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Whither stratigraphy?

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Abstract

There have been three revolutions in sedimentary geology. The first two began in the 1960s, consisting of the development of process–response sedimentary models and the application of plate-tectonic concepts to large-scale aspects of basin analysis. The third revolution, that of sequence stratigraphy, began in the late 1970s and helped to draw together the main results of the first two: the knowledge of autogenic processes learned through facies analysis, and the understanding of tectonism implicit in the unravelling of regional plate kinematics. Developments in the use of seismic-reflection data and the evaluation of a hypothesis of global eustasy provided considerable stimulation for stratigraphic research.

Current developments in the field of sequence stratigraphy are focusing on three areas. (1) Elaboration of the sequence-architecture models for various configurations of depositional environment and sea-level history. (2) Exploration of various mechanisms for sequence generation, especially tectonism and orbital forcing. (3) Attempts to improve the level of precision in stratigraphic correlation and to refine the geological time scale, as a means to test the model of global eustasy.

The growth in the power of computers and our knowledge of physical and chemical processes has led to the evolution of an entirely new way of evaluating earth history, termed quantitative dynamic stratigraphy. Mathematical modelling and numerical simulation of complex earth processes are now possible, and require the collection and integration of a wide array of quantitative and qualitative data sets. Applications include the study of the geodynamic evolution of sedimentary basins, modelling of stratigraphic sequences and global climates, studies of Milankovitch cycles (cyclostratigraphy) and simulation of fluid flow through porous media. The Global Sedimentary Geology Program has brought many of these areas of study together in multidisciplinary, global-scale studies of the sedimentary history of the earth. The results of these studies have wide application to many problems of importance to the human condition, including the past history of global climate change and other environmental concerns. The study of stratigraphy is at the centre of the new view of the earth, termed earth-systems science, which views earth as an 'organic' interaction between the lithosphere, biosphere, hydrosphere, and atmosphere.

1. Introduction

The science of stratigraphy has undergone enormous changes during the last three decades, with an explosion of knowledge regarding the physics and chemistry of sedimentation and the nature of crustal and mantle processes. For the 100th volume of *Sedimentary Geology* it seems appropriate to offer this brief review of developments in stratigraphy, to demonstrate the broad scientific base of the discipline, and to point out where the stratigraphic data base and strati-

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graphic research methods may have application to broader problems beyond the immediate purpose of the subject, which is to document the sedimentary history of the earth. Several entirely new fields of research have emerged in recent years. In order to highlight these several key terms are given in italics.

2. The first two revolutions in sedimentary geology

Stratigraphy has long been thought of as a descriptive science, providing documentation of past events on earth but without adding much to our store of fundamental, theoretical knowledge of global processes—a good example of the 'stamp collecting' variety of science that was derided by Lord Rutherford and his ilk, early in this century. However, this is no longer the case. The first modern revolution, in my view, was the explosion of knowledge of the physical and chemical processes of sedimentation that began in the late 1950s and early 1960s, stimulated and, in large measure, carried out by petroleum geologists, such as the famous Shell Development Group in Houston, and the group led by Harold Fisk at Esso. The emergence of the flow-regime concept as a unifying theory to explain hydrodynamic sedimentary structures (Simons et al., 1965; Harms and Fahnestock, 1965), and the detailed documentation of sedimentary products and processes in carbonate environments, such as the Bahamas Banks and the Persian Gulf (Ham, 1962), were among the many developments that formed the basis for the revolution in the generation of *process–response models* in the 1960s and 1970s. The science of sedimentology matured from a study of thin-section petrography, one of its primary focuses in the 1930s, into an analysis of facies, facies successions, and sedimentary processes, and of regional stratigraphic patterns (Dunbar and Rodgers, 1957; Potter, 1959; Pettijohn, 1962; Potter and Pettijohn, 1963; Krumbein and Sloss, 1963). Textbooks edited by Reading (1978) and Walker (1979) were amongst the first to synthesize the new developments in the field of facies analysis and process–response models, including the many facies models that began to appear at this time.

This revolution was built on the Lyellian basis of 'uniformitarianism', which at first placed undue emphasis on slow, evolutionary, steady-state processes of the type that can be observed all around us every day. It took some time for the importance of rare convulsive or catastrophic events to become apparent, because our first-hand knowledge of such events is so incomplete (Ager, 1980, 1993; Dott, 1983; Hsü, 1983; Clifton, 1988). The gradual piecing together of the evidence for the terminal Cretaceous impact event since the classic paper by Alvarez et al. (1980) has had a significant effect on our views of sedimentology (and many other sciences), as noted later in this paper.

