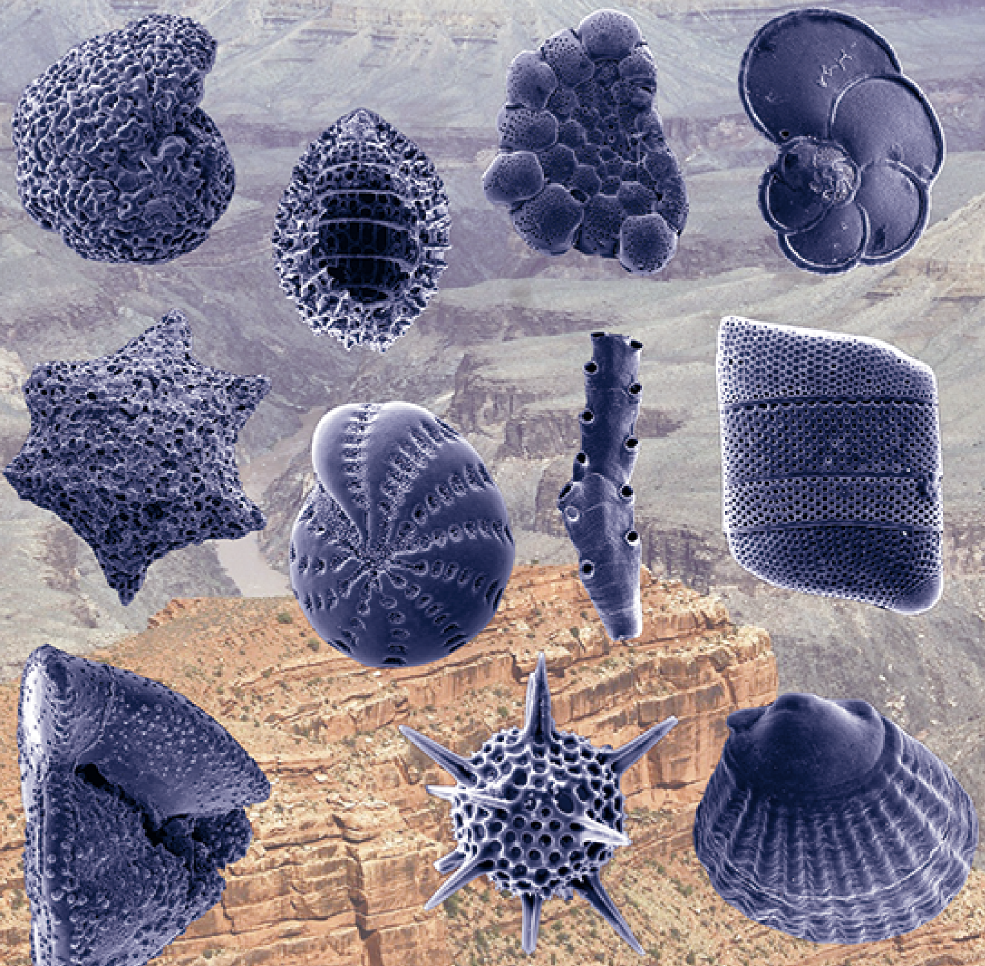
M. Dan Georgescu

Microfossils through Time: An Introduction

First Steps in Micropaleontology



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With 269 figures

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Georgescu: Microfossils through Time: An Introduction
First Steps in Micropaleontology

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Book cover

Front (from left to right and top to bottom): *Lobatula*, *Canutus*, *Planorbulina*, *Globorotalia*, *Baculogypsina*, *Elphidium*, *Crisia*, *Isthmia*, *Globorotalia*, *Hexacontium*, juvenile bivalve.

Back (from left to right): *Paterula*, *Icriodus*, asterozoan vertebra, sponge spicule, *Kloedenia*.

Chapter title pages

Section A. Canadian Rockies in the proximity of the City of Calgary.
Section B. Stromatolite.
Section C. Silicoflagellate *Distephanus* in a siliceous ooze.
Section D. Foraminifer *Contusotruncana* (left top), radiolarian *Canutus* (right middle) and foraminifer *Trachelinella* (left bottom).
Section E. Seed fern *Sphenopteris*.
Section F. Sponge *Euplectella* (upper left corner), gastropod *Buccinum* (upper right corner), bivalve *Pitar* (lower left corner) and echinoid *Eupatagus* (lower right corner).
Section G. Conodont *Ancyrodella*.
Section H. Acritarchs identified as *Cymatiosphaera*-like by (Kaźmierczak & Kremer 2009); © Acta Palaeontologica Polonica; published with permission.
Kaźmierczak, J. & Kremer, B., 2009: Spore-like bodies in some early Paleozoic acritarchs: clues to chlorococcalean affinities. – Acta Paleontol. Pol. 54: 541–551.
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Contents

Rationale

It takes several years to train a micropaleontologist and the process starts at undergraduate level. Traditional education in micropaleontology consisted of one initiating course focused mostly on several groups with importance in biostratigraphy such as foraminifers, radiolarians, ostracods, etc; a second course focused on paleoalgology and palynology was offered by some universities. The two courses were spread over one entire academic year. This basically describes the system followed by many universities around the world in the 1980s, and of which I benefited as student. Following this basic training consisting of two curriculum courses all the other aspects of micropaleontology could be further developed either in the academic stream or in industry. After three decades the big picture changed significantly.

1988 is the year that probably is best known in geology as the year in which sequence stratigraphy was released as method to study primarily the sea-level changes. It became the standard method in oil industry shortly afterwards and the famous "red book" published by the Society of Economical Paleontologists and Mineralogists in which the method was presented as an integrated approach became the standard reference for the industry micropaleontologists by mid 1990s, including myself. Sequence stratigraphy provided an effective method in industry but posed at the same time a major challenge in teaching micropaleontology in academia for it required a significant change of weight towards applied studies. But sequence stratigraphy came with a "Trojan horse" that was represented by paleoclimate study; often involving the study of stable isotopes, micropaleontology shifted towards geochemistry and in short time the number of articles on this topic increased dramatically at the detriment of those focused on industrial applications. Less micropaleontologists and biostratigraphers in general started to be hired by the industry with some companies preferring the in-house training after hiring. It was a signal insufficiently well-weighted but now, long time after the events we can evaluate that the shift of micropaleontology towards paleoclimate study took this science out from the front lines of the oil industry-related endeavours.

One positive challenge for the teaching of micropaleontology that came about the same time was the effect of this science's growth and was given by the larger number of fossil groups that proved effective in biostratigraphy and paleoenvironmental reconstructions. In a wonderful response to this challenge specialists from industry and academia joined their efforts and provided our community with one of the most elaborate tools for teaching micropaleontology namely the "Introduction to Marine Micropaleontology" edited and partly authored by Haq and Boersma (1978, with a second edition published in 1998); I would briefly characterize this book extensively used as textbook for more than two decades as a rich resource of clear concepts and sound interpretations. But this work is written at the level of graduate students or young specialists and only a small fraction of it could be covered in a one-semester course taught at undergraduate level. No efforts were put further in developing a more effective textbook for undergraduates and this field remained mostly uncovered for the decades to come. Unfortunately, micropaleontology teaching system was severely affected by another phenomenon that happened in the scientific community, when starting about the mid-1960s a lot of philosophical ideas and interpretations found their place in publications that were and are still considered scientific by tradition and history; in their candor and naiveté many micropaleontologists did not realize the danger behind this dubious input from scientific perspective. Concepts of idealistic philosophy were resurrected as was that of “figured stones” together with pseudo-science, anti-science, etc all aiming ultimately towards the Theory of Evolution; such ideas do not produce scientific results and adopting them in one way or another in a textbook can be only detrimental to the student performance on both short and long term.

A significant change in the academic communities worldwide, which does not influence only teaching micropaleontology, is the change of generations. Rivers of ink flew on the millennial generation and changes it produced in the educational process; therefore, I do not intend to make an extensive presentation on this topic. Instead I will focus on my observations that the “millennials” have a higher degree of independence and much higher expectations from their instructors when compared to the older generations… including mine. These two features are enough to determine a major change in the way micropaleontology is taught by switching from *ex-cathedra* teaching to active learning. And this changes everything.

The format and content of the present textbook were set after a careful analysis of the evolutions and trends in micropaleontology in the last decades, starting with the 1950s when the classical teaching system for this science was developed. I tried as much as I could to provide solutions to most, and hopefully all the micropaleontology challenges experienced in the last decades as previously outlined. The main goal of the textbook is to present the student with a coherent perspective on micropaleontology and microfossil groups in general. Throughout the textbook the basic taxonomic level is that of genus and the illustrated specimens are mostly identified at this level. I avoided throughout the methods to identify genera, which I consider more appropriate for hands-on labs that should be designed by instructors. Applications are only briefly outlined and without a detailed presentation; such a detailed presentation of applications would shift the textbook level towards that of graduate student/young specialist.

Microfossil groups are given in the classical paleontological classification in which the divisions and phyla are presented in systematic order. Microfossil classification according to the chemical and mineralogical nature (e. g., organic, phosphatic, siliceous, calcitic, etc) was avoided due to the lack of precision; for example, in the past foraminifera were included in these classifications amongst the calcitic microfossils although over 10000 species of species with organic, agglutinated and siliceous test are recognized. A presentation in systematical order also gives the sense that we deal with vestiges of ancient life forms and not with “forms” and “shapes”.

The amount of information included in the textbook is at a medium to high level, but this is a subjective evaluation based solely on my teaching experience. The data included are weighted to match the amount necessary for student presentation with an additional load for more curious and interested students. Notably, the matter covered through classical *ex-cathedra* lectures would be substantially reduced when compared to that through active learning because students will most likely assimilate with more ease concepts presented by other students than instructors.

Readers and especially instructors might note one significant difference when compared to other textbooks: it is the relatively high amount of historical data. In many books of this specialty the historical data are a compendium of errors and I wished to correct this. One objection that can be brought to this strategy is the widespread colloquial opinion that “students are not interested in history”; I would answer simply: if badly taught. Besides the historical presentation, there is the sense of fairness that can be developed through such approach in which the merits of our predecessors are acknowledged.

