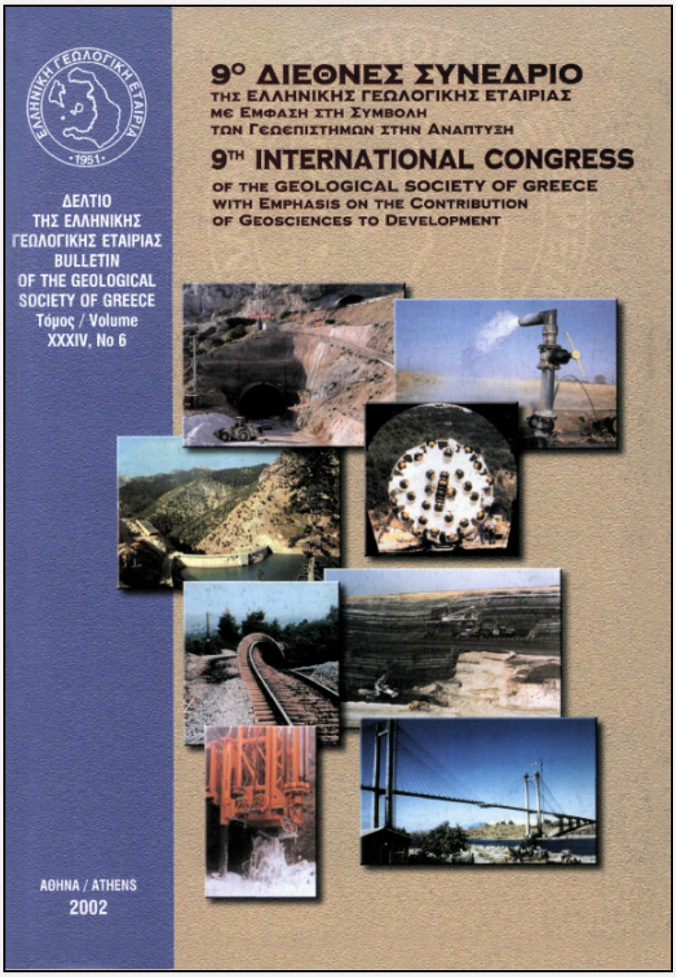
Bulletin of the Geological Society of Greece

Vol. 34, 2002



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https://doi.org/10.12681/bgsg.16858

To cite this article:

DERMITZAKIS, M. (2002). New tendencies and advances in modern Statigraphical Research. *Bulletin of the Geological Society of Greece, 34*(6), 2141-2148. doi:https://doi.org/10.12681/bgsg.16858

Δελτίο της Ελληνικής Γεωλογικής Εταιρίας, Τομ. XXXIV/6, 2141-2148, 2002 Bulletin of the Geological Society of Greece, Vol. XXXIV/6, 2141-2148, 2002
Πρακτικά 9ου Διεθνούς Συνεδρίου, Αθήνα, Σεπτέμβριος 2001 Proceedings of the 9th International Congress, Athens, September 2001

NEW TENDENCIES AND ADVANCES IN MODERN STRATIGRAPHICAL RESEARCH*

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1. INTRODUCTION

Stratigraphy is the key to understanding the earth, its materials, structure and past life. It encompasses everything that has happened in the history of the planet. Simply defined, stratigraphy is the study of rock units and the interpretation of rock successions as a series of events in the history of the earth. The role of the stratigrapher is to describe, order and interpret rock units in terms of events and processes, and to correlate this information in time in order to build up this record of earth history. Fundamentally, stratigraphy provides the perspective of time; a perspective which makes geology almost unique within the physical sciences.

Understanding the principles and terminology of stratigraphy is essential to geologic study of sedimentary rocks because stratigraphy provides the framework within which systematic sedimentologic studies can be carried out. It allows the geologist to bring together the details of sediment composition, texture, structure, and other features into an environmental and temporal synthesis from which we can interpret the broader aspects of Earth history.

All geologists are in some way stratigraphers, since almost all-pure geological research is an attempt to unlock the secrets of the earth. Stratigraphy provides the frame of reference which underpins this research. Applied studies also rely on stratigraphy, as, for example, it is crucial in the exploration for oil and gas reserves, and it provides a sound basis for the understanding of the properties and extent of geological units in civil engineering.

The aim of this paper is to provide reviews of some of the most important principles and practices in modern stratigraphy.

