GAC MEDALLIST SERIES

Logan Medallist 3. Making Stratigraphy Respectable: From Stamp Collecting to Astronomical Calibration

Andrew D. Miall

Department of Earth Sciences
University of Toronto
Toronto, Ontario, M5S 3B1, Canada
Email: miall@es.utoronto.ca

SUMMARY
The modern science of stratigraphy is founded on a nineteenth-century empirical base – the lithostratigraphy and biostratigraphy of basin-fill successions. This stratigraphic record comprises the most complete data set available for reconstructing the tectonic and climatic history of Earth. However, it has taken two hundred years of evolution of concepts and methods for the science to evolve from what Ernest Rutherford scornfully termed "stamp collecting" to a modern dynamic science characterized by an array of refined methods for documenting geological rates and processes.

Major developments in the evolution of the science of stratigraphy include the growth of an ever-more precise geological time scale, the birth of sedimentology and basin-analysis methods, the influence of plate tectonics and, most importantly, the development, since the late 1970s, of the concepts of sequence stratigraphy. Refinements in these concepts have required the integration of all pre-existing data and methods into a modern, multidisciplinary approach, as exemplified by the current drive to apply the retrodicted history of Earth's orbital behaviour to the construction of a high-precision 'astrochronological' time scale back to at least the Mesozoic record.

At its core, stratigraphy, like much of geology, is a field-based science. The field context of a stratigraphic sample or succession remains the most important starting point for any advanced mapping, analytical or modeling work.

RÉSUMÉ
La science moderne de la stratigraphie repose sur une base empirique du XIXe siècle, soit la lithostratigraphie et la biostratigraphie de successions de remplissage de bassins sédimentaires. Cette archive stratigraphique est constituée de la base de données la plus complète permettant de reconstituer l'histoire tectonique et climatique de la Terre. Cela dit, il aura fallu deux cents ans d'évolution des concepts et des méthodes pour que cette activité passe de l'état de « timbromanie », comme disait dédaigneusement Ernest Rutherford, à l'état de science moderne dynamique caractérisée par sa panoplie de méthodes permettant de documenter les rythmes et processus géologiques.

Les principaux développements de l'évolution de la science de la stratigraphie proviennent de l'élaboration d'une échelle géologique toujours plus précise, l'avènement de la sédimentologie et des méthodes d'analyse des bassins, de l'influence de la tectonique des plaques et, surtout du développement depuis la fin des années 1970, des concepts de stratigraphie séquentielle. Des raffinements dans ces concepts ont nécessité l'intégration de toutes les données et méthodes existantes dans une approche moderne, multidisciplinaire, comme le montre ce mouvement actuel qui entend utiliser la reconstitution de l'histoire du comportement orbital de la Terre pour l'élaboration d'une échelle temporelle « astrochronologique » de haute précision, remontant jusqu'au Mésozoïque au moins.

Comme pour la géologie, la stratigraphie est une science de terrain. Le contexte de terrain d'un échantillon stratigraphique ou d'une succession demeure le point de départ le plus important, pour tout travail sérieux de cartographie, d'analyse ou de modélisation.

Traduit par le Traducteur

STRATIGRAPHY AS A DESCRIPTIVE, EMPIRICAL SCIENCE
Stratigraphy is the study of layered rocks. It has a reputation as a dull, descriptive science. It could well have been one of the disciplines Ernest Rutherford, the eminent geophysicist, was thinking about when he made his famous remark early in the twentieth century: "All science is either physics or stamp collecting." My own introduction to the subject, as a student in the early 1960s, contained lengthy lists of formation names and detailed descriptions of lithologies and fossil content, with little in the way of enlightenment about what it all meant. In

Geoscience Canada, v. 42, http://www.dx.doi.org/10.12789/geocanj.2015.42.072 pages 271-302

truth, then, it did not mean much. However, the stratigraphic record is the major repository of information about Earth history, including paleogeography and climate, and the course of evolution. Modern methods, described here, have evolved into a powerful multidisciplinary science.

