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Résumé de l'article

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La paléontologie demeurera une ave-nue importante étant donné sa capacitéà fournir des échelles de temps qui per-mettent d'estimer la durée et les ré-gimes des processus physiques. La bio-stratigraphie sera davantage intégrée àla stratigraphie physique grâce à desconcepts nouveaux tels la stratigraphiede séquences ou d'événements. Lesdonnées paléoécologiques et paléo-biogéographiques, que seuls les fos-siles fournissent, seront étudiées plus àfond afin de raffiner la modélisation desprocessus se déroulant dans lesbassins. L'étude des phénomènes d'ex-tinction et de radiation du biote de laTerre en fonction du temps, nous per-mettra de mieux comprendre l'évolutionbiologique et ses relations avec l'évolu-tion physique de la Terre. La volonté detester l'hypothèse Gaia sera à l'origined'une grande partie de ces recherches.

L'utilisation de nouvelles tech-nologies améliorera grandement lesmoyens non-destructifs à notre disposi-tion pour l'étude des organismes fos-siles. Les techniques de l'informatiquepermettront de mieux gérer, manipuler,et visualiser, à la fois les données et lesimages, rehaussant ainsi nos capacitésd'interprétation.

L'intégration de la paléontologie et dela géochimie aboutira à une profondamélioration de notre compréhensionde la paléo-océanographie et de la paléo-biogéographie. La chimie des océansse reflétant dans la chimie des organ-ismes fossiles qui y ont vécus, nouspourrons en déduire les grandes tend-ances évolutives, et mieux comprendredes événements comme les extinctionset les radiations. En adoptant le point devue de la chimie organique, la paléon-tologie s'intéressera aux phénomènesmoléculaires. Ces recherches iront audelà des recherches de biomarqueurspour des motifs économiques, pour seporter vers l'établissement de la dis-tribution dans le temps des moléculeset de leur signification dans l'évolution.

La compréhension de l'évolution de labiosphère est d'une importance pri-moridale pour l'interprétation deschangements à l'échelle du globe, sujetpour lequel l'intérêt public ira croissantau cours des prochaines décennies.Pour mieux apprécier les répercussionset la rapidité des changements à l'é-chelle du globe dans les biosphères passées et ainsi que la biosphère ac-tuelle, il est nécessaire de mieux com-prendre le concept de biodiversité. Lestendances récentes indiquant un déclindes activités en paléontologie sys-tématique et en biologie devront êtreinversées si nous voulons acquérir unevue d'ensemble des changements àl'échelle du globe. La recherche sur lesbiosphères du passé sont de plus enplus importante pour l'avenir de notreplanète — spécialement pour sa popu-lation — au moment où il devient de plusen plus évident que la survie même desespèces n'est plus assurée.

L'explication et l'interprétation des ré-sultats au profit du grand public doit êtrel'une des composantes essentielles destravaux scientifiques à venir Le dé-veloppaient d'un alphabétisme scien-tifique (capacité de comprendre lascience) est peut-être le plus grand desdéfis qui se présentent à la commu-nauté scientifique.

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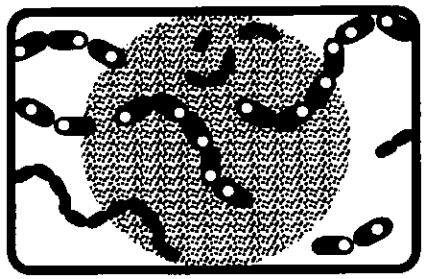

The Ancient Biosphere

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ABSTRACT

The origin and development of life on Earth is intimately linked to the physical evolution of the planet's surface and upper lithosphere. The future of research on the ancient biosphere is filled with as much excitement and uncertainty as the future of the Earth itself. The trend will be to build on traditional strengths, such as biochronology, paleoecology and paleobiogeography, and to seek completely new research directions driven by new technology, new concepts, and new requirements for information.

The traditional strength of paleontology in providing the time scale necessary for evaluating the duration and rates of physical processes will remain important. Biostratigraphy will be more closely integrated with new concepts in physical stratigraphy, such as event and sequence stratigraphy. Paleoecological and paleobiogeographical data, which only fossils can provide, will be more fully interpreted to produce refined models of basin processes. Studies of extinction and radiation of the Earth's biota through time will lead to a fuller understanding of biological evolution and its relationship to the physical evolution of the Earth. The desire to test the Gaia Hypothesis will spur much of this research.

The application of new technologies will greatly enhance our ability to study fossil organisms without damaging specimens. Computer technology will permit better data management, and manipulation and display of both data and images, thus enhancing our interpretive skills.

The integration of paleontology with geochemisty will result in a profound improvement in our understanding of paleo-oceanography and paleobiogeography. The chemistry of fossils, reflecting the chemistry of the oceans in which they lived, will allow interpretation of large-scale trends, and greater understanding of events such as extinctions and radiations. In terms of organic geochemistry, paleontology will be taken to the molecular level, moving beyond the economically driven study of biomarkers to elaboration of the temporal distribution of biomolecules and their implications for evolution.

Understanding the evolution of the biosphere is of crucial importance to interpreting global change, an issue that will grow in public importance during the coming decade. In order to appreciate the impact and rate of global changes in the ancient and present biosphere, there is a requirement for a clearer understanding of biodiversity. Recent trends indicating a decline of systematic paleontology and biology will have to be reversed if we are to gain a comprehensive view of global change. Research on the ancient biosphere is of increasing importance to the future of the planet — particularly to its human population — as it becomes more evident that the continuing survival of the species is in doubt.

A prime component of future scientific work must be the explanation and interpretation of results to the general public. Development of scientific literacy is perhaps the most pressing challenge facing the scientific community.