2. FROM YESTERDAY TO TOMORROW: STRATIGRAPHY AS A MODERN DISCIPLINE

Geology has a long history dating back to the Renaissance, but arguably, formal acceptance of the guiding principles of the subject – uniformitarianism, superposition and relative chronology – followed from the publication of Charles Lyell's (1797-1875) classic book *Principles of Geology* in 1830. Its publication heralded the "golden age" of geology, riding on the crest of the great wave of public enthusiasm for the natural sciences (Bowler 1992). Text and classbooks on geology proliferated, and geologists such as Lyell and his contemporaries were public figures. Examining one of these texts today, such as Lyell's own *Students' Elements of Geology* (1878) or Page's *Advanced Textbook of Geology* (1861), one is struck by a simple fact: that the study of geology was synonymous with stratigraphy.

The most important contribution from this time was the development of the Chronostratigraphical Scale, a truly international standard which provides a framework of relative time within which all rock units may be compared. The systems that make up this scale were mostly established within the first 50 years of the nineteenth century. For example, the Cambrian, Silurian, Devonian and Permian systems were all erected by Roderick Murchison and Adam Sedgwick within a period of just six years, between 1835 and 1841 (Berry 1986). The rapid development of the Chronostratigraphic Scale was made possible by refinement of the basic principles of biostratigraphy, first laid down by William Smith at the turn of the nineteenth century, and was driven by the need for tools to establish and interpret the sequence of rock units on a global scale. At the same time that the Chronostratigraphical Scale was emerging, the application of the uniformitarian principles championed by Charles Lyell and James Hutton and the development of the concept of the facies by Armanz Gressley provided the mechanism for the interpretation of rock units as the products of ancient processes.

