto-evolutionary thinking (Dieckermann 1955, Crocker 1968). The scientific arguments to demonstrate species extinctions were brought neither by de Mapertuis nor Diderot. Species extinction was accepted later by Georges Louis Leclerc, Compte de Buffon (1707–1788), who noted that some species known as fossils are not known as well as living species. This idea occurs in the monumental *The Epochs of Nature*, one of the most influential works of geology during the second half of the eighteenth century (de Buffon 1780).

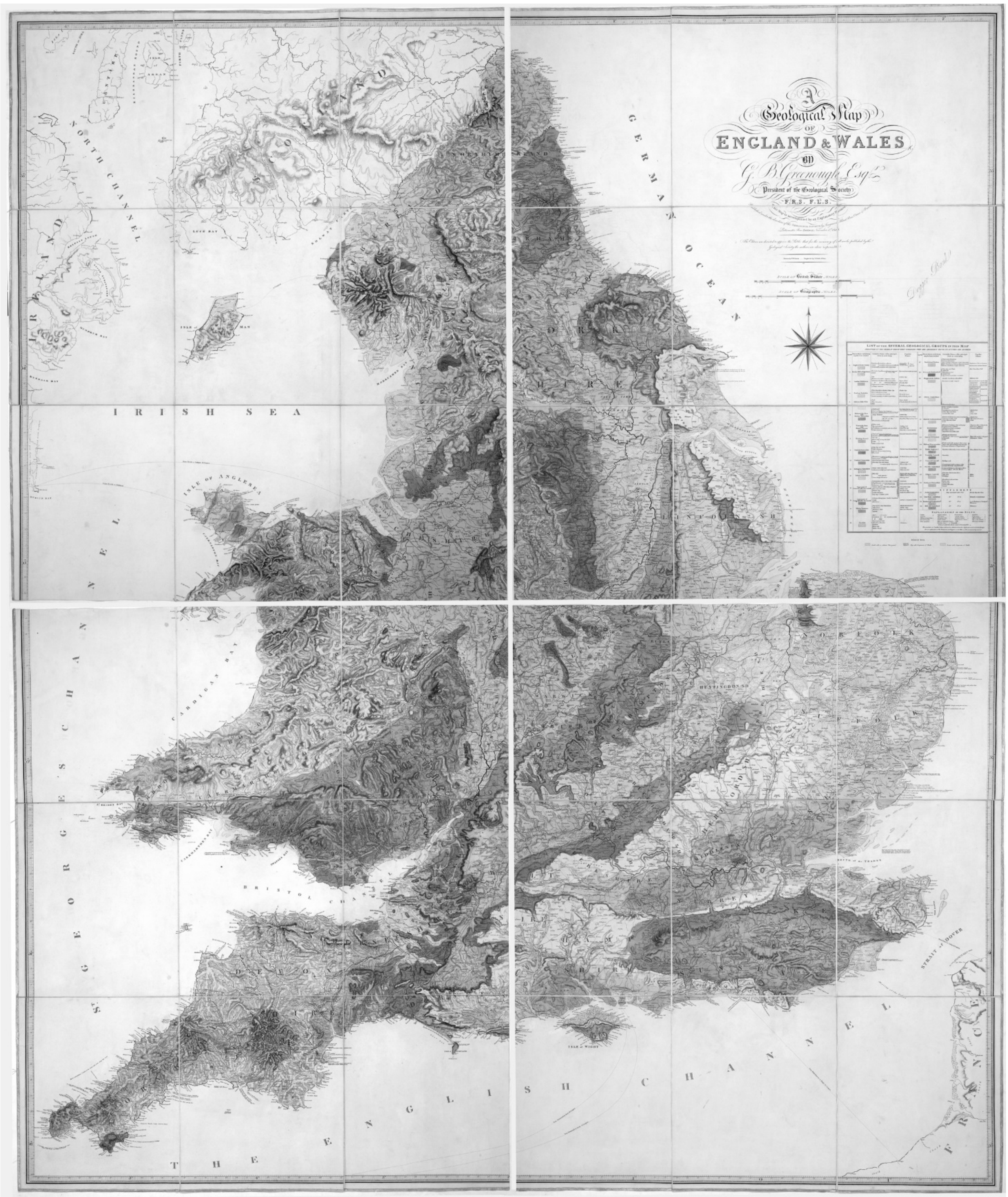

Fig. 2. Geological map of England, Wales and southern part of Scotland (Smith 1815). Courtesy of the National Museum of Wales, published with permission.

The year 1799 is another milestone in the development of stratigraphy. It is the year that Alexander von Humboldt (1769–1859) described and recognized the first stratigraphical unit that today is formalized at system level: the Jurassic. This system was originally termed "Jura-kalkstein", and the name was used for the first time by Alexander von Humboldt a few years earlier in 1792 (Sissingh 2012). The observation data for the description of the Jurassic were collected from southern Germany and Switzerland; subsequent studies showed that according to the original definition it encompassed only the middle and upper parts of the Jurassic System according to the modern acceptation of the term. Shortly after its recognition in 1799, the Jurassic was further subdivided into the Lias, Dogger and Malm intervels, then into stages, and finally into zones. This process represented the tip of the lance in the advance of stratigraphy in the nineteenth century. Moreover, following the definition of the Jurassic System, other systems of the geological time scale started to be described, and in circa 80 years all the systems of the Paleozoic and Mesozoic Erathems were recognized. But all these developments from the nineteenth century would not have been possible without the use of the fossil content of the respective successions of layers, and this required the development of a methodology for such use: biostratigraphy.

1.2 Sir William Smith and the emergence of biostratigraphy

There is near unanimity among geologists today that the beginnings of biostratigraphy as a distinct branch of stratigraphy are to be found in the works of a civil engineer who produced the first geological map of England, Wales and the southern part of Scotland at the beginning of the nineteenth century: Sir William Smith (1769–1839). This was the first geological map realized at the scale of one whole country (Fig. 2). Not being a geologist, Sir William Smith heard of Steno's influential *Prodromus* of 1669 only late in his life (Hancock 1977); therefore, in his unique enterprise he had to review critically all the concepts used in the study of rocks and fossils from the very beginning up to the birth of the new branch of stratigraphy (Fig. 3). Of great help in understanding the succession of events that led Sir William Smith to the development of biostratigraphy is the biographic work by one of his nephews, which was published five years after the death of author of the map that would shape so much of the geological practice and thinking in the decades to come (Phillips 1844).