The second revolution, that of plate tectonics, began at about the same time, but carried different kinds of implications for sedimentary geologists. That the structure, stratigraphy and facies of sedimentary basins could be reliably related to plate-tectonic evolution was suggested by Dewey and Bird (1970), and was thoroughly explored by Dickinson (1974) in a paper that still makes for useful reading. From these studies geologists learned the importance of horizontal plate motions for the generation of vertical movements of the earth's crust. The power to make logical predictions of stratigraphy from plate kinematics —the documented passage of a tectonic plate through various tectonic events and climatic zones—became apparent in papers such as that by Berger and Winterer (1974). Another new field, that of *geodynamics*, developed from investigations relating plate tectonics to deeper crustal and mantle processes. The classic study of McKenzie (1978) was amongst the most important in this field. It was the first fully quantitative model that related basin subsidence to crustal processes, in this case the crustal attenuation and thermal changes accompanying continental rifting. This paper provided the basis for the predictive modelling of stratigraphic architecture in response to regional tectonic and eustatic controls, a subject to which I return below.

Studies such as these provided descriptive stratigraphy with an underpinning of theoretical knowledge about basinal controls—the surface environmental aspects that comprise the study of sedimentology—and the deeper crust and mantle processes that are the realm of geophysics. In the 1960s the science of stratigraphy began the move away from the descriptive and qualitative to the predictive and quantitative. The foundations for a powerful new technique were beginning to appear, that of numerical modelling of earth processes aided by graphic simulation, as discussed later in this paper.

Facies analysis concerns itself with local and small-scale characteristics of the sedimentary record. Plate tectonics and its related study, that of geodynamics, help to explain sedimentary patterns on a continental and global scale. In the 1960s facies analysis focused the attention of sedimentologists on local sedimentary controls, the so-called autogenic processes, such as the meandering of rivers and the progradation of carbonate platforms in response to the local distribution of sediment and energy. Plate tectonics helped us to understand the larger scale of controls, the allogenic mechanisms of tectonism, sea-level change and climate.

The combination of plate tectonics, geodynamics, and sedimentology became a powerful one, forming the basis of what came to be known in the 1970s as *basin analysis*, the study of the origin and development of sedimentary basins, including their depositional and structural history (Miall, 1990; Allen and Allen, 1990). Vast numbers of regional basin studies have been undertaken, using the techniques that evolved at this time.

Although it overlaps in time and, to some extent, scientifically, with the third revolution, the Decade of North American Geology project (DNAG) of the Geological Society of America and the Geological Survey of Canada, which was planned as a major commemoration of the centenary of the Geological Society of America in 1988, is in large measure a product of the explosion of research techniques and energy that took place in the 1960s and 1970s, of which basin analysis was an important part. DNAG succeeded in bringing together hundreds of scientists to generate a modern synthesis of the geological history of the continent and its adjacent oceans, and has resulted in a collection of some 28 regional volumes, 6 volumes of field guides, and various other products. The European Geotraverse has been a similarly ambitious project (Blundell et al., 1992). In both cases stratigraphy and basin analysis form a large part of the research product.

3. Sequence stratigraphy: the third revolution in sedimentary geology

Many of our ideas regarding the relationships between sedimentation, sea level, and tectonics emerged in the nineteenth century and the early part of the twentieth century through the work of such individuals as Suess, Gressly, Walther, Barrell, and Grabau. However, modern concepts of *sequence stratigraphy* essentially began with the work of Wheeler (1958, 1959), Sloss et al. (1949), and Sloss (1963). Wheeler attempted to systematize our concepts of time, as applied to the stratigraphic record, while Sloss and his colleagues searched for regional order in the wealth of descriptive stratigraphic detail from the North American continent, and found a pattern of continent-wide transgression and regression pointing to repeated sea-level changes. As pointed out by Ross (1991), all the basic ideas that form the modern framework of sequence stratigraphy were essentially in place by the early 1960s, but the revolution did not take place then, partly because sedimentologists became engrossed with the process–response model, and in part because of a lack of the necessary regional stratigraphic data.

One of Sloss's graduate students, Peter Vail, began to apply what he had learned about regional stratigraphy to the interpretation of regional data sets while working for Exxon Corporation in the 1960s and early 1970s. He was amongst the first to make use of reflection seismic data for the interpretation of large-scale stratigraphic architecture (and certainly the first to publish such ideas), at a time when the petroleum industry had been devoting large resources to the seismic method primarily for the purpose of exploring the structural geology of basins. The results exploded on the stratigraphic scene in 1977 with the publication of the now famous AAPG Memoir 26 (Payton, 1977). Vail's work contained two important new concepts, firstly, that stratigraphic architecture, on a large scale, could be related to cycles of rising and falling sea level and, secondly, that these cycles could be correlated globally, suggesting that global sea-level change, or eustasy, is the major controlling process. It was pointed out most clearly by Carter et al. (1991) that these concepts are independent, and need to be considered so by working geologists. This is a point of some importance, because, while the sequence-architecture approach to stratigraphy has become a powerful and increasingly discriminating method of analysis, the global-eustasy model is becoming increasingly controversial.