* ΑΠΟΨΕΙΣ, ΝΕΕΣ ΤΑΣΕΙΣ ΚΑΙ ΠΡΟΟΠΤΙΚΕΣ ΤΗΣ ΣΤΡΩΜΑΤΟΓΡΑΦΙΚΗΣ ΕΡΕΥΝΑΣ ΣΤΗΝ ΕΛΛΑΔΑ

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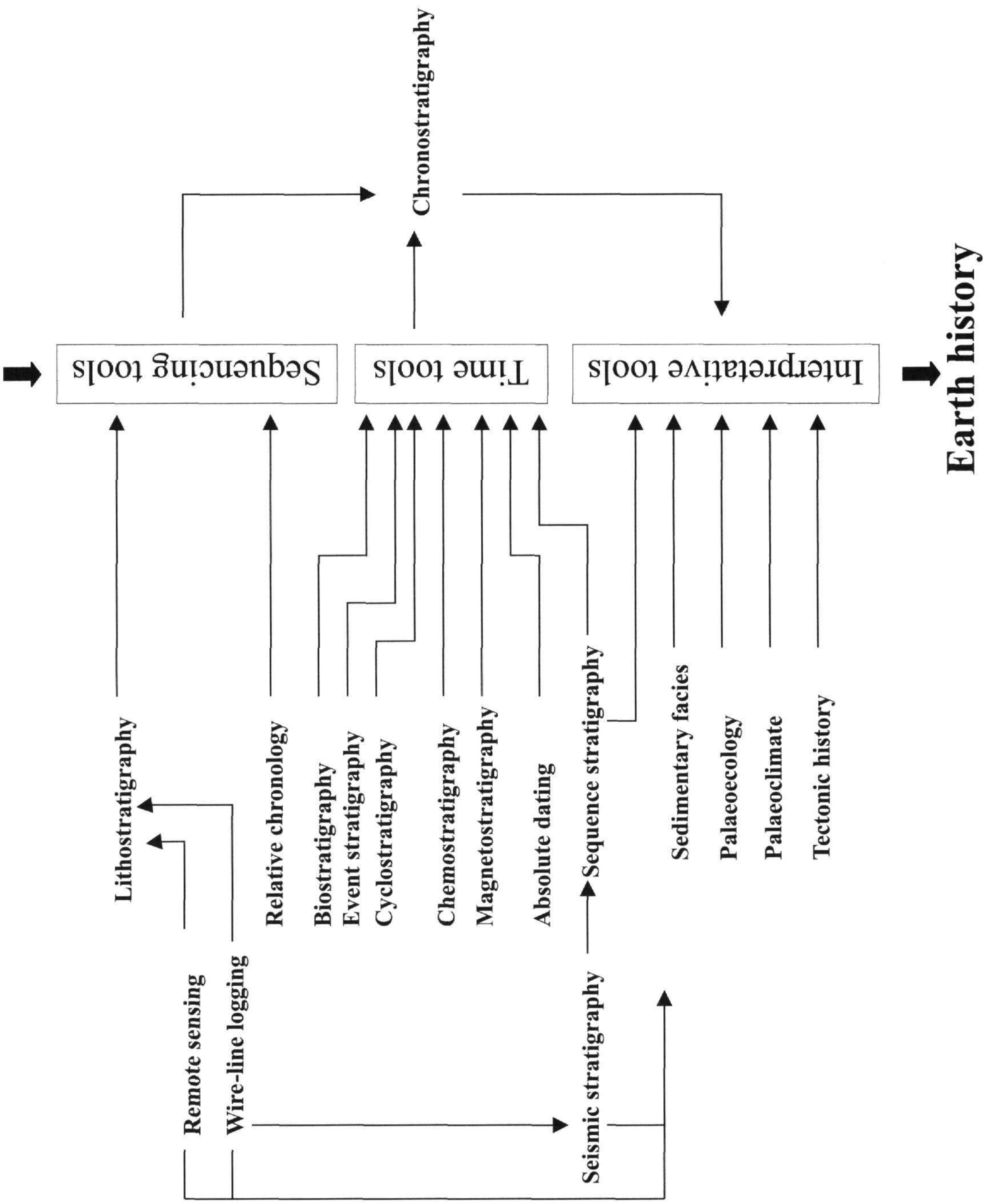
The nineteenth century was clearly a period of rapid advance not only in terms of the development of the tools of stratigraphy, but also in terms of our understanding of earth history (Bowler 1992). By the mid-twentieth century, however, stratigraphy had lost its place as the intellectual heart of geology and the subject slowly degenerated into a simple catalogue of units and names. Some of the worst and least imaginative aspects of the subject are dated from this period. The source of this decline is complex, but it primarily reflects a failure of the geological community to provide a convincing explanation for global tectonic activity. From the days of James Hutton, stratigraphers had recognized the great importance of angular unconformities as evidence of denudation of fold mountains followed by subsequent marine flooding episodes, but what created the mountains? James Hall and James Dwinght Dana in America evolved their geosynclinal theory in the mid to late nineteenth century, through the examination of the linear fold belts welded to the ancient cratonic interiors of most of the continents. Challenged only by the then bizarre notion of continental drift by Alfred Wegener in the early part of the twentieth century, there was no dynamic force in stratigraphy. There was an absence of interpretative models capable of making sense of the complex, often conflicting picture, of earth history that was emerging (Hallam 1990). Geologists retreated to their introspective studies and were content to catalogue their local successions.

Prior to the 1960s, the discipline of stratigraphy was concerned particularly with stratigraphic nomenclature; the more classical concepts of lithostratigraphic, biostratigraphic and chronostratigraphic successions in given areas; and correlation of these successions between areas. Lithostratigraphy, Biostratigraphy and Chronostratigraphy are still the backbone of Stratigraphy; however today's students must go beyond these basic principles. They must also have a thorough understanding of depositional systems and be able to apply stratigraphic and sedimentological principles to interpretation of strata within the context of global plate tectonics. This means, among other things, becoming familiar with comparatively new branches of stratigraphy that have developed since the early 1960s an new concepts and methods of studying sedimentary rocks and other rocks by remote sensing techniques have unfolded.