My hope is that students, instructors and all those that intend to take the first steps in micropaleontology will find this textbook a useful teaching and learning tool, an agreeable lecture and a source of inspiration for further readings. At the final, some words to the students. Micropaleontology is not an easy science; in contrary, it is quite difficult and making progress in this field requires a lot of effort. It is a long process until someone reaches those portions of this science where the true scientific advances happen; it is worth trying getting there. Along the way there are many difficulties and my advice to you is this: keep going… even if some concepts are not understood at the first or second lecture or the results are different from what you expected, just keep going.

The author
Calgary, February 3, 2017

About the author

M. Dan Georgescu received a Ph.D. in 1994 from the University of Bucharest (Romania) with a dissertation focused on the Upper Jurassic and Cretaceous planktic foraminiferal biostratigraphy in the Western Black Sea offshore. Three post-doctoral stages further contributed to the training in the field of micropaleontology: Senior Fulbright Fellow (1998–1999: Rutgers, The State University of New Jersey), North Atlantic Treatise Organization (2002: University of Milan) and Smithsonian Fellow (2005–2006: National Museum of Natural History, Smithsonian Institution, Washington, D.C.). Following an early career in the oil-industry as biostratigrapher and consultant, he joined the academic environment and taught a variety of courses related to paleontology, micropaleontology, stratigraphy, geology and petroleum geology at the Memorial University of Newfoundland and Labrador, the University of Saskatchewan and the University of Calgary.

The main area of his expertise is in Cretaceous planktic foraminifera but this is complemented by benthic foraminifera and charophyte algae. In various applications he uses the representatives of a wide variety of fossil and microfossil groups. Practical studies he developed are related to biostratigraphy, sequence stratigraphy and applications of micropaleontology in basin evolution. The most recent projects are in the development of the foraminiferal evolutionary classification, in which most of the studied fossil material comes from the wells drilled worldwide under the auspices of the Deep Sea Drilling Project and Ocean Drilling Program.

He authored over sixty scientific articles in international journals and chapters in books, two textbooks, two books and edited two volumes in which is also the main contributor. In the recent years, and particularly after joining the Department of Geoscience at the University of Calgary, he took an increased interest in teaching and realized the necessity of a new generation of textbooks in the fields of micropaleontology and paleontology to assure a solid and efficient professional training of the future specialists.

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Section A – Micropaleontology; preliminary concepts and generalities

Chapter 1: Preliminary concepts

Micropaleontology is a complex branch of geology that requires a large number of concepts of geology and paleontology presented to students before its study can begin. It is the main reason why the opening chapter is dedicated to a brief presentation of the concepts necessary in the main part of the textbook. This is also the chapter where the terminology and its usage are defined. Such a section appears necessary being given the increasing number of published articles in which questionable scientific content can be accessed easily by students. Such questionable and frequently wrong ideas have the potential of affecting student determination, productivity and even capacity to understand micropaleontology as science. Therefore, setting the stage for a correct assimilation of concepts is crucial for student's success.

1.1 Science and non-science

Micropaleontology is a science and therefore has all of its attributes. The data are collected through direct observations and experiments and then interpreted to formulate hypotheses. Hypotheses are then tested and as the result of this process can be validated, partly validated or proved wrong; the testing process in science results in an increased accuracy of our scientific knowledge. A hypothesis validated by subsequent observations and experiments can be transformed into a theory. In science the word theory is used for accepted scientific fact or explanation and this contrasts with the every day use of the word, which is associated with incertitude. For example, Theory of Evolution represents in science the fact of evolution and not that evolution is a controversial concept associated with incertitude and doubt. The scientific approach is thoroughly used in micropaleontology, and no other method can be used in its scientific study.

Pseudosciences are not accepted in micropaleontology. A pseudoscience is defined in general as a method of study that does not respect all the principles of science. For example, science does not accept directionality: scientists do not want to prove something but study one phenomenon; scientific creationism, which seeks to demonstrate scientifically the act of religious creation, does not respect this and for such reason is considered pseudoscience. Similarly, intelligent design does not respect the fact that science has an unlimited field of study and development, and for this reason is a pseudoscience. Mixtures between pesudosciences and science are not accepted as parts of science. The term pseudo-science was used for science not necessarily valid because of the wrong assumptions and interpretations, etc (Osborn et al. 2015).

Science is a relative method to understand the natural reality. In science one theory is accepted as scientific fact until a new theory that provides a better explanation of a natural phenomenon or process is developed; when this happens the old and at least partly obsolete theory is abandoned. The only absolute components of science are its principles and use of scientific method as unique method to acquire data. Philosophy is another relative method developed to explain the natural reality; by contrast to science, in philosophy the data can be collected not only from science, but also from arts, religion, logic, law, etc. For this reason the use of philosophical ideas must be carefully and critically examined in order to avoid the introduction of non-scientific data and concepts into science. The use of philosophical concepts in science can be mainly recognized by the absence of advance in scientific knowledge and occurrence of sophisms, false problems, etc. Scientists try to develop science by studying natural objects and phenomena and interpreting them directly, without using intermediary concepts and notions from philosophy, religion, sociology, etc.

Evaluating the quality of science is a complex process based mainly on how the principles of science are respected, scientific method applied and direct interpretation followed. Scientists try to gain prominence in the scientific community by providing more and more accurate explanations to the natural phenomena and processes. Acceptance of one scientist's ideas by the scientific community is a sign of prestige, but acceptance alone cannot represent a criterion indicating good science; therefore, the degree of acceptance is only a collateral criterion to recognize high quality science.

On the overall we should keep in mind that science is a positive and constructive method we use to interpret and explain the natural reality. It is a very dynamic method in which information is verified and challenged, accepted or rejected upon the strength of the arguments supporting or contradicting it respectively. It is also diverse, and different explanations for the same process or phenomenon can coexist. In science there can exist different currents of thinking or schools that put the accent on particular components to explain a phenomenon or process.

1.2 Fossils, fossilization and the fossil record

Fossils are vestiges of ancient life forms; a living organism is transformed into a fossil after death through fossilization. Fossils can be formed in all the environments from continental to aquatic and can occur in rocks and sediments. Most of the fossils occur in sedimentary rocks (e. g., sandstones, claystones, limestones, etc). Metamorphic rocks can contain fossil debris only if they are weakly metamorphosed (e. g., low-grade rocks such as slates); fossils are only rarely found in medium-grade metamorphic rocks (e. g., schists) and no fossils are yet reported from high-grade metamorphic rocks (e. g., migmatites). The diversity of the fossilization process can be demonstrated by the large number (eight) frequent kinds of fossilization: permineralization (fossils with porous internal structures in which the pores are filled with one or more generations of post-mortem deposited minerals), recrystallization (transformation of the original mineralogy of the hard body parts into a different one), impregnation or metasomatosis (soft body parts of a dead organism are impregnated with an inorganic substance and fossilized in this way), carbonization (removal of all other elements but carbon from the original dead organism chemical composition), dehydration, mummification or desiccation (preservation of the soft body parts through the evaporation of the body fluids), fossilization in amber (a natural resin produced by some conifer species), congealment (preservation at low temperatures) and preservation in tar pits (in zones of alteration where the oil from subsurface reached the Earth's surface). The most important factor in the process of fossilization is the burial; a rapidly buried organism has more chances to become a fossil.

In one organism we can recognize the soft body parts, which are non-mineralized (e. g., cytoplasm, nucleus or nuclei, organs, tissues and systems), and hard body parts that consist mostly or entirely of mineral substances (e. g., tests, skeletons, etc). The hard body parts can be fossilized easily, whereas the soft body parts are fossilized more rarely and in such cases we can speak of exceptional preservation. Individual molecules do not fossilize and this characteristic of the fossilization process impacts significantly our knowledge on the earlier life forms on Earth until the evolution of mineralized skeletal parts. Notably, some organisms (e. g., acritarchs, dinoflagellates, etc) evolved thickened protective organic structures that are resistant to fossilization; fossils of such organisms can occur in the fossil record quite frequently but the samples must be prepared using specific techniques.

The term subfossil was used occasionally in the past for fossils younger than the end of the last Ice Age (11700 years). The differentiation between subfossils and 'true' fossils that are older than 11700 years is considered obsolete by many specialists in the field, especially those that study the recent faunas and floras in sample successions that cross this threshold. Younger organic debris, which are found in sediments accumulated in historical times, several hundred years old are not referred to as fossils.

The totality of fossils on Earth forms out planet's fossil record. The nature of the fossil record is paramount to paleontologists because it is the main source from which the data used in this science are collected. Fossil record is incomplete: the vast majority of organisms without hard body parts is not fossilized and vanishes mostly through organic matter decay; only a part of the organisms with hard body parts are fossilized. Many fossils are destroyed as result of erosion or processes related to plate tectonics (e. g., plate subduction, basin destruction, etc). Interpreting the fossil record is a dynamic procedure and new data are added permanently to our existing knowledge. This refines our interpretations that help to recognize patterns in the fossil record despite its incompleteness.

1.3 Geological time

The concept of geological time started to be developed after the establishment of the Geological Society of London in 1660 after the English Civil War; such an act made science itself for the first time represented at institution level and marks without equivocal the beginnings of the Modern Science. It is evident that the application of the scientific method happened earlier and compelling evidence exist to document that modern science existed much earlier than its recognition as institution (Copernicus 1543; Bacon 1620). The choice of the year of 1660 as date of birth of the modern science is supported herein mainly by the argument that after this event of magnitude at the scale of human history the scientific approach was consistently applied and consequently was followed by a marked development of all the disciplines of science. Looking back at the beginnings of science we can note that at that time the knowledge of scientific nature was substantially smaller when compared to the modern knowledge and in some fields it was almost completely lacking. For example at that time it was considered that the age of the Earth was that given in the biblical account, which was calculated at several thousand years.

Calculation of Earth's age and what we consider now to be the 'geological time' was and is a long process. It started when the first set of principles that govern the sedimentary layer formation was provided based on the study of the rocks of Tuscany (Steno 1669). This scientist was the first one who noted that in a succession of undisturbed sedimentary layers, the oldest ones are situated at the bottom of the sequence and younger layers occupy a higher position within the succession, that at the time of formation of one layer only fluid was situated above it, that originally the layers were horizontally arranged and the lack of original horizontality reflected the irregularities at the basin floor, and that originally the layers formed over the entire surface of one sedimentary basin unless the sedimentation process was interrupted by barriers such as islands, shorelines, etc. These principles are often referred today as Steno's Principles of Layer Formation and demonstrated that layers that can be observed in outcrops were formed in long periods of time, which induced the necessity to reconsider the biblical age of the Earth. Our knowledge on the strata succession in the Earth's crust substantially increased in the next one hundred years and by the end of the eighteen century Georges Luis Leclerc, Chevalier Compte de Buffon realized one of the most important advances in the history of science. In a scientific world in which the biblical creationism was a norm, it was demonstrated through experiment that the age of our planet in older than 70000 years (de Buffon 1774); this estimation is more than ten times longer than the religious record. Practically, 1774 was the year when creationism influence was eliminated from science.