RÉSUMÉ

L'origine et le développement de la vie sur la Terre sont intimement liés à l'évolution de la surface de la planète ainsi que de la partie supérieure de sa lithosphère. Tout comme l'avenir de la planète, les recherches dans le domaine des biosphères du passé comportent beaucoup d'exaltation et d'incertitudes. Les nouvelles avenues de recherche devront s'établir à partir de domaines de recherches déjà bien établis tels ceux de la biochronologie, de la paléoécologie et de la paléobiogéographie. Elles devront également s'élaborer selon des avenues de recherche vierges,

en profitant des nouvelles technologies, de concepts nouveaux, et des nouveaux besoins d'information.

La paléontologie demeurera une avenue importante étant donné sa capacité à fournir des échelles de temps qui permettent d'estimer la durée et les régimes des processus physiques. La biostratigraphie sera davantage intégrée à la stratigraphie physique grâce à des concepts nouveaux tels la stratigraphie de séquences ou d'événements. Les données paléoécologiques et paléobiogéographiques, que seuls les fossiles fournissent, seront étudiées plus à fond afin de raffiner la modélisation des processus se déroulant dans les bassins. L'étude des phénomènes d'extinction et de radiation du biote de la Terre en fonction du temps, nous permettra de mieux comprendre l'évolution biologique et ses relations avec l'évolution physique de la Terre. La volonté de tester l'hypothèse *Gaia* sera à l'origine d'une grande partie de ces recherches.

L'utilisation de nouvelles technologies améliorera grandement les moyens non-destructifs à notre disposition pour l'étude des organismes fossiles. Les techniques de l'informatique permettront de mieux gérer, manipuler, et visualiser, à la fois les données et les images, rehaussant ainsi nos capacités d'interprétation.

L'intégration de la paléontologie et de la géochimie aboutira à une profond amélioration de notre compréhension de la paléo-océanographie et de la paléobiogéographie. La chimie des océans se reflétant dans la chimie des organismes fossiles qui y ont vécus, nous pourrons en déduire les grandes tendances évolutives, et mieux comprendre des événements comme les extinctions et les radiations. En adoptant le point de vue de la chimie organique, la paléontologie s'intéressera aux phénomènes moléculaires. Ces recherches iront au delà des recherches de biomarqueurs pour des motifs économiques, pour se porter vers l'établissement de la distribution dans le temps des molécules et de leur signification dans l'évolution.

La compréhension de l'évolution de la biosphère est d'une importance primoridale pour l'interprétation des changements à l'échelle du globe, sujet pour lequel l'intérêt public ira croissant au cours des prochaines décennies. Pour mieux apprécier les répercussions et la rapidité des changements à l'échelle du globe dans les biosphères passées et ainsi que la biosphère actuelle, il est nécessaire de mieux comprendre le concept de biodiversité. Les tendances récentes indiquant un déclin des activités en paléontologie systématique et en biologie devront être inversées si nous voulons acquérir une vue d'ensemble des changements à l'échelle du globe. La recherche sur les biosphères du passé sont de plus en plus importante pour l'avenir de notre planète — spécialement pour sa population — au moment où il devient de plus en plus évident que la survie même des espèces n'est plus assurée.

L'explication et l'interprétation des résultats au profit du grand public doit être l'une des composantes essentielles des travaux scientifiques à venir. Le développment d'un alphabétisme scientifique (capacité de comprendre la science) est peut-être le plus grand des défis qui se présentent à la communauté scientifique.

INTRODUCTION

The incredible diversity of life on Earth through time has resulted in a fossil record that is extremely rich in information. It provides unique data representing the history of the Earth's biota, and reflects the interactions of organisms with the environment. The physical evolution of the Earth's surface and upper lithosphere and the evolution of its biota are intimately linked. Perhaps the most fundamental example of this relationship is the very origin of life on Earth and development of organisms, such as algae and cyanobacteria, that probably played a fundamental role in the development of the Earth's atmosphere. Their presence on Earth has been traced back 3.6 billion years, and they have probably acted through much of their early history to continuously remove carbon dioxide from the Earth's atmosphere and to serve as its source of atmospheric oxygen. Without an oxygenated atmosphere, life would not have evolved as it has. The relationship is intimate indeed.

The fossil record is particularly important for three main reasons. Firstly, the fossil record reveals a complex history of life on Earth that has not repeated itself. Evolution is a one-way street, and this lack of repetition makes it radically different from other more quantifiable physical parameters that are used to study Earth history. While such methods as chemostratigraphy, magnetostratigraphy and sequence stratigraphy are valuable approaches, the fossil record provides unique and independent chronological control through a succession of faunal and floral assemblages that are unmistakably distinct from one another. Furthermore, the clock established by organic evolution cannot be reset by subsequent events.

Secondly, biological diversity is so great that the amount of data that can be derived from the fossil record is enormous. The morphological complexity of a single fossil specimen is such that it may be readily classified and interpreted. When many fossils of different taxonomic groups can be isolated from any given horizon, the quantity of information on the biota itself and the certainty of interpretation about its environment and age are greatly increased. Care must be taken, however, to identify post-mortem mixing in death assemblages.

Thirdly, although the development of the fossil record is intimately intertwined with many physical processes, there are some processes for which it can provide relatively independent tests. For example, the information derived from fossils is, to some extent, independent of tectonic modelling. Paleontological information is derived from biological evolution, whereas tectonic interpretation is based on crustal evolution, and although crustal evolution may affect biological evolution (*e.g.*, through the development of land bridges and oceanic barriers), it is only one of many factors. Paleoenvironmental interpretations based on the fossil record are not based on the same assumptions used to develop tectonic hypotheses, so they can act as relatively independent tests of those hypotheses and can, in fact, contribute significantly to the understanding of crustal evolution (Smith, 1988).

