APPLIED STRATIGRAPHY

TOPICS IN GEOBIOLOGY

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Applied Stratigraphy

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Inserts:
Thin section of fossil wood showing false and true growth rings, Irati Formation (Upper Permian), *Fig. 9.1A of L. S. R. Alves and M. Guerra-Sommer, photo by L. S. R. Alves.*

Trace fossil association characteristic of the Teredolites ichnofacies, *Fig. 13.4 by S. George Pemberton and James A. MacEachern.*

Center:
GEOLOGY AND PALAEONTOLOGY, Vincent Brooks Day & Son, Lith., by Duncan, Peter Martin (editor), 1896, Cassell's Natural History, 6 vols. in 3, London, ca. 380 p., 26 cm, wood-engraved plate, *photo by E. A. M. Koutsoukos.*

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"Indeed, what is there that does not appear marvelous when it comes to our knowledge for the first time? How many things, too, are looked upon as quite impossible until they have been actually effected?"

Pliny the Elder (23 AD - 79 AD), Natural History.

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"Let us suppose that an ichthyologist is exploring the life of the ocean. He casts a net into the water and brings up a fishy assortment. Surveying his catch, he proceeds in the usual manner of a scientist to systematise what it reveals. He arrives at two generalisations:
(1) No sea-creature is less than two inches long.
(2) All sea-creatures have gills.
These are both true of his catch, and he assumes tentatively that they will remain true however often he repeats it.

In applying this analogy, the catch stands for the body of knowledge which constitutes physical science, and the net for the sensory and intellectual equipment which we use in obtaining it. The casting of the net corresponds to observation; for knowledge which has not been or could not be obtained by observation is not admitted into physical science.

An onlooker may object that the first generalisation is wrong. "There are plenty of sea-creatures under two inches long, only your net is not adapted to catch them." The icthyologist dismisses this objection contemptuously. "Anything uncatchable by my net is *ipso facto* outside the scope of icthyological knowledge. In short, "what my net can't catch isn't fish." Or--to translate the analogy--"If you are not simply guessing, you are claiming a knowledge of the physical universe discovered in some other way than by the methods of physical science, and admittedly unverifiable by such methods. You are a metaphysician. Bah!"

Sir Arthur Eddington (1882-1944), *The Philosophy of Physical Science,* Ann Arbor Paperbacks, The University of Michigan Press, 1958, p. 16.

Contents

Aims & Scope *Topics in Geobiology* Book Series

Topics in Geobiology series treats geobiology – the broad discipline that covers the history of life on Earth. The series aims for high quality, scholarly volumes of original research as well as broad reviews. Recent volumes have showcased a variety of organisms including cephalopods, corals, and rodents. They discuss the biology of these organisms – their ecology, phylogeny, and mode of life – and in addition, their fossil record – their distribution in time and space.

Other volumes are more theme based such as predator-prey relationships, skeletal mineralization, paleobiogeography, and approaches to high resolution stratigraphy, that cover a broad range of organisms. One theme that is at the heart of the series is the interplay between the history of life and the changing environment. This is treated in skeletal mineralization and how such skeletons record environmental signals and animal-sediment relationships in the marine environment.

The series editors also welcome any comments or suggestions for future volumes.

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Foreword: The Age of Applied Stratigraphy

Few, if any, fundamental disciplines in the Earth Sciences have seen so many dramatic changes and developments as stratigraphy. Its beginnings can be linked to the very earliest human observations of Earth processes, and to philosophical enquires and speculations about the nature of natural phenomena.

Nearly 200 years ago, William Smith studied fossils collected from successive levels of sedimentary strata, and enunciated the first major principle of stratigraphy by stating "the deeper, or lower, layers of rock must be older than the layers of rocks which lie above them." Subsequently, the discipline has come to be applied progressively, and indispensably, to nearly all branches of the Earth Sciences: ranging among such diverse studies as the meticulous investigation of archeological sites, the geological evolution of sedimentary basins, the study of ancient ecosystems, and the origin and evolution of life.

Applied stratigraphic researches have increased spectacularly during the last decades of the 20th century, especially in response to intensive exploration and exploitation of mineral- and hydrocarbon-bearing sedimentary sequences conducted globally in both continental and marine settings. In particular, the past two decades have witnessed a major renaissance in stratigraphy, through the integration of biostratigraphy, magnetostratigraphy, isotope stratigraphy, and seismic-reflection data within two entirely new disciplines, cyclostratigraphy and sequence stratigraphy.

Currently, at the beginning of the new millennium, international efforts are concentrating on the development of interactive, integrated stratigraphic databases that are to be made readily accessible to the international geoscience community via the internet. Such initiatives are vital steps in promoting global scientific cooperation, coupled with the dissemination of well-defined stratigraphic standards. Moreover, exciting opportunities and challenges for earth scientists will undoubtedly arise in ensuing decades from as yet largely unforeseen or unrealized innovations and new applications in cognate scientific fields.

This book aims to incorporate many of the major aspects and essential elements underpinning the modern applications and perspectives of stratigraphy. It focuses on traditional and innovative techniques and how these can be utilized in the reconstruction of the geological history of sedimentary basins and in solving manifold geological problems and phenomena. Each chapter reviews the historical background; includes a synopsis of study principles and methodology; and discusses recent developments and significant applications. These sections are followed by selected case histories that demonstrate the applications and efficacy of stratigraphic and related techniques.

Conceptually, the book consists of four parts. The introductory chapter *(Evolution of a Concept)* provides a historical background to the breadth and diversity of stratigraphic studies, whose roots lie at the very origin of all Earth Science. The second part *(The Search for Patterns: Ordering the Framework)* commences with an overview of chronostratigraphy as applied to the study of regionally extensive stratigraphic sections.

