GEOLOGY

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Contents

Summary. Geology: Its Place in the World of Today

Geology has long had the tag of a "derived science" and long shared a slight stamp of inferiority with disciplines like geography or biology, towards the primary disciplines of physics, mathematics, chemistry, and—in days gone by—philosophy. While geology has been taught as a subject of its own at European universities for about 200 years now, it is still little taught (even in comparison with biology or geography) in secondary schooling around the world and few recognize its importance beyond the applied field of mining. This is surprising: the breakthrough of plate tectonics undoubtedly counts as one of the biggest advances in science made in the twentieth century and ranks with discoveries like the understanding of the relativity principle or the unraveling of the human genome. Moreover, in today's world, a large range of disciplines in science and engineering are now unthinkable without geology. This ranges from the cement industry (drawing upon clay mineralogy and sedimentary geology) or astronomy (drawing upon planetary geology), all the way to the petroleum industry (relying on sedimentary geology, seismology, or palynology), or environmental technology (using hydrogeology and environmental geology), or tunneling and road construction, for which engineering geology has become an important aspect.

The theme on geology in the *Encyclopedia of Life Support Sciences* (EOLSS) on-line, 2002, presents an overview of many aspects of geology, although geochemical, geophysical, and geographical aspects are largely excluded from the volume, as they are also discussed as parts of other themes within the EOLSS project. In this theme level contribution we provide an overview of the aspects dealt with in the theme, and discuss some philosophical and historical aspects of geology. We also provide a brief overview of some first-order explanatory models in geology.

1. Introduction

In its broadest sense, geology is the science of the earth. It shares the study of earth and her sibling rocky planets, moons, and asteroids with a host of other natural sciences: the shape of the earth is the subject of geodesy; the study of the earth's and her siblings' gaseous envelopes is shared by meteorology and climatology; earth's hydrous envelope is the subject of hydrography, oceanography, and limnology; biology studies its inhabitants; the study of the mutual relationships of its natural environments as forming the abode of humans is the proper subject of geography. The boundaries of all of these fields of study are fluid and one nowadays speaks of them collectively—except biology—as the earth sciences. The earth sciences continuously enlarge their compass to embrace more and more of the extra-terrestrial objects, including the stars, gradually evolving into the sciences of the universe.

The present state, composition, and structure of the earth's solid components in their relation to the planet are included in the domain of geology. Its many sub-disciplines, such as mineralogy, petrology, geochemistry, geomorphology, sedimentology, stratigraphy, structural geology, geophysics (all of which may be grouped under the umbrella of physical geology) study the various present-day aspects of the solid earth.

However, the history of the earth, in the entirety of all of its systems, is within the proper domain of geology alone. Thus, geology may be said to consist of two main subdivisions: 1) physical geology that shares the study of the present-day earth system with many other natural sciences; 2) historical geology that alone studies the past of the entire earth-system.

However, there are many other schemes according to which a subdivision may be made (Figure 1). Indeed, there is no unique or complete scheme that identifies the sub-disciplines of geology, and their boundaries are ill-defined. Like biology, geology is a science originally derived from the "primary" sciences of physics, chemistry, and mathematics. As such, it draws upon the tools of all these primary sciences and applies them to geological features: rocks. Interestingly, the general theme "geology" is understood to include different sub-disciplines in different countries and continents. In European universities, for example, it is common to discern between studying and teaching on one side "geology and paleontology", which are concerned with problems of structural geology, tectonics, and historical geology, and on the other side "geochemistry, mineralogy, crystallography, and petrology," which are concerned with questions from the fields of crystal structure, thermodynamics, and crystal chemistry. The study of "geophysics" on the other hand is generally grouped with meteorology or astronomy, and not necessarily thought of as an integral part of the tectonic understanding of our planet. In contrast, in the Anglo-Saxon world geology is often used synonymously with "earth science" and is taught in university departments for "earth science" or even "earth and atmospheric science," with the only sub-discipline that is often treated in an external way being paleontology (often grouped with biology). Moreover, the Anglo-Saxon world has long recognized geophysics as an integral part of our tectonic understanding of our planet and has closely linked geophysics with fields like tectonics or structural geology. These examples illustrate that any subdivision of the field of geology (including those shown in Figure1 is all but arbitrary.