Taken together, these three observations serve to make information in the fossil record pivotal to the understanding of the evolution of the upper lithosphere and surface of the Earth.

THE GROWTH OF GAIA AND CHAOS

The idea of coevolution has been prominent in the biological sciences in the past decade. Briefly stated, this involves the examination of interactions of evolving populations of organisms and the role these interactions have in

evolution (Futuyama and Slatkin, 1983). The idea promotes the understanding of relationships between organisms, such as that between butterflies and flowers, and its role in the course of evolution of both groups. For paleontologists, this is a useful concept that is difficult to apply because of the difficulty of establishing organism relationships from the fossil record. In its strictest definition, the idea of coevolution refers to the relationships between ecologically intimate species, but some have chosen a broader definition that encompasses relationships between groups of species and physical parameters such as climate (Ehrlich, 1991). Clearly, the biological sciences are moving toward a more holistic approach to the study of evolution.

A bolder step in the direction of holistic science is the Gaia Hypothesis, first formulated by Lovelock (1972) and developed in subsequent works (Lovelock, 1979, 1991). It postulates that "the physical and chemical condition of the surface of the Earth, of the atmosphere, and of the oceans has been and is actively made fit and comfortable by the presence of life itself" (Lovelock, 1979, p. 152). This is directly opposite to the idea that life has adapted itself to changing physical conditions. The hypothesis, however, demands that we think of life as a phenomenon of planetary scale. It tends to break down the barriers between disciplines, particularly biology and geology. It promotes the joint study of environmental and biological evolution and views them as strongly coupled, some would say indivisible. In contrasting coevolution and the Gaia Hypothesis, Lovelock (1991, p. 4) suggests that coevolution is "rather like a platonic friendship. Biologists and geologists remain friends but never move on to an intimate, close coupled, relationship". A fascinating series of articles on the Gaia Hypothesis is available in Schneider and Boston (1991).

The fossil record clearly has a strong role to play in the testing and validation of this hypothesis, and there is an implicit demand that biologists and geologists develop closer working relationships. The earth scientists best placed to facilitate this interaction are paleontologists.

The Gaia Hypothesis is accepted to varying degrees by scientists, and Kirchner (1991) has attempted to characterize them from "weak" to "strong", suggesting that a weak concept of Gaia has been around a long time and simply allows that the Earth's biota plays a significant role in certain physical areas such as temperature and atmospheric composition. The popular perception that the Gaia Hypothesis suggests the Earth is a living organism is extreme, and rates as a metaphor (Kirchner, 1991). The testing of the Gaia Hypothesis, to whatever degree it is accepted, is no easy matter. Experimentation is difficult, perhaps impossible, and thus one of the strongest tools is the data that can be derived from the fossil record. One of the most potent ways of pursuing this goal is through the combination of geochemistry and paleontology (see below).

One of the obvious aspects of the Gaia Hypothesis is that it is nonlinear and may lend itself to analysis by chaos theory. Nonlinear dynamics and chaos are fast-growing fields (Middleton, 1991) that will have a great impact on all areas of science, particularly in the analysis of natural systems. The roots of the topic lie in the study of dynamics, but ecologists, biologists, astronomers, economists and chemists have all found chaos in their disciplines. Earth scientists are just beginning to delve into the field (*e.g.*, Turcotte, 1990; Jie and Turcotte, 1990) and it is certain that patterns such as extinction and radiation of biota on Earth through time can lend themselves to study through nonlinear dynamics. Perhaps we shall discover that the patterns of radiation and extinction are normal products of nonlinear dynamics and do not necessarily require the invocation of extra-terrestrial phenomena and drastic climate changes as causes. This is an exciting area for future collaboration between earth scientists and other scientists, because the earth scientists hold so much of the hard evidence. The application of nonlinear chaos to analysis of natural systems will be an important trend in the near future. Even if it proves to be a fad and fizzles out, it will, like the Gaia Hypothesis, have provoked a wealth of fresh interdisciplinary research.

A MATTER OF TIME

The great practical and historical strength of paleontology is in biostratigraphy. In the early 18th century, William Smith used fossils to distinguish stratigraphic units for his pioneering geological maps, and this application served as the basis for future development of biostratigraphy (Nowlan, 1986). The sheer size of Canada and the diversity of its geology means that there are many outstanding rock sections for each geological system. It is no accident that the internationally accepted base for the Phanerozoic is in Canada (in eastern Newfoundland) and it is not surprising that Canada has world-class candidates for many other systemic boundaries, for example, the Cambro-Ordovician (in western Newfoundland) and the Ordovician-Silurian boundary (on Anticosti Island). The presence of this magnificent rock record, combined with the strong demand for stratigraphic information related to the exploration for resources during the past 150 years, has influenced Canada's paleontologists to excel as pragmatic biostratigraphers. Indeed, biostratigraphy remains the practical cornerstone of paleontology and it will continue to be of vital importance in the future.

During the past 170 years, biochronologies for each of the Phanerozoic systems have been developed and continually refined. Every horizontal line on a geological time scale is ultimately based on fossils, and thus biozonations are the basis for unit distribution on large-scale geological maps. The biochronology of most systems is now refined to the point that each zone embraces approximately one million years. In some cases, however, such as the conodont zones for the Upper Devonian, the duration is much shorter (a few hundred thousand years or less).

Like the fossils on which it is based, biostratigraphy has evolved. It has come a long way since the first recognition of its usefulness by William Smith in the early 19th century as a means of geological mapping. The evolution has been one of addition of interpretive tools, rather than any great shift from its basic paradigm.