The subsequent chapters review and elucidate current paleontological applications in biochronostratigraphy, event stratigraphy, paleoenvironmental syntheses, and paleobiogeographic reconstructions of Phanerozoic marine and continental sedimentary basins, thus providing insights into ancient ecosystems and their evolution through geological time. The third part *(The Search for Clues: Analyzing and Sequencing the Record)* presents comprehensive and authoritative surveys of diverse geoscience disciplines applied to the analysis of the stratigraphic record, including correlation, paleoclimatic and paleoenvironmental reconstructions, sequence stratigraphy, cyclostratigraphy, and "biosteering." The fourth part *(Modelling the Record)* discusses the development of quantitative stratigraphy and graphic correlation techniques, both of key importance to the refinement of chronostratigraphic frameworks as these pertain to interactive stratigraphic databases and basin modelling.

Stratigraphy has evolved and matured to constitute the most multifaceted and complex of disciplines within the Earth Sciences, with data deriving from and contributing to an impressive array of geological and paleobiological researches, both applied and "pure." These include such endeavours as charting the course and complexities of the evolution of life through time, understanding how ancient ecosystems developed and operated, and furnishing data pivotal to strategic mineral exploration. It is hoped that this book will provide the reader with key insights into all these aspects and applications. Supplemental reading can be found in the extensive reference lists.

Rio de Janeiro
May 2004

Eduardo A. M. Koutsoukos

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Part I

Evolution of a Concept

Chapter 1

Stratigraphy: Evolution of a Concept

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1.1 Introduction

Stratigraphy, from the Latin *stratum* and the Greek *graphia*, is the study of rock successions and the correlation of geological events and processes in time and space. It is a fundamental science of all geological studies, allowing to reconstruct the sequence of events of Earth history, and the evolution of life on Earth.

Stratigraphy is a science as old as philosophy itself, originated with the early observations by the ancients of Earth's natural phenomena and their philosophical speculations on the nature of Earth's structure and processes. From Central Asia to Greece, to Egypt, different views were adopted among the various ancient civilizations according to their individual perception of the natural world, and tied to the prevailing religious

E.A.M. Koutsoukos (ed.), Applied Stratigraphy, 3-19.

and philosophical doctrines and myths. The Chinese regarded the Earth as eternal and immutable; to the Indians it changed according to infinite cycles of creation of the universe. To the Western cultures, particularly the Greeks, the Earth was continuously changing over time, and its processes were controlled by natural laws. In that scenario powerful enquiring minds established the foundations of the scientific method of investigation by careful observation of the physical world and related natural phenonema, and tended to treat scientific theories as extensions of philosophy.

1.2 The Ancient Greeks and Romans: The Naturalism

The major contribution of the early observations made by the ancient Ionian philosophers on the Earth's structure and processes is that they were attributed to natural phenomena and not to supernatural causes. However, many of the ideas expressed by the ancients on the natural history of the Earth were not to resurface until the Renaissance.

The term "fossil" comes from the ancient Latin *fossilis*, meaning virtually anything dug from the Earth. Thus, originally it was used to indicate not just "fossils" that resembled living organisms, as we would define them today, but also minerals, crystals, rocks, and even geological strata. At those early times two hypotheses had been proposed for the origin of "fossils" that resembled living organisms. According to the Greek philosopher Aristotle (384–322 B.C.), precursor of the inorganic theory for the origin of fossils, forms resembling extant organisms present in rocks were produced by a "formative force" (*vis formativa*), i.e., produced by natural causes imitating living shapes which naturally grew in the rocks. Aristotle's thoughts on Earth sciences can be found in his treatise *Meteorology*, where he discusses the nature of the Earth and the oceans.

However, the organic view of the origin of fossils, that is the idea that they were indeed the remains of once living beings, appeared even before Aristotle. In the 6th and 5th Century B.C. both Pythagoras (ca. 582–ca. 507 B.C.) and Herodotus (ca. 484?–425? B.C.) mentioned marine shells which occurred in mountains and on land places far from the sea, arguing these to be the remains of organisms which once thrived in former seas that later withdrew and became land. Herodotus thought the disc-shaped nummulitid foraminifera (genus *Nummulites*) found in the Eocene limestones of which the Sphinx and the pyramids of Egypt were built, were lentils fed to the slaves who built the pyramids which had accidentally spilled and turned to stone. The Greek Xenophanes of Colophon, Ionia (ca. 570–ca. 480 B.C.), a pre-Socratic Greek philosopher and Pythagorean, reported the occurrence of marine fossils on mountain tops and quarries. For Xenophanes this was proof that the physical arrangement of the Earth changes with time, and that the remains of extant forms were buried in the dried sea mud owing to the blending of land and sea in ancient times.

The Romans assimilated the more practical scientific accomplishments of the Greeks, but added little. Pliny the Elder (Caius Plinius Secundus; ca. 23–79 A.D.), Roman naturalist and encyclopedist killed by the eruption of the Vesuvius on 23–25 August 79 A.D., wrote a major encyclopedia of natural sciences (*Historia naturalis*). Pliny's compilation consisted of 37 volumes and contained a summary of ancient knowledge on the nature of the physical universe, a work mostly summing up what the ancient Greek authors had written. In the early centuries after Christ the idea of the organic origin of fossils took root and spread, although in different form with respect to the early Greeks. According to the Roman Carthaginian, theologian and Christian apologist Tertullian (Quintus Septimius Florens Tertullianus; ca. 155–222) fossil shells found in the mountains were proof of the Universal Flood described in the Old Testament. Both the controversy between the organic and inorganic views and the *Universal Flood* theory would survive until the beginning of the 18th Century.