The study of successions of layers and bodies of rocks in the Earth's crust led to the development of the geological relative time scale (Fig. 1). According to it the Earth's crust is subdivided into layers and bodies or rocks or groups of such units and in this system the Earth history is subdivided into four eons: Hadean, Archean, Proterozoic and Phanerozoic. Hadean includes the earliest portion of the Earth history for which there is no rock record. Oldest rocks are included within the Archean eon and the earliest fossils on our planet are known from the rocks of this eon. With an age of nearly two billion years the Proterozoic is the longest eon; most of the fossils encountered in the rocks of this eon are microscopical but multicellularity was developed by some algal groups and animals. Large-sized animals occur in the terminal part of the Proterozoic, but throughout its duration the Proterozoic is dominated by stromatolites, organo-sedimentary structures produced by prokaryotes. Phanerozoic records the most diverse fossil record and is also the second shortest eon (~545 million years) after the Hadean. Eons are further subdivided into eras, periods and other stratigraphical units of lower ranks.

Various estimations of the Earth's age were given in the next decades based on calculations of certain geological processes such as erosion, sediment accumulation, change in salinity, etc but all of them are indicative for a major gap in our knowledge at that time: the lack of a method to calculate the age of the Earth and geological processes throughout its history with a consistent level of precision. This changed when Sir Arthur Holmes used isotopes and natural radioactivity as true chronometers to calculate the ages of minerals found in the Earth crust. It became possible during the twentieth century to calculate a numerical age practically for every event in the Earth's geological and fossil record. The method was further improved over the last decades and this resulted in a series of successive narrowings of the margins of errors for numerical or absolute ages

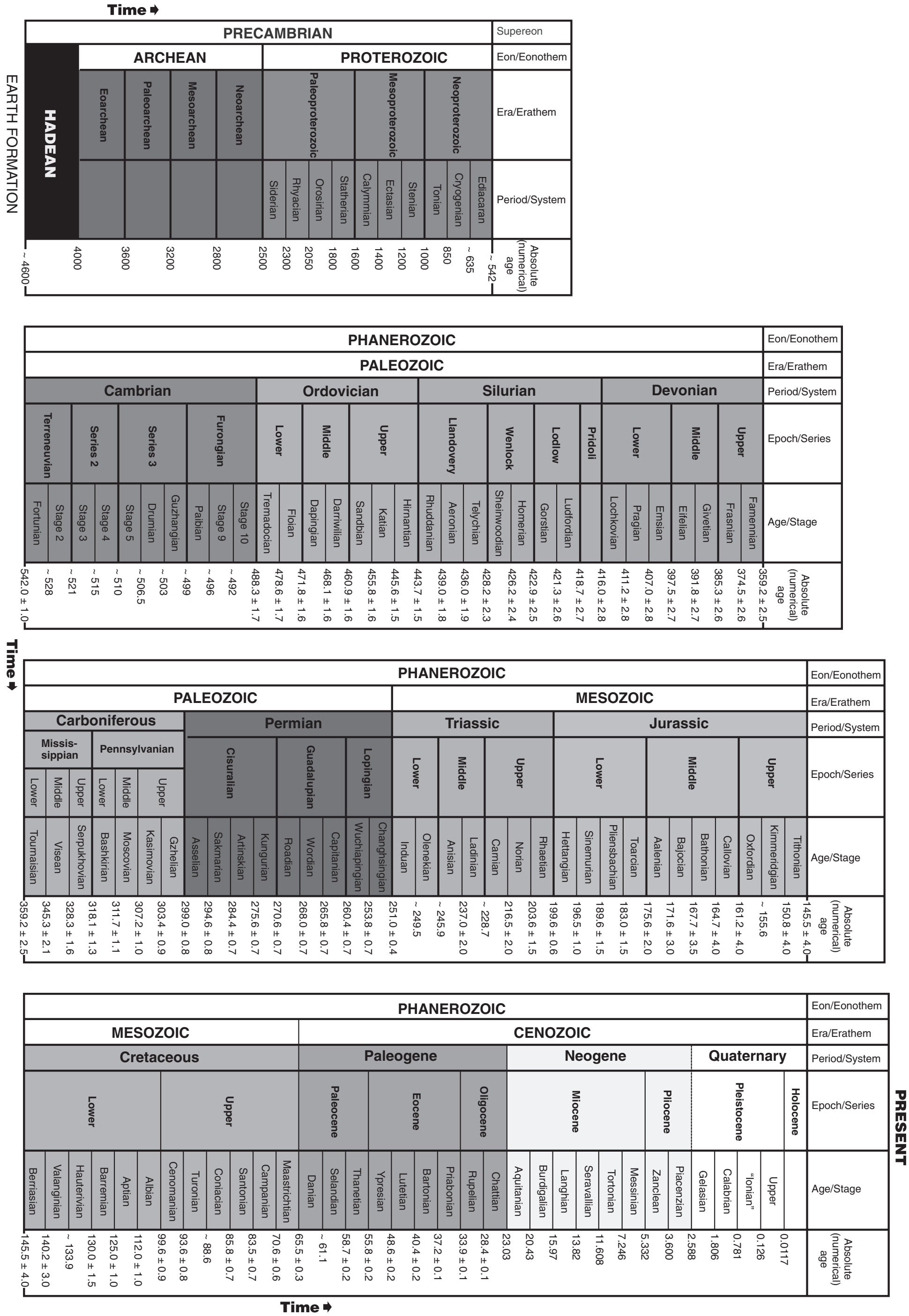

Fig. 1. Geological time scale (Gradstein et al. 2004; with modifications).

of the various events in the Earth history, including boundaries between stratigraphical subdivisions (Fig. 1).

1.4 Lithostratigraphy, time-rock stratigraphy and time stratigraphy

The succession of layers and bodies of rocks in the Earth crust is studied by stratigraphy, which is one branch of geology; the name stratigraphy is derived from the words stratum (=layer) and graphia (=layout, arrangement). There are many branches of stratigraphy defined according to the features taken in consideration to recognizing such successions in Earth history, but three are extensively used in dating fossils and events in the history of life: lithostratigraphy, time-rock stratigraphy and time stratigraphy.

Lithostratigraphy is the oldest method to subdivide the rocks in the Earth crust and correlate them according to their lithological characteristics. The fundamental unit in lithostratigraphy is that of Formation, which represents a layer, group of layers or body of rocks with distinct development in space and time and different lithological characteristics when compared with other units of the same rank; most of the formations have a local or regional distribution and rarely encountered at continental or intercontinental scale. A higher rank than Formation is that of Group, whereas below are those of Member and Bed. Intermediary ranks can be defined upon the geological settings in a certain region; for example higher than the Group is the Supergroup and lower the Subgroup, all of them hierarchically above the level of Formation. A lithostratigraphic unit has the first letter capitalized (e. g., Histria Formation, Unirea Member, etc).

Time-rock stratigraphy follows the succession of rocks (sedimentary, igneous and metamorphic) and sediments in the Earth crust; time stratigraphy follows the successions of events in time. The units of the geological relative time scale are named differently in the time-rock stratigraphy and time stratigraphy. For example Aptian is an Age in time stratigraphy (Phanerozoic Eon, Mesozoic Era, Cretaceous Period, Lower Epoch) and Stage in the time-rock stratigraphy (Phanerozoic Eonothem, Mesozoic Erathem, Cretaceous System, Lower Series) (Fig. 2). Another difference in the terminology of the time-rock stratigraphy and time stratigraphy is apparent in naming formal and informal

Time stratigraphy units	Example	Time-rock stratigraphy units
Eon	**Phanerozoic**	**Eonothem**
Era	**Mesozoic**	**Erathem**
Period	**Cretaceous**	**System**
Epoch	**Lower**	**Series**
Age	**Aptian**	**Stage**

Fig. 2. Time stratigraphy and time-rock stratigraphy unit hierarchy.

subdivisions of one unit. For example the Jurassic is subdivided into lower, middle and upper in time-rock stratigraphy and early, middle and late in time stratigraphy. In a simplified presentation, the Lower, Middle, Upper terminology is used in the case of sediments and rocks, whereas the Early, Middle, Late refer to the age of the respective units.

1.5 Sedimentary environments and organism mode of life

There are three realms in which sediments accumulate at the surface of the Earth and subsequently are transformed into sedimentary rocks through lithification: continental, transitional and marine (oceanic). The continental and marine realms, which are the most widespread, are separated by the shoreline; at the boundary between them occurs the transitional realm that has a discontinuous distribution.

Continental realm is the place where terrestrial sediments accumulate. Such sediments can be formed at the surface of the crust in subaerial conditions through the eolian transportation of solid small-sized clasts. Other sediments formed in the continental realm are those accumulated under the action of running water (e. g., alluvial fans, rivers and associated flood plains), glacier transport, and in lacustrine environments.

Transitional realm occurs in the proximity of the shoreline, both above and below the average sea level. Sediments of the transitional realm accumulate in tidal flats (parts of the shoreface between the lowest and highest tide level), deltas (below the lowest tide level), and barrier islands and beaches.