SPECIAL EVENTS

Recent trends in stratigraphic study have tended toward the recognition of significant surfaces, either those that represent rare events, as in event stratigraphy (Seilacher, 1981; 1984), or those that bound depositional sequences, as in sequence stratigraphy (Mitchum *et al.*, 1977). A solid footing in systematic and stratigraphic paleontology is the

primary basis for study of the temporal relationships of major regional surfaces that may represent short-term events or important stratigraphic boundaries. The concepts of event stratigraphy and sequence stratigraphy are still quite new, and were developed independently of a well-defined chronology. They have been founded on a belief that the effects in the stratigraphic record of eustatic sea-level changes and other global or extra-terrestrial events can be clearly understood and correlated with confidence. There is a strong danger of circular reasoning if physical stratigraphy is used as a form of chronology. Clearly, we cannot know whether physical events correlate worldwide without having the events accurately dated at each locality. Increasingly, detailed biochronology is applied to sequence stratigraphy, and magnificent opportunities exist for the application of refined biostratigraphy to a valuable interpretive concept.

Depositional sequences have time-stratigraphic significance only to the extent that all strata within a sequence were deposited in the same broad time interval. The surfaces separating sequences may be unconformities representing hiatuses of millions of years, or correlative conformities in the deep basin. Biostratigraphy can be used to define the age of sequence boundaries, the degree of diachronism of these surfaces, the duration of the interval separating the underlying and overlying sequences, and correlation of units between sequence boundaries, thus ensuring that we are dealing with the same unit or event in different places. Since sequence boundaries are conventionally considered to reflect broad-scale sea-level fluctuations, the paleoecological interpretation of fossils on both sides of sequence boundaries provides valuable data for interpreting the fluctuations. Depositional sequence boundaries are generally recognized and interpreted from seismic profiles, and the combination of seismic stratigraphy with biostratigraphy provides a better geological history than either method could achieve alone.

For example, Cenozoic strata of the Beaufort-Mackenzie Basin have been interpreted to have been deposited in a series of nine sequences (McNeil *et al.*, 1990). The basin is a cratonic foreland basin developed on the margin of North America that accumulated about 15 km of sediment during the late Cretaceous and Cenozoic. McNeil *et al.* (1990) have combined the techniques of seismic stratigraphy and biostratigraphy for Cenozoic strata assigned to an already established transgressive-regressive sequence model. Seismic stratigraphy is uniquely capable of recognizing large-scale stratigraphic units and defining their geometry and relationships to other units. Biostratigraphy not only provides age constraints, correlations and biofacies interpretations within sequences, but also identifies sequences in those areas where the seismic record is inconclusive, and predicts facies patterns in areas lacking other data. McNeil *et al.* (1990) were able to demonstrate that biostratigraphic data can be used to distinguish and correlate sequences and to identify facies within sequences. Distinctive foraminiferal assemblages characterize different stratigraphic settings, and patterns of distribution can be interpreted in terms of local, basin-wide and even possibly global phenomena. However, they note the difficulty of correlating the nine sequences identified with Vail cycles or supercycles (Vail *et al.*, 1977) because of the lack of precision in dating the Arctic strata. Clearly, additional studies in other Cenozoic basins around the world are required in order to establish the validity of applying physical stratigraphic cycles globally. Equally clearly, this type of study needs to be conducted at other levels in other basins.

DEATH ON THE HORIZON

Extinction events represent one of the most exciting areas of paleontological study at the present time. The magnitude, breadth and periodicity of extinction events have typically been described from compilations of literature. The early compilations raised controversy as to whether extinction events were instantaneous or gradual; however, the data were inadequate for resolving the questions raised. Although literature compilation is an effective tool for plotting the generalities of evolution, it is too blunt an instrument for deciphering precise timing and short-term rates of extinction because it is based partly on outdated and inexact taxonomy that exists in much of the literature. There is no substitute for outcrop or core-based studies to establish range truncation data for each species. Once detailed analyses have been conducted in several sections worldwide, local paleoenvironmental influences can be filtered out, and conclusions can be drawn as to which species actually become extinct and at what levels. The few rigorous field or core-based studies conducted to date have produced evidence for catastrophic and gradualistic extinction in specific cases, but they have also shown that many extinctions occurred in a stepwise fashion (*e.g.*, Sharpton and Ward, 1990).

Analysis of the distribution of fossils through ever more finely sampled sections is not the only tool used in the examination of events in the geological record. It is increasingly important to take into account the many other tools that exist to help understand events and processes. Much recent work has been focussed on the geochemical signatures left in the rock and fossil record as a means of interpreting significant stratigraphic events. Examination of these chemical signatures can be undertaken on either the fossil material itself or the enclosing sediments. The idea that the chemistry of fossil skeletal materials reflects the chemistry of the oceans in which they were precipitated has led to much research to establish patterns of ocean temperature, salinity and redox conditions (see Brand and Morrison, 1987 for a review) and is clearly one of the main trends of research in the future.

The trace element chemistry of strata has been combined with biostratigraphic data in a number of recent studies to try to pinpoint levels of elemental enrichment that might correspond to significant biological events (*e.g.*, Goodfellow *et al.*, 1992). In addition, shifts in the total biomass can be traced using carbon isotope ratios, and studies have been conducted for many extinction events (*e.g.*, McLaren and Goodfellow, 1990). Sulphur isotope ratios are used to establish degrees of oxygenation in basins, and patterns of paleotemperature can be traced through examination of oxygen isotope ratios. Paleoredox variations in ancient oceans have been measured using rare earth element concentrations in apatite of fossil conodonts and fish (Wright *et al.*, 1987). When all these techniques are combined with biostratigraphic data, some remarkable results can be obtained that enable detailed understanding of paleooceanography and extinction events. These data can shed light on oceanic

conditions that affect the distribution of organisms globally, and lead to understanding of barriers and pathways for oceanic migration.