With the collapse of the Roman Empire in the 5th Century and the coming of the Dark Ages, many of the ancient scientific works passed into the hands of the Muslims, who by the 7th and 8th Century had extended their influence through much of the world surrounding the Mediterranean. All of the Greek works were translated into Arabic, and commentaries were added. The Arabs thus preserved the scientific works of the ancients and added to them, introducing also other contributions from Asia. This body of learning first began to be discovered by Europeans in the 11th Century.

1.3 The Middle Ages and Renaissance: The Principles

During the Middle Ages and the Renaissance, the Aristotelian School, through a Muslim, the Persian philosopher and physician Ibn-Sina (Avicenna, 980–1037), influenced many European scholars who attributed the occurrence of fossils to failed abortive attempts of a natural creative "plastic force" *(vis plastica*, or *virtus formativa)* to shape living beings in a process of spontaneous generation of life.

The scientist, philosopher, and theologian Albertus Magnus (ca. 1206?–1280), born at Lauingen, Swabia, and later Leonardo da Vinci (1452–1519), were the first to correctly speculate on the nature of fossils as the remains of once-living ancient organisms. The *Leicester Code* is a collection of numerous manuscripts with handwritten notes of Leonardo's scientific and technical observations. Among them there are drawings of rock formations and of various fossil shells (mostly Cenozoic mollusks), which are probably recollections of his experiences and observations on the hills of Tuscany, Romagna or the Po River plain, during his service as an engineer and artist at the court of Lodovico Sforza, Duke of Milan, from 1482 to 1499. From his notes Leonardo appears to have noticed the mechanisms of sedimentary deposition on mountains and rivers, the role that rivers play in the erosion of land, and the principles of the law of superposition, which would later be demonstrated fully by Nicholaus Steno in 1669. He also appear to have grasped that distinct layers of rocks and fossils could be traced over long distances, and that these layers were formed at different times. After Leonardo's death his notes were scattered to libraries and collections all over Europe. While portions of Leonardo's technical treatises on painting were published as early as 1651, the scope and caliber of much of his scientific work remained unknown until the 19th Century. Yet his geological and paleontological observations and theories foreshadow many later breakthroughs. Nearly three hundred years later, the rediscovery and elaboration of these principles would make possible modern stratigraphy and geological mapping.

Georgius Agricola, latinized form of Georg Bauer (1494–1555), a physician and geologist born in Glauchau, province of Saxony, made fundamental contributions to stratigraphic geology, mineralogy, structural geology, and paleontology. His greatest work, *De Re Metallica* ("On the Nature of Metals"), posthumously published in 1556, is a systematic study of ore deposits and of strata, and was to remain the standard text on mining geology for two centuries. In his profusely illustrated book Agricola noted that rocks were laid down in definite layers, or strata, and that these layers occurred in a consistent order and could be traced over a wide area. Agricola's observations would become important in understanding the arrangement and origins of the rocks of the Earth. Agricola is considered the founder of geology as a discipline.

In the mid-16th Century the first engravings of fossils were published by the Swiss physician Conrad Gessner (1516–1565).

Nicholaus Steno, latinized form of Niels Stensen (1638–1686), a Danish anatomist and geologist, who in Italy was converted to Roman Catholic faith and became a Roman Catholic prelate, pointed out the true origin of geological strata and of fossils. He wrote the first real geological treatise in 1667, while living in Tuscany, Italy. In 1669 he was the first recorded person to apply to the study of a sedimentary rock outcrop what is now referred to as **Steno's law of superposition** (which states that layers of rock are arranged in a time sequence, with the oldest on the bottom and the youngest on the top, unless later processes disturb this arrangement), his most famous contribution to geology. In addition, Steno postulated other general principles of Stratigraphy: the **principle of original horizontality**, which states that rock layers form in the horizontal position, and any deviations from this position are due to the rocks being disturbed later; and the principles of **strata continuity** (material forming any stratum was continuous over the surface of the Earth unless some other solid bodies stood in the way) and **cross-cutting relationships** (if a body or discontinuity cuts across a stratum, it must have formed after that stratum). The data and conclusions of Steno's work on the formation of rock layers and fossils were crucial to the development of modern geology, and were enough to have earned him the title of "Father of Stratigraphy".

Steno's contemporaries, the British natural scientists John Ray (1628–1705), Robert Hooke (1635–1703) and John Woodward (1668–1728), also argued that fossils were the remains of once-living animals and plants. However, the opinion was still universal that fossils represented life destroyed by the Universal Flood, a theory championed especially by the Swiss naturalist Johann Jakob Scheuchzer (1672–1733). Robert Hooke was perhaps the greatest experimental scientist of the seventeenth century. He was the first person to examine fossils with a microscope, to note close similarities between the structures of fossil and living wood and mollusc shells, and to observe, two and a half centuries before Darwin, that the fossil record documents the appearance and extinction of species in the history of life on Earth. Hooke believed that the Biblical Flood had been too short in time to account for all fossils, and suggested that earthquakes had likely destroyed ancient life forms. John

Ray always supported the theory that fossils were once living organisms, buried in liquid rock that then cooled, but was reluctant to accept the idea of extinction, explaining that fossils which did not resemble any living organism were due to our ignorance of the full range of extant forms. Ray expressed fully his belief in the "natural theology" view of studying the natural world as God's creation, a doctrine which remained influential for well over a century after his death. John Woodward related fossils to specific rock formations and atempted to classify them. In 1695 he published *Essay Toward a Natural History of the Earth*, which advanced a theory to explain stratification and the fossils embedded in them by the deposit of debris out of the Flood.

1.4 The Eighteenth and Nineteenth Centuries: The Dilemma of Catastrophism *versus* Uniformitarism and Gradualism

At the beginning of the 18th Century the organic nature of fossils as remains of ancient beings was decisively established, and the inorganic theory abandoned. However, the Biblical Flood theory persisted up to the threshold of the 19th Century.