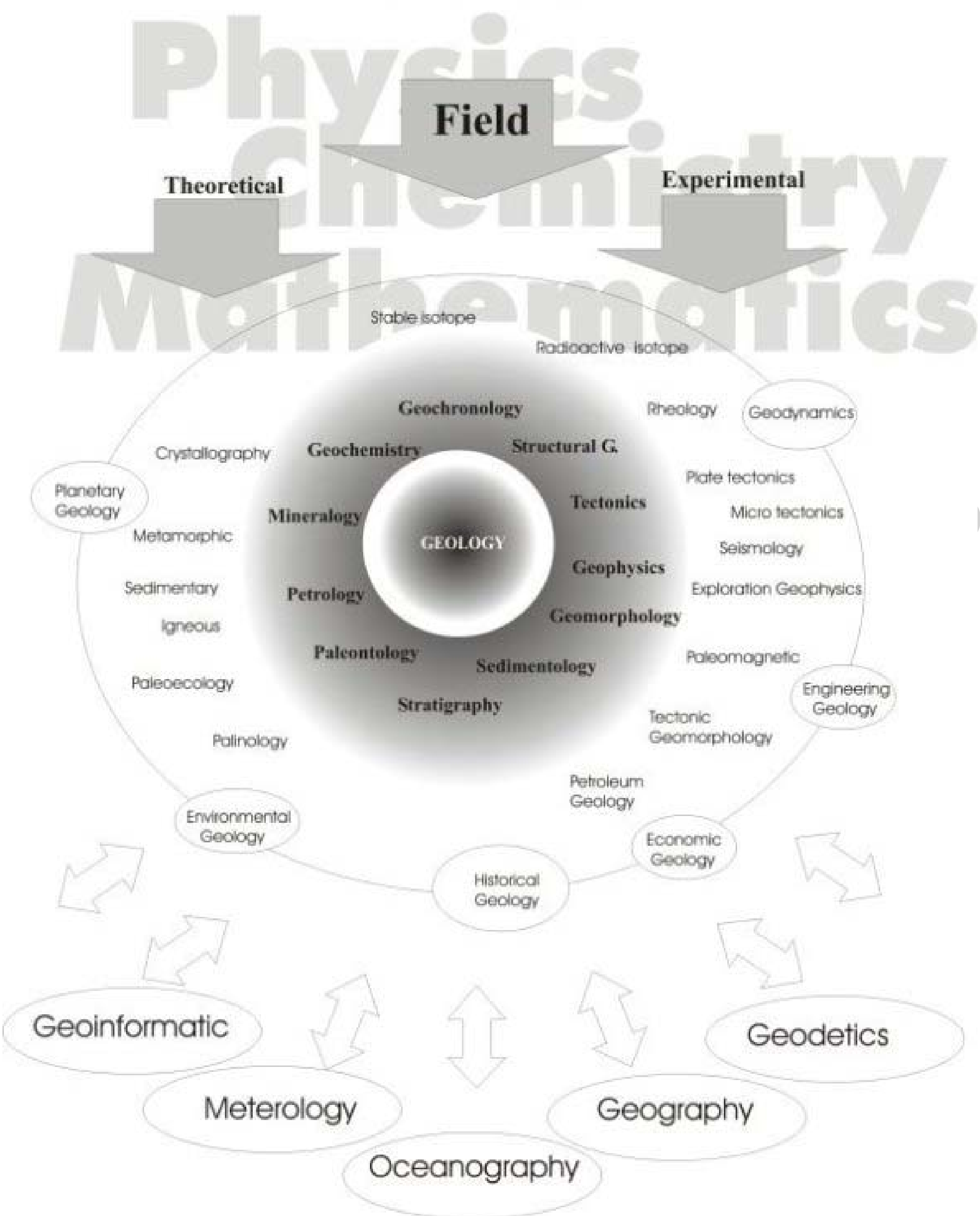

Figure 1. Geology and its sub-disciplines. Geology acts in front of a background of physics, mathematics, and chemistry and is based in the first instance on field observations, supported by experimental and theoretical studies.