Most of the sediments on Earth form in the marine realm, which consists of the seas and oceans that today cover about 70 % of our planet surface. There are three environments within the marine realm that can be recognized in a section through an oceanic basin (Fig. 3). Shelf environments occur in the marginal portions of the marine realm between the shoreline and shelf break. The waters are shallow and in general the lowest depths are at -200 meters. The shelf can be informally subdivided into inner and outer shelf, which are situated landward and seaward respectively; occasionally a three-fold subdivision into inner, middle and outer shelf can be recognized. Slope environments

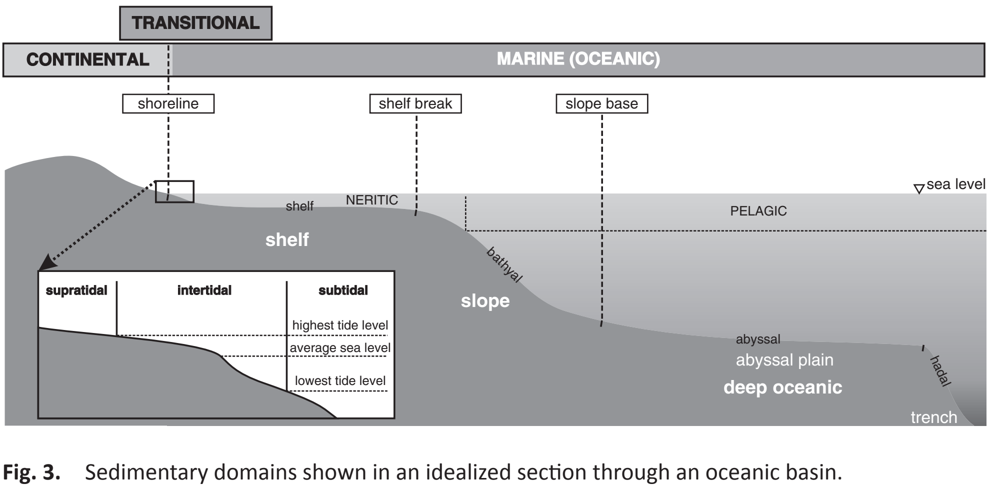

Fig. 3. Sedimentary domains shown in an idealized section through an oceanic basin.

occur between shelf break and slope base and are characterized by a rapid deepening of the basin floor; the slope base that represents the lower boundary of these environments is in general situated at a depth of -500 meters. The deep oceanic environments occur in the central portions of the marine realm, which are also its deepest ones; they include the abyssal plains, oceanic trenches, etc.

The shoreline does not remain in a constant position. Two sea-level positions that have a critical influence in the occurrence and distribution of the environments in the proximity of the shoreline can be defined: highest tide level and lowest tide level. These two levels define three distinct environments: supratidal (above the highest tide level and permanently emerged), intertidal (between the highest and lowest tide levels and submerged only during the flux) and subtidal or sublittoral (below the lowest tide level and permanently submerged) (Fig. 3).

One important feature that plays a crucial role in organism distribution is the water salinity. There are three types of waters according to this characteristic of the aquatic environments: fresh (<0.5‰), brackish (0.5–30‰) and marine (30–40‰). Aquatic environments with higher salinities are also known and they are termed hypersaline (40–51‰).

There are three major modes of life of the organisms in the aquatic environments: benthic, planktic and nektic. Benthic organisms live at the basin bottom or in the most superficial portion of the basin floor sediments; they can be free, attached to substratum or other organisms or burrowers. The nektic organisms are free and active swimmers through the water column. Planktics are in general small-sized, often microscopical organisms that float passively within the water column; photosynthetic planktics are abundant in the superficial photic zone, where the solar light can easily penetrate through the water. The three modes of life can be also found in various works as benthonic, planktonic and nektonic (Emiliani 1991).

The characteristics of the life forms together with the morphology (especially bathymetry) of the basin are used for two subdivisions of the marine (oceanic) realm; notably, these are widely used in paleontology and related sciences (Fig. 3). The first subdivision is that at the sea floor: shelf zone that includes the shelf environments, bathyal zone that occurs in the slope regions, abyssal zone for the abyssal plains and hadal zone in the oceanic trenches, which are the deepest portions of the oceans (e.g., Mariana Trench). The second classification regards the upper part of the oceanic water column. In this twofold classification there can be recognized a neritic zone that corresponds to the shelf and upper slope and a pelagic zone corresponding to the lower slope and abyssal plains and is situated in the central portions of the oceans.

1.6 Theory of Evolution in paleontology

The fossil record on Earth cannot be explained without the use of the Darwinian Theory of Evolution. This theory is widespread across the sciences that study the living and fossil life forms on Earth, which include paleontology, biology and genetics. According to our scientific knowledge on the evolution of life on our planet, the life emerged from inorganic substances circa 4.0 billion years ago. It gradually evolved through different mechanisms of evolution, natural selection being one of them. Natural selection, which was also the first recognized mechanism of evolution, was described for the first time by James Hutton (1726–1797) in an unfinished and unpublished manuscript from his last year of life (Bailey 1967, Pearson 2003). The same mechanism was described independently and successively two times at the beginning of the nineteenth century (Wells 1818, Matthew 1831). For the fourth time it was independently discovered 15 years before the publication of the Origin of Species (Darwin, 1844-unpublished manuscript); the fifth and last discovery betfore 1859 resulted in the publication in a scientific journal, and paved the way towards the Darwinian scientific revolution (Wallace in Darwin & Wallace 1858). The hypothesis of the Theory of Evolution was formulated earlier (Wallace 1855); the final step, which is represented by the leap to the theory level appears a necessity from this succession of events and scientific advances (Darwin 1859). Noteworthy, the Theory of Evolution was born as part of science, and all its advances in developing our knowledge on the life evolution on Earth were made through the application of the scientific method.

A distinct branch of paleontology, which focusses on the study of different taxa and ancestor-descendant relationships between them, is the evolutionary paleontology. It is developed through the integration of data from the fossil morphology and other subdisciplines of geology and paleontology (paleoecology, biostratigraphy, sedimentary petrology, sedimentology, geochemistry, etc). Evolutionary paleontology is not a simple arrangement in a simple-to-complex sequence of the different fossils based on their degree of resemblance. Scholars and scientists recognized such a "chain of beings" long before Darwin (Bonnet 1764, Lamarck 1809). The term "progress" was often used afterwards for such an arrangement based on morphological complexiy and should not be confused for the true Theory of Evolution. A synonymy between the "chain of beings" and Theory of Evolution was accepted and often advocated by some philosophers but such synonymy is wrong from a scientific perspective.

1.7 Taxonomy and classification methods in paleontology

Classification represents the separation of the fossil organisms into groups; such subdivision is realized with the aid of a variety of features and principles derived from the fossil record, which are studied through a distinct branch of science: taxonomy. Taxonomy and classification were always topics of major scientific debate and this is partly because sometimes not only science but also ideology appears included by some authors in their classification frameworks. There are several methods used in the scientific classification of fossils and they were briefly described by Mayr (1968). This perspective on the different classification methods is largely followed herein and the different methods are presented in the chronological order of their appearance.

Essentialism was developed by Aristotle of Stagira (384 B.C.–322 B.C.) at the end of the Greek Classical period and the very beginnings of the Hellenistic period. In this classification method organism grouping is entirely based on their morphological resemblances. It was widely adopted first by the scholars of Antiquity, passed in its original form through the Dark Ages and started to be developed again in the times of Renaissance. It is the most used classification method today. The essentialist classification is hierarchical and consists of around 35 classification levels; the fundamental unit is that of species. According to this method morphologically resembling species are grouped into one genus, genera that share one or a number of characters considered important can be grouped into one family, etc. The main hierarchical levels are in ascending order those of species, genus, family, order, class, phylum and kingdom. Other hierarchical levels can be derived from them wherever necessary; for example in the case of one order the following levels in ascending order can be named by adding different prefixes: infraorder, suborder, order and superorder. The nomenclature system used in essentialist classification can be binomial or trinomial; in the trinomial system one name is formed by adding in order the genus name, species name and subspecies name (e. g., *Allotheca spinifera acutangula*), whereas in the binomial nomenclature the subspecies name is not included (e. g., *Allotheca spinifera*). One rule in the essentialist classification is to write the names of species and genera using italics. In the first edition of the work that is mostly known by the shortened name *Systema Naturae* was provided a classification based on the essentialist principles (Linnæ 1735); the 1758 edition of this work is used as reference for the modern essentialist classification. The 'Linnaean classification' was accepted by convention and should be more accurately referred as Aristotelian classification.

Empiricism is a method in which significant amounts of quantitative data are collected through the measurement of large number of specimens from one or more populations. Defining groupings of individuals through such numerical data may appear objective as it has the strength conferred the use of mathematical approaches. Besides this there is a major deficiency of the method, which is represented by the fact that the importance of the morphological features used in classification cannot be properly weighted and therefore, such groupings of organisms cannot fit into a rigorous evolutionary framework and an accurate evolutionary classification framework can be derived from it. Empiricism has an occasional role in the modern classifications especially at species level, but on the overall the method appears to lack the level of accuracy required for the modern evolutionary perspectives. This is not unexpected for a method that started to be developed circa one century before the birth of the Theory of Evolution.

Nominalism is a classification method according to which the species of the essentialist classification are not objective natural units and only specimens should be taken in consideration in classification (Robinet 1768). Using the words of the method's discoverer, "species are nothing but an illusion". Practically this classification method draws the attention that a rigorous essentialist classification cannot be achieved. Nominalism occurred in a small number of works especially in France in the last two decades of the eighteen century, but not used at all after the year 1800.

Evolutionary classification was prefigured in the Origin of Species, where it was noted that species related by ancestor-descendant relationships present morphological resemblances that are the result of common ancestry and also morphological differences derived from the divergence in the course of the evolutionary process (Darwin 1859). The theoretical fundaments of the method were further developed, and the name chosen for it was that of evolutionary classification (Mayr 1968). Attempts were made to develop this method by various scientists in the next decades but the most important advance happened when the lineage was defined as fundamental unit in evolutionary classification (Georgescu 2014). The method is at the beginnings, is applied at this time only in some planktic foraminifera and its development requires a high quality fossil record. The main advantage is that it provides a practical and scientific procedure to include the differences derived from the divergent charcter of the evolutionary process between the taxa related by ancestor-descendant relationships in a rigorous classification framework.

Organism classification is not unique. At the time when Aristotle of Stagira provided the first classification of the animals, his collaborator Theophrastus of Eresos (~371 B.C.–~286 B.C.) realized the first classification of the known species of plants, a work that survived to the present times and was written around the year 318 B.C. For a taxonomist the work of Theophrastus is of primordial importance for the 'Father of Botany' wrote a short account on the plurality of classifications. For a long period of time one classification proved enough in the study of living and fossil organisms, and this was the essentialist classification. This classification in which organisms are grouped according to the degree of resemblance is simple because it is based on the natural inclination of humans to group objects with similar properties and/or features.

A general term used of a unit used in classification is that of taxon (plural: taxa). This term has no formal usage and is used in two classification methods: typology and evolutionary classification.