3.1. The sequence-architecture model

Developments in the field of sequence stratigraphy have revolutionized the regional study of sedimentary rocks during the last decade. Sequence-architecture models predict the distribution of sedimentary facies based on the response of depositional environments to changes in base level. These models have provided a powerful basis for regional subsurface stratigraphic prediction and correlation, and have become widely used in the field of petroleum geology. Early sequence studies evolved from the model of global eustasy, in which it was hypothesized that sequence stratigraphies around the world were controlled primarily by global changes in sea level (Vail et al., 1977). If this is indeed the case, it permits us to build a global stratigraphic template for correlation based on regional stratigraphic successions.

However, these developments in sequence stratigraphy have proved controversial (Kerr, 1980), and this has stimulated a considerable body of research into basin subsidence processes, the causes of sea-level change, and the response of depositional systems to the various allogenic forcing processes: tectonism, eustasy and climate change. Early sequence-architecture models (Posamentier et al., 1988) proved to be simplistic. In the case of fluvial deposits the response of rivers to base-level change and to other influences, such as climate change and tectonism, is much more complex than had been suggested, and sequence models for this environment are therefore still evolving (Miall, 1991; Schumm, 1993; Wescott, 1993; Shanley and McCabe, 1994; Blum, 1994). Studies of carbonate sedimentation on continental platforms and slopes show that carbonate environments respond very differently to sea-level change than do clastic environments, and are very sensitive to other controls, such as changes in water temperature and suspended-sediment concentration. Architectural models must be adapted, accordingly. In particular, carbonate sedimentation is most active during sea-level highstands, developing thick platform deposits and slope debris aprons (the products of 'highstand shedding'), in contrast to clastic deposits, the thickest accumulations of which are commonly those deposited on the continental slope during lowstand (James and Kendall, 1992; Schlager, 1992). The architectural implications of erosion and oceanward sediment transport during falling base level, is also a recent addition to the body of sequence concepts, leading to modifications in our understanding of the timing of beach-barrier systems and submarine fans (the 'forced regressions' and 'falling-stage systems tracts' of Posamentier et al., 1992; Hunt and Tucker, 1992).

The original sequence models were developed for extensional continental margins, and it is now being shown that in other types of tectonic setting, especially foreland basins, sequence architecture and composition are quite different (Swift et al., 1987; Jordan and Flemings, 1991; Posamentier and Allen, 1993).

3.2. The global eustasy model and other allogenic mechanisms of sequence generation

The question of global eustatic control of sequence architecture has led to two distinct developments. One critical test of global eustasy is to explore the global correlation of sequence successions, and this has stimulated a renewal of interest in the global time scale, the data upon which it is based, and the accuracy and precision with which it can be applied. Considerable effort is being extended to develop new techniques of chronostratigraphic dating and correlation, such as the use of strontium isotope concentrations, which vary systematically through time (Williams, 1990; Smalley et al., 1994). Increasingly refined results are being obtained from magnetostratigraphy (see MacFadden, 1990, and the special issue of the *Journal of Geology* to which this is the introduction), and biostratigraphy, especially by the use of graphic correlation methods (see review in Miall, 1994). The global time scale is undergoing constant iterative refinement and updating through the integrated use of new data bases (e.g., see the Cenozoic time scale of Berggren et al., 1985 and the Mesozoic time scale of Gradstein et al., 1994. Time scales are reviewed in detail by Harland et al., 1990), and this is providing the basis for increasingly sophisticated tests of the global eustasy model. For example, Aubry (1991) carried out a detailed examination of early Eocene events, and concluded that there was no clear signal of global eustasy in the stratigraphic record. Miall (1991, 1992, 1994) argued that the chronostratigraphic record is still too imprecise to permit reliable tests of global correlation of the higher-frequency cycles: those of 1–10 m.y. duration, the so-called 'third-order' sequences that constitute the main basis for recent versions of the Exxon curves (Haq et al., 1987). However, late Cenozoic glacioeustatic fluctuations have generated systematic variations in oxygen isotope concentrations in the Milankovitch band (Shackleton and Opdyke, 1973), and this is providing the basis for a reliable time scale for the last few million years of geologic history (Imbrie et al., 1984; Williams, 1988, 1990), and for the growth of a new discipline, that of *cyclostratigraphy* (discussed below).

The second development has been a renewed interest in the deep structure of the earth and the fundamental mechanisms that control sea-level change and the elevation of the continents. On most continents deep reflection-seismic experiments, that were begun in the 1970s by government–industry consortia (e.g., Oliver, 1982), have produced profiles of the continental crust that reveal the structural complexity of orogens and continental margins down to depths of tens of kilometres, typically to the Mohorovicic discontinuity. Amongst the surprise discoveries, the existence of extensional and compressional detachment surfaces cutting to the base of the crust at steep angles from the horizontal, and the overthrusting of continental margins by tens to hundreds of kilometres in collisional orogens (Allmendinger et al., 1987; Mooney and Braile, 1989; Blundell et al., 1992).