Fig. 3. Some of the original fossils used by Sir William Smith in drawing the first geological map at the scale of one country. Courtesy of the National Museum of Wales, published with permission.

The scientific advances made by Sir William Smith happened over a period of more than two decades, and the account given in the above-mentioned biographical work is followed herein. The first step was in the form of collaboration with another researcher without a geological background, namely Rev. Benjamin Richardson. As further noted by the biographer, the two complimented each other and while Sir William Smith "… had no knowledge of the laws of stratification and the connection between the forms of organic life and the order of superposition of the strata", Rev. Benjamin Richardson "… had very little knowledge on the true nature of these organic forms, and their exact relation to analogous living types" (Phillips 1844, p. 28). There are short notes on this idea by Sir William Smith written between 1796 and 1798, which demonstrate that the methodology was crystallized at the conceptual level well before its publication. The first version of the stratigraphical succession of the layers from the surroundings of Bath was provided in the form of a table dictated by Sir William Smith to Rev. Benjamin Richardson, and this happened in the house of Rev. Joseph Townsend, another personality with an interest in the subject but without a geological background (Phillips 1844, p. 29) (Fig. 4). It was the year 1799, the same year in which in Prussia Alexander von Humboldt recognized the Jura–kalkstein by lithological characteristics and through the use of the Principle of Superposition.

Strata.	Thickness.	Springs.	Fossils, Petrifactions, &c. &c.	Descriptive Characters and Situations.
1. Chalk	300	Intermitting on the Downs	Echinites, pyrites, mytilites, dentalia, funnel-shaped corals and madrepores, nautilites, strombites, cochliæ, ostreæ, serpulæ	Strata of Silex, imbedded.
2. Sand	70			The fertile vales intersecting Salisbury Plain and the Downs.
3. Clay	30	Between the Black Dog and Berkeley.		
4. Sand and Stone	30			Imbedded is a thin stratum of calcareous grit. The stones flat, smooth, and rounded at the edges.
5. Clay	15	Hinton, Norton, Woolverton, Bradford Leigh.		
6. Forest Marble	10		A mass of anomiæ and high-waved cockles, with calcareous cement	The cover of the upper bed of freestone, or oolite.
7. Freestone	60		Scarcely any fossils besides the coral	Oolite, resting on a thin bed of coral.—Prior Park, Southstoke, Twinny, Winsley, Farley Castle, Westwood, Berfield, Conkwell, Monkton Farley, Coldhorn, Marshfield, Coldashton.
8. Blue Clay	6	Above Bath.		
9. Yellow Clay	8			
10. Fuller's Earth	6			Visible at a distance, by the slips on the declivities of the hills round Bath.
11. Bastard ditto, and Sundries	80		Striated cardia, mytilites, anomiæ, pundibs and duck-muscles.	
12. Freestone	30		Top-covering anomiæ with calcareous cement, strombites, ammonites, nautilites, cochliæ hippocephaloides, fibrous shell resembling amianth, cardia, prickly cockle, mytilites, lower stratum of coral, large scollop, nidus of the muscle with its cables	Lincombe, Devonshire Buildings, Englishcombe, Englishbatch, Wilmerton, Dunkerton, Coomhay, Monkton Coombe, Wellow, Mitford, Stoke, Freshford, Claverton, Bathford, Batheaston and Hampton, Charlcombe, Swanswick, Tadwick, Langridge.
13. Sand	30		Ammonites, belemnites	Sand burs.
14. Marl Blue	40	Round Bath.	Pectenites, belemnites, gryphites, high-waved cockles	Ochre balls.—Mineral springs of Lincombe, Middle Hall, Cheltenham.
15. Lias Blue	25		Same as the marl with nautilites, ammonites, dentalia, and fragments of the enchrini	The fertile marl lands of Somersetshire. Twerton, Newton, Preston, Clutton, Stanton Prior, Timsbury, Paulton, Marksbury, Farmborough, Corston, Hunstreet, Burnet, Keynsham, Whitchurch, Salford, Kelston, Weston, Pucklechurch, Queencharlton, Norton-malreward, Knowle, Charlton, Kilmersdon, Babington.
16. Ditto White	15			
17. Marl Stone, Indigo and Black Marl	15		Pyrites and ochre	A rich manure.
18. Red-ground	180		No fossil known	Pits of riddle. Beneath this bed no fossil, shells, or animal remains are found: above it no vegetable impressions. The waters of this stratum petrify in the trunks which convey it, so as to fill them, in about fifteen years, with red watricle, which takes a fine polish.—Highlittleton.
19. Millstone.				
20. Pennant Street			Impressions of unknown plants resembling equisetum.	
21. Grays				Fragments of coal and iron nodules.—Hanham, Brislington, Mangotsfield, Downend, Winterbourn, Forest of Dean, Pensford, Publow, Chelwood, Cumptondando, Hallatrow near Stratford-on-Avon, Stonebench on the Severn, four miles from Gloucester.
22. Cliff			Impressions of ferns, olive, stellate plants, threnax-parviflora, or dwarf fan-palm of Jamaica	Stourbridge, or fire-clay.
23. Coal				

Fig. 4. The succession of layers of rock and embedded fossils from the surroundings of the city of Bath as considered by Sir William Smith before 1815 (from Phillips 1844, p. 30 – partial).