Preliminary studies have been conducted for many of the systemic boundaries and other significant stratigraphic horizons; for example, the Late Ordovician extinction event (Goodfellow *et al.*, 1992), the Frasnian-Famennian event in the Devonian (Geldsetzer *et al.*, 1987), and the Permian-Triassic boundary (Holser *et al.*, 1989). At some of these horizons, significant iridium anomalies have been discovered, leading to interpretation of the event as resulting from a bolide impact.

Iridium anomalies are best known on a global scale for what is perhaps the most studied extinction event, the demise of the dinosaurs at the Cretaceous-Tertiary (K-T) boundary. In addition to iridium enrichment, shocked quartz (believed to result from the percussion of the impact) is commonly recognized at the boundary, and its average size has even been plotted globally to indicate that the impact site (or sites) probably lies in the Caribbean. Recently, Hildebrand *et al.* (1991) suggested that the actual site of the impact may have been found as a circular structure known as the Chicxulub Crater on the Yucatan Peninsula of Mexico. The debate rages on, however, with the publication in the April 1992 issue of *GSA Today* of suggestions that none of the sites purported to represent the K-T impact crater is valid (Officer *et al.*, 1992). Many of the data used to argue against the validity of the craters as K-T impacts are biostratigraphic in nature and need to be clarified by appropriate experts. In other words, fine resolution biostratigraphic data are essential to the understanding of extinction events.

Such data are important for more than just the dating of individual sections, as has been recently shown by Sweet and Braman (1992), working on terrestrial flora at the K-T boundary in western Canada. A distinctive claystone containing an iridium anomaly, shocked quartz, and evidence for a biological crisis occurs in sediments spanning the K-T boundary across western North America. An extremely detailed palynological study has shown that distinctive pollen and spores are present below the boundary, in the boundary claystone, and above the boundary. Those in the claystone are related to the underlying Cretaceous flora, implying that the claystone predates the main event. Those above the claystone represent opportunistic plant species from various environmental niches. Their distribution patterns suggest that opportunistic species were derived from local surviving flora, as opposed to a model that suggests that a completely new flora recolonized a totally denuded landscape. Sweet and Braman (1992) demonstrate that perturbations in the flora occur both immediately before, as well as immediately after, the event, implying perhaps a sequence of events rather than a single cataclysm. These results are fascinating, and demonstrate that detailed examination of fossil distributions in space and time can contribute in many ways to the study of events of which they are the ultimate victims. The proposed project of the Canadian Continental Drilling program to drill coreholes through the K-T boundary in western Canada should provide exciting new results. The unweathered nature of corehole samples will be important for the geochemical assessment of this globally significant horizon.

It is obvious that much work remains to be done on this important aspect of the history of the Earth. Understanding mass extinction events will provide important information on the degree to which the biota has been perturbed in the past, and provide scenarios for events not yet experienced by its human inhabitants. When the knowledge that multiple extinction events have occurred on the Earth in the past is linked to the disastrous effects of humans on the global environment, the question is inevitably asked: Are we the architects of a new global mass-extinction event? The stratigraphic terminology for this event has already been proposed, with the Kerocene or Weshouldhavecene to succeed the Holocene (Prosh and McCracken, 1985).

THE CHANGING BIOSPHERE

One of the major themes of research on the ancient biosphere in the past few years has been that of global change. There is an urgent need for research that leads to reconstruction of the Earth's past climates and environments on a regional and global scale. The evidence preserved in the geological record can shed light on the natural fluctuations of world climate in the past. The existence of lush forests of Eocene age in the northernmost reaches of Canada (Christie and McMillan, 1991) and the broad distribution of glacial sediments in the Pleistocene are potent examples of how dramatically the Earth's climate has changed with time. In addition to these dramatic shifts in climate, the more subtle response of ecosystems to climate change can be traced in the fossil record. Many physical changes leave evidence that can be interpreted from the fossil record, including changes in the composition and circulation of the oceans, changes in oceanic productivity, and changes in sea level and climate.

The subject is of such broad content and interest that there has been a flurry of popular books published on the subject that make valuable reading for scientists who need to see the larger picture and where their research might fit in the context of global change (Budyko *et al.*, 1988; Dotto, 1988; Mungall and McLaren, 1990). In the scientific community, there has been much debate on the appropriate time scale for research into global change. Some advocate a time scale of the last 2000 years, others suggest we should examine at least back to the last naturally warm period, the Pliocene, while still others argue that any global event of whatever age may elucidate aspects of global change (Shackleton *et al.*, 1990). The main programs developed through the International Geosphere-Biosphere Program (IGBP) support research on a time scale of millennia, with special reference to the last 2000 years (IGBP, 1990, 1992), whereas the National Aeronautics and Space Administration (NASA) in the United States takes a broader view (NASA, 1986). It is clear that there are events of global importance known from the fossil record that have not occurred on Earth in the historical past (*e.g.*, major bolide impacts, major continental glaciation, oceanic inversions), but that may occur at any time in the near future. The existence of these requires that all events that may act as agents of global change be studied. However, it is a profound reality that current environmental studies are driven mainly by legislation and probably will continue to be so for the foreseeable future. Therefore, we have to develop a blend of research that will contribute both to the drawing up of good legislation and to a holistic understanding of global change. In other words, we should concentrate on the

short time scale research (the last million years) without neglecting information that can be derived from evidence in the whole fossil record.

Biotic distribution, abundance and diversity in oceanic, freshwater and terrestrial environments react sensitively to changes in atmospheric, oceanic and physical conditions. Thus, they are excellent indicators of regional or global change. Similarly, changes in the biota directly affect the physical environment. In the most commonly cited modern case, removal of the tropical rain forests results in a change in surface albedo and may affect the gas balance in the global atmosphere. Similarly in the oceanic setting, organisms are strongly affected by redox levels, currents and upwellings or inversions. Changes in these conditions can be recognized in the geological record using biogeochemical methods, and the results compared with fossil distributions before, during and after the event. In this way, natural fluctuations in atmospheric, oceanic and physical conditions can be related to ancient biotic distributions. The potential then exists to decipher the differences between global changes caused by man and naturally occurring fluctuations.