A variety of tectonic mechanisms has been explored by theoretical studies, numerical simulation and the accumulation of careful regional case studies. A new field, called *computational geodynamics*, has emerged "in which computer models of mantle convection are used in the interpretation of contemporaneous geophysical observations like seismic tomography and the geoid as well as of time-integrated observations from isotope geochemistry" (Gurnis, 1992). These developments are of great significance, and their implications for stratigraphy have yet to be fully realised. Gurnis (1988, 1990, 1992) developed the concept of *dynamic topography*, in which the earth's elevation and that of the oceans is related to the thermal properties of the mantle. The heat that accumulates beneath supercontinents can generate continental-scale upwarps of up to 1 km over periods of 100 m.y., whereas subduction of cold oceanic slabs and the downwelling that occurs as continental fragments converge generates regional continental depression of several hundred metres. These processes are the explanation for epeirogeny—the vertical motions of the continents—a feature commonly interpreted from the stratigraphic record (e.g., Sloss, 1963; Bond, 1976, 1978), but hitherto unexplained. To determine their effects on sea level at a given location they must be integrated with changes in sea level itself (eustasy), the causes of which are discussed later.

In another series of developments it has been shown that horizontal, *in-plane stresses* generated by the kinematics of plate-tectonics impose long-wavelength, low-amplitude flexural effects on continental and oceanic plates, leading to regional tilts and broad upwarps and downwarps (Cloetingh et al., 1985; Cloetingh, 1988; Cloetingh and Kooi, 1990). Periodic brittle failure of the crust under a continuously applied compressive stress in converging plate environments may lead to periodic adjustments to the flexural load in adjacent basins (Peper et al., 1992; Waschbusch and Royden, 1992), and this may prove to be one of the most important mechanisms for the development of high-frequency stratigraphic sequences (those of 10^4–10^6-year duration). In fact, the 'need' for eustasy as a mechanism to generate sequences is receding (e.g., Peper, 1994; Yoshida et al., in prep.), and this makes global correlation, as a test of eustasy, even more important.

At the same time, a rigorous evaluation of early ideas about *orbital forcing*—the so-called *Milankovitch effects*—has confirmed that the processes are real (Berger et al., 1984), and much work on the geological record is demonstrating that sequences in the Milankovitch band have developed at many times in the geological past (Fischer, 1986; De Boer and Smith, 1994). Orbital forcing profoundly affects climate, and at certain times climate change has been severe enough to trigger major episodes of continental glaciation, leading to periodic draw-down of sea levels. Even without sea-level change, orbital forcing can generate significant stratigraphic cyclicity by its effects on oceanic and atmospheric circulation, evapotranspiration, and organic productivity (Perlmutter and Matthews, 1990).

3.3. Causes of first- to fifth-order stratigraphic cycles

The subdivision of stratigraphic cycles into five broad classes, based on duration, derives from the work of Vail et al. (1977). A summary of this classification is shown in Table 1, with notes on causal mechanisms. These notes are expanded on in this section. It must be emphasized that the five-fold subdivision is quite arbitrary, and is used nowadays purely for convenience in referring to the time scales of the various cycle types. Ideas about the causal mechanisms are still actively evolving, and it is becoming clear that many are not independent. For example, mantle convection drives both vertical motions of the crust and

Table 1
Stratigraphic cycles and their causes

Type [a]	Terminology	Duration, (m.y.)	Probable causes
First-order		200–400	Major eustatic cycles caused by formation and breakup of supercontinents.
Second-order	Supercycle (Vail et al., 1977); sequence (Sloss, 1963)	10–100	(1) Eustatic cycles induced by volume changes in global mid-ocean spreading centres. (2) Regional extensional downwarp and crustal loading.
Third-order	Mesothem (Ramsbottom, 1979); megacyclothem (Heckel, 1986)	1–10	Regional cycles caused by intra-plate stresses. Most are probably not of global extent.
Fourth-order	Cyclothem (Wanless and Weller, 1932); major cycle (Heckel, 1986)	0.2–0.5	(1) Milankovitch glacioeustatic cycles, astronomical forcing. (2) Regional cycles caused by flexural loading, especially in foreland basins.
Fifth-order	Minor cycle (Heckel, 1986)	0.01–0.2	(1) Milankovitch glacioeustatic cycles, astronomical forcing. (2) Regional cycles caused by flexural loading, especially in foreland basins.

[a] Hierarchy modified from Vail et al. (1977).

causes variations in the volume of the ocean basins, which affects eustasy. The resulting effects on sea level at a given point are complex.