Three works by Sir William Smith contain his most important contributions and represent the beginnings of biostratigraphy. The earliest one, published in 1815, is that in which the geological map was shown: *A Memoir to the Map and Delineation of the Strata of England, Wales with part of Scotland*. This work focused on the layer descriptions and occurrences, and the methodology of representation on the map. Smith's next work, the shortened title of which is *Strata Identified by Organized Fossils*, went into more detail on different elements of the previous work. The first two parts of this work (which remained unfinished) were published in 1816, with a third part coming out in 1817 (Hancock 1977). The third and last of Smith's major works was published in 1817 and is mostly known through the shortened title of *Stratigraphical System of Organized Fossils*. Most of this work consists of descriptions of the fossils used in the construction of the map. The introductory part of this work is particularly important for it shows beyond doubt three major characteristics of the methodology developed in the succession of three works: practicality, empiricism and predictability. It appears evident that the author was aware of the importance of his scientific advances: "The result of my labours is a settled plan for doing this, and therefore the identification of Strata by the help of organized Fossils, becomes one of the most important modern discoveries in Geology. It enables the Geologist clearly to distinguish one Stratum from another in Britain, and also trace their connection with the same Strata on the continent" (Smith 1817, p. vii). The fact that this method was indeed one of the most important geological discoveries of the early nineteenth century was demonstrated in excess in the next two centuries.

An extraordinarily accurate account on the importance of the works of Sir William Smith was given circa 160 years afterwards: "The importance of Smith's work is greater than that of any subsequent contributor to the theory of our science. His lack of formal education and his very limited reading of earlier authors meant that he was remarkably unbiased by previous ideas. His approach was completely empirical, and he never tried to draw conclusions beyond the evidence he had found himself, let alone to speculate why each stratum had its own peculiar fossils. This work is completely free from grandiloquent attempts at a unitary theory of all geology, and equally free from any interaction with theology" (Hancock 1977, p. 5). I would add that the whole scientific work of Sir William Smith is extremely rich in something else, namely crucial concepts in biostratigraphy that were discovered, used and left for further definition and detailed study: species first occurrence, species extinction, stratigraphical range, absence of taxa repeatability in the fossil record, biocorrelation, fossil assemblages, etc. All of these were described and studied in detail in the years to come and are major components of modern biostratigraphy. In addition, these contributions had another effect: the accurate perspective of the fossil record of the layers occurring in different stratigraphical successions opened the path towards the development of a relevant paleontological input for the Theory of Evolution.

The newly invented method would be termed biostratigraphy at the beginning of the twentieth century, nearly one century after it emerged as a distinct branch of stratigraphy (Dollo 1910). It contributed decisively towards many subsequent discoveries in geology, and especially stratigraphy. The legacy of Sir William Smith is colossal and received almost immediate recognition in the scientific society: no less than seven stratigraphical units of System rank, which we actually acknowledge in the geological time scale, were recognized in his lifetime and based on his methodology. They are the Carboniferous and Cretaceous in 1822, Quaternary in 1829, Triassic in 1834, Cambrian and Silurian in 1835, and Devonian in 1839. Furthermore, all these accomplishments show that Sir William Smith was probably one of the most innovative scientists in the history of geology if we take into account how little was known in the field before his contributions, and how fast the subsequent advances happened with the use of the new methodology represented by the combination of the rock and fossil records.

1.3 Steps towards an independent fossil-based methodology

With the method set in place things started to advance fast and another stream in biostratigraphical practice was soon defined. This new stream resembled the methodology developed by Sir William Smith by following the succession of fossils, but fundamentally differed from it by not having the species stratigraphical ranges tied to the lithology of the layers in which they occurred.

It started at a time when rocks of the geological scale were subdivided into Primary, Secondary, Tertiary and Quaternary, with the subdivision of the Tertiary and Quaternary rock successions into three units of lower rank based on the fossil content and irrespective of the lithology (Deshayes 1830, 1831). The three subdivisions were defined according to the resemblances of their fossil content with the modern (living) organisms. Such large-scale generalization required from the start a separation between fossil and rock records because the data used in comparing the fossil record and modern organisms were collected from a large number of sections that showed a considerable lithological variability. The three subdivisions were simply named in stratigraphical order as the first, second and third units, but were not assigned proper names. About the same time, a similar methodology was developed based on the Secondary and Tertiary fossils of Italy (Bronn 1831).

A different trend was to define stratigraphical units based on the fossil record and independently from lithology at a rank higher than that of system. This methodology resulted in the definition of the Palaeozoic, Mesozoic and Kainozoic (Phillips 1840, 1841). These three units are used even today in the geological time scale as Paleozoic, Mesozoic and Cenozoic and are formalized at the erathem level.

Such steps forward showed without equivocation that the construction of biostratigraphical frameworks based on the representatives of the fossil record and without any connection to lithology was possible. But to define the new methodology it was necessary to reach the level of a fundamental unit in the same way in which the Smithian biostratigraphy that connected the rock and fossil records reached the level of formation, which even today represents the fundamental unit in lithostratigraphy.

The subdivision of systems into narrower stratigraphical units marked the next step in the development of biostratigraphy. The pioneering work here is that for the Jurassic System, which is considered a classic exemple of high-quality stratigraphical research. The Jurassic System was subdivided into Schwarzer Jura (Lias), Brauner Jura (Dogger) and Weisser Jura (Malm), with the three subdivisions defined according to lithology, rock color and fossil content (von Buch 1837); the three units are recognized today at epoch level as the Lower, Middle and Upper Jurassic. These units were further subdivided into narrower units based on the Smithian principle of combining the data from the rock and fossil records: six units for Lias, six for Dogger and seven for Malm (Quenstedt 1846). They had a relatively limited use and this advance was overshadowed by another major development in stratigraphy: the definition of stages.