The Swiss naturalist Charles Bonnet (1720–1793) in his work *Principles of Catastrophism*, suggested that at periodic intervals throughout Earth's history all living things have been destroyed by catastrophes or cataclysms (e.g. floods or earthquakes) and they accounted for fossils. He thought that after each catastrophe life forms would be replaced by an entirely different changed population, and that all creatures would rise one level, so after a future catastrophe man would be angels and apes, man. Bonnet was the first to use the term *evolution*. Catastrophism is becoming more actual now that the various Ediacaran, latest Ordovician (Hirnantian), Permian–Triassic, and Cretaceous-Paleogene boundary mass-extinction events are better understood.

The theoretical foundation for much of modern geology was postulated by the Scottish geologist James Hutton (1726–1797) in his *Theory of the Earth* (1795), where he stated that "the Earth must be millions of years old". He first advanced the basic concept of what became known as the Uniformitarian Principle, which holds that the geologic forces and processes that shaped the Earth in the geologic past were referrable to the same ones still in operation on the Earth's surface and could be observed directly. Hutton believed that igneous processes were the chief agent in rock formation, thus representing the Plutonist (or Vulcanist) view, i.e., that some rocks had formed from molten magma either deep in the Earth or from volcanoes. In contrast the so-called Neptunist view maintained that the origin of all rocks was aqueous, related to a primeval ocean and its subsidence, and thus began the Neptunist–Plutonist controversy. In 1751 the French geologist, botanist, and natural historian Jean-Étienne Guettard (1715–1786) was the first to recognize the volcanic nature of the Puy de la Nugère and the lava flow descended from it near Volvic, as well as some seventeen other neighboring volcanic craters and domes in the Auvergne region, central France, and thus became the first known Vulcanist and founder of the school, though years later he proposed that basalt originated as a precipitate out of an aqueous fluid. This controversial Neptunist theory was supported by the German geologist Abraham Gottlob Werner (1750–1817), and also by the German lyric poet, novelist, dramatist, and scientist Johann Wolfgang von Goethe (1749–1832). Werner, who first demonstrated the chronological succession of rocks and the concept of the geological time scale, believed that rock strata were either sediments originally deposited at the bottom of the sea or were crystallized deposits precipitated from sea water, but could not explain the origin of insoluble igneous rocks. Goethe and the German writer Friedrich von Schiller (1759–1805) satirized attempts of attributing basalts in Germany to volcanoes, seeing in this a patriotic attempt to equal Italy; Goethe also satirized the Vulcanist theory in his drama Faust (1808), attributing mountain buildings to the parts of the devil. The Uniformitarian doctrine was further simplified and popularized by the British geologist John Playfair (1748–1819) in his *Illustrations of the Huttonian Theory of the Earth* (1802), which elucidated the methods and principles of uniformitarianism, establishing it as the foundation of the new science of geology.

William Smith (1769–1839), English engineer and canal builder, studied fossils collected from sedimentary rocks. He was the first to recognize the importance of fossils for the historical investigation of Earth's strata, and introduced the **principle of faunal succession**, that different sedimentary rock units contain distinct fossil assemblages. Smith noted that the sequence of fossils in any given stratigraphic record follows a specific order, as a result of evolution; and that the same sequence can be found in isolated strata elsewhere, and thus correlated between them. The principle is still applied today in biostratigraphic correlations, although within the limits of biogeographic distribution of index fossil species. Smith published the first large-scale geological map in 1814–1815, of southern England and Wales, using for the first time the principle of fossil succession as a tool for mapping rocks by their stratigraphic order, and not necessarily by their composition.

However, for most of the late 18th and mid-19th Century, as a consequence of apparently contradicting current religious beliefs (e.g. the accepted biblical chronology and the Flood), the uniformitarism doctrine was largely overshadowed by the opposite one of catastrophism, which also stated that during these catastrophic events the Earth's surface, such as mountains and valleys, would be shaped. Catastrophism was more easily correlated with religious doctrines, and as a consequence remained for some time the interpretation of the Earth's history adopted by the great majority of geologists. The French naturalist Georges L. Cuvier (1769–1832) was one of its major supporter. Cuvier suggested that four main worldwide catastrophes had occurred, the last one being the Biblical Flood. The taxonomic classification scheme introduced by the Swedish botanist Carolus Linnaeus (1707–1778) in his *Systema Naturae* (1735), was extended by Cuvier to fossils, which he recognized as organic remains of extinct animals. He is therefore known as the founder of paleontology as a science separate from geology. However, Cuvier rejected the theory of evolution and Jean-Baptiste Lamarck's (1744–1829) theory of inheritance of acquired characteristics, proposed in *Zoological Philosophy* (1809). He believed that new life forms would be created after periodic sea-level changes; in his view some animals died and some survived, but none evolved. In 1811 Cuvier wrote with the French geologist, mineralogist, and chemist, Alexandre Brongniart (1770–1847), the work *Essai sur la géographie minéralogique des environs de Paris*, in which a system of stratigraphy was developed that relied on the use of fossils for the precise dating of strata, introducing into France William Smith's principle of faunal sucession and method of field work.