First-order cycles are now thought to be caused by the thermal effects related to the formation and breakup of supercontinents. Worsley et al. (1984, 1986) and Veevers (1990) discussed the Phanerozoic record, and Hoffman (1991) presented a plate-tectonic scenario for the assembly and dispersal of the major continents that would allow us to extend the interpretation back to about 1 Ga. The most important stratigraphic effect of these long-term plate-tectonic movements is the variation in the long-term rate and global extent of sea-floor spreading. Lengthy, active spreading centres are thermally elevated and displace ocean waters onto the continents. The breakup and dispersion of supercontinents therefore tends to be accompanied by rising sea levels, such as those that characterized the earth during the rapid opening of the Atlantic, Indian and Southern Oceans during the Cretaceous. Plate collisions lead to the development of a new supercontinent, a lull on seafloor spreading (with a consequent global sea-level lowstand), and the gradual buildup of heat beneath the new continental mass, leading eventually to the initiation of a new round of rifting and continental dispersal. The work of Gurnis (1988, 1990, 1992), who has explored the implications of these mantle processes for the vertical motion of the continents (dynamic topography), has been referred to briefly above.

The interregional cycles of Sloss (1963) are the classic examples of *second-order cycles*. There is increasingly convincing evidence that many of these are global in scope, and are generated by cycles of eustatic sea-level change lasting several tens of millions of years (see review in Miall, 1990, Ch. 8). The primary mechanism is probably variations in global sea-floor spreading rates superimposed on the first-order cycle discussed above. Such variations reflect continental-scale adjustments to spreading patterns in response to plate rifting and collision events. The mechanism was first suggested by Hallam (1963), and Pitman (1978) is credited with the theoretical research that led to general acceptance of the idea, although in detail the process is far more complex than first described by Pitman (Kominz, 1984; Gurnis, 1992).

Cycles of base-level change can also be generated by crustal movements at continental margins. On extensional margins crustal thinning and post-rift cooling leads to subsidence on a time scale of tens of millions of years (McKenzie, 1978; Watts, 1981). Second-order clastic wedges are also generated by flexural loading during convergent and strike-slip tectonics, especially in foreland basins, where wedges of nonmarine 'molasse' spanning several millions of years to more than 10 m.y. are common (Beaumont, 1981; Jordan, 1981; Allen and Homewood, 1986). Tectonic cycles generated by regional plate-tectonic events are regional to continental in scope, not global, as demonstrated by several regional studies (e.g., Welsink and Tankard, 1987; Hubbard, 1988).

The processes which lead to second-order eustatic sea-level changes, such as changing rates of sea-floor spreading, also lead to tectonic adjustments of the continents (e.g., initiation of the rifting–thermal subsidence cycle, and subsidence over cold subducting slabs), so that actual changes in sea level in any given basin may have multiple causes that are not necessarily readily interpretable in terms of eustasy. Much work remains to be done to document and correlate these cycles globally in order to evaluate the various mechanisms.

Third-order cycles form the main basis for the Exxon global cycle chart (Haq et al., 1987), but the existence of a global framework of such cycles has been questioned (as discussed above), and no satisfactory mechanism of synchronous global change on a third-order time scale has been developed. An increasing body of evidence is indicating that cycles of this type can be generated by tectonic mechanisms, and are therefore likely to be regional to continental in extent, but not global. If this is the case they cannot be used as the basis for a global stratigraphic time scale. The intraplate-stress theory of Cloetingh (1988) is finding widespread application in the study of third-order (10^6-year) stratigraphic cyclicity. For example, Cloetingh and Kooi (1990) developed a paleostress curve for the U.S. Atlantic margins based on studies of regional plate kinematics. These indicate changes in plate configuration and rotation poles at about 2–16 m.y. intervals. Such changes would have resulted in changes in the in-plane stress and in the flexural response of the continents, resulting in regional transgressions and regressions. In the case of foreland basins, it has long been known that flexural loading by nappes and thrust-sheet stacks is the main cause of long-term (10^7-year) basin subsidence (Price, 1973; Beaumont, 1981; Jordan, 1981), but it is now being suggested that intraplate stress may act on much shorter time scales in response to load changes brought about by movement of individual structures. Tectonic cyclicity may therefore be generated with a 10^4–10^6-year periodicity (Peper et al., 1992; Heller et al., 1993; Peper, 1994). As Karner (1986) noted, basin margin and interior regions should experience opposite base-level movements, which would not be the case for cycles generated by eustatic sea-level change. This offers an excellent opportunity to test generative mechanisms through careful dating and correlation of the stratigraphic record but, as noted above, except in certain special cases this is still beyond our ability.