Stages started to be defined by Alcide Desalines d'Orbigny in a series of works published during a ten-year period (1842–1852); herein, the last-published title in this series is taken as the reference (d'Orbigny 1852). The whole succession of stratigraphical units known at that time was taken into consideration by A.D. d'Orbigny, but the concept of stages as subdivisions of systems is best developed in the case of the Jurassic and Cretaceous Systems (Fig. 5). The Jurassic was subdivided into ten stages of which eight are still in use today, whereas the Cretaceous was subdivided into seven stages. The uppermost stage of the Cretaceous System was named Danian, and it forms the lowermost part of the Paleogene System in the modern geological time scale. The stages were defined using basically the Smithian methodology, with data of a lithological nature used in correlation with data provided by the fossil record, and with the boundaries recognized with the aid of unconformities (discordances). The fossil record of each stage was carefully studied and used in the characterization of each stage, but it alone was not used in the definition of any of the recognized stages. One aspect of the stratigraphical works by A.D. d'Orbigny that puzzled some historians of science was the fact that he used frequently the word "chronology", and this was interpreted as an indication of a shift towards the "time-stratigraphy". A careful study of A.D. d'Orbigny's works shows however that the term "chronology" was just used instead of "succession", and that the methodology for either a "time-stratigraphy" or a fossil-based biostratigraphy independent of the rock succession was not developed yet.

The succession of discoveries and scientific advances that started with Alexander von Humboldt and lasted till A.D. d'Orbigny led to the definition of a portion of the stratigraphical unit hierarchy that we still use today, circa 150 years afterwards. This succession is represented in ascending order by the stage–series–system sequence.

ROCHES SÉDIMENTAIRES STRATIFIÉES.		ROCHES PLUTONIQUES NON STRATIFIÉES.
PÉRIODES OU TERRAINS.	ÉTAGES.	
6e PÉRIODE. CONTEMPORAINE	ÉPOQUE ACTUELLE............	Amphigénite. Péridolite. Basalte. Basanite. Dolérite. Trachyte. Leucostite. Phonolite. Mimosite.
5e PÉRIODE. TERTIAIRE.	27. Subapennin.............. 26. Falunien................. 25. Parisien................ 24. Suessonien............	
4e PÉRIODE. CRÉTACÉE.	23. Danien.................. 22. Sénonien................. 21. Turonien................. 20. Cénomanien.............. 19. Albien................... 18. Aptien................... 17. Néocomien..............	Minosite. Porphyres pyroxéniques. Basalte?
3e PÉRIODE. JURASSIQUE.	16. Portlandien............... 15. Kimméridgien............ 14. Corallien................ 13. Oxfordien............... 12. Callovien................ 11. Bathonien............... 10. Bajocien................. 9. Toarcien.................. 8. Liasien.................. 7. Sinémurien..............	Porphyres pyroxéniques. Granit? Syénite?
2e PÉRIODE. TRIASIQUE.	6. Saliférien................ 5. Conchylien..............	Porphyres argiloïdes. Lherzolite. Granit? Syénite?
1re PÉRIODE. PALÉOZOIQUE.	4. Permien.................. 3. Carboniférien............. 2. Devonien................. 1. Silurien. { Supérieur....... Inférieur........	Porphyre pétrosiliceux. Ophite. Aphanite. Ophitone. Porphyre protoginique. Porphyre dioritique. Porphyre pyroméride. Porphyre syénitique. Syénite. Granit.
AZOIQUE.......	Groupe des Talcites.......... Groupe des Micacites......... Groupe des Gneiss...........	Serpentine. Diorite. Syénite. Armophantite. Pegmatite. Granit.

Fig. 5. The succession of stratigraphical units according with A.D. d'Orbigny (1852, p. 263). Most of the Jurassic and Cretaceous stages are in use today.

1.4 Development of the independent fossil-based stratigraphy

The parallel subdivision of the Jurassic System into stages based on Smithian principles, namely with the fossil content and lithology of the strata in which they occur combined, reached its limit towards the middle of the nineteenth century. A fresh breakthrough was necessary in order to increase further the biostratigraphical resolution; this happened with the work titled *Die Juraformation Englands, Frankreichs und des südwestlichen Deutschlands* by Carl Albert Oppel (1831–1865) that was published in 1858.

Bett des Amm. spinatus.	Zone des *Amm. spinatus.*	Bel. breviformis. „ crassus Ziet. Rhynch. quinqueplicata. Ter. subdigona. „ subovoides. „ punctata. Spirif. Haueri. Chemnitzia nuda. Lima Hermanni Ziet. Inoceramus substriatus.* Pecten aequivalvis.* Gryphaea cymbium.* Rhynch. amalthei.* (Pleurotom. anglica.) (Lyonsia unioides.)
Oberes Margaritatus-bett. **Margaritatusbett.**	Obere Zone des *Amm. margaritatus.*	Amm. Zetes. Bel. compressus. „ lagenaeformis. Chemnitzia undulata. Turbo paludinaeformis. Pleurotomaria rotundata. Leda acuminata. „ complanata. Cypricardia caudata. Pinna Moorei. Pecten Philenor. „ sublaevis. Cardium truncatum. Pentacrinus laevis. Rhynch. scalpellum. Spirifer Tessoni. Amm. Normanianus* (Amm. Henleyi.)
Unteres Margaritatus-bett.	Untere Zone des *Amm. margaritatus.*	Amm. globosus. „ fimbriatus.* Bel. umbilicatus.* „ longissimus.* Avicula sexcostata.* (Bel. elongatus.)
Davöibett.	Zone des *Amm. Davöi.*	Amm. capricornus. Pleurotomaria heliciformis. Inoceramus ventricosus. Cidaris Edwardsi. Palaeocoma Milleri. Pentacrinus subangularis.
Ibexbett.	Zone des *Amm. ibex.*	Amm. bipunctatus. „ Maugenesti. „ Actaeon. „ Centaurus. „ Loscombi.* Rhynchonella rimosa.*
Jamesoni-bett.	Zone des *Amm. Jamesoni.*	Hauptlager der Terebratula numismalis. Amm. brevispina, pettos. „ Masseanus, Lynx. „ arietiformis, Zieteni. „ Taylori, submuticus. Mytilus numismalis. (Gryphaea obliqua.) Pinna folium. Astarte arealis. Opis Carusensis. Rhynch. Thalia.
(Armatusbett ?)	*Amm. armatus?*	Pholadomya decorata. Rhynchonella tetraedra, Quenst. Spirifer Münsteri.
Raricostatusbett.	Unterer Lias.	