Stratigraphy is at its core a descriptive science, like most of the rest of the traditional geological disciplines and, indeed, like most field-based sciences, such as biology and oceanography. All such disciplines have fallen victim to 'physics envy,' which refers to "the envy (perceived or real) of scholars in other disciplines for the mathematical precision of fundamental concepts obtained by physicists" (from Wikipedia). To a degree this is understandable. The rise of geology in the mid- to late nineteenth century following the fundamental contributions of Charles Lyell and his generation, was followed by the rise of physics. Eminent physicists, such as William Thomson (Lord Kelvin), began to make pronouncements about the Earth, and helped to create physics envy by such statements as "what cannot be stated in numbers is not science" (Mackin 1963). It is one of the better known stories about the history of geology that Lord Kelvin's estimate of the age of the Earth (a few tens of millions of years) conflicted with the Hutton–Lyell concepts of deep geologic time, but was mistakenly accorded considerable respect because it was based on calculations by a physicist (Hallam 1989). The conflict was not resolved until the discovery early in the twentieth century of radioactive decay and the realization that this provided a source of internal heat that rendered obsolete the idea of an Earth that had merely cooled from a primary molten state – the hypothesis favoured by Kelvin. Ernest Rutherford was one of the leading figures in developing ideas about radioactive heat that challenged Lord Kelvin, but nonetheless, although his work supported the conclusions that geologists had been arriving at about the length of geologic time, based on their field observations and deductive reasoning, Rutherford contributed to the rise in the authority of physics as the preeminent science.

In a landmark paper on cycles and rhythms in geology, and the measurement of geologic time, written shortly after the discovery of the concept of radioisotopic dating, Barrell (1917, p. 749) complained about physics and physicists thus:

> *Not only did physicists destroy the conclusions previously built by physicists, but, based on radioactivity, methods were found of measuring the life of uranium minerals and consequently of the rocks which envelop them. … Many geologists, adjusted to the previous limitations, shook their heads in sorrow and indignation at the new promulgations of this dictatorial hierarchy of exact scientists. In a way, this skepticism of geologists was a correct mental attitude. The exact formulas of a mathematical science often conceal the uncertain foundation of assumptions on which the reasoning rests and may give a false appearance of precise demonstration to highly erroneous results.*

Barrell's self-confidence seems not to have been typical of the times, however. J. Tuzo Wilson (1985), a leading Canadian geologist who (much) later developed several of the key concepts about plate tectonics, and did much to explain and popularize the subject in the 1970s, captured well the flavour of this period of physics dominance:

> *… on returning to the University of Toronto in 1927 I applied to transfer from a major in physics to one in geology. My professors were appalled. Physics was then in its heydey, but geology was held in very low esteem. Ernest Rutherford had compared it to postage-stamp collecting for it consisted of making maps by identifying and locating rocks and fossils. Instruments and methods were primitive and geology lacked general theories, which were scorned as "armchair geology." This was in striking contrast to the precise theories common in physics, but few considered that Wegener's concept of continents slowly drifting about had any merit, and no one, that I can recall, realized that therein lay the explanation for the lack of theories in geology.*

Hallam (1989, p. 233) has a slightly different view on this subject: "Rutherford may have had his tongue in his cheek when he uttered his notorious dictum, 'All science is either physics or stamp collecting', but Kelvin would doubtless have earnestly approved of this reductionist attitude, for he is on record as saying that data that cannot be quantified are hardly worthy of a scientist's attention."

The problem persisted. Baker (2000) commented thus:

> *In his history of earth science, entitled* The Dark Side of the Earth, *British geophysicist and science writer Robert Muir Wood argues that geology reached its intellectual peak around 1900. During the twentieth century, according to Wood, geology's intellectual decline coincided with the rise of modern physics, chemistry, and biology. In the 1960s and 1970s, however, a new earth science developed, replacing anachronistic "geological" concerns and methods with the global view and scientific methodologies of geophysics. Geochemist and science minister of France, Claude Allègre offers somewhat similar views on how much modern geochemical science has supplanted the "mapping mentality" of geology. According to these scholars, rigorous, scientific geophysical, geochemical and (presumably) geobiological approaches are now replacing the outmoded geological one.*

Torrens (2002, p. 252) noted that "Robert Muir Wood asserted in 1985 that 'stratigraphy and fossil correlation [were] the backbone of [old] Geology', whereas the new 'Earth Science is revealed by geophysics and geochemistry' (Muir Wood 1985, p. 190). Torrens (2002, p. 252) also cited Robert Dietz, who noted (1994, p. 2) that: "Geology had evolved from an observational and field science into largely a laboratory science with instrumental capabilities that have improved data collection and data processing by orders of magnitude."