Fourth- and fifth-order cycles, are common in the late Cenozoic record, and also in the late Paleozoic stratigraphy of the northern hemisphere (the cyclothems of Wanless and Weller, 1932). They have long been attributed to glacioeustatic processes, those of Late Paleozoic age being related to the widespread Gondwanan glaciation of the same age range (Wanless and Shepard, 1936; Crowell, 1978). J. Croll was the first to realize, in 1864, that variations in the earth's orbital behaviour may affect the distribution of solar radiation received at the surface of the earth by latitude and by season, and the Serbian mathematician Milutin Milankovitch carried out the necessary calculations in the 1930s. Emiliani (1955) was the first to obtain direct observational evidence for the processes, in the form of variations in the marine Pleistocene oxygen isotope record. As noted above, orbital forcing, the so-called Milankovitch processes, are now universally accepted as the cause of high-frequency (10^{4-5}-year) periodicity (Berger et al., 1984; De Boer and Smith, 1994). In fact, as noted above, cyclostratigraphy is becoming the basis for a new standard of geologic time for the late Cenozoic.

However, as discussed earlier, it is now known that tectonic processes can drive cycles of base-level change with a periodicity within the range of what is commonly (but in this case misleadingly) referred to as the Milankovitch time band. In fact, as demonstrated by Algeo and Wilkinson (1988), many autogenic and allogenic processes generate cycles that can be demonstrated to have time spans within the Milankovitch time range. Where glacial processes cannot be directly proven by isotopic signatures, it is unwise to attribute stratigraphic cyclicity to orbital forcing mechanisms without rigorous testing of cyclic spectra (Fischer, 1986). Attempts to relate calculated cycle durations to specific orbital parameters are questionable for the distant geologic past because of the wide margin of error in dating techniques, and uncertainty regarding changes over time in the orbital frequencies. Berger and Loutre (1994) provided a discussion of the latter point.

4. The new quantitative dynamic stratigraphy

In the preface to his book (Cross, 1990), Timothy Cross noted many of the same developments touched on in this review, and stated that "the history of these developments indicates an increased focus among earth scientists to formulate more exacting and quantitative relations among processes and responses of complex natural systems. It also indicates a progressive expansion in the types of variables, processes and responses included in stratigraphic or sedimentary basin models—there is a trend toward combining models formulated within traditional subdisciplines and integrating them in more comprehensive models of basin evolution." Cross suggested that we are in the midst of an evolving form of stratigraphic analysis which he termed *quantitative dynamic stratigraphy*, and this became the title of his book and the basis for a new acronym: QDS. Cross defined QDS as "the application of mathematical, quantitative procedures to the analysis of geodynamic, stratigraphic, sedimentologic and hydraulic attributes of sedimentary basins, treating them as features produced by the interactions of dynamic processes operating on physical configurations of the earth at specific times and places." As described by Cross and Harbaugh (in Cross, 1990), quantitative models permit the working through of complex geological relationships that are beyond the power of intuition to fully understand, and allow for the rapid testing of new ideas. There are two important types of model, forward models, that simulate sets of processes and responses, given predetermined input variables, and inverse models, that use the structure of a forward model to simulate a specific result, such as an observed basin architecture (Cross and Harbaugh, in Cross, 1990). The following paragraphs describe some of the main areas of current QDS research.

(1) Models of basin subsidence mechanisms based on mantle thermal behaviour, plate kinematics, crustal rheology, and local structural geology. This is the oldest and most mature area of quantitative stratigraphic research. The main breakthrough in the development of a fully operational basin model was that of McKenzie (1978), who focused attention on the crustal attenuation that occurs during continental extensional tectonics, and its thermal and mechanical consequences. A methodology termed *backstripping* was developed to account for the incremental burial, loading and compaction of sediments during basin evolution (Steckler and Watts, 1978; Sclater and Christie, 1980), and this permitted the development of sophisticated numerical models for basin subsidence, thermal evolution and petroleum generation (Watts, 1981, 1989; Royden et al., 1980). The same principles were soon applied to basins generated by supracrustal (flexural) loading (Beaumont, 1981; Jordan, 1981), and became increasingly elaborate with the use of two- and three-dimensional numerical modelling programs (Quinlan and Beaumont, 1984; Beaumont et al., 1988; Stockmal et al., 1986).

(2) Stratigraphic simulations that build sequences based on models of the three main controlling parameters, subsidence, sea-level change and sediment transport. There are many different approaches to such modelling, but most are geometrical exercises that do not attempt to simulate the physics of sedimentary processes (Burton et al., 1987; Jervey, 1988; Strobel et al., 1990; Reynolds et al., 1991). That by Jordan and Flemings (1991) incorporates transport coefficients for marine and nonmarine deposition and the determination of depositional slope by calculation rather than setting it as an input variable. However, it treats subsidence simplistically, and does not incorporate flexural loading as a feedback into the model, a feature addressed by Reynolds et al. (1991).