Fig. 6. Example of ammonite-based biostratigraphical framework developed for the Liassic (Lower Jurassic) by C.A. Oppel; the figure illustrates a portion of the middle Liassic, which represents the Pliensbachian Stage according with the modern acceptation (from Oppel 1858, p. 117 – partial). The ammonite zonation is in use today.

The most important novelty of this work was represented by the complete separation of the fossil record from the rock record. Rocks were used to describe and characterize wherever possible the stratigraphical units described with the aid of fossils. The main subdivisions of the Jurassic System were also taken into consideration (von Buch 1837, Quenstedt 1846, d'Orbigny 1852), but the conceptual advance was represented by the definition of narrower units called zones based solely on the fossil content.

Practically all the fossils encountered in the respective stratas were used in the definition of the zones. Most of them were invertebrates (e.g., cephalopods, bivalves, brachiopods, echinoderms, etc.). The dominant group in terms of frequency and importance was represented by cephalopods, chiefly ammonites. By this, C.A. Oppel recognized for the first time the paramount role of ammonites in Jurassic biostratigraphy; this idea about the role of ammonites in Jurassic biostratigraphy has continued into modern times, with the representatives of this group forming the biostratigraphical framework of reference for Jurassic biostratigraphy. Twenty-eight zones were defined for a stratigraphical interval that encompasses most of the Jurassic System, namely the Hettangian-Kimmeridgian stratigraphical interval, according with the modern stratigraphical subdivisions. Each zone was named with the aid of one species, a methodology that in time would result in the development of the concept of index or marker species; the species with which the zones were named were selected from amongst those occurring in the respective zone and considered significant for biostratigraphical purposes by the author.

Zone boundaries received particular attention in this study, and C.A. Oppel defined each of them with the aid of two or more (mostly more) taxa. Such a new methodology differed sharply from the assemblages considered by Sir William Smith in the definition of the assemblage zones, where boundaries were not defined with fossil taxa but rather lithological features. These types of biostratigraphical units defined with the aid of an assemblage of taxa and lower and upper boundaries defined with two or more taxa are known today as Oppel zones. Moreover, the priority of the fossil record over lithology is apparent in the way in which the layers of rocks were named. For example, the layers corresponding to the *Ammonites ibex* Zone were named "*ibex* bett", which literally translates as the "bed (layer) with *ibex*". Therefore, C.A. Oppel renounced in the definition of the layers of rocks the informal lithological terms. Another practice developed by C.A. Oppel is represented by the subdivision of some zones, which in most cases is informal; one such example is the *Ammonites margaritatus* Zone, which is subdivided into lower and upper subzones.

Another interesting aspect of this breakthrough work by C.A. Oppel was the extraordinarily high level of accuracy of the biostratigraphical framework. This is best illustrated in the case of the Sinemurian–Pliensbachian stratigraphical interval, where ten zones were recognized (Oppel 1858). Nine of them are still in use and the Pliensbachian biostratigraphy developed by C.A. Oppel, which also represents the orthostratigraphical framework, is completely accepted today (Fig. 6).

The revolution realized by C.A. Oppel marked the complete separation of biostratigraphy from lithostratigraphy. One succession of layers was traditionally considered as reflecting a succession of events, which were represented by the respective layer formations. Such an interpretation was supported by one of Steno's principles of layer formation, which postulated that at the time of the formation of one layer, only fluid was above it. As a result, the "time-rock stratigraphy" was used for the Smithian methodology in which rock and fossil records were considered together. However, time is immaterial and cannot be found in the rocks but is inferred from the chronological events documented in the rock and fossil record. The separation of the succession of events provided by the fossil record from those of the rock record by C.A. Oppel resulted in a different methodology, which was named afterwards "time-stratigraphy". In this case the use of the concept of time was misleading for it is applied to a methodology that developed at least a century before we could calculate with any level of precision the numerical ages of the events in the Earth's history. Therefore, herein the use of the expression "fossil-based stratigraphy" instead of "time-stratigraphy" is preferred, with the mention that the stratigraphical units in fossil-based stratigraphy are not time units. The calculation of the numerical ages of different events and bioevents in the Earth's history is the topic of a distinct subdiscipline of geology, namely geochronology; the main method in geochronology is the study of stable isotopes.

One result of the separation between the fossil and rock records is represented by the increased accuracy in biocorrelation, which is most apparent in the correlation of the different facies formed within a sedimentary basin. The concept of facies was introduced as a result of the realization that the lithological and paleontological characteristics of one layer were determined by the position within the sedimentary basin at the time of formation of the respective layers (Gressly 1838). Therefore, by using the data of the fossil record independently from those from the rock record it became possible to correlate coeval facies within a sedimentary basin and recognize lithological variability at a higher level of accuracy. Such applications of Oppelian biostratigraphy are extensively used in modern biostratigraphical practice in fundamental and industry-related studies. Moreover, the very existence of such applications represents one of the keys to further developments in biostratigraphy.

1.5 First large-scale use of biostratigraphy

Biostratigraphy was born as a combination of fundamental and applied science. It is fundamental because it brings crucial contributions to the study of geological time, the evolution of life on Earth, continent position and movement in time, etc. The practical aspects of biostratigraphy are mostly seen in its applications in industry, where it plays a paramount role in recognizing layer arrangemens on the surface and in the subsurface, the morphology of the ancient sedimentary basins and their changes through time, and changes in sedimentary paleoenvironments, etc.

The applicability and importance of the new methodology was quickly demonstrated. The beginnings of biostratigraphy can be recognized without doubt in the works of Sir William Smith in which the geological map of a whole country was produced for the first time. Subsequent advances at conceptual and practical levels through the definition of a fossil-based stratigraphy by C.A. Oppel allowed for accurate correlation between distant regions of the world if they contained a relevant fossil record. Practically, these scientific advances provided the methodology that would lead to the development of the first geological map of the world, which would be realized towards the end of the nineteenth century.