As Hallam (1989, p. 221–222) argued, these views display a serious misunderstanding of the nature of Geology, especially the need for the traditional stratigraphic data base from which to build geological histories that could now incorporate the new plate-tectonic principles. And not all have agreed that the move from field to laboratory has been such an advance. Many eminent, field-based geologists have felt the need to downplay the primacy of numerical, experimental data of the type that would be familiar to a physicist or a chemist, and to restate the importance of carefully structured field observations, and the building of temporary, inductive hypotheses, followed by further observation and testing, employing the methods of multiple working hypotheses. Read (1952), a petrologist, is famous for his remark that the "best geologist is the one who has seen the most rocks" (cited by Ager 1970). Francis Pettijohn, one of the founders of modern sedimentology, issued a warning in his memoirs in 1984, likening the rush into the exotic peripheries around what he saw as the true core of geology – with stratigraphy at its centre – to "a doughnut with nothing in the middle" (Pettijohn 1984, p. 203). Earlier he had said (Pettijohn 1956, p. 1457) "Nothing, my friends, is so sobering as an outcrop. And many a fine theory has been punctured by a drill hole." More recently, Dewey has rightly noted (1999, p. 3), "core, field-based geology is [still] the most important, challenging and demanding part of the science."

As modern laboratory techniques have grown in importance and as the computer has become ever more central to scientific activities this emphasis on the field has become ever more important. Geology deals with a complex Earth; the rock record is the product of numerous interacting processes acting simultaneously over a wide range of time scales; and earth history is explored using a wide array of interrelated techniques, some based on direct field observation, some based on remote sensing, some on sampling followed by laboratory measurement, and with numerical simulation and modeling assuming ever greater usefulness. All these data must be reconciled, and, beyond the kinds of basic stratigraphic prediction that Pettijohn was referring to in his remark about outcrops and drill holes (cited above), few of the conclusions about the geological past are amenable to direct testing, as would be a hypothesis in physics or chemistry. This is what makes geology different, and this is why many of the philosophical and methodological discussions about science are not applicable to geology.

Hallam (1989, p. 221) stated:

> *There has often in the past been some tension between geologists and physicists with a common interest in problems of earth history, which is a natural consequence of their difference in aptitude, training, and outlook. Geologists tend to be staunchly empirical in their approach, to respect careful observation and distrust broad generalization; they are too well aware of nature's complexity. Those with a physics background tend to be impatient of what they see as an overwhelming preoccupation with trivial detail and lack of interest in devising tests for major theories, and with the geologists' traditional failure to think in numerate terms.*

Torrens (2002, p. 252) suggested that "Largely as a result of contemporary changes in attitude toward old and new, the teaching of stratigraphy has declined to a surprising extent. It is a complex and 'difficult' subject, which became no longer seen as central." However, as explained below, stratigraphy is no longer the descriptive 'stamp collecting' enterprise that it might once have been. The meticulousness of modern inductive observational methods is matched by an array of deductive methodologies that have entirely changed the science over the last half-century. I leave it to the likes of Vic Baker, Carol Cleland, Robert Frodeman, and others to explain philosophies of science and to answer the complaint quoted by Baker from former GSA president H. L. Fairchild that "Geologists have been far too generous in allowing other people to make their philosophy for them" (V. Baker, p. v, in Baker 2013).

However, the tension between geology and the more experimental and numerical 'hard' sciences has persisted to the present day. As recently as 2008 an eminent Canadian geophysicist explained to me that he did not like working with geologists or supervising students of geology, because, he said, "Geologists can't count."