The most advanced models are now being used to test specific tectonic hypotheses, such as the role of short-term flexural loading and intraplate stress in foreland-basin subsidence (Peper, 1994). A different class of advanced models simulates some of the actual physics of sedimentation in simple continental-margin settings, for example, the SEDSIM program of Tetzlaff (1990), which makes use of bedload transport equations.

(3) Climate models that simulate global circulation and temperature distribution. An extensive literature has developed in this field, particularly since the success of the CLIMAP project in reconstructing global climates during the late Cenozoic ice ages (CLIMAP, 1976). Research has focused particularly on the Cretaceous (Barron et al., 1981; Barron, 1983), and the late Paleozoic climates of Pangea (Parrish, 1993). Of particular interest are attempts to reconcile global models, with their large cell sizes, with the details of local topography and the documented record of stratigraphic events, such as climates deduced from facies studies and paleoecology (e.g., Dubiel et al., 1991) and wind directions obtained from paleocurrent analysis (e.g., Parrish and Peterson, 1988).

(4) *Cyclostratigraphy*, the construction of a time scale and a stratigraphic record based on the parameters of orbital forcing. As stated by Fischer et al. (1990) "only cyclostratigraphy can yield the chronostratigraphic resolution and the insight into ancient climates that are necessary to understand climatic change. At the same time, instrumental methods of scanning sedimentary se-

quences for variations in physical and chemical characteristics have come into use, as have the processing of large data sets and the analysis of time series by computer." The principles are now being applied to the late Cenozoic sedimentary record, with the resulting development of very refined sequence stratigraphies (e.g., Feeley et al., 1990; Williams, 1990).

House (1985) suggested using calculated periodicities to calibrate time scales, and discussed the use of interpreted Milankovitch cycles in the Jurassic record to refine the geological time scale determined by biostratigraphic and radiometric means. At present this seems premature, because of the uncertainties regarding orbital changes in the past. In addition, as discussed earlier, there remains considerable uncertainty regarding the precision of the geological time scales within which Milankovitch refinements are to be calculated. A method for independently testing the periodicity of metre-scale cycles, termed the gamma method, was devised by Kominz and Bond (1990), and is providing a useful quantitative approach for the resolution of these problems.

(5) Flow models for the production of petroleum from complex, heterogeneous reservoirs and the dispersion of contaminants in the shallow subsurface. By using such methods as finite-element modelling, standard hydrologic methods for the calculation of flow through porous media can now be applied to complex stratigraphic units showing variations in porosity and permeability in three-dimensions (e.g., Høimyr et al., 1992; Lake and Malik, 1993). A detailed knowledge of stratigraphic architecture is required, which brings in sedimentary facies analysis at a critical stage of project development work, when decisions must be made regarding placement of injection and extraction wells in the petroleum reservoir or contaminated rock body. Facies studies in core and outcrop (Miall and Tyler, 1991), and 3-D seismic reflection data (Brown, 1991), are critical components of such architectural reconstructions. Continued monitoring of pressures and fluid compositions (termed *surveillance geology* by production geologists) permits *history-matching* of the predicted with the actual performance of the fluid system, and incremental adjustment and improvement of the architectural model. For example, Hopkins et al. (1991) used monthly fluid production data to test the applicability of fluid-flow models to a water-injection production situation in estuarine sandbodies of the Upper Mannville Sandstone of Alberta. Blair et al. (1991) examined the flow of pentachlorphenol in groundwaters around a chemical plant.

The value of these different kinds of models is that they offer the opportunity to vary the input, to experiment with relationships between the variables and observe the outcome. Iterative experimentation, increasing improvement of the real-world test data sets, and ever more sophisticated numerical modelling, hold the promise for orders-of-magnitude improvements in our knowledge about how the earth works. New programs for inverse modelling are evolving that permit the iterative adjustment of forward models for the simulation of specific sets of geological conditions. These promise to provide unique solutions for complex problems. For example, The long-standing problem of determining the relative importance of variations in subsidence, sediment supply and sea-level change in the construction of given basin stratigraphies (Burton et al., 1987) may be on the verge of resolution (Lessenger, 1993; T. Cross, pers. commun., 1995).

5. Discussion

The research described here has led to a close symbiotic relationship between the specialties of stratigraphy, tectonics, and crustal geophysics, with geophysical theoreticians, climatologists and numerical modellers making increasing use of stratigraphic data sets as inputs and constraints on new dynamic models. The test of global eustasy has also put pressure on specialists in the field of chronostratigraphy to upgrade and integrate their data, involving the studies of stable and radiogenic isotopes, the earth's magnetic field, and biostratigraphy. The field of stratigraphy has therefore considerably extended its reach, and now represents a major interdisciplinary science tackling questions about the earth's past on a broad front. We are assembling an increasingly precise record of the geological past, including the history of regional and global sea-level change, regional plate kinematics and its effects on structural geology and basin evolution, and the evolution of global climates.