1.8 Typification

Nomenclature stability is particularly important in paleontology for stable names for the species and supraspecific units are paramount in comparing studies realized by different scientists at different times. For this reason a system of specimen nomenclature within one species was defined in essentialist classification. According to this system the specimens of one species are of different kinds and the most frequently used are: holotype, paratype, lectotype, paralectotype, neotype, topotype and hypotype. The holotype is selected only by the author of a publication in which one new species is described; it is the name bearer of the species and often referred to as the most important individual of one species. This specimen is selected from the original population of individuals; the remaining specimens of the original population after the extraction of the holotype are referred to as paratypes and only the author of one species can designate paratypes. If one author did not selected a holotype but figured one or more individuals from a species he/she discovered and named then new types are necessary; another scientist can select one figured specimen, which is in some cases the only specimen illustrated by the original author, and designate it as lectotype. A lectotype has all the characteristics and strengths of a holotype; after the lectotype designation all the remaining of the originally illustrated specimens are referred to as paralectotypes. If the holotype or subsequently designated lectotype is lost, and this happens mostly due to a natural calamity or war, then a neotype is designated; the neotype has all the attributes of a holotype but is a different specimen and designated afterwards. Topotypes are specimens collected from the locality from which the holotype and paratypes were originally designated; they can be collected afterwards by the species author or another individual. All the other specimens of one species are referred as hypotypes. Specimen typification became part of the typological classification and for this reason the essentialist classification is often referred to as the Linnaean typological classification. A more accurate expression for it would be that of Aristotelian typological classification.

Specimen typification is not a singular process in our attempts to increase the precision of the names assigned to different entities of the fossil record. For example it appears necessary to mark with precision the position of the original populations or assemblages in space and time. The geographical location from which one species was described and therefore holotype and paratypes designated is referred to as type locality. In paleontology the stratigraphical level from which the species was described and holotype and paratypes designated is referred to as the type level. The type locality marks the position of the original population or assemblage is space, whereas the type level that in time. In neontological sciences (e. g., biology, genetics) the type level is not designated for the new species is described from living populations.

This system that was designed to assure nomenclatural stability had an adverse effect that should not be overseen. In order to demonstrate the validity of their species identifications many authors illustrated only specimens that morphologically resemble the holotype, creating the false impression that one species is morphologically relatively stable. This is the so-called holotype syndrome and it created a false perspective on the fossil record (Masters 1977). Moreover, it was subsequently inferred that the holotype syndrome is apparently one of the reasons that led to the development of perspectives on evolution that are closer to idealistic philosophy rather than modern science (Georgescu 2016).

An attempt to correct the problems induced by the typological system and difficulties in definition of the concept of species was through the definition of the concept of paradigm (Simpson 1940). A paradigm consists of a carefully selected number of specimens to bear the name of one species. Such a concept does not eliminate all the problems of representation of one taxon. Typification was completely abandoned in the evolutionary classification (Georgescu 2016); the main argument brought for this methodology is that one type specimen or paradigm are static entities and cannot be representative for the dynamic units of the evolutionary classification (i. e., lineages).

1.9 The concept of species and species evolution

The concept of species is paramount in the life sciences both in fundamental and applied studies. The earliest such concept was given by Aristotle of Stagira in his work titled “Metaphysica”; notably, in the same work this author also defined the concept of genus. Therefore, the most used concepts in biology, genetics and paleontology were originally defined in a work of metaphysical philosophy. The sense of the concept of species changed afterwards and the most frequently used today is that of Linnaean species. This is not a rigorous concept and according to it, one species includes specimens that have a certain and reasonable degree of morphological resemblance; moreover, Linnaean species can be also regarded as a convention because C. Linnæ did not define such a concept but rather adopted it is the sense used by his predecessors from the Renaissance times. In paleontology the Linnaean or typological species is often referred to as morphospecies.

The concept of paleontological species was provided during a major development in the Theory of Evolution known as The Modern Synthesis (Simpson 1951). During this period of considerable scientific advances was acknowledged that one concept of species can be defined for each of the main three branches that study the life forms on

Earth: biology, genetics and paleontology. In brief, a paleontological species consists of a succession of populations, with its own evolutionary trends in space in time. The concept of composite paleontological species was defined in order to avoid the general nature of the concept of paleontological species, and focus on the empirical nature of these taxonomical units (Georgescu & Huber 2007). In evolutionary classification, where species are not accepted as valid taxonomical units this concept was further developed to define the stage of morphological relative stability as component of one lineage (Georgescu 2014).

Species evolution is a very important process in defining natural units in the fossil record. Initially it was considered that species evolved gradually and continuously in the fossil record and this evolution pattern was later termed "phyletic gradualism" (Darwin 1859) (Fig. 4). In the subsequent editions of the "Origin of Species" and and based on the comments from other other specialists, C.R. Darwin admitted that species evolve in a relatively short period of time and remain morphologically stable over longer periods of time. The concept of "punctuated equilibria" was defined over one century later (Eldredge & Gould 1972). Punctuated equilibria give an oversimplified perspective on the evolution, which is closer to idealistic philosophy. In fact the name of this concept is misleading and gives the wrong impression that the living world is stable rather than changing. A combination between phyletic gradualism and punctuated equilibria was proposed with the definition of punctuated gradualism (Kieser & Groencveld 1985).

There are some features recognized in the life span of each taxon, including species. The earliest occurrence in the stratigraphical record is referred to as evolutionary occurrence or evolution. The highest occurrence in the fossil record of one species or one taxon in general is referred to as extinction; once extinct one taxon does not reappear in the fossil record. Notably, this terminology is not applicable in the case of living taxa where the highest occurrence is in the present time and therefore, is situated within their life span. The duration in time between evolutionary occurrence and extinction is termed the stratigraphical range of the taxon of any rank; the stratigraphical ranges of the known

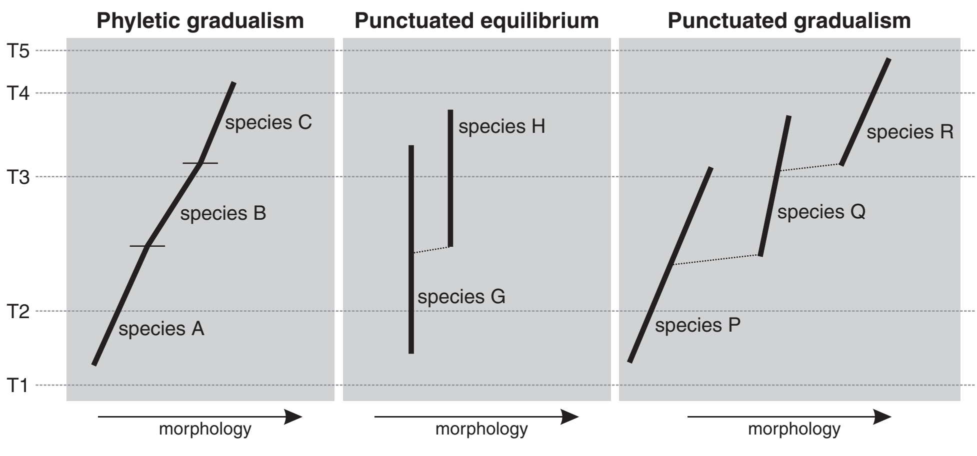

Fig. 4. Models of species evolution.

species are highly variable and in general marine species have longer stratigraphical ranges than the terrestrial ones.

The graphical representation in the case of one species can raise some confusion because often scientists represent the stratigraphical range of one species as a continuous line that connects the evolutionary occurrence and extinction. Quite unfortunately, scholars with inclination for idealistic philosophy interpreted such graphical representation as evidence that species are unchanged over their lifespan and this misinterpretation cannot be accepted valid in science. Our overwhelming evidence shows that species morphology changes over their lifespans and evolutionary changes can be recognized at the level of feature or groups of features in the case of fossil species.

1.10 Major crises in the history of life

Paleontologists noted when studying the fossil record that diversity presents a distinct growing trend from the earlier part of the earth history to the modern times. This trend is not linear and consists of periods in which the diversity increases followed by periods in which the trend is opposite. Practically, the number of speciations (evolution of new species) is higher than that of extinctions, whereas in the latter case the number of extinctions dominates over speciations. Five major crises in the Phanerozoic history of life were recognized by plotting the number of families of marine organisms (Raup & Sepkoski 1982): in the late Ordovician, in the late Devonian, at the Permian/Triassic boundary, at the Triassic/Jurassic boundary and at the Cretaceous/Paleogene boundary. These crises reflected in the phenomena of mass extinction were extensively studied in the decades to come. It proved that the most severe of them was that at the Permian/Triassic boundary when more than 90 % of the species in both continental and marine environments became extinct; this major crisis is often referred to as the “Great dying”. The causes that triggered each of these crises were carefully studied and probably the most spectacular of them proved that at the Cretaceous/Paleogene boundary when an asteroid impact precipitated the extinction of the dinosaurs and several other invertebrate and vertebrate groups that thrived during the Mesozoic Era.

The mass extinctions have a distinct significance in the history of life for when a large number of species become extinct the ecological niches are depopulated and this opens new opportunities for innovations in the evolutionary process. Therefore, crises should be considered as much more than simple mass extinction events. The evolutionary innovations following the major crises reshaped the life forms on Earth and produced significant changes when compared to the pre-crisis period. This is the reasoning for adopting herein a new system of crises in the history of life, by evaluating the nature of crisis and magnitude of innovation that followed each of them instead of simple mathematical plotting. Therefore, four major crises are used in this work and they are briefly presented in stratigraphical order (Fig. 5).