The crucial role of biostratigraphy has been acknowledged by geologists of different specialties since its development. The nineteenth century was the time when geological surveys from many countries started to be produced and then used in large-scale biostratigraphy studies to eventually produce geological maps. This process continues in present times at a higher level of detail.

1.6 A new challenge

The nineteenth century was a period of significant change and evolution in human society. Part of this process was generated by the continuation of what started during the industrial revolution. One of the events that epitomized the technological advances during the industrial revolution was the invention of the steam engine by James Watt (1736–1819) in the second half of the eighteenth century; by powering the engines in manufacturing factories, on ships and subsequently in the railway system, this invention changed the course of human history forever. Steam engines required coal to function and as a result the demand for this natural fuel gradually increased after the year 1775. But the steam engine was not the only one that required coal. At the beginning of the nineteenth century, and following almost two decades of experimentation, some larger cities in Europe and the United States started to implement the public gas illumination. In 1820, Paris became the first city that officially adopted this type of public illumination. The gas necessary for the new application was obtained through the gasification of coal; in principle this process involves mixing oxygen, steam and the gases produced by coal at high temperatures, without combustion, to produce synthesis gas, which is a fuel. This further increased the demand for coal in the nineteenth century, which reached the peak towards the end of this period. During this time, and shortly after its beginning as a distinct methodology, biostratigraphy proved helpful and efficient in the exploration for coal, especially in the subsurface. It contributed to the discovery of new sources of coal that were further exploited. Drawing geological maps at the surface and mapping mining galleries in the subsurface was realized especially with invertebrate taxa (mostly cephalopods, brachiopods and bivalves), plants and other groups of lesser importance. All these fossils are macroscopical and do not require in general the use of a microscope for study.

Another invention that in time led to the increase in the demand for coal in the nineteenth century was the internal combustion engine. The first patent for such an engine was issued in 1794 to Robert Street; the fuel for this prototype was turpentine, a type of oil that resulted from the distillation of modern trees, mostly conifers. This was followed by a series of improvements and other inventions that included the gas-fired internal combustion engine, atmospheric gas engine, four-cycle engine, two-stroke gasoline engine, etc. These developments culminated in the invention of the (Rudolf) Diesel engine in 1890s. The internal combustion engine made possible the appearance of cars, motorcycles and planes, and it improved considerably the efficiency of ships, as reflected in speed and navigability. Great inventors, engineers and industrialists contributed to this revolution and some of their names resonate even today; for example, the four-cycle engine was patented by G.W. Daimler (1834–1900) and W. Maybach (1846–1929), whereas the two-stroke gasoline-based engine was developed by W. Benz (1844–1929). Probably the key word at this point is that of "gasoline", a highly efficient fuel that would shortly be adopted worldwide and become of strategic importance. The internal combustion engine required a different type of natural resource, namely oil, and the natural gas with which the crude oil was frequently associated in subsurface reservoirs further increased its importance.

Discovering new reserves of crude oil and natural gas required considerable advances in technology and exploration methodology for they occurred in the subsurface at greater depths. One such technological advance for extracting the two substances was the rotary drilling method, which started in the 1860s and was implemented for hydrocarbon extraction in the 1890s. Rotary drilling enables the relatively fast cutting through layers of rocks with a drilling bit with blades or encrusted artificial diamonds attached. The drilling process requires a fluid or drilling mud that is circulated through the borehole and has two primary roles: it prevents the drill bit overheating and transports the detached rock chips from the borehole bottom to the surface. This brief description shows that the rocks are reduced to small-sized fragments in the course of the drilling process that can then be analyzed as they reach the surface in order to recognize the stratigraphical succession of the layers intersected by the borehole, as well as the characteristics of the layers. The process is destructive because the rocks, including macrofossils, are fragmented into such small pieces that in most cases they are beyond recognition. Therefore, the classical macrofossil-based biostratigraphy proved useless in the conditions imposed by the new technology. The solution to this problem was to start developing new biostratigraphical frameworks based on microfossils, which were far less affected by the drilling process.

1.7 Early uses of microfossils for biostratigraphical purposes

The first practical use of a taxon included in a group that was traditionally amongst those studied in the field of micropaleontology came shortly after the birth of biostratigraphy. The foraminiferal genus *Nummulites* was used to characterize some Eocene layers in northern Italy and the Paris Basin (Brogniart 1823). In this study, *Nummulites* was grouped together with the invertebrate macrofossil taxa. This can be explained by the average size of the representatives of the genus *Nummulites*, which are in general larger than one centimeter in diameter and therefore, can be recognized easily even without the use of a microscope. Due to such large sizes, *Nummulites* was also the first reported microfossil genus by Strabo of Amasia and subsequently illustrated during the Renaissance (Gesner 1565). The name of this genus was given a long time after the first report and illustration (Lamarck 1801). An examination of this report shows that *Nummulites* was used in a typical Smithian sense, in which the occurrences of the same species in layers with similar lithology in distant regions could be used for correlation.

The next report marked a significant change, with the transition to a group of microfossils that required a microscope for adequate study. Moreover, it was directly related to the birth of micropaleontology as a science through the studies of C.G. Ehrenberg (1795–1876), and in particular the publication of his main work *Mikrogeologie* in 1854 (Pokorný 1958, Georgescu 2018a). A new group of fossils, which were actually known as planktic foraminifera with chambers alternately added with respect to the growth axis of the test (or biserial planktic foraminifera), were reported from the chalky rocks of Europe in one of the most influential articles of micropaleontology published in the nineteenth century (Ehrenberg 1839) (Fig. 7). In fact, this was one of a succession of articles in which C.G. Ehrenberg demonstrated that the widespread chalk of Europe consisted in great part of microfossils and that foraminifera represented a considerable part of it. Shortly afterwards, in the 1840s, one of the Ehrenberg's collaborators in the United States of America, Jacob Whitman Bailey (1811–1857), reported the first such foraminifera from North America, studied from a micropaleontological perspective with some samples of limestones collected from Egypt, Syria and Lebanon. Based on the occurrences of biserial planktic foraminifera in rocks from northern Africa and the Middle East, which J.W. Bailey found to be identical with those from Europe and North America (Missouri and Mississippi), a Cretaceous age was assigned to them (Bailey, in Hitchock 1843). As acknowledged later, this represented the earliest known application of Cretaceous planktic foraminifera in biostratigraphy (Georgescu 2013b). Moreover, it was also the first biostratigraphical application of an exclusively microscopical group. A careful study of J.W. Bailey's report indicates that the correlation is in a strict Smithian sense, with the planktic foraminiferal taxa in close connection with the carbonate rocks (limestones and chalks) that yielded them.