An example of current research that reflects future trends is the work being conducted through the global change observatories. Of particular interest to Canadians is the attempt to obtain a high-resolution paleoclimatic history for the Holocene of North America. Severe drought is a recurrent feature on the prairies, yet they are an important agricultural area. A study of the Palliser Triangle will include examination of cores from several lakes and dried lake basins, with focus on fossils (diatoms, ostracodes, plant macrofossils, and pollen) and the physical and chemical characteristics of the sediment. In this way, past lake levels can be reconstructed and a paleoclimatic record inferred. An initial study has been completed for one lake in southeastern Alberta (Vance *et al.*, 1992) showing that there have been high-stand phases characterized by silicate-rich sediments and low-stand phases, as now, when carbonate and sulphate-rich laminae-containing plants tolerant of saline conditions were deposited. These studies are closely calibrated through the use of accelerator mass spectrometry ^{14}C dates. At present, the resolution is on the order of centuries, recording, for example, a series of droughts between 900 and 1350 AD during the Medieval Warm Period. As the number of lakes studied increases and the time framework is refined, resolution of the overall record to the decade level is expected to be developed. In finely laminated sediment, resolution to the annual or even seasonal level may be possible.

Similar studies are under way to try to understand Neogene paleoclimate through outcrop and cored sections in Alaska and Yukon. The sections are located away from the influence of the continental edge, where massive paleodeltas like that of the Mackenzie-Beaufort region rework the sedimentary record into a complicated puzzle, in areas where sedimentation was dominantly lacustrine or paludal. This data will be crucial for understanding the Arctic environment. The combination of data from many regions of the globe should provide a much clearer picture of the paleoclimatic history of the Earth in the past few thousand to million years.

FOSSIL MOLECULES

All living organisms contain essential polymers, such as nucleic acids, proteins and carbohydrates, as well as a host of other organic compounds. In the past two decades, interest in the characterization of oils has led to identification of biomarkers, which are organic compounds whose structures can be unambiguously linked to precursor compounds occurring in the original source material. Biomarkers have played a significant role in the exploration and characterization of fossil fuel resources, especially crude oil.

Biomarkers are chemical fossils. Their study, biomolecular paleontology, deals with the molecular record of ancient life. It has been shown that sediments and fossils contain large amounts of molecular material derived from once-living organisms. Biologically derived organic molecules are known from strata as old as Precambrian (Jackson *et al.*, 1986) to the Recent. Obviously, the preservation of such material varies widely with the nature of the original material, depositional environments, and subsequent diagenesis, but many sites with well-preserved material are known (Eglinton and Curry, 1991).

These biomolecules represent a record of life that one would expect to show some evolutionary patterns. This expectation and the knowledge that if the age distribution of biomarkers were better known then determination of source rocks for oils would be simplified (Peters and Moldowan, 1992), clearly creates opportunities for a more rigorous analysis of the temporal distribution of biomolecules. When this is conducted in the context of organic evolution based on whole fossils, the results should be exciting. Major evolutionary events, such as the origin of land plants, should be reflected in the biomolecular record. Similarly, extinction and radiation events of global magnitude should have effects on the biomarker record. Studies of trace elements and stable isotopes in fossil materials and sediments is currently revolutionizing understanding of oceanic events (see above). Surely organic biomolecules could be put to use in analysis of oceanic anoxia, glaciation and other global scale events.

Biomolecular paleontology is an interdisciplinary field that is closely tied to developments in analytical chemistry. It will develop rapidly as new analytical techniques are perfected. At present, the amount of data is limited and there is enormous potential for contribution of new data and interpretations to many fields of science. Of economic interest is the understanding of the processes that result in preservation or decay of organic molecules. It is probable that future studies will contribute significantly to understanding of the mechanisms of evolution itself, particularly through extraction of ancient genetic material from fossils (*e.g.*, Horai *et al.*, 1991; Golenberg, 1991). One can speculate that damaged fossil DNA or RNA may be repaired using new biochemical techniques, and that sequencing of sections of fossil molecules will be undertaken (Eglinton and Logan, 1991). Perhaps theme parks featuring Jurassic creatures (Crichton, 1990) are not too far from reality.

LIFESTYLE HINTS

The fossil record not only provides a history of the species present on Earth, it also affords clues to their behaviour. One of the new paths opening up in paleontology is the search for evidence of disease and injury in fossil specimens. Paleopathology is a valuable tool for understanding the lifestyles of extinct organisms or those for which there

are modern analogues or relatives. Such studies can help trace the history of disease in antiquity. Just as the study of footprint patterns preserved as trace fossils permits interpretation of the gait and herding behaviour of the organisms that made them, so too can detailed examination of ancient disease and injury.

For example, osteoarthritis is known to have been present in dinosaurs, although the condition was rare, as well as in Tertiary marsupials and mammals (Rothschild and Tanke, 1992). Bone injuries are one of the most readily assessed pathological conditions because the evidence is sometimes well preserved. Such injuries in dinosaurs have been related to mating activities, and some authors have even speculated about the postures assumed by mating dinosaurs based on the frequency and location of bone injuries (Halstead, 1975; Fritz, 1988).