The First Crisis happened in the proximity of the Hadean/Archean boundary, circa four billion years ago and was determined by the massive asteroid bombardment in the earlier history of the Solar System. There are no records on Earth of this event due to the subsequently initiated plate tectonics that obliterated all the evidence; but there is such evidence on the nearby planets such as Mercury and Mars and on the Earth’s natural

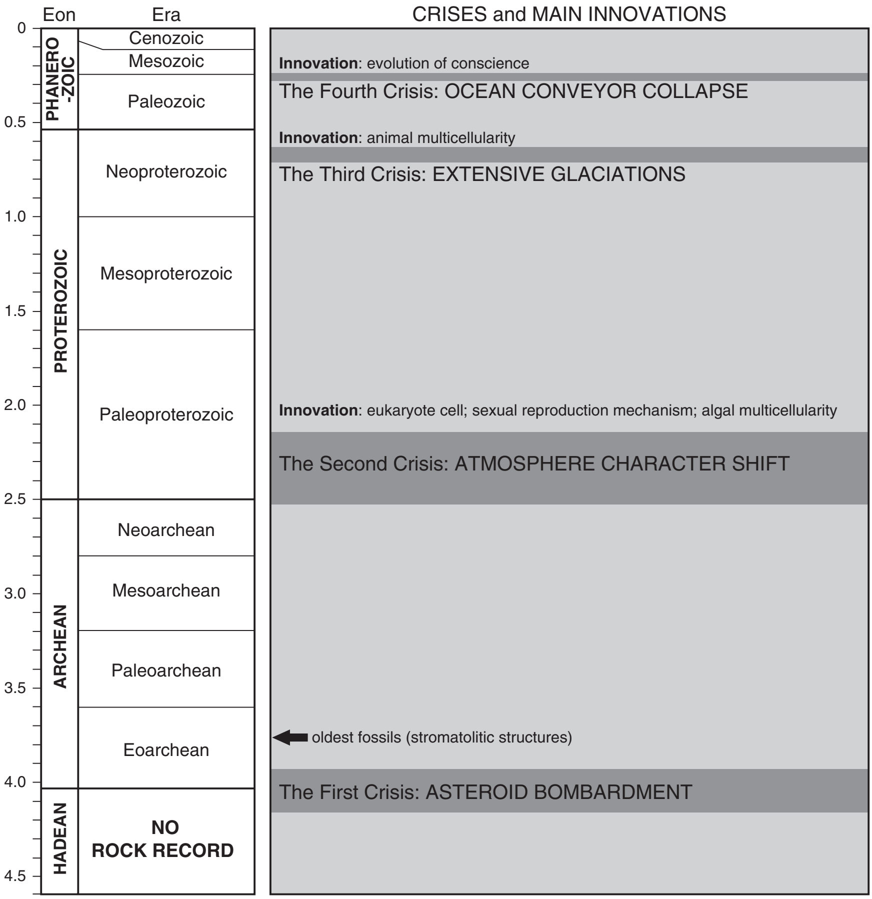

Fig. 5. The four major crises in the history of life and main innovations they brought. Ages in billion years (Gradstein et al. 2004).

satellite, the Moon. Extrapolating the data yielded by crater stratigraphy on these celestial bodies we can draw the conclusion that the massive asteroid bombardment happened on Earth circa 4.2–3.95 billion years ago. It is calculated that the time interval during which such massive impacts with large-sized asteroids capable to vaporize an entire ocean was between 4.3–3.8 billion years ago (Sleep et al. 1989). At the beginning of its history the life on Earth was represented by microscopical simple organisms consisting of a much smaller number of molecules when compared with the modern ones; most likely they were obliterated several times during the massive asteroid bombardment. This was a crisis when the very existence of life was challenged and the innovation at its end was life itself. The oldest known fossils are 3.7 billion years old.

The Second Crisis is recorded in the proximity of the Archean/Proterozoic boundary and most of the Paleoproterozoic, circa 2.5–1.8 billion years ago and was generated by the shift in the Earth's atmosphere character from reducing to oxidizing. Stromatolites reached global distribution by the Neoarchean times and released vast amounts of free oxygen in the Earth's atmosphere throughout the Archean. This process is apparent especially in the rock record and is best illustrated by the worldwide formation of banded iron formations around the Archean/Proterozoic boundary and accumulation of limestones and red beds afterwards in the Proterozoic and Phanerozoic times. Oxygen is a toxic gas for many anaerobic prokaryotes and the occurrence of significant amounts of this gas represents the nature of this crisis. Organisms had to evolve in order to survive and this resulted in the development of new cell architecture, namely the eukaryotic one. This evolution leap is apparent in the development of sexual reproduction mechanism that allows a higher number of mutations to occur during the reproduction process when compared with the prokaryote mitotic reproduction. In the fossil record eukaryotes occur above the Archean/Proterozoic boundary and in a relatively short period of time red algae evolved multicellularity.

The Third Crisis happened in the Neoproterozoic and was due to an extensive glaciation that led to the development of an ice sheet that covered much of the surface of the Earth including North America, Baltica and the continents forming Gondwana. This is the period known informally as the "snowball Earth" (Hoffman et al. 1998). Three glaciation pulses occur in the late Cryogenian and one in Ediacaran. Earth surface freezing was a major challenge to the life on our planet, which resulted in the evolution of animal multicellularity documented by sponge fossils from rocks dated at circa 750 million years, which matches the oldest pulse of the "snowball Earth". Ediacaran fauna that follows the "snowball Earth" is the earliest known multicellular animal diversification event.

The Fourth Crisis is the "Great dying" at the Permian/Triassic boundary. This crisis was produced by the collapse of the Ocean Conveyor and this led to the most severe mass extinction in the Phanerozoic times. Many Paleozoic groups became extinct, and this opened new paths to life evolution that happened gradually especially during the Triassic. The most important innovation that followed this crisis is herein considered the evolution of the mammalian group from cynodont therapsids in the Late Triassic times; this is of primary importance because conscience and the highest levels of intelligence in the evolutionary history of life on Earth were achieved by lineages of the mammalian group.

One final mention on this topic is that subjectivity cannot be avoided when dealing with the crises in the history of life. Even the mathematical plotting of the ranges of known taxa and quantification of the mass extinction events cannot provide an objective answer to the question on where the threshold between a major and a minor crisis should be acknowledged. In addition, evolutionary innovations occur after every mass extinction event and this further complicates the problem raising the question if there is not a hierarchy of crises in the Earth history. Despite these uncertainties the recognition of the four crises as accepted herein provides an accurate view on this topic from a pedagogical perspective.

Chapter 2: Micropaleontology and microfossils

Paleontology is one of the subdisciplines of geology and studies the vestiges of ancient life forms, which are the fossils, found in the Earth's crust. It is a vast science that is further separated into narrower branches according to the type of studied fossils. For example and in very general terms paleoalgology is the study of fossil algae, paleobotany studies the fossil land plants, palynology includes but is not restricted to the study of the fossil spore and pollen grains, invertebrate paleontology represents the study of metazoans without a vertebrate column, vertebrate paleontology the study of organisms that have a vertebrate column, whereas micropaleontology is the study of the microscopical fossil remains. The separation between branches is neither rigorous nor unanimously accepted by paleontologists and the overlapping between paleoalgology and palynology on one hand and micropaleontology on the other is evident.

Some groups of organisms with abundant and diverse fossil record such as foraminifers, ostracods and brachiopods claim their own branch of paleontology as foraminiferology, ostracodology and brachiopodology respectively and the specialists in these fields are frequently referred to as foraminiferologists, ostracodologists or brachiopodologists. At the opposite pole is the study of the conodonts which are remains of the chewing apparatus of organisms that did not have the axial skeleton in the form of a vertebral column but a more primitive one consisting of a notochord; conodonts were included by many authors in the past amongst the invertebrate fossils because they lack a well-developed vertebrate column, whereas others consider it as part of micropaleontology for the fossils left by this group are mostly microscopical in size.

Each of the six larger branches of paleontology namely paleoalgology, paleobotany, paleoalgology, invertebrate paleontology, vertebrate paleontology and micropaleontology are often associated with other subdivisions derived from paleontology such as biostratigraphy, paleobiogeography and paleoecology; these three are regarded by paleontologists as both distinct branches of paleontology and applications of it. Biostratigraphy represents the study of the fossil distribution in space and time and is the main application of paleontology in the exploration for hydrocarbons. Paleobiogeography focuses mainly on the space distribution of fossils and fluctuations in the distribution areals in time. Both biostratigraphy and paleobiogeography study the distribution of fossils but the former focuses on the distribution in time whereas the latter on that in space. Paleoecology is the study of the relationships between the fossilized organisms and surrounding environments, biotic and abiotic, at the time these organisms were alive; paleoecological studies are extensively used in recognizing paleobathymetrical settings, which is another major input derived from the study of fossils in the exploration for hydrocarbons. Other applications of paleontology include reconstructions of sedimentary paleoenvironments, paleoclimates, etc but they are not so developed to have defined a distinct branch.

2.1 Microfossils

It is a general consensus among paleontologists that micropaleontology represents the study of microfossils, but there are significant differences on what microfossils should be considered. Some fossil groups and their living representatives in case they exist are entirely microscopical (e. g., silicoflagellates, chitinozoans, etc). Other groups are both microscopical and macroscopical; for example, most of the foraminiferal taxa are microscopical but frequently in the reefal and peri-reefal environments foraminifers evolved large-sized specimens, which can be up to several centimeters in maximum dimension and therefore, are true macrofossils. Some representatives of other groups such as diatoms, which are microscopical in size, can form up colonies that can be as large as seven centimeters; similarly, the radiolarians that are typically microscopical organisms can produce colonies with a dimension of up to a few meters. Other microscopical organisms that live in clusters can precipitate calcium carbonate and form large-sized organo-sedimentary structures that occasionally preserve the fossilized microorganisms that produced them. Most of the invertebrate groups occur as microscopical fossils in the form of juvenile specimens and fragments of endoskeletons and exoskeletons. Similarly, fragments of the endoskeleton and dermal structures of vertebrate organisms can occur as microfossils.

Such a diversity of provenance sources of microfossils was differently treated by the specialists in the field. Some considered only the groups that are entirely or mostly microscopical (e. g., foraminifers, radiolarians, diatoms, etc) in the field of micropaleontology and ignored most of the microfossils left by metazoans with the exception of ostracods, and structures produced through microorganism metabolism; the metazoan debris irrespective of their size were frequently considered in the range of invertebrate or vertebrate paleontology. Probably the most complete perspective of the wide range of the groups included in the field of study of micropaleontology was given by Bignot (1985). One of the goals of this work is to provide an as complete as possible view of the microfossil groups. Therefore, the following definition of micropaleontology is adopted herein: branch of paleontology that studies the fossils of microscopical organisms, microscopical fossils of larger organisms and structures produced through the metabolic processes of microorganisms.

2.2 Birth of micropaleontology as science

The name of micropaleontology was first given as “micro-palæontology” (Ford 1883). The first use of the name of this branch of paleontology should not be confused for its beginnings. There are different versions on when should be considered that micropaleontology began and various authors that studied this aspect of rather historical nature came up with different conclusions. For example, foraminiferologists use to emphasize the importance of their field in the birth of micropaleontology due to the foraminiferal group diversity, occurrence and often abundance in the fossil record and modern seas and oceans, and importance in industry especially in the exploration for hydrocarbons. Despite these arguments to which the fact that this is the first reported microfossil group there can always be brought the counterargument that the foraminifers represent only a part of micropaleontology. But names such as those of A. d’Orbigny, H.B. Brady, J. Grzybowski and J.A. Cushman are still credited by many scholars as the founders of micropaleontology or at least foraminiferology for their major developments in this field during the nineteenth century and the first half of the twentieth century. A milestone in the development of micropaleontology is represented by the publication of the first book dedicated to this field (Glaessner 1945); such an interpretation is definitely closer to micropaleontology rather than foraminiferology.