The inner cicle around "geology" lists (in bold) a number of fields well-accepted as "sub-disciplines" of geology. Around those are fields that may be seen as "sub-sub-disciplines" of those. The fields in circles along the outer circle list scientific fields that constitute themselves of a range of sub-disciplines. For example, "Geodynamics" draws upon structural geology, geophysics, sedimentology, etc. All "sub-disciplines" of geology interact closely with the disciplines listed at the bottom row. Note that the scheme shown here is by no means unique or complete and many other schemes may be devised.

1.1. Layout of Theme

Under the theme of "geology" we have long discussed an appropriate subdivision of the field: in particular in the light of related themes discussing similar aspects (Figure 1). We have come to the conclusion that a useful division of the theme includes nine different topics, which are listed below:

- Introduction to the earth.
- Geodynamics and tectonics.
- Igneous and metamorphic petrology.
- Sedimentary geology, stratigraphy, and paleontology.
- Overview of the mineralogical sciences.
- Geology of metallic and non-metallic mineral resources.
- Regional geology.
- Geology of petroleum, gas, and coal.
- Environmental and urban geology.

Clearly, this division is artificial and there is infinite overlap between the different topics leading to endless discussion of an appropriate division. To name but one example, it may be argued that paleontology has no place in the theme "geology" at all and should form a theme of its own with all its sub-disciplines like paleobotany, vertebrate paleontology, actuo-paleontology, and many more. We also emphasize that some of these topics are also dealt with in EOLSS themes related to this theme of "Geology." The EOLSS project includes a number of related themes, including "Earth systems: history and natural variability." Within that theme there are topics covering the earth's materials and the earth's position in the universe, which are also part of this topic. Other related themes are "Geography," "Geoinformatics," and most importantly "Geophysics and Geochemistry," all of which could also be seen as subdisciplines of "Geology," just as many of the subdisciplines discussed here could be seen as meriting a volume on their own.

Regardless of such discussion, we have taken the prosaic view to formulate a hierarchical order and level of importance that roughly reflects the distribution of scientists in academic institutions hosting research in "geology." Accordingly, the nine different topics are subdivided into articles and, in some cases, subtopics, containing articles. They are written by authors from sixteen countries, from academic institutions in all six inhabited continents.

2. Historical Review

Geology—as a freestanding science on its own—is generally considered as one of the youngest sciences. Being originally derived from the "primary sciences" like physics, mathematics, chemistry, or, long before this, from philosophy, it shares the stamp of a derived science with fields like geography, biology, or astronomy. However, it may be considered as a science on its own, at least since the eighteenth century. The discovery of plate tectonics was undoubtedly one of the most significant advances in our understanding of our planet in the twentieth century, and reconfirmed the position of geology as a science of its own. While the theory of plate tectonics is a fantastic example for the synthesis of many observations into a unifying scheme, the concept of synthesizing global observations is by no means new to the twentieth century. Throughout the history of geology, the body of geological knowledge was never made up of unrelated ideas and hypotheses, but was characterized by global syntheses, the critique of which was the cradle of scientific progress. While we cannot emphasize strongly enough the dependence of new concepts on old ones and the importance of linking between individual ideas, the length of this contribution does not allow us to elaborate on such connections in much detail. We refer the reader to the fantastic philosophical treatment of geological synthesis through time by Sengör (2001). Here, we provide a mere few key dates to historical aspects.

2.1. The Birth of Geological Sciences

Long before geology was first taught as a science at European universities, geological observations and interpretations were made by philosophers, miners, and priests of the old worlds. Traceable roots of geological investigations go back to the very origins of mankind long before the written word. We know of copper trading in Sinai and the building of the first pyramids in Egypt around 2700–2600 B.C., both of which are undoubtedly associated with geological activities like prospecting or quarrying. Minerals like malachite and native gold are probably among the first minerals recognized and mined as such. Quarrying for flint stone goes even further back in Europe to 5000 B.C. and the mining of clay for brick-making is common from 4000 B.C. onwards. The prospecting, mining, and smelting of iron ore for making tools and weapons began in Asia Minor at about 1300 B.C., and became common in Western Europe around 500 B.C. However, geological thinking aside from the applied fields of mining and quarrying—for the sole purpose of understanding how our planet functions—first became relevant in the classical period.