Studies of paleopathology are the result of collaboration of paleontologists, physicians, veterinarians and biologists of all sorts. As a result, the studies are characterized by the use of high-technology equipment not in common use by other paleontologists. Indeed, in many cases, it is the development of new technology that has made the studies possible. Routine radiological techniques are applicable to fossil specimens, but the advent of computer tomographic (CT) scanning techniques permit non-destructive three-dimensional visualizations of fossils with resolution as fine as one millimetre (Conroy and Vannier, 1985). Magnetic resonance imaging (MRI) can also be applied to fossils, permitting more detailed examination of internal structures in three dimensions. The non-destructive nature of both of these techniques suggests that they should be of great value in the future.

Soft tissue in well-preserved fossils has been identified and described using X-rays (Stuermer and Bergström, 1973). Another example of the application of standard medical techniques to fossil materials is the attempt, through histological preparations, to isolate identifiable tissue from extinct organisms such as conodonts (Fåhræus and Fåhræus-van Ree, 1987). The results obtained in this particular case from conodont elements were ambiguous because the tissue differed markedly from known biomineralized tissue. However, it is clearly a new and relatively untried avenue of research that may help to elucidate biological relationships.

Will we still be making thin sections of fossils a decade from now? Perhaps we will be deriving three-dimensional images through non-destructive techniques that allow us to evaluate growth patterns and pathology, as well as basic morphology.

ORGANISMS, CONTINENTS AND COMPUTERS

The advent of paleomagnetism as a tool to portray past configurations of continents through time has produced a profound change in the value of the paleontological database. The production of the first world paleogeographic maps for the Phanerozoic (Smith *et al.*, 1973) increased the importance of paleontological data as an independent test of paleomagnetism. These maps have evolved over the last twenty years and, while those for the late Mesozoic and Cenozoic have become sound, the paleomagnetic data for successively older epochs is less reliable, and these maps need considerable improvement. There is an increasing realization that, for the Paleozoic at least, paleontological data is crucial to production of paleogeographic maps. In a recent compilation dealing with Paleozoic paleogeography, McKerrow and Scotese (1990) likened the precision of the new generation of maps to that of the 16th century maps of Asia and the New World. They specifically appealed to the paleontological community to plot data on existing paleogeographic interpretations and provide suggestions for improvement of the paleogeographic relationships based on the paleobiogeographical interpretations of organisms.

The improvement of paleogeographic maps should be a high priority for the next decade. There is need for databases of paleontological information for as many groups of organisms from as many localities as possible. Computer technology exists that could be put to good use in making evaluations of paleobiogeographically significant data. It is time to come to grips with paleontological mapping of plate (and microplate) boundaries so that provenance of suspect terranes can be assessed even more effectively than at present.

It is important to point out that global assessments of paleobiogeography are dependent on uniform taxonomic concepts with global application. Needless to say, the major challenges confronting any paleontologist who wishes to plot biogeographic data in a meaningful way include rationalization of varying taxonomic schemes, inadequate description or illustration of species, inadequate knowledge of their ecological niches, and gaining access to the great body of unpublished information that exists in many institutions worldwide. International co-operation is particularly important in this field.

BIODIVERSITY

The greatest challenge facing paleontologists is the taxonomic description of the enormous diversity of fossils. Without current taxonomy, few reliable conclusions can be drawn from fossil data and few advances can be made. Unfortunately, there is a contradiction between the current decline in the study of systematics and the need for study of biodiversity. Recent estimates of the number of species that exist on Earth at present vary from 3 to 80 million, of which approximately 1.5 million have been described (Gaston and May, 1992). If we do not know, even within an order of magnitude, the total number of species on Earth at present, how can we assess current rates of extinction or radiation and how can we compare them to the geological record? In biology, the decline in systematists has been major news. When the British Natural History Museum released its corporate plan for 1990-95, which included a scheme to concentrate on specific themes, thus reducing the scientific staff by 100 and abandoning whole areas of research, there was a strong reaction with 800 letters coming from worried scientists all over the world. The decline in systematic work in paleontology and biology is steep (Feldmann and Manning, 1992), seemingly reflecting in the scientific community a fundamental lack of understanding of the importance of systematics.

The causes of this decline may be that taxonomy is considered somehow unfashionable and a step removed from obvious practical applications. Systematic work is not expensive, but it is time consuming. These two factors may be important in an age when the amount of money requested or spent on a project is taken as a measure of the significance of the research, and frequent outputs are required. Whatever

the cause, it is leading to decreased professional opportunities, reduced funding, and the assignment of a higher priority to other disciplines. Ironically, this is happening in a time when Gould (1989) is able to capture the public imagination with tales of major new taxa being described from the fossil record. Even if a paleontologist chooses to do systematic work, he or she must disguise the fact in his or her application for funding so that the project is couched in other terms. The decline of systematic paleontology has serious repercussions for the value of paleontological data: if the specimen cannot be identified with certainty, it is of no value for biostratigraphy, paleoecology, paleoclimatology, paleobiogeography or any other practical application. Besides, the magnitude and control of biodiversity through time is a central problem of evolution, and a key problem for science as a whole. Systematic paleontologists may die out faster than the species they are trying to study, thus becoming a seriously endangered species.

Even if there were a new and sudden influx of funding into systematic research, the tragedy is that it would take a generation to attract and train replacements. We have already lost many specialists (and therefore specialties) who have not been replaced; thus, the opportunity for mentoring has been forfeited. A typical systematist has seen and interpreted much more in a lifetime than can be put down on paper, and therefore even a highly productive specialist may be able to pass on orally a great deal more information, significantly flattening the learning curve for the novice.

Wilson (1988) has estimated that the investment required to describe all species on Earth at present is 25,000 professional lifetimes, and that their publications would fill 60 metres of library shelf for each million species. Assuming that there are many more species when one considers the whole geological record, but also recognizing that only a proportion is actually preserved, the task of describing the world's extinct biota is certainly greater than the task of describing living forms. Ironically, a study by the National Science Foundation (Edwards *et al.*, 1985) showed that only 5% of taxonomists in the United States worked on fossils. Similar conditions exist in Australia (Gaston and May, 1992) and, possibly, the rest of the world.