Examination of the history of the reports of microfossil groups and innovations brought forth to the scientific community shows that the earliest fossils that were later assigned to microfossil groups were reported from the Antiquity times but no clear description was given and there is no sign that their organic nature was recognized. It took nearly 1600 years until such fossil was illustrated but its nature could not be correctly recognized (Gesner 1565); today we know this fossil belongs to the large-sized foraminiferal genus *Nummulites*. The invention of microscope towards the end of the sixteenth century triggered a new kind of studies in which the opportunities of observation created by the new instrument became more and more apparent. For example, the work *Micrographia* has descriptions and illustrations of many microscopical objects and structures can be considered a work presenting to the scientific community the possibilities opened by the microscope to make accurate and high-resolution observations (Hooke 1665); this work includes the first illustrated test of a foraminifer examined with the aid of a microscope. For nearly one hundred years there were relatively rare reports of microfossils, most of them foraminifers, which demonstrate the transition from the observations with the unaided eye to those aided by microscope. The number of articles and scientific works increased around the year 1800 when new microfossil groups started to be discovered and this setting persisted in the next decades following the Napoleonian wars.

The change happened in the first half of the nineteenth century and is related to the studies of C.G. Ehrenberg (1795–1876) who described a variety of new fossil and living groups of microfossils and living microorganisms respectively from around the world. He also described several thousand of new species and genera of foraminifers, radiolarians, silicoflagellates, diatoms, phytoliths, etc. These discoveries of C.G. Ehrenberg revealed the vast complexity of microfossils and microorganisms in general and this is mostly apparent in his work *Mikrogeologie*, one work he published in 1854. The meaning of Ehrenberg's *Mikrogeologie* is practically the same with what micropaleontology is considered today (Pokorný 1958). Therefore, it appears reasonable to consider that C.G. Ehrenberg is the founding father of micropaleontology. At the same time it is necessary to mention that this major event in the history of micropaleontology could not have been possible without the reports of fossils that belong to groups of fossils currently studied by micropaleontologists that began more than 1800 years before.

The collection of microfossils of C.G. Ehrenberg is deposited in the Museum of Natural Sciences (Naturkundemuseum) in Berlin. The specimens are preserved between slides of mica kept together with Canada balsam, which is a natural resin. There are more than 40000 slides and thousands of raw samples in the collection (Lazarus 1998, Lazarus & Jahn 1998). Of great interest is the collection of 3000 original drawings, which are superb illustrations of the microfossils drawn by C.G. Ehrenberg many of them further used in publications (Fig. 6). The specimens themselves may be studied by specialists, but the photographs of the trays with mica slides and drawings collection are available online on the museum's website thanks to a laborious curatorial work. The collection of C.G. Ehrenberg witnesses for the innovative work necessary for the birth of micropaleontology as distinct branch of paleontology.

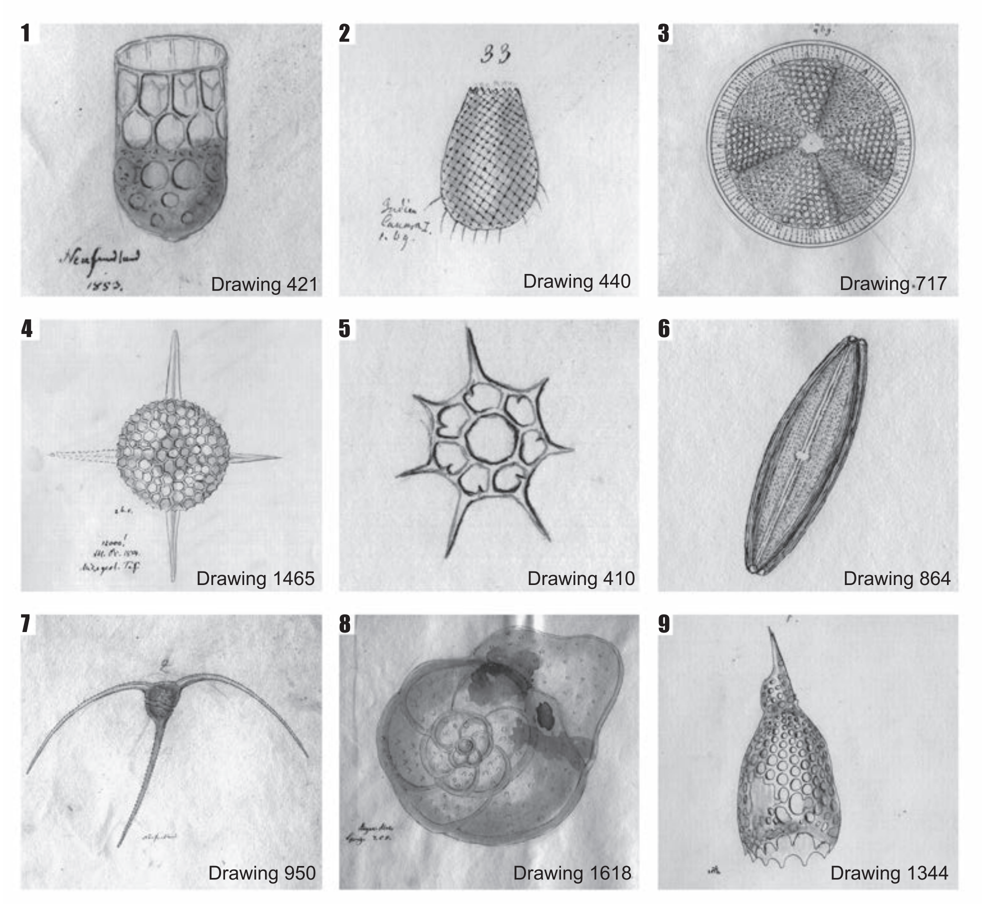

Fig. 6. Examples of microfossil drawings from the Ehrenberg Collection at the Museum of Natural Sciences, Berlin; published with permission. No scale is implied.

2.3 Studying microfossils

The study of microfossils begins with the disintegration of the micropaleontological samples, which are chunks of rocks collected from cropping out rocks or cores and side walls from drilling boreholes. Samples are processed differently according to the nature of the microfossil chemical and mineralogical composition; for example the calcitic microfossils are mostly or completely destroyed if the sample is disintegrated with acids. Sometimes it is quite difficult if not impossible to extract the microfossils from a sample of indurated rocks as most of the limestones are; in such cases the fossil content is studied in thin sections, which are produced by polishing a rock down to a thickness at which light can pass through it. Extensive presentation of the different microfossil extraction methods are given in general in specialized works (Kummel & Raup 1965).

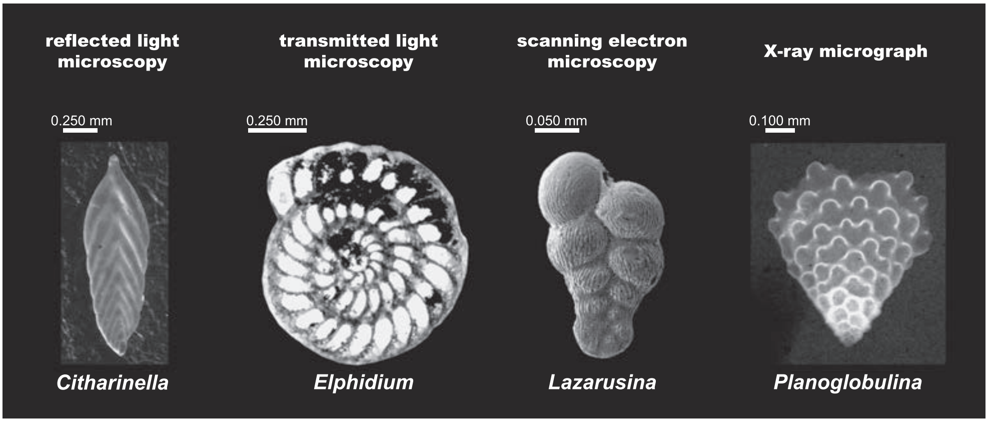

Fig. 7. Examples of microfossil illustrations through the most frequently used four study methods.

Once the microfossils are extracted they can be studied using a variety of techniques. Four of the most frequently used are: reflected light microscopy, transmitted light microscopy, scanning electron microscopy and X-ray micrographs (Fig. 7). These methods can be used separately or in combination of two, three or all of them. They are complementary and provide observation data that can be further used in classification and applied micropaleontological studies.

Reflected light microscopy implies the use of the classical optical stereomicroscope. In this technique the light source is situated above the sample which it illuminates; the principle of the method was given by H.S. Greenough in the last years of the nineteenth century. The most significant limitation is the low magnification factor, which is of maximum X300; in micropaleontology the most frequently used magnification factors are up to X20, occasionally X40. Reflected light microscopy is extensively used in the case of the microfossils detached from the rocks and presents the major advantage that the microfossils can be oriented, one operation that is commonly realized with the aid of a wet brush. Therefore, the method allows a thorough examination of the microfossil morphology and is recommended for those groups in which a highly accurate identification requires the observation of morphological features in two, three or more views (e.g., foraminifers, ostracods, etc).

Transmitted light microscopy is a method in which the light source is situated below the studied specimen and therefore, light literally passes through the specimen. The method implies the use of an optical microscope and is strongly limited to transparent samples; an opaque specimen cannot be investigated using this method. It is the oldest microscopy technique: it was invented in the second half of the sixteenth century by Z. Jensen and adapted to the study of microorganisms by A. van Leeuwenhoek circa half century later. Notably, van Leeuwenhoek discovered with its aid the single-celled organisms and this discovery is considered a milestone in the history of science; micropaleontology could not have existed without this discovery. The magnification factor used in micropaleontology is in general of X2 to X20 but the method itself allows magnifications of up to X1000. Transmitted light microscopy is extensively used in the study of microfossils preserved in indurated rocks from which they cannot be extracted, and is a standard in the case of those that occur in carbonate rocks and archived in Canada balsam between mica or glass slides from older collections, such as the samples from the Ehrenberg Collection. The most significant limitation of the method is that the specimens cannot be oriented and are studied in a single view. Moreover, in the case of thin sections much if not most of the morphological features of the microfossils are lost through grinding.