2.2. Geology in the Classic Period

Scientific aspects of geological theory are first reported from ancient Greece. There, both "Neptunistic" and "Plutonistic" ideas were developed that infer origins of geological materials from water and from fire, respectively. For example, Thales of Milet (sixth century B.C.) inferred that all geological materials must have their origins in water, and Xenophanes of Kolophon (sixth century B.C.) interpreted the mud-like nature of the ocean floors from fossils found on land. Herodotus (fifth century B.C.) made observations of the annual floodings of the Nile and pondered the implications for the slow filling of the Mediterranean and the Arabian Gulf. In contrast, "Plutonistic ideas" were formulated by philosophers who observed volcanic activities. For example, Heraclitus (*c*. 500 B.C.) or Aristotle (384–322 B.C.) discussed the rise and subsidence of continents based on fire. Aristotle was also amongst the first to find scientific arguments that the earth is not flat: for example, the observation that Earth's shadow on the Moon is curved, or that the height of the North Star in the sky changes when traveling north. The first detailed descriptions of volcanic eruptions—of Etna and Vesuvius—are found in the works of Empedocles and Pliny. What can possibly be considered as the first mineralogy book ever written was by Theophrastus (374–287 B.C.), a book that dominated geological thinking up to the Middle Ages. However, unfortunately, this book also suggests that fossils may not be the record of living beings in the past. The history of geology in the classic period can also be associated with some of the great, classical astronomers, first of all Claudius Ptolemy (*c*. A.D. 100–170), whose thirteen-volume treatise on astronomy, the *Almagest*, compiled the achievements of his predecessors. Ptolemy is also known for advancing the first general theory of cosmology—"the study of the structure and motions of the universe"—although his work drew heavily on that of perhaps the greatest Greek astronomer, Hipparchus. His geocentric model explained both the structure of the known universe (essentially the seven "planets") and how those planets moved through space. One of the most astonishing, elegant, and curious stories in the history of earth science is the determination of the circumference of the earth by Eratosthenes (276–196 B.C.) in 250 B.C. Eratostenes lived in Alexandria and measured the height of the sun there at the longest day of the year. Legend states that his only additional information was that, on the same day, the sun shone onto the water level of a well in Syene (Aswan), implying that Syene lies on the tropic of Capricorn, of which he knew the distance only in number of days camel ride. From this he calculated the circumference of the earth to be 40,000 km, which is within 5 percent of the now known circumference. A similar, if not so famous, calculation was performed by Posidonius about 100 years later, who used the star Canopus and the distance between Rhodes and Alexandria as his base line. However, his estimate is of some historical importance as it was substantially too small. More than 1,500 years later the explorers of the Renaissance period relied on Posidonius's estimates. It is curious to ponder if the fearless attempts around this time to circumnavigate the globe would have been made if it had been Eratosthenes' estimate that was used.

2.3. The Big Break

In the Western world much of this advanced scientific thinking vanished with the rise of Christianity. Even advanced concepts like the knowledge of the diameter of a spherical earth and concepts for the planetary motions disappeared, or at least were not advanced, for one and a half millennia under the influence of the Catholic Church. It is only in the Arab world that some advances in geological thinking are known to us from the eighth to the eleventh centuries A.D. However, it should be said that this period was not only influenced by the Church, but also by a general age of trust in the writing of others, rather than direct observation, as illustrated by the famous question: "How many legs does a spider have?" It was Aristotle who had stated that spiders have six legs and it was not until two millennia later that Lamarck bothered to count eight legs on spiders, rather than believe the written word. Among the few noteworthy names of the Middle Ages were Thomas Aquinas (1225–1274) who was one of the few scientists in Europe who attempted to weave Aristotle's and other classical scientists' concepts into a single Bible-conforming system covering all aspects of life. Also in the thirteenth century, Vincent de Beauvais and Bartholomew the Englishman kept alive the ideas of the early writers.