During the 1830's fossils were first recognized for use in age correlation of rocks by the German geologist and paleontologist Friedrich August Quenstedt (1809–1889) through his work on Jurassic "time-rock units" defined by ammonites. Quenstedt recognized the base unit, the biostratigraphic "zone", characterized by a particular assemblage of fossils. By the late 1830s, most of the presently known geologic periods had been established based on their fossil content and their observed relative stratigraphic position (see Fig. 1.1, and Moore, 1955, for a review). The twofold modern subdivision of the Cenozoic Era (from the Greek word kainos: recent) in Paleogene and Neogene (from palaeos: ancient, neos: new, and genos: birth/born) goes back to combination of subdivisions proposed by C. Lyell (1833), R. Hoernes

Era	System	Author & Year	Place first recognized
Cenozoic	Neogene	Hoernes, 1853	Austria
	Paleogene	Hoernes, 1866	Austria?
Mesozoic	Cretaceous	J.J. D'Omalius d'Halloy, 1822	France
	Jurassic	Alexander von Humboldt, 1795 Leopold von Buch, 1839	France, Switzerland, Germany, England
	Triassic	Friedrich August von Alberti, 1834	Germany
Paleozoic	Permian	Murchison, 1841	Russia
	Carboniferous	W.D. Conybeare and W. Phillips, 1822	Northern England
	Devonian	Murchison and Sedgwick, 1839	Southern England
	Silurian	Roderick Impey Murchison, 1835	Welsh Borderland
	Ordovician	Charles Lapworth, 1879	Wales
	Cambrian	Adam Sedgwick, 1835	North Wales

Figure 1.1 Phanerozoic systems and their original definitions.

(1853), and C. F. Naumann (1866) – the terms Tertiary and Quaternary are no longer recommended, as being antiquated like Primary and Secondary, all described by Giovanni Arduino, in northern Italy, in the 1760's.

Cuvier's successors, as d'Orbigny, Agassiz, and Barrande, still maintained the catastrophic theory well into the 19th Century. The naturalist and paleontologist Alcide Dessalines d'Orbigny (1802–1857) published in 1850 *"Prodrome de Paléontologie stratigraphique universelle"*, a major treatise comprising a catalogue list of 18,000 fossil species, and proposed a subdivision of the geological record in 27 stages. His most important work was the founding of the science of stratigraphic paleontology based on observations of exposed fossil-bearing strata in the Paraná Basin, southern Brazil, reported in his work *Voyages dans l'Amerique méridionale*, published in several parts between 1835 and 1847. D'Orbigny's study of foraminifera, pollen grains and spores found in sedimentary rocks for the purpose of dating stages began the science of micropaleontology. The Swiss-American naturalist Jean Louis Rodolphe Agassiz (1807–1873) promoted and defended Cuvier's geological catastrophism and classification of living and fossil animals. His study of glaciers revolutionized geology. The French paleontologist Joachim Barrande (1799–1883) studied fossil remains and their distribution in the various strata in Bohemia. The results of his extensive studies on the Silurian system of Bohemia are contained in his great work *"Système silurien de centre de la Bohême"*, published in 22 volumes from 1852 to his death.

Uniformitarianism finally became widely accepted as a result of the work of the Scottish geologist Sir Charles Lyell (1797–1875), author of the three-volume *Principles of Geology* (1830–1833), published through 11 editions between 1830 and 1872, which presented and popularized James Hutton's work and uniformitarianism. The uniformitarian (uniformity of natural laws and geological processes) and gradualist (uniformity of rates) views expressed in Lyell's work probably influenced the formulation of Charles Darwin's (1809–1882) theory of evolution and facilitated its acceptance. Darwin's theory of evolution through gradual variation and natural selection was published in his revolutionary work *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* (1859), often abbreviated to *The Origin of Species*, which was a turning-point for the evolution theory and also greatly influenced Geology in the late XIXth Century. Lyell's Uniformitarism and Gradualism and Darwin's theory would dominate the Earth Sciences for nearly 150 years.

Darwin's theory explained Smith's principle of faunal succession which, combined with Steno's law of superposition, allowed the application of fossils to stratigraphic dating and correlation, and the modern conceptualization of the biozone in 1856 by one of Friedrich Quenstedt's student, the German stratigrapher Albert Oppel (1831–1865). Oppel devised a scheme to divide geologic formations into zones based on the overlapping stratigraphic range of two fossil species (defining what are presently known as Oppel Zones). The progressive establishing of locally defined biostratigraphic zonal schemes led to the rapid development of an improved relative time scale and the emerging of the standard subdivisions of the modern Chronostratigraphic Scale, which has been continuously refined since (e.g. Moore, 1955; Heirtzler *et al.*, 1968; Harland *et al.*, 1982, 1990; Berggren and Van Couvering, 1978; Berggren *et al.*, 1995b; Gradstein *et al.*, 1999; website of the International Commission on Stratigraphy – ICS/IUGS – www.stratigraphy.org).

1.5 The Twentieth Century & Beyond: The Age of Applied Stratigraphy

The history of stratigraphy during the 20th Century is largely the history of the individual specialized branches as they developed into the traditional and new techniques by which they are recognized today.

1.5.1 Plate Tectonics

The earliest hint of plate tectonics was made around 1800 by one of Abraham G. Werner's most famous student, the German naturalist and explorer Alexander von Humboldt (1769–1859). Humboldt first suggested that the South American and African continents had once been joined, as apparent in their complimentary coastlines, but this proposal was largely ignored by the scientific community of that time. It would not be until the early 20th Century, in 1912, when the German astronomer, meteorologist and geophysicist Alfred Wegener (1880–1930) published his first works (*Die Entstehung der Kontiente*, Petermanns Mitteilungen, 1912, pp. 185–195, 253–256, and 305–309; and a somewhat different version with the same title in Geologische Rundschau, Vol. 3, No. 4, 1912, pp. 276–292) outlining his theory of "continental drift". After 1912, Wegener's work was interrupted first by an expedition to Greenland and then by the First World War. In 1915 Wegener published the first edition of *Die Entstehund der Kontinente und Ozeane (The Origin of Continents and Oceans)*. In this book Wegener claimed that the continents had once been connected and formed a single supercontinent mass called Pangaea (from the Greek for "all the Earth"), about 300 million years ago, which had since split into pieces that have drifted to their present positions. As supporting evidence for the proposed theory Wegener noted the often matched large-scale geological features on separated continents, such as the close similarity of strata and fossils between Africa and South America and the close fit between their coastlines, and that fossils found in certain places often indicated past climates utterly different from today's. Wegener's revolutionary theory of continental drift took decades to win general acceptance among scientists, remaining controversial until the 1960's. For most of that lapse of time stratigraphy was to stand still, with no significant progress. In 1959 and 1962, Harry Hammond Hess proposed the sea-floor spreading or plate tectonics theory, subsequentely confirmed by Vine and Matthews (1963), which complemented Wegener's continental drift theory, and gave a much needed renewed impetus into the science of stratigraphy. Nevertheless, Wegener's basic insights remain sound nowadays and the same lines of supporting evidence are being continuously complemented and expanded by ongoing research.