Scanning electron microscopy for which the acronym SEM is frequently used is the method through which the highest resolution in the study of microfossils can be achieved. Detached specimens are studied in the vast majority of cases, but it can also be applied to samples containing small sized microfossils that cannot be observed with the classical optical stereomicroscope (e. g., diatoms, silicoflagellates, etc). The specimens are usually coated with a thin film of metal (e. g., gold, platinum, palladium, iridium, etc or alloys of them) then they are scanned with a focused beam of electrons that interact with the coated microfossil producing different signals, which are further used to produce a micrograph of the microfossil architecture based on the surface relief. The SEM method has a variety of techniques derived from it that use its basic principle. The principle of the scanning electron microscope as we use today was given by von Ardenne in 1938 (Bogner et al. 2007). The method started to be used extensively in micropaleontology in the late 1960s. Scanning electron microscopy is frequently used in micropaleontology at a magnification factor of X30 to X500, but the method allows magnifications of up to X100000. This is the most used technique in the observation of the high-resolution morphological features of certain microfossils; for example, ornamentation of the silicoflagellate skeletons. Notably, the developments of an evolutionary classification framework in Cretaceous planktic foraminifera are direct results of the extensive use of the SEM. The only limitations of this method are that it is time-consuming and presents reduced possibilities of specimen reorientation.

More rarely used is the X-ray technique. This is applied only in some groups such as foraminifera in order to make accurate observations on the chamber arrangement and growth patterns. It was most frequently used to fundamental studies based on detached microfossils; specimen reorientation is possible but rarely performed.

2.4 Microfossil classification

The basic classification of microfossils is essentialist but there are more than one perspective in the general classification of the living and fossil organisms in the field of micropaleontology. In general paleontologists acknowledge the existence of five kingdoms: Bacteria, Protista, Fungi, Plantae and Animalia (Fig. 8). A sixth kingdom that includes the viruses, which are organisms that never evolved mineralized structures, is known only as living organisms and has not a fossil record. Notably, some modifications to this general framework are necessary and the most apparent of them is the use of superphylum Lophophorata including the phyla Phoronida, Entoprocta, Brachiopoda and Bryozoa; the superphylum rank does not occur in the classification adopted for this work (Anderson 1993). In addition, the phylum rank is maintained only for Animalia and animal-like Protista, whereas the division rank is used for the representatives of Bacteria, Plantae and plant-like Protista at the same taxonomical level; this traditional scheme contrasts to that of the adopted classification where the phylum rank was used throughout the six kingdoms of life.

The units of the essentialist classification are extensively used in micropaleontology for several reasons. Probably the most important of them is that such classification is

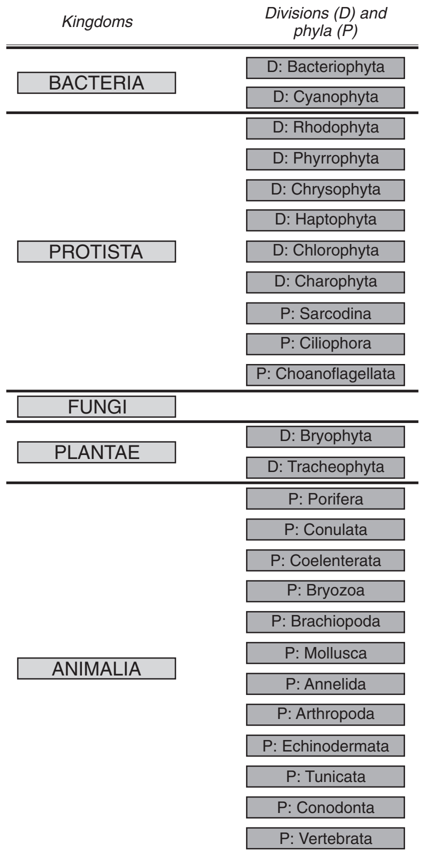

Fig. 8. Basic classification framework of the life forms on Earth (Anderson 1993; with modifications). Abbreviations: D-division, P-phylum.

relatively easily to build based on what can be considered taxonomically significant features. In addition to this, once the classification framework is realized specimens can be quickly assigned to the respective units. With such qualities it is evident that the essentialist classification can be readily used in practical studies such as biostratigraphy, paleobiogeography, paleoecology, etc. But the essentialist classification units are not necessarily evolutionary units and this means that the species of one genus are not necessarily related through ancestor-descendant relationships. Moreover, as we look at higher levels of classification there are even smaller chances for the genera of one family to be related by direct ancestor-descendant relationships, and the chances further decrease in the case of orders within a class, etc. The main cause of such settings is that taxa are grouped only according to morphological similarities and through convergent evolution similar structures often occur in distant lineages. Practically it appears impossible to evaluate where exactly the morphological resemblances resulted from either direct decent or evolutionary convergence. Such considerations are necessary because one of the major goals of the classification methodologies is to define natural groupings of taxa and the ancestor-descendant relationships confer such an objective character to a method. This classification problem is approached differently by scientists. Some consider that refining the essentialist classification framework is possible through the definition of units that can be arranged in a succession according to the ancestor-descendant relationships between them; such a taxonomic project requires nomenclatural experimentation and this comes in contradiction with the internationally accepted rules that govern the essentialist classification and are basically designed to assure nomenclatural stability. A second methodology is to develop distinct classifications: one to remain essentialist in nature and be used for applied studies and quick reference and one, which is the evolutionary classification, that uses taxa groupings based on ancestor-descendant relationships; the development of an evolutionary classification framework requires a high-quality fossil record and there is only a small number of fossil groups that can fulfil such requirement. However, the two methods do not exclude each other because two classifications based on the thorough application of the scientific method and providing different perspectives on the groupings of life forms cannot be regarded as antagonistic.

One question that was often asked especially by specialists in the fields of applied micropaleontology is why evolutionary relationships are necessary? The answer to this question resides in the complexity of the field of study of micropaleontology, which cannot be considered restricted to applications.

Numerical taxonomy is a classification method used especially by biologists and also a smaller number of paleontologists. According to this method the degree of resemblance can be quantified and these numerical values are sufficient to recognize evolutionary relationships between taxa; this premise is not always true. In addition, the transformation of the extremely complex evolutionary process, which is a process with a high number of variables that fluctuate simultaneously, into a simple quantitative analysis, is a fundamental error. Acceptance between the numerical taxonomy users plays an important role in the method's propagation but this cannot hide the absence of true scientific results in deciphering the evolution of life on Earth. The application of numerical taxonomy resulted in the development of a large number of high-rank units, such as regna, phyla, classes, etc and units without a classification rank (Cavalier-Smith 1998, 2004, Adl et al. 2005, 2012); they cannot be considered evolutionary units unless evidence to demonstrate that the claimed ancestor-descendant relationships exist in reality.

The essentialist classification is thoroughly use herein. At introductory level in micropaleontology this method of classification can set the stage for a clear understanding of the microfossil groups and morphological differences that separate them. It is evident that a classification based on the ancestor-descendant relationships is preferable to the essentialist one at higher levels, namely those of graduate student, industry professional and specialist. It should be taken in consideration the fact that the development of evolutionary classification at a relevant scale appears today a distant goal, and the use of numerical taxonomy and branches derived from it can only result in a collapse of the scientific standards of any work.

2.5 Micropaleontological data: sources and nature

Scientists use a variety of data in the field of micropaleontology. The basic data classification is according to source. As the science name indicates it, most of the data are collected from microscopical fossils; the name “micropaleontology” is derived from four

Greek words: *mikros* = small, *palaios* = old or ancient, *ontos* = being and *logos* = reason or in a more general sense, science. From this perspective, micropaleontology is a subdiscipline of paleontology.

Living microorganisms are studied by micropaleontologists and neontologists, the latter as part of biology and genetics. Some of these microorganisms are known only from living microfloras and microfaunas, and a wide array of groups with living representatives are also known from the fossil record. In such cases the micropaleontological data, which focus on the microorganism parts that can occur in the fossil record, are correlated and used in concert with data from biology and genetics. Mostly micropaleontological data are used in the case of microorganism groups that occur only as fossils. This is because genetical data are not available in the case of extinct organisms, and biological data can be only extrapolated according to the Principle of Actualism; such extrapolation of the data and interpretations from the living species to the extinct ones are not always successful. There is not a standard method of interpretation of the data from these three disciplines of natural sciences (micropaleontology, biology and genetics), and in general a certain emphasis is put on any of them according to the field of expertise of the specialist that realizes the study.

Another fundamental classification of the micropaleontological data is according to their nature: qualitative and quantitative. Most of the data are qualitative. For example, the shape of one feature can be described as circular, elongate, elliptical, rectangular, subrectangular or polygonal, with direct reference to a geometrical shape or form. When numerical data are obtained by measuring or counting certain morphological features, the data become quantitative. Interpretation of both qualitative and quantitative data in micropaleontology requires extreme care due to the incompleteness of the fossil record. Overcoming the effects of fossilization and sampling that are the main factors in biasing the fossil record, requires a high level of training. Practically, is necessary to evaluate the effects of four kinds of morphological variability that can be apparent in one fossil organism and across an assemblage: ontogenetic (changes during growth during the life cycle), genetic (occurrence of one, two or more morphologies in one single species), ecological (determined by ecological factors such as suprapopulation, amount of nutrients, etc) and evolutionary (resulting from the evolutionary descent of one taxonomic unit). Semi-qualitative or semi-quantitative data are relatively rare, and occur only in cases where descriptive terms are superimposed on numerical ranges obtained through the measurement of a certain morphological feature.

Data acquisition and interpretation in micropaleontology is realized only through scientific method and in the light of the principles of science. In general, the works of micropaleontology include a distinct and often extensive part in which the primary data are presented and methods used in their acquisition described. One method was developed in the last two decades in some international journals as the studies gradually increased in complexity; the method implies the presentation of the primary numerical data as an online resource, separate from the body of the article. In this way the authors provide the primary data for the use by other specialists that share the same interest in a certain field of micropaleontology.

2.6 Elements of biostratigraphy

Microfossils and their distributions in space and time together with their relationships with the organic and inorganic paleoenvironments have a wide variety of applications