2.4. The Renaissance to the Dawn of Plate Tectonic Theory

The sudden rebirth of scientific geological thinking began during the Renaissance. During this time a large number of scientists developed many of the concepts still known to us as the basics of geology. Agricola (Georg Bauer, 1494–1555) is considered as the founder of the science of mineralogy. Agricola lived in the mining district of Saxonia in Germany. His geological interest reached far beyond the study of crystals and minerals, and he published on mining technology, as well as the results from his geophysical, hydrographical, seismological, and tectonics research. His classic book *De Re Metallica* was published in 1556 and gives clear descriptions of mining engineering and geological activities of this time. The universal genius Leonardo da Vinci (1452–1519) inferred correctly that fossils indicate the former presence of ocean on parts now covered by land. He also studied sedimentary strata in the Po basin, coming to the conclusion that they are some hundreds of thousands of years old and that, consequently, the age of earth must be orders of magnitude older. However, his foresight was made redundant by the infamous scientific endeavor of James Ussher who in 1650 made the first ever concrete estimate of the age of earth, based on the genealogies of the Bible. He concluded that the earth must have formed on October 22 4004 B.C., a date that was long after supported by the Church and formed the basis of many geological studies in the century thereafter. In the sixteenth century, the first systematic books on rocks appeared. For example, Conrad Gesner published in 1565, in Switzerland, a book with the title *All about Fossils, Stones and Gems*. Nicolaus Steno (1638–1686) was from Denmark, but lived for large parts of his life as a teacher and medical doctor of anatomy in Padua and Florence. He published geological profiles throughout the Apennines and discussed uplift and erosion processes, published on crystal growth and comparisons between fossils and modern living creatures. His law on the constancy of interfacial angles in crystals is still being taught as "Steno's Law" to every first year student of geology, and he is considered generally as the "father of stratigraphy." Steno never published a summary volume of his findings and converted to Catholicism in 1667, after which he essentially stopped his scientific investigations. The concept of a geological map using different colored symbols was introduced by Martin Lister in 1684 and first applied by George Fuchsel (1722–1773) in one of the first geological maps ever published. As geology today very much trends towards an understanding of earth in terms of physical concepts using mathematical models, the notable mathematicians of this time are also relevant figures in the history of geology as we see it today. Names like Isaac Newton (1643–1727), Jean Baptiste Fourier (1768–1830), Euler (1707–1783), or Lagrange (1736–1813) must be seen as fathers of today's geology, as they are of physics and/or mathematics.

Geology is often considered to have become a science of its own in the eighteenth century, when it became fashionable to record findings in nature. James Hutton (1726–1797) is regarded as the "father of modern geology" and is most famous for his principle of uniformitarianism, stating that the past history of the earth must be interpreted in terms of the processes we observe at present. He also described the use of cross-cutting relationships to establish relative chronology of geological events. The principle of uniformitarianism was also established by Charles Lyell (1779–1875), who wrote a book called *Principles of Geology* (1830). The year 1775 is commemorated for being the date when geology was first taught at university level, by Abraham Werner in Freiburg, Germany. It was not until the nineteenth century that the concept of geological time was first consolidated by the introduction of the geological time scale (Figure 2) and by scientists such as Charles Darwin (1809–1882), Lord Kelvin (1824–1907), and many others, as well as the onset of systematic geological mapping around the world, by, for example, Julius Haast in New Zealand. However, the next large breakthrough in geological science was undoubtedly the emergence of plate tectonics in the early twentieth century.