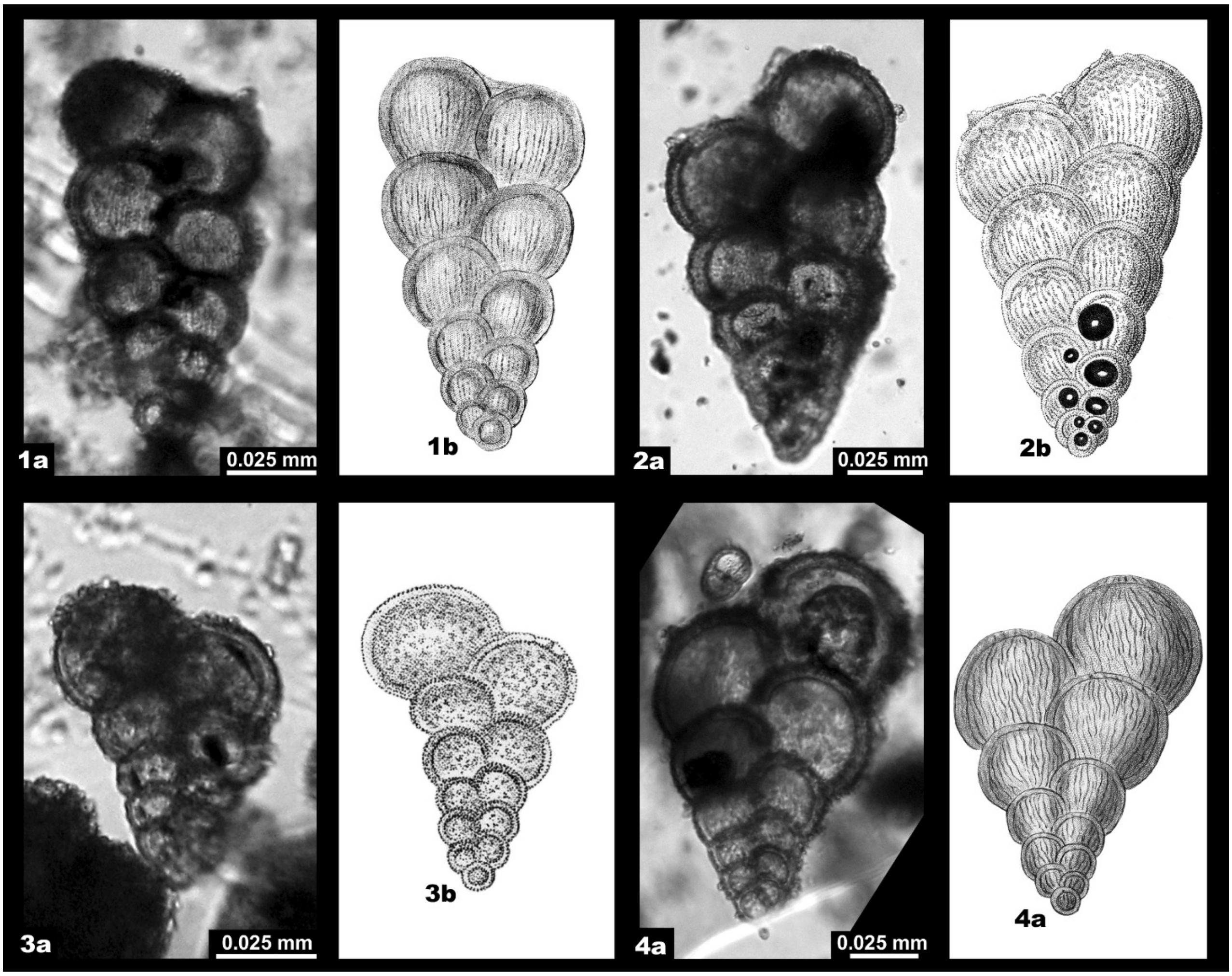

Fig. 7. Specimens of serial planktic foraminifera collected by C.G. Ehrenberg from chalk of the Late Cretaceous (Campanian–Maastrichtian age), and that belong to the species *Ehrenbergites striata* (Ehrenberg 1839) according to the most recent taxonomic revision of the original material (Georgescu 2013a); all specimens are curated at the Museum of Natural History, Berlin. Ehrenberg's original illustrations are those he published in *Mikrogeologie*, which are at a higher level of detail than those of the first article that contains species descriptions and drawings (Ehrenberg 1839). 1: specimen illustrated as *Textilaria striata* by Ehrenberg (1854, pl. 27, fig. 3) from Meudon (France); actual specimen in the collection (1a) and original illustration (2b). 2: specimen illustrated as *T. striata* by Ehrenberg (1854, pl. 28, fig. 6) from Gravesend (England); specimen in the collection (2a) and original illustration (2b). 3: specimen illustrated as *T. leptotheca* by Ehrenberg (1854, pl. 28, fig. 11) from Gravesend (England); actual specimen in the collection (3a) and original illustration (3b).4: specimen illustrated as *T. sulcata* by Ehrenberg (1854, pl. 29, fig. 21b) from the Moen Island (Denmark); actual specimen in the collection (4a) and original illustration (4b).