The discovery of sea-floor spreading through the work of scientists such as Fred Vine, Drummond Matthews and Harry Hess in the 1960s did much to revolutionize geology and to breathe new life into stratigraphy. Indeed, new techniques in the subject, particularly in the study of the record of the earth's magnetic reversals (magnetostratigraphy), led to the recognition of the alternate magnetic "strips" of the spreading ridge basalts, and the widespread acceptance of plate tectonics. The advent of the "new global tectonics", as it was then called, reinvigorated the subject of stratigraphy. Stratigraphical studies provided the means by which plate tectonic theory learned from the present day could be applied to the geological past. Perhaps the most seminal work in this respect was the stratigraphical and palaeontological studies of the North American geologist J. Tuzo Wilson, who confirmed the existence of an early Palaeozoic, proto-Atlantic ocean; the Iapetus Ocean of later authors (Wilson 1966). Placed in a plate tectonic context, this led to the concept of the Wilson Cycle, the opening and closing of ocean basins, which provides the interpretative framework so long demanded by the stratigraphical fraterntity. Gone was the need to invoke elaborate "land-bridges" in order to explain away difficult palaeogeographical and palaeobiogeographical conundrums thrown up by the stratigraphical record (e.g. Oakley & Muir-Wood 1949; Wills 1951). Stratigraphy was once again placed at the heart of geology, as it was needed to provide the framework within which to apply plate tectonics in the geological past; complex tectonic belts could be teased apart and placed into a new global tectonic setting. Furthermore, precision in relative and absolute dating of events and more detailed interpretational models were needed to meet this new challenge.

As the models of our global environment – plate tectonic, climatic and biological – have become even more sophisticated, the demand for high-resolution stratigraphical records has accelerated. In recent years there has been a rapid advance in the sophistication and resolution of stratigraphical tools (e.g. Hailwood & Kidd 1993). Cyclostratigraphy, chemostratigraphy, seismic stratigraphy, event stratigraphy and sequence stratigraphy have all been developed over the past two decades, allowing the more detailed subdivision and accurate correlation of rock successions across the globe. Application of these new concepts and techniques makes possible subdivision of stratigraphic successions into relatively small units, e.g., <1000-3000 years for Quaternary strata to 225 thousand to 2 million years for Triassic strata. Such fine-scale stratigraphic resolution in now commonly referred as high-resolution stratigraphy.

International co-operation is redefining the Chronostratigraphical Scale with greater precision, and developing globally accepted protocols for litho- and biostratigraphy (e.g. Hedberg 1976; Whittaker et al., 1991). Stratigraphy has new challenges, and needs new and refined techniques to meet these challenges. Yet the basic principles and aims of stratigraphy remain the same as they did in the early days of the subject: those of establishing the sequence of rock units and then interpreting them as events within earth history.


Chronostratigraphy
Sequencing tools
Time tools
Interpretative tools
Earth history
Lithostratigraphy
Relative chronology
Biostratigraphy
Event stratigraphy
Cyclostratigraphy
Chemostratigraphy
Magnetostratigraphy
Absolute dating
Sequence stratigraphy
Sedimentary facies
Palaeoecology
Palaeoclimate
Tectonic history
Remote sensing
Wire-line logging
Seismic stratigraphy

3. METHODS AND TECHNIQUES

As a consequence of recent advances in stratigraphy driven by increasingly more specific questions posed by the integrative models of earth history, modern stratigraphers are faced with a bewildering array of tools and techniques at their disposal. This "stratigraphical tool kit" (Doyle et al. 1994) becomes ever more complex as these ideas advance continually. Generally, however, it is possible to recognize two types of stratigraphical tool: 1. Those tools primarily involved with establishing the sequence of rock units; and 2. Those primarily involved in the interpretation of rock units as events in the development of the earth. The principal subjects, techniques or tools within the "stratigraphical tool kit" are shown in Fig. 1.

The first duty of any geologist working in an unknown area is to establish the geological sequence in that area. In order to achieve this, a set of "sequencing tools" is used (Fig. 1). This involves the observation, description and distinction of the main lithological units, through the process of *lithostratigraphy*. Lithostratigraphy recognizes basic chronology, using the principle of superposition and way-up criteria. Other methods of lithostratigraphical analysis and correlation can be achieved through electrical and magnetic properties of rocks, which may be derived from subsurface boreholes and wireline logging techniques.

Recognition of lithostratigraphical units is usually carried out by all field geologists and usually leads to the development of a geological map, but today, the lithostratigraphical exploration of large tracts of impenetrable or inhospitable terrain may be successfully carried out using remote sensing techniques which serve as valuable sequencing tools within the stratigraphical repertoire.

The initial recognition of lithostratigraphical units and the determination of their relative chronology are insufficient for correlation with either other units in adjacent regions, or with the Global Chronostratigraphical Scale. Traditionally, *biostratigraphy* has provided the basis for most correlations, and is still the most important method of correlation with the Global Standard Stratigraphy.

Modern biostratigraphy relies intimately on a biological understanding of fossils. Although quantitative studies are becoming increasingly common, most biostratigraphy still relies simply on presence/absence data for particular fossil taxa.