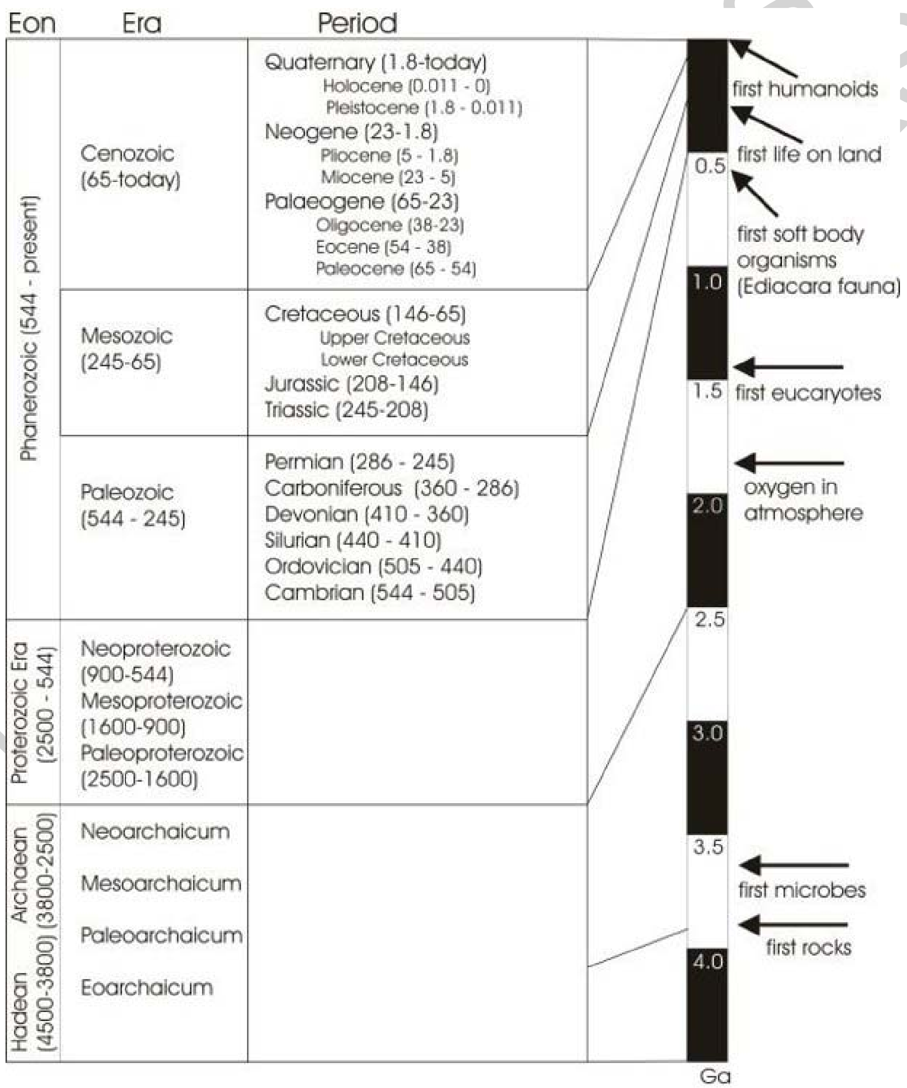

Figure 2. The geological time scale. Except for the Hadean (the period before the occurrence of rocks on earth before 3,800 ma) the subdivision shown is that defined by the International Commission on Stratigraphy, and accepted by the International Union of Geological Sciences. "Periods" of the Proterozoic are not shown.

Subdivisions of “periods” into “ages” are only shown for periods younger than the Cretaceous. On the very right, an absolutely scaled time-bar is shown with some important events in the evolution of the earth.

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Biographical sketches

Kurt Stüwe studied at the universities of Graz, Innsbruck, and Leoben in Austria, and graduated from there in 1984 with a M.Sc. on gold deposits in Alaska. He completed his Ph.D. at the University of Melbourne, Australia in 1988 with a thesis on the metamorphic evolution of eastern Antarctica. From 1990 to 2000 he held various positions as research fellow at the universities of Monash and Adelaide in Australia, and as a visiting professor at the universities of Graz and Vienna in Austria, where he was involved with research projects in Antarctica, central Australia, the Himalayas, and the European Alps. Since 2001 he has held a professorial position at the University of Graz, Austria, where he teaches geodynamics. His current research interests span a wide range of topics, including geophysical, petrological, structural, and geomorphological aspects. In his research, he has always attempted to combine different geological sub-disciplines to solve integrated geodynamical problems. He is editor and editorial board member of a range of national and international journals, and has published roughly 150 publications, about half of which are in top internationally refereed journals. He has also had several years away from the academic world, working as a climbing guide in Alaska in 1984 and 1985, and as a consultant geologist in Zimbabwe in 1989. Aside from geological field trips, he has organized more than ten climbing expeditions to the highest peaks of all continents. He is married, has two children, and lives in Graz.