1.5.2 Geochronology – Radiometric Stratigraphy

Geochronology, the science of absolute dating of rocks and determining the time sequence of geological events in Earth's history, particularly by radiometric dating, developed largely at the turn of the 20th Century and during its first three decades with the advent of atomic and nuclear physics and quantum theory (e.g. Holmes, 1911; see also Hole, 1998, for a review). It provided the framework of absolute time within which the relative chronostratigraphic scale could be calibrated.

1.5.3 Magnetostratigraphy

The work of Rutten (1959) presented a chronological scale of polarity reversals of the Earth's magnetic field based on K–Ar radiometric dating in a sequence of volcanic rocks, and gave birth to the new science of magnetostratigraphy. Harrison and Funnel (1964) discovered that magnetic polarity reversals (chrons) are also recorded in marine deposits, which further improved the applicability of the technique. Subsequent works aimed to match and calibrate the reversals with conventional stratigraphic tools (ISSC, 1979; Tarling, 1983; Galbrun, 1984), and use the unique non-periodic pattern of reversals to date and correlate diferent rock sequences. In combining the marine magnetic anomalies measured over the sea-floor record in the South Atlantic spreading profile with their dates of chrons on land, Jim Heirtzler and colleagues in 1968 laid the foundation for the modern timescale based on Cretaceous through Paleogene marine magnetic anomalies, also known as the Geomagnetic Polarity Time Scale (GPTS). The Cande and Kent (1995) GPTS is the currently accepted timescale that is in most widespread use.

1.5.4 Stratigraphic Classification, Terminology and Procedure

In 1976 the International Subcommission on Stratigraphic Classification (ISSC) of the International Commission on Stratigraphy (ICS) published the first edition of the *International Stratigraphic Guide* (edited by Hollis D. Hedberg), as a means to promote international agreement on the principles of stratigraphic classification, terminology, and rules of procedure. In 1983 the North American Commission on Stratigraphic Nomenclature proposed a version of the stratigraphic code, which expanded considerably its original scope. The standard international stratigraphic classification was finally approved in 1987 by the ISSC, and updated in 1994 in a second edition of the Guide (Salvador, 1994). An abridged version was published by Murphy and Salvador (2000), and made available on the ICS website. General comments on stratigraphic principles and procedures have also been presented by various authors, such as Reading (1978), Ager (1984), Blatt *et al*. (1991), and Whittaker *et al*. (1991), among others.

1.5.5 Facies Stratigraphy

The term and concept of stratigraphic facies (from Latin: appearance, aspect, face, form), meaning the combined lithological and paleontological characteristics of a stratigraphic section, were introduced in 1838 by the Swiss geologist and paleontologist Amanz Gressly (1814–1865) from his studies in the Jura Mountains. Gressly's pioneer contributions on the genesis and applications of sedimentary facies, stratigraphic correlations, and paleogeographic reconstructions are fundamental to modern stratigraphy (Cross and Homewood, 1997). Later in the course of the 19th Century the term was assigned to a variety of descriptive meanings by geologists, paleontologis and ecologists, which somehow confused the original definition. Facies analysis in the modern sense restored the concept to its original meaning, aiming at the description, interpretation and reconstruction of the depositional and paleogeographic setting of sedimentary units, combining lithological and paleontological data (Reading, 1978, 1996; Walker, 1979, 1992; Walker and James, 1992). It provides the basic framework to reconstruct the environmental evolution of the stratigraphic record through time (see Pirrie, 1998, for a review).

1.5.6 Quantitative Stratigraphy

Various graphical, numerical and experimental methods applied to refining stratigraphic resolution and basin modelling studies, have been continually developed since the 1960's (e.g. Shaw, 1964; Ager, 1973; Miller, 1977; Van Hinte, 1978, 1982; Gradstein *et al.*, 1985; Mann and Lane, 1995; Harbaugh *et al.*, 1999; Paola *et al.*, 2001). These techniques have jointly the greatest potential to achieve the finest biostratigraphic resolution possible in correlating different rock sequences, in studies of regional *versus* global correlation of geological events, in helping to reconstruct the geological history of sedimentary successions, and in petroleum reservoir correlation and modelling. The methods are greatly assisted by the universal adaptation of microcomputers to digital programming with colour graphics output.

1.5.7 Sequence Stratigraphy

Modern stratigraphy had a major impetus by the mid-20th Century, with the increase of petroleum exploration activities, the development of new technologies (e.g. of seismic reflection data in the 1970s) and the application of stratigraphic models to petroleum research (e.g. Sloss, 1962). In 1949 L. L. Sloss and coworkers coined the term sequence to represent a set of sedimentary cycles limited by unconformities. The notion of unconformity-bounded stratigraphic units received further support in the late 1950s with the works of H. E. Wheeler (1958, 1959a and b), who also introduced the concept of the chrono-lithostratigraphic chart. In 1963 Sloss consolidated the term stratigraphic sequence and its usage in regional chronostratigraphic correlations. These studies provided the basic framework to the later formulation of the sequence models, which was to incorporate the use of high-quality seismic-reflection data in modelling subsurface stratal patterns and general geometry, and the expected seismic reflection features of different lithofacies asssociations.