Recently, however, a raft of new techniques has helped refine correlations where recourse to fossils is difficult because of preservational or environmental conditions. These include the recognition of *depositional event horizons*, rhythmic *Milankovitch cycles*, and the use of *stable isotopes* from carbonate and other sedimentary rock sequences. *Seismic* and *sequence stratigraphies* are concerned with the correlation of geometrical packages of sediments, initially from seismic sections, but now commonly using onshore rock successions. These correlation tools also provide an extremely important mechanism for the interpretation of the development of sedimentary basins, and in the analysis of basin fill, and provide a crossover into interpretation tools.

Finally, *unstable isotopes* provide not only a continuously refinable method of absolute dating of the rock record through comparison of the ratio of parent to daughter nuclides, but also an efficient method in some cases of relative chronology in multiple igneous bodies and metamorphic events.

The interpretation of rock units as the products of events in earth history is an extremely important part of stratigraphy, and it forms the basis for our understanding of the global environment through time. As such, it is reliant upon the recognition of chronology, because it is important to be able to observe geological units in a series of equivalent time-slices. Interpretation of the ancient environments in each time-slice, and through each time-slice in a succession, is reliant upon facies analysis; that is, the interpretation of the sum total of the characteristics of a rock body in order to determine its environment of deposition. Geometry, rock type, sedimentary structure and fossils are just some of the environmental indicators which help decipher past environments. Facies analysis is therefore the most important interpretation tool. The recognition of relative changes in sea level through time is possible using basic facies analysis, and through the interpretation of the sedimentary package geometries provided by seismic and sequence-stratigraphy techniques.

Fossils provide an important interpretative tool, as, using uniformitarian principles, it is possible to reconstruct ancient ecologies and to extrapolate the ecological tolerances of living to fossil organisms. In many cases simple tasks, such as distinguishing between marine and non-marine sediments, are only actually possible through the presence/absence of marine fossils, for example.

In the framework of the International Senckenberg Conference "Paleontology in the 21st Century", September 3-9, 1997, Frankfurt, Germany, there was suggestion for a possible major palaeontological initiative, which the General Assembly put before the entire palaeontological community for discussion. This initiative is worldwide and can be compared to other larger scientific initiatives, such as the human genome and planetary flyby. It is a fact that the paleontological and stratigraphical community will launch a broad interdisciplinary and process-oriented analysis of the interactions between life and Earth through geological time. Scientists wish to understand the patterns and process of evolution that gave rise to the biological diversity that surrounds us today. They also wish to obtain a better understanding of how past changes in the biota have resulted from and impacted on the global environment. The fact that life has been a major forcing factor in the development of the Earth system places those who have studied the geological history of life in a strong position to lead this endeavor. The initiative of the Workshop "Paleontology in the 21st Century provides the following goals as targets to be achieved by the year 2018.

Improve high-revolution geochronology based on the integration of biostratigraphy with radioisotopic dating and geophysical and astronomical data to establish the precise temporal framework necessary for historical analysis. Only with such data can scientists determine the rates and relationships of tectonic, climatic, oceanographic and biological processes.

Collaborate with the biological community in determining the evolutionary tree of all life. Paleontological data are necessary to resolve and calibrate phylogenetic trees and understand the history of ecosystems.

Move more fully toward a quantitative characterization of the history of life, drawing upon a synthesis of phylogeny and quantitative morphology for important biological groups, within a well-constrained, quantitatively-based, temporal framework.

Develop more complete and integrated paleontological, geophysical, geochemical, and geologic databases, to establish the environmental context of biological evolution during times of both stability and rapid change. This is necessary in order to understand the interactive dynamics of the biota and the physical environment. In particular, paleontologists will document the major perturbations in the history of life, establish their causes, and consider their likely effects on the biosphere were they to recur.

From the preceding develop a set of predictive rules for the biotic response to and generation of changes in the global environment".

The new research trends have already appeared in sections such as Vertebrate Paleontology and Micropaleontology, which represent the most popular biostratigraphic methods and techniques.