A.M. Celal Sengör studied at the State University of Albany, New York and received his B.Sc. in 1978. He then proceeded with M.Sc. and Ph.D. studies under J. F. Dewey and graduated from Albany in 1982. From 1986 to 1992 he was reader at the Istanbul Technical University where he is now a full professor in the geology department. He has worked in a wide range of disciplines of the earth sciences and is well known as one of the best experts on the regional geology of the world today. While his expertise is mainly in the field of tectonics his expertise in palaeontology has reached far enough for him to have several fossils named after him. He has published more than 150 papers in refereed journals, holds a large range of awards from a range of countries around the globe, and works as an editor for a number of the highest profile specialist journals. He has a reputation in the field of history and philosophy of the earth sciences, about which he has recently published a textbook. His current research is on the tectonics of Asia, extensional tectonics with emphasis on the Aegean region, and the evolution of orogenic belts in general.

Bernhard Grasemann studied at the Institute of Geology of the University of Vienna, Austria, and finished a Ph.D. in 1993 with a thesis on numerical thermal modeling of inverted metamorphism at the Main Central Thrust in the north-west Himalayas (India). During a six years assistant position he was mainly involved in numerical thermal modeling of tectonic processes for interpretations of geochronologically-derived cooling curves and their translation into exhumation rates, with examples from the Himalayas and the western Alps. For this work he received in 1998 the Otto Ampferer Award of the Austrian Geological Society. Since 2000 he has held the position of professor for structural geology and tectonics at the Institute of Geology of the University of Vienna. His current research interests are the kinematic of deformation in orogenic wedges (north-west Himalayas), emplacement of high-pressure rocks (eastern Alps), exhumation of metamorphic core complexes (western Aegean, Greece), and numerical modeling of quantitative kinematic indicators. In 2002 he became a member of the editorial board of journal *Geology* (Geological Society of America) and *Mitteilungen der Österreichischen Geologischen Gesellschaft* (Geological Society of Austria).

Benedetto De Vivo studied at the University of Napoli "Federico II" and graduated from there in geological sciences in 1971. From 1971 to 1976 he worked as a consulting geologist for private companies operating in Italy, Africa (Sudan, Mozambique, and Ghana), and Central America (Santo Domingo) in the field of ore deposits, geochemical prospecting, environmental geology, and hydrogeology. From 1976 to 1987 he worked as research fellow at the Centro di Studio per la Geocronologia e la Geochimica delle Formazioni Recenti, CNR, Roma. From 1987 to 2000 he held the position of associate professor in applied geochemistry at Dipartimento di Geofisica e Vulcanologia, University of Napoli "Federico II" and in 2000 was appointed to the position of full professor in geochemistry at the same university. He has held different research fellowships in the United States (Colorado School of Mines in 1978; US Geological Survey, Reston, Va. in 1982 and 1992) and was invited to the Japan Geological Survey in 1990, to be the visiting scientist by the EC–Japan Center for Industrial Co-operation. He has been chairman of the Working Group "Inclusions in Minerals" of the International Mineralogical Association and is a member of the Board of Associate Editors (since 1996) of *Mineralogy and Petrology*. His current research interest span a wide range of topics including geochemical prospecting, fluid and melt inclusions studies applied mostly to the study of volcanic and sub-volcanic systems, and environmental geochemistry. He has published 140 papers (more than half of which in top internationally referred journals) and has edited different special volumes of *J. Volcanol. Geotherm. Res*., *Eur. J. Miner*., *Inst. Mining and Metallurgy*, and *Mineralogy and Petrology*. He is also the author of two text books (in Italian) in geochemical prospecting and environmental geochemistry. In 2001 has was nominated a Fellow of the Mineralogical Society of America for "his outstanding contributions to the fields of mineralogy, crystallography, geochemistry, and petrology."