In a series of publications starting in the late 1970s, Peter Vail, coworkers and colleagues presented a revolutionary stratigraphic method of basin analysis for what became known as "Sequence Stratigraphy" (e.g. AAPG Memoir 26, edited by Payton, 1977; Vail, 1987; Van Wagoner *et al.*, 1987, 1988, 1990, 1991; Posamentier *et al.*, 1988, 1992; Posamentier and Vail, 1988; Vail *et al.*, 1991; Schlager, 1992; Walker and James, 1992; and Posamentier and Allen, 1994, among others). Sequence models constitute a powerful tool for unraveling basin-fill history, and as such have been applied to most stratigraphic studies of basin modelling. The method is based on the study of the relationships between global relative sea-level changes and large-scale sedimentary cycles within time-equivalent depositional successions bounded above and below by a significant gap in the stratigraphic record, i.e., by surfaces of erosion (unconformity-bounded units) or nondeposition. Suess (1906) was the first to propose that sea-level changes could be global. The global eustatic sea-level variation curve proposed by Vail *et al.* (1977a, b), and later refined by Haq *et al.* (1987, 1988) and Ross and Ross (1988), for the Phanerozoic sequences, was based on the approximate correlation of seismic sequences from a number of passive continental margins. In 1989 Galloway proposed the model of genetic sequences bounded by maximum-flooding surfaces, which implied a certain discrepancy with the unconformity-bounded depositional sequences of Vail *et al.* (1977a) and Van Wagoner *et al.* (1987), based essentialy on seismic stratigraphy. Galloway's approach, based mostly on sedimentological interpretation of depositional systems, facies relationships and geometries, is particularly significant in stratigraphic successions with little or no available seismic data, due to difficulties in marking and tracing regional unconformities.

Despite some controversies behind the main theoretical basis for the sequence stratigraphy paradigm (e.g. Miall, 1991, 1994, 1997), the method brought about a major revolution in the science of stratigraphy, leading to new research to be carried out on complex clastic and carbonate successions around the world. By gathering within a single stratigraphic framework information derived from diverse disciplines of sedimentary geology, such as seismic stratigraphy, biostratigraphy, paleoecology, paleogeography, and sedimentology, among others, the sequence models permitted a much broader, integrated and sharper research approach in basin analysis.

1.5.8 Episodic and Cyclic Sedimentation: Event Stratigraphy and Cyclostratigraphy

In the past decades of the 20th Century new theories developed in the geoscience community which represent a synthesis of Lyell's Uniformitarism and Gradualism combined with a revival of Cuvier's Catastrophism, recognizing that both play a significant role in geological processes and the evolution of life. Theories such as the *actualistic catastrophism* (Hsü, 1983), the *punctualism* (Gould and Elderedge, 1977; Gould, 1984; Goodwin and Anderson, 1985), and the *episodic sedimentation* (Dott, 1983), are fundamented on the assumption that most of the stratigraphic record was produced during episodic events, and that abrupt environmental changes have modulated speciation and mass extinctions (e.g. Signor and Lipps, 1982; Flessa, 1986; Hallam, 1989a, b). Major catastrophic events, such as extraterrestrial impacts (e.g. Alvarez *et al.*, 1980; McLaren and Goodfellow, 1990; Becker *et al.*, 2001) and cataclysmic volcanic activity (e.g. McLean, 1985; Courtillot, 2000; Wignall, 2001) are also thought to have greatly affected the evolution of life on Earth.

In 1982, G. Einsele and A. Seilacher discussed extensively the processes of cyclic and event sedimentation, introducing the principles of what would be later known as *Event Stratigraphy* (e.g. Kauffman, 1987, 1988; Walliser, 1996; Einsele, 1998). The method deals with the integrated study of episodic and short-term sedimentary and biotic processes in the stratigraphic record, and has the potential to improve substantially the resolution of geological correlations.

Rhythmic stratigraphic cycles observed in pelagic siliciclastic and carbonate sequences have been related to the so-called "Milankovitch cycles", after the Serbian astrophysicist Milutin Milankovitch (1879–1958) who in 1941 presented a firm mathematical basis that related periodic variations in Earth's rotational and orbital motions (eccentricity, obliquity, precession) to long-term climate changes. However, the hypothesis of astronomically forced climate cycles was advanced already in the 19th Century to the Pleistocene ice ages by the French mathematician Alphonse Joseph Adhémar (1797–1862), in his work *Les Revolutions de la mer* (1842), and by the Scottish geologist James Croll (1821–1890), who in the 1860's and '70s proposed an Astronomical Theory of the Ice Ages, subsequently published in his *Climate and Time* (1875) and *Climate and Cosmology* (1885). These orbital-forced cycles control the intensity of seasonal and latitudinal distribution of solar radiation (insolation) reaching the planet's surface, and directly influence global climate, depositional processes and biotic productivity (e.g. Fischer and Arthur, 1977; Bottjer *et al.*, 1986; Fischer, 1986, 1991; Schwarzacher, 1987; Fischer and Bottjer, 1991; Weedon, 1993; Satterley, 1996; Perlmutter *et al.*, 1998). The detailed investigation of regular cyclic patterns in the stratigraphic record produced by the interaction of tectonic and Milankovitch-type climatic processes is the study of a new branch of stratigraphy named Cyclostratigraphy (Schwarzacher, 1993; Fischer, 1993, 1995; Gale, 1998). The method allows a way for estimating the time span of biozones and the magnitude of unconformities, improvement of the stratigraphic framework, and for a better understanding of sedimentary and climatic processes (e.g. Perlmutter and Matthews, 1989, 1992). For instance, the modern Neogene timescale now depends on precise orbital tuning of marine and continental cyclic sequences, and evolved into an astronomically tuned (polarity) timescale (APTS), which proved to be far more precise and accurate (e.g. Hilgen, 1991a, b; Wilson, 1993; Shackleton *et al.*, 1995; Hilgen *et al.*, 1995; Zachariasse, 1999).