In particular Vertebrate Paleontology, which in the past was mainly involved with systematics, can contribute to subjects that concern mankind today, such as drastic reductions in terrestrial biodiversity as habitats are reduced or altered by human activities. The geological history of terrestrial ecosystems is an important topic for both biologists and earth scientists, who are involved with the problem of environmental fragmentation versus biodiversity. Therefore the investigation of changes in terrestrial ecosystems during the closest geological past – mainly the Neogene- a time interval that has witnessed enormous geographical and environmental changes, represents one of the main stratigraphical and paleontological research aspects, as it allows us to understand the past floral an faunal change by reference to present day ecosystems.

Ongoing research on the marine record aims at the modeling of marine environmental/depositional systems. However modeling of terrestrial paleoenvironments, which is a prerequisite to understand the total earth system, lags behind other studies, showing no recent advances in high resolution chronology, and paleogeographic reconstructions. For these reasons the scientific community turns now to examine terrestrial ecosystems in the framework of a new generation of spatial and temporal reconstructions, and in particular to study the temporal and spatial paleoecological patterns of mammal communities in the context of ranked changes in paleogeography and paleoenvironments/paleoclimate inferred from non-mammal terrestrial and marine evidence. These studies will lead to a better understanding of the dynamics and sensitivity of terrestrial ecosystems and the dynamics of mammal biodiversity in terms of the response to locally, regionally or globally-induced environmental perturbations. The intergration of data and interpretations from the terrestrial and marine records is expected to result to the understanding of the episodes of major biotic change during the Neogene in order to put geological and paleontological constraints on the modeling and prediction of ecosystem change, collapse and recovery.

Within a multidisciplinary context accurate dating and high-resolution correlations between terrestrial and marine sequences, and within well-resolved time-stratigraphic, biogeographic and environmental frameworks it will become feasible to address in detail the kind of basic ecological questions that cannot be answered by studying the living world owing to the lack of temporal depth (Brown, 1995).

On the other hand Micropaleontology –which represents the backbone of biostratigraphical analyses focuses evidently to environmental studies contributing to the effort of synthesizing the knowledge gained from field studies into a set of models that reflect our understanding of the ocean carbon cycle.

The ocean and the atmosphere are tightly linked in the global climate system, and any changes in either can affect the other. Scientists are studying the cycling of carbon in the ocean to understand the natural processes that control the size and distribution of the ocean carbon reservoir. They also observe the effects that human activities are having on these processes, such as the increase in CO2 in the atmosphere, which is contributing to rising temperatures. Our ability to predict and perhaps to alter the course of climate change requires a detailed understanding of the ways in which carbon in the ocean is transformed, transported, recycled or buried in the sediments of the sea floor. One route that carbon takes into the deep ocean is via what scientists call the "biological pump". This pathway begins as Phytoplankton, the single-celled organisms that form the base of the oceanic food web, take up CO2 and nutrients through the process of photosynthesis and form organic matter.

Consequently research trends focus mainly on phytoplankton and in particular on calcareous nannoplankton – which is one of the most abundant groups of extant phytoplankton.

Therefore the increase interest of micropaleontological studies in nannoplankton paleoecology and paleoceanography has been paralleled by a renaissance of studies of extant nannoplankton, with an increase focus on ecological aspects (Young et al., 2000).

4. NEW TENDENCIES IN STRATIGRAPHY

Cyclostratigraphy is a new subdiscipline of stratigraphy that deals with the identification, characterization and correlation of cyclic (periodic or near-periodic) variations in the stratigraphic record and, in particular, with their application in geochronology by improving the resolution of time-stratigraphic frameworks.

It is mainly restricted to the study of the sedimentary record produced by climatic cycles of regular frequency, tens to hundreds of thousand years in duration, which are generated by variations in the earth's orbit and are known as Milankovitch Cycles. Cycles driven by global climate have the most use in stratigraphical correlation. Cyclostratigraphy is concerned particularly with these cycles and the precise identification of their frequency. This has enabled geologists to develop an orbital timescale graduated in tens or hundreds of thousands of years for parts of the geological column. Cyclostratigraphy also investigates the frequently complex way in which orbital cycles have influenced earth's climate, oceans and ice caps, and attempts to interpret how the cycles seen in the stratigraphical record have formed.

The subject is a young one: the term cyclostratigraphy is less than 10 years old, and was first used at a meeting in Perugia in Italy in 1988. However, the idea that orbital cycles might affect the earth's climate was suggested first by Croll (1875), and their potential use in developing geological timescales was discussed in an extraordinarily prescient paper by Gilbert (1895), who identified bedding cycles in the Cretaceous and interpreted them as the product of orbital forcing.