BIG BRAINSTORMS

Before we propose a new megaproject entitled *Global Biodiversity Through Time*, perhaps we should take a look at the overall effect of scientific megaprojects on the progress of science. The longest running large-scale scientific project is the Ocean Drilling Program (ODP), which began its first cruise in 1985. It succeeded the Deep Sea Drilling Project that operated between 1968 and 1983. This sustained program of drilling has resulted in the recovery of cores from late Mesozoic and Cenozoic sediments around the globe, providing the raw materials for study of biota in the oceanic environment that would otherwise have been inaccessible. The resulting studies have contributed significantly to studies of Earth's climatic history during the last few million years, enabling examination of both long-term and short-term climatic fluctuations. They have also made enormous contributions to the understanding of paleooceanography, including the history of circulation patterns and their effect on climate, as well as the global carbon cycle. The vast wealth of data accumulated will permit analysis of the response of the biota to changing oceanic conditions and global climate, thus providing another avenue for the testing of the Gaia Hypothesis.

Megaprojects are expensive and difficult to maintain in recessionary times, but they are one of the main avenues for international science, and a sustained approach is desirable. As was evident during discussions concerning the Kaon Project in British Columbia, scientists themselves can be circumspect about megaprojects because there is a feeling that they pull money away from other funding areas. They may also be perceived as favouring certain disciplines over others.

Megaprojects such as ODP provide data that is unobtainable any other way, and must be sustained. They represent the co-operation of many nations and, through their joint support, agreements could be made to continue the projects without every nation supporting the project every year. Within participating countries, this might deflect concerns that the project takes too much funding into areas that hold little or no opportunity for many scientists. On a national basis, megaprojects should be set up with a finite time-frame (five to ten years) so that they can be rotated with other projects, thus spreading funds through many different areas of research.

THE FUTURE OF THE PAST

The future of research on the ancient biosphere is filled with as much excitement and uncertainty as the future of the Earth itself. The goal remains that of deciphering the intricate interrelationships of the Earth's biota and the physical development of Earth's surface and upper lithosphere, embracing everything from the evolution of the atmosphere, the successful exploitation of energy and mineral resources, and the damage being done now by human activity.

The traditional strengths of providing the time scale necessary for assessing rates and duration of physical processes will remain important. So, too, will the capability of fossils to provide ecological and biogeographical data. We have only scratched the surface, particularly in Canada, where the landmass is so vast and the work force so small. For this reason, there will continue to be fossil discoveries each year that revolutionize the understanding of regions and problems.

Great opportunities exist for the integration of biostratigraphy with new concepts in physical stratigraphy, such as sequence and event stratigraphy. The trend will be one of concentrating on finer intervals, with more emphasis on individual events and surfaces, leading to new understanding of specific events and episodes in Earth history. Such studies will ultimately lead to greater understanding of the mechanisms of biological evolution and the physical evolution of the Earth. The desire to test the Gaia Hypothesis may spur much of this research.

There is a crying need for an increase in activity in systematic biology and paleontology. This is probably the most serious challenge facing those who wish to interpret both modern and ancient diversity, ecology and biogeography.

The use of new technology currently being used in other disciplines (*e.g.*, the medical profession and organic geochemistry) will spread to become more commonplace in examination of fossil specimens. This is one of the most significant advantages of broadly multidisciplinary work. Similarly, the need for more rigorously collected and de-

scribed data that can be compiled on a global basis underscores the importance of paleontological data being accurately recorded and stored in a flexible, preferably electronic, medium. It is self-evident that computer systems will play an ever-increasing role, from data management, manipulation and display to digital imaging of specific specimens. However, since the studies must be global in scope, allowances will have to be made for new data emanating from the developing world. The practical reality of uneven levels of global development, however, will dictate a mix of the technologically advanced and the mundane. Standards for data collection, recording and storage will have to be set, a major challenge in itself.

The integration of paleontology with many aspects of geochemistry will continue to have a profound impact on our ability to interpret paleo-oceanography. The chemistry of fossils, reflecting the chemistry of the ocean in which they lived, will allow us to interpret large-scale trends and patterns, and to more clearly understand individual events such as extinctions and radiations. Biomolecular paleontology will develop rapidly, moving beyond the economically driven study of biomarkers to the study of the temporal distribution of biomolecules and the implications for evolution. In all of these studies, there is a need for better understanding of the diagenesis of fossil skeletons and sediments so that primary and secondary chemical signatures can be interpreted.

The importance for our future of the possibility of drastic global change will clearly shift the balance of expertise required for study of the ancient biosphere. Specialist paleontologists with knowledge of those groups of organisms capable of providing the necessary information for the last thousands to one million years will be in increasing demand. A renaissance of systematics, fuelled by the requirements for study of global change, may provide a boost to the diversity of the paleontological profession.

Research on the ancient biosphere is of crucial importance to the future of this planet. Understanding the evolution of the Earth, in both biological and physical context, is of greater importance now than at any time in the past, because it has become a serious question whether the human species can continue to survive on this planet. We live in a period that has produced spectacular science, but increasingly, anti-intellectual attitudes developed in many areas of the world are taking a toll on support for intellectual pursuits, including science. In this context, scientists *must* reach out to their fellow citizens and convince them of the necessity for, and value of, scientific research. A prime component of future research in any science must be the explanation and interpretation of the results to the general public. Establishment of scientific literacy among the people of the world is perhaps the most pressing challenge facing the scientific community. We cannot afford to be complacent. Science must re-establish itself at the decision-making tables of the world.

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