A subsequent report regards one fusulinid species of Carboniferous age. The report was published first in a letter sent to the editorial board of the *American Quarterly Journal of Agriculture and Science* in 1846, and partly published. It was written by the French geologist Edouard de Verneuil (1805–1873) who travelled and made scientific observations, especially of a stratigraphical nature, through a variety of regions of the United States of America. In Ohio, E. de Verneuil recognized the foraminiferal species *Fusulina cylindrica* in the median portion of a stratigraphical succession of sedimentary rocks of Carboniferous age. The brief fragment of this letter that was published in 1846 included one note on the distribution of the species that occurred in Russia and the United States of America; equally important was the mention of the fact that it was absent in Western Europe, for example in Germany and the British Isles. The conclusion drawn from these occurrences was that the layers containing *F. cylindrica* were coeval (de Verneuil 1846). Another letter with the same ideas was sent by E. de Verneuil to the editors of the *Bulletin de la Société Géologique de France*; the letter was communicated in the same year by Adolphe d'Archiac to the Geological Society of France. The reported fusulinid species was frequently used in modern biostratigraphy as an index for biozones defined within the Moscovian Stage of the Carboniferous System in sections from some countries of the Eastern Hemisphere (e.g., Russia, Iran). The author of the two letters continued his work as one of the leading stratigraphers of Europe and the world; his work on the North American rocks from where the large-sized Carboniferous benthic foraminifer was used for intercontinental correlation was published one year later (de Verneuil 1847).

Another study published a few years later on the succession of macrofossils and microfossils of the Purbeckian facies of the late Tithonian–early Berriasian age further showed the important role that could be played by microfossils in biostratigraphy. The non-marine Purbeckian facies occurred in Britain and continental Europe. A succession of three assemblages was recognized, and based on this, the Purbeckian facies of England was subdivided into three parts: lower, middle and upper (Forbes 1851). The microfossils of the three assemblages included ostracods of the genera *Cypris* and *Cyprideis* and unidentified charophyte gyrogonites; the macrofossils were dominated by bivalves and gastropods. It is evident from the article that the ostracod taxa were used as components of the assemblages, but without playing a major role in the characterization of the respective assemblages. As for the boundaries between the assemblages, it was noted that "… the lines of demarcation between these sections are not lines of disturbance, nor indicated by striking physical characters or mineral changes" (Forbes 1851, p. 81). This shows a shift in meaning from the methodology coined by Sir William Smith and A.D. d'Orbigny towards a truly fossil-based biostratigraphy, which would be fully developed towards the end of the decade by C.A. Oppel. But this study can also be interpreted as a demonstration of the independent succession of fossils from the rock record at a narrow, sub-stage stratigraphical scale that was quite different from that demonstrated at a large scale two decades earlier (Deshayes 1830, 1831, Bronn 1831).

All these early uses of microfossils in biostratigraphy show that despite frequency and diversity, the level of knowledge on microfossils was way behind that on macrofossils. This situation was about to change, as the middle and late parts of the nineteenth century witnessed the discovery and accurate interpretation of most of the fossils and living groups included in modern micropaleontology. Another stream of studies started to cast light on the stratigraphical distribution of the various microfossil groups. However, it was not until the pressures induced by economic changes became acute that microfossil biostratigraphy emerged as distinct branch of biostratigraphy and shortly afterwards started developing at a high rate.

1.8 The emergence of microfossil biostratigraphy

History and experience show that microfossils proved suitable for studying and dating the layers intersected by wells. Their small sizes and often hard skeletal parts that survive the fossilization process make them quite resistant to the mechanical action of the drilling bit and transportation to the surface via drilling mud. Rotary drilling aimed in its early decades only at cutting through the rocks intersected by the well; the lithological components of the intersected formations and their micropaleontological content were analyzed at the surface. Drilling fluid was usually injected through the hollow central space of the drilling string and raised to the surface through the space between the drilling string and the borehole walls. The precision of the interpretations depended considerably on the calculation of the lag time necessary for the rock chips detached from the borehole bottom to reach the surface. Although the methodology for using microfossils brought a wealth of data that filled the gap left by the absence of macrofossils in the ditch cuttings, it was imprecise, especially in the calculation of the depth from which the ditch cuttings and associated microfossils were collected. Errors in the calculation of the lag time affected the quality of the interpretations. Contamination along the borehole during transport to the surface further complicated the problem. By contamination we understand the detachment of chips of rocks from the borehole walls from higher stratigraphical levels. The methodology developed to overcome these difficulties involved the extraction of cores, which represent fragments of fresh rocks of the drilled stratigraphical succession. Core extraction was invented in the twentieth century in the mining industry by B. Newsom and subsequently applied for oil industry wells (Boone 1943). Microfossils started to be used in biostratigraphy in the last decade of the nineteenth century, in the period between the large-scale implementation of rotary drilling and the development of coring technology.

Fossil foraminifera collected from borehole samples started to be studied in the second half of the nineteenth century (e.g., Jones 1884, etc.). The breakthrough in the use of microfossils in the biostratigraphy of sedimentary rocks intersected by wells was realized in the Cretaceous and Paleogene stratigraphical successions of southern Poland by Józef Grzybowski (1869–1922) (Fig. 8). The research that led to the emergence of microfossil biostratigraphy was published by J. Grzybowski in a suite of ten articles during 1894 and 1901. The microfossil group used in biozonation and correlation is represented by foraminifera, especially those with agglutinated tests. The paramount contribution of J. Grzybowski to the emergence of microfossil biostratigraphy or microbiostratigraphy was emphasized by many subsequent researchers (Szajnocha 1923, Bieda 1967, Liszka & Liszkowa 1981, etc.). The biozones recognized in these pioneering studies consisted of a large number of species and were named using one (rarely more) species that was considered biostratigraphically important; the importance of one species in biostratigraphy was recognized either by abundance within the respective stratigraphical interval, or strict occurrence within it (Grzybowski 1898). The pioneering works of J. Grzybowski went even further, for in order to recognize the different assemblage components he had to clarify the taxonomical position of each of the species and genera encountered in the sample; this is quite apparent in the number of new species described by this author. Such taxonomic studies associated with economic developments that ultimately resulted in a significant increase in the diversity of the microfossil group through time set a pattern for biostratigraphy that would be followed for decades to come. The continuous increase in the number of species and