It was a Serbian mathematician, Milutin Milankovitch, who calculated the orbital variations accurately for the first time, and showed quantitatively how these determined the amount of solar radiation reaching the earth (Milankovitch 1941). He proposed that these orbital cycles were responsible for climatic changes leading to ice ages. His work was not treated seriously at the time, because the changes in solar energy he calculated seemed much too small to have caused glacial and interglacial periods.

Milankovitch cycles remained unproven in the stratigraphical record until 1976, when Hays et al. (1976) demonstrated regular cyclicity of 100Ka, 41Ka, 23Ka and 19Ka in oxygen isotope and other data, in deep sea cores covering the last 500Ka. The periodicity exactly matched major orbital cycle frequencies previously calculated by Milankovitch and demonstrated that orbital cycles acted as a pacemaker to the ice ages. This work led to the establishment of an orbital timescale, which now extends back 20Ma to the base of the Miocene (e.g. Shackleton et al. 1995).

Identification of orbital cycle frequencies in older sediments has not enjoyed such dramatic success. This is probably because the signal is blurred by the numerous other time-dependent variables which affect sedimentation, such as rapidly changing accumulation rates and hidden hiatuses (Schwarzacher 1993).

Sequence stratigraphy is presently regarded as one of the most important unifying concepts in sedimentary geology. It seeks to explain the depositional patterns of sediments on a basinal scale, with reference to changing sea level and tectonic subsidence.

Although it has been greeted as a totally new approach to the description and correlation of bodies of rock, sequence stratigraphy does have a past. From the time of James Hutton, unconformities have been used to separate major rock units; in some cases, the differences between rocks on either side of the unconformities have been so profound, that they have been used as the division between systems.

Sequence Stratigraphy grew from seismic stratigraphy and was almost entirely the product of a small team working at the Exxon Production Research Company, under the leadership of Peter Vail.

Sequence Stratigraphy has fundamentally changed the way in which we interpret the stratigraphical record. The main strengths of the model are its ability to explain the depositional patterns of sediments on a basinal scale with reference to changing sea level, subsidence and sediment supply, and to provide a chronostratigraphical template for correlation. The key idea of the concept is the integration of information within a consistent spatial and temporal framework. Sequence Stratigraphy is a genuine evolution in geological thought, and it provides a new tool to master when using Sedimentary Geology in the petroleum exploration.

What is the foreseeable evolution? We can expect:

A rapid spread of the concepts and their application in geoscience;

A decline of the inconsistencies which result from different data types or tools;

The development of robust tools for stratigraphic modelling and automated processing;

The creation of a common reference system for the different specialist techniques of Sedimentary Geology, including Organic Geochemistry (the evaluation of source rocks and of their petroleum characteristics requires an understanding of the deposition of these rocks; this field has yet to be more fully explored);

The establishment of links between stratigraphic architecture, sedimentary facies (reservoirs, source rocks, seals), petrophysical properties, ecosystems and synsedimentary tectonics.

The integration of high-resolution sequence stratigraphy and cyclostratigraphy can lead to a better understanding of the sedimentary systems and of how they react to sea-level, hydrodynamic, climatic, physical, chemical and biological changes.

5. CONCLUSIONS

Stratigraphy is an essential and dynamic discipline in modern geology. As our understanding of global processes accelerates, there is a clear and increasing demand for high-resolution stratigraphical data. In recent years this has led to the development of a bewildering array of specialist, and increasingly sophisticated, analytical tools. Despite this, the fundamental aims of stratigraphy remain unchanged: those of establishing the sequence of rock units and then interpreting them as events in earth history.

In the new century perhaps the general trend in stratigraphic research would be combine and integrate the subdisciplines rather than subdivide and discriminate them. There may be no more need to increase new stratigraphic categories. On the contrary comprehensive of the mutual relation between the categories and precise designation of stratigraphic terminology may be more necessary.

Stratigraphers are commonly using the following phrase "past is the key for the future", in order to reinforce the importance of stratigraphy in the complex of geosciences, but during the last years, there is one more phrase appearing, which reflects the current scientific trends, "the present unlocks the past". Probably the truth is somewhere between both of them. And the science of stratigraphy is strongly called to face successfully a period of unprecedented progress as new technologies and data analytic approaches are integrated, in order to establish solutions/directions, as it enters the next millennium.

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