The discipline of stratigraphy now requires the practitioner to acquire, evaluate and integrate diverse data sets of varying quality and type, from the descriptive to the rigorously numerical. It is a perfect example of the geological art, which draws on all the 'basic' physical sciences, and requires an imaginative brain trained in many techniques of widely varying type, including the quantitative (e.g., statistics, numerical modelling) and the qualitative (e.g., pattern recognition). This is a unique range of skills, leaving limited room for independent work by narrow specialists. The future of stratigraphy will depend on the abilities of generalists, and on coordinated group projects by a wide range of individuals. Are there implications for this research beyond the field of stratigraphy?

The improvements in techniques and the documented record it has generated are of great value in the field of petroleum exploration and production, from the initial stages of frontier-basin exploration to the design of field-scale enhanced production programs for heterogeneous reservoirs. Exploration programs are guided by improved knowledge of what to look for in frontier regions, and a wider range of interpretive skills is available to make sense out of the results. The principles of sequence stratigraphy quickly became a standard methodology in the industry during the 1980s. Programs for frontier exploration and exploitation have become much more successful, efficient, and cost-effective in recent years, as practical applications of the research described here became available; but these successes are in danger of disappearing as a result of the 'downsizing' that has been the fashion in the major corporations during the last few years; research departments have been amongst the first to be eliminated.

Many areas of environmental geology also make use of stratigraphic research methods and data bases. For example, the migration of toxic wastes from landfill sites and chemical plants can be investigated using principles that are very similar to those used in enhanced petroleum recovery.

The Global Sedimentary Geology Program (GSGP) has brought much of the new data and the new research techniques together in focused attacks on selected intervals of geological time, first the Cretaceous (Ginsburg and Beaudoin, 1990) and, more recently, the late Paleozoic (Klein, 1994), two periods when the earth was in very different plate-tectonic and climatic configurations than at the present day. During the Cretaceous, global sea levels reached an all-time high and the earth's climate was in a 'greenhouse' condition, while during the late Paleozoic the earth's continents had assembled into the Pangea supercontinent, sea levels were low, and the climate was in the 'icehouse' condition. Integrated studies of the type sponsored by GSGP are of considerable relevance to studies of present-day global change, including the current fears regarding dramatic climate change triggered by human interference. Not only does the stratigraphic record contain detailed analogs of a wide spectrum of past conditions, but a study of this record can yield invaluable insights on how the earth's climate system works. What are the major controlling mechanisms? How do they interact? How fast do they interact? What are the major sensitivities that lead to change? and is anything we do now likely to have an effect on the earth's climate in the immediate future?

Another field of research that has had a significant effect on our view of earth history and how we go about investigating it is the bolide-impact hypothesis for the extinction of the dinosaurs. What started life as a category of enquiry in the realm of amateur speculation became a serious concern with the discovery of the famous iridium layer in Cretaceous–Tertiary boundary clays (Alvarez et al., 1980). From this beginning has grown new theory about the nature of catastrophic events in earth history (Hsü, 1983), new evidence for many other extinction events and new ideas about the importance of such events in the evolution of life (Raup and Jablonski, 1986), and a multidisciplinary investigation into the nature of bolide impacts and their consequences, culminating in the discovery of a crater in Mexico that may be the location of the terminal Cretaceous impact event (Hildebrand et al., 1991).

The nature of modern stratigraphic data bases, the research techniques that have evolved, and the kinds of questions that stratigraphers can now ask and answer, place stratigraphy at the very centre of *earth-system science*, a new, multidisciplinary approach to the study of the earth that emphasizes "the interactions between the different parts of the Earth—the atmosphere, hydrosphere, biosphere, and the solid Earth—and about the balance in the global environment that exists as a result of those interactions" (Skinner and Porter, 1995). In many respects the emergence of the concept of earth-system science is validating the power of the Gaia hypothesis: the view of the earth as an 'organic' self-regulating entity (Schneider and Boston, 1991).

So, whither stratigraphy? The answer at present seems to be an increasing refinement of our abilities to collect precise data and to integrate it more effectively based on dynamic models of sedimentary processes. This will lead to a far more sophisticated understanding of complex earth systems, with consequent improvements in our ability to predict outcomes of importance to the human condition. Stratigraphy is no longer 'stamp collecting' but, like the so-called 'hard' physical sciences, now consists of sets of rigorously acquired data and quantitative, testable hypotheses. It has come of age.

Will the earth develop a runaway greenhouse effect? Will we run out of nonrenewable energy? Can toxic waste dumps and poisonous landfills be cleaned up? How did life really begin? What is the danger of another bolide impact of the magnitude that wiped out the dinosaurs? If you want answers to these questions, ask a stratigrapher. The data are in our files.

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