1.5.9 Chemostratigraphy

Chemostratigraphy is a relatively new technique, developed mainly during the last decade (e.g. Humphreys *et al*., 1991; Ehrenberg and Siring, 1992; Pearce and Jarvis, 1992, 1995; Racey *et al.*, 1995; Pearce *et al.*, 1999). It uses the primary geochemical variation in the whole-rock elemental composition of siliciclastic sediments and sedimentary rocks to correlate stratigraphic sequences, as well as to gather inferences on basin paleotectonic history, source rock lithologies, depositional pathways, and paleoclimates.

1.5.10 Isotope Stratigraphy (Sr, C, O)

Over the last decade there have been a substantial number of works concerned with defining the Sr isotopic evolution of the oceans during the Jurassic, Cretaceous and Cenozoic (see Hess *et al.*, 1986, and McArthur, 1998, for a review). Such a high-resolution Sr-isotope curve can be used as a global correlation tool and, over some intervals, have a stratigraphic resolution superior to that of biostratigraphy.

Recent research on isotope stratigraphy has also been forefront in defining and refining carbon- and oxygen-isotope curves for the Mesozoic and Cenozoic, based on the analysis of carbonate rocks and fossils and of terrestrial organic matter (e.g. Holser, 1984; Faure, 1986; Shackleton, 1985; Holser and Margaritz, 1989). The oxygen-isotope curve has been primarily used for estimating the Cenozoic record of water-mass temperatures (e.g. Frakes *et al.*, 1992; McCauley and DePaolo, 1997). When of characteristic shape and form, the carbon-isotope curve can be used for intercontinental correlation (e.g. for sections across the Cenomanian–Turonian boundary; Kuhnt *et al.*, 1990; Gale *et al.*, 1993; Pratt *et al.*, 1994), as well as to allow inferences on patterns of the long-term organic carbon cycle (e.g. Scholle and Arthur, 1980; Arthur *et al.*, 1985), and hence to indicate important periods of petroleum source-rock deposition.

1.6 Future Perspectives

The growth of applied stratigraphy in the 20th Century has been unprecedented. Whereas a particular problem might have been studied by a single investigator a century ago, or by a small group of scientists just a few decades ago, today such a problem is dealt in by a multidisciplinary legion of highly experient researchers.

In the foreseeable future stratigraphy holds out many promises, as well as a number of scientific problems. Research on isotope stratigraphy will include modelling strontium-, carbon- and oxygen-isotope variations determined from analysis of fossils in an attempt to understand significant oceanographic and other variables that have controlled the chemistry of ancient oceans. High-resolution chemostratigraphy will be used to improve stratigraphic correlation in barren siliciclastic beds and between continental and marine sequences, and to add important information to the reconstruction of a basin depositional history and paleoclimatic evolution. Cyclostratigraphy will involve the comparison of orbital time-series derived from different sequences in an attempt to improve the absolute resolution of the geological time scales, to identify and quantify the magnitude of gaps in the stratigraphic record, and to delineate paleoclimatic belts. Sequence stratigraphy will aim to document paterns of sequence development in conjunction with modelling studies at regional scale, as well as used in high-resolution studies applied to oil and gas reservoir correlation and modelling (e.g. Cross *et al.*, 1993). Advanced theorectical and experimental studies on fractal geometry and complexity theory will be applied to modelling of complex natural systems, such as ecosystems and anisotropies in oil and water reservoirs. Altogether, these studies will be complemented by the development of highly refined frameworks of biostratigraphy, paleoecology, and event stratigraphy, and further integrated into interactive chronostratigraphic and stratigraphic databases to allow global comparisons of sedimentary cycles and events on continental and marine sections, to analyse the relationship between environmental changes, biotic evolution and extinction, and to identify relationships between sea-level changes and major perturbations in Earth's climatic, oceanographic and sedimentary systems.

Among the many challenges faced by geoscientists are practical and critical ones, some of profound sociological implications, such as how to best explore and exploit Earth's natural resources, by attaining a sustainable development of human communities and simultaneousy preserve Earth's ecosystems' biodiversity. In this broad sense the science of stratigraphy has recently turned towards a more profound holistic non-traditional approach, by gathering information from nearly all disciplines in the geosciences to collectively aiming to provide an unified picture of Earth history. In a way similar to how its early foundations were laid upon in ancient times, the modern since aims to understand and reconstruct Earth's history on a planetary context, the origin and evolution of life on Earth and, ultimately, predict and help to preserve its future (Fig. 1.2).

The Ancient Greeks and Romans: The Naturalism	
Pythagoras (ca. 582–ca. 507 B.C.)	Aristotle (384 – 322 B.C.)
Xenophanes of Colophon (ca. 570 – ca. 480 B.C.)	Pliny the Elder (ca. 23 – 79 AD)
	Tertullian (ca. 155 – 222)

The Middle Ages and Renaissance: The Principles	
Avicenna (980 – 1037)	John Ray (1628 – 1705)
Albertus Magnus (ca. 1206? – 1280)	Robert Hooke (1635 – 1703)
Leonardo da Vinci (1452 – 1519)	Nicholaus Steno (1638 – 1686)
Georgius Agricola (1494 – 1555)	John Woodward (1668 – 1721)
Conrad Gessner (1516 – 1565)	Johann Jakob Scheuchzer (1672 – 1733)

Figure 1.2 Timeline of stratigraphic thought.