THE SIGNIFICANCE OF FIELD CONTEXT

The answer to my rude geophysicist colleague then and now is to explain field context. All the elaborate, refined geochemical probing and geophysical sensing of rocks, and the digital models and computer visualization of them, are of zero value if we don't know where the rocks come from. This is not just a matter of geographic location or of sample position in a stratigraphic section, but relates to the complete geological background of the rocks of interest. Torrens (2002, p. 254) said "The history of stratigraphy … reveals how, now that we can measure many things so precisely, it is important that we understand exactly what our measurements are attempting to reveal." Later in this paper I detail the many vital strands of the stratigraphic science that now enable us to reconstruct, in substantial detail, the geological history and significance of sedimentary sections, which may include, for example, the regional geological history, structural, geochemical, magmatic or metamorphic development, or paleoclimatic or paleoceanographic evolution, of the section under study. Indeed, it is largely from the sedimentary record that our knowledge of the details of earth history comes. Field context means acute observation and recording of many visually observable and measurable details, the requirements and parameters of which are determined by the advanced applications now being applied to the sedimentary record. Field context may include three-dimensional position, vertical and lateral stratigraphic relations, the nature of bedding and bed contacts, the nature of surrounding lithofacies, observable sedimentary structures, fossil content, ichnofacies, and so on, at all scales from that of the largest outcrop to the sub-microscopic. Geology owns field context. At its core, this is what geology is about.

Here are some examples of the importance of field context. Figure 1 illustrates an apparently continuous succession of shallow marine limestone beds characterized by flat to undulating bedding planes, and minor channeling. Close inspection reveals abundant intraclast brecciation. Lithofacies appear similar throughout, and there is nothing about this outcrop to suggest that geochemical or geophysical characteristics would vary significantly from top to bottom. However, the bedding surface at the level of the geologist's shoulder is the boundary between the Sauk and Tippecanoe sequences, a craton-wide unconformity that can be traced for several thousand kilometres, and represents millions of years of missing time. Careful 'old fashioned' mapping, including the collection and analysis of fossil content for the purpose of assigning chronostratigraphic ages, was required in order for this outcrop to be assigned to its correct geological position.

Figure 2 illustrates an example of the modern approach to the documentation of elapsed time in the rock record. The outcrop has been designated a Global Stratigraphic Section and Point for the Cambrian–Ordovician boundary on the basis of its rich fauna. Facies studies demonstrate that the mudstone layers are deep-water deposits, and contain such open marine fossils as graptolites, whereas the interbedded limestone layers originated as shallow water deposits with a rich shelly fauna (trilobites, brachiopods, etc.), and were transported to a deep water setting by sediment gravity flows down the ancient Lau-

Figure 1. An outcrop of the Sauk-Tippecanoe contact, Aguathuna Quarry, near Port au Port, western Newfoundland.

rentian continental margin. Under ideal circumstances, ages of rocks such as these may now be assigned with accuracies in the 10^5 year range, based on quantitative methods of biostratigraphic correlation (Sadler et al. 2009).

Figure 3 illustrates one of the products of highly detailed biostratigraphic study representing more than one hundred years of intense research. These are three of thirteen sections, each about 5 m thick, measured over a distance of about 80 km, representing the Inferior Oolite formation (Aalenian-Bathonian) of southern England. Modern chronostratigraphic calibration has shown that the sections span a total of about 10 million years. There are 56 faunal horizons in these sections, averaging 180,000 years in duration, but none of the sections contain all of these horizons and in none of them is the preserved record the same.

Overall, it is impossible to distinguish any ordered pattern to the record of sedimentation and erosion in these sections. How typical is this of shallow marine sedimentation in general? Does the availability of an unusually detailed ammonite biostratigraphy enable us to develop a much more detailed record of local change than would otherwise be available? And should this section therefore be regarded as a model for the interpretation of other shallow marine carbonate sections? Would it be correct to conclude that many other shallow marine (and nonmarine?) successions should similarly be regarded as containing numerous local diastems? If so, what does this tell us about short- to long-term sedimentary processes? No clear answers are available to any of these questions, but without the detailed biostratigraphic and facies observations none of them could even be asked.

Figure 4 illustrates a succession of thin-bedded turbidites. Calculations of sedimentation rate and of the elapsed time represented by successions of this type are notoriously difficult, but careful examination of the sedimentary facies of each bed can offer guidance. The turbidite sandstone beds each accumulated in the space of a few hours to days, whereas the elapsed time represented by the intervening mudstone is very difficult to estimate, and depends on the depositional process. Finely laminated mudstone beds may represent pelagic deposits accumulated over tens to hundreds of thousands of years, or longer, but it is increasingly being recognized that mud is commonly transported and rapidly deposited within active current regimes. Petrographic studies show that mudstone layers are commonly deposited as silt-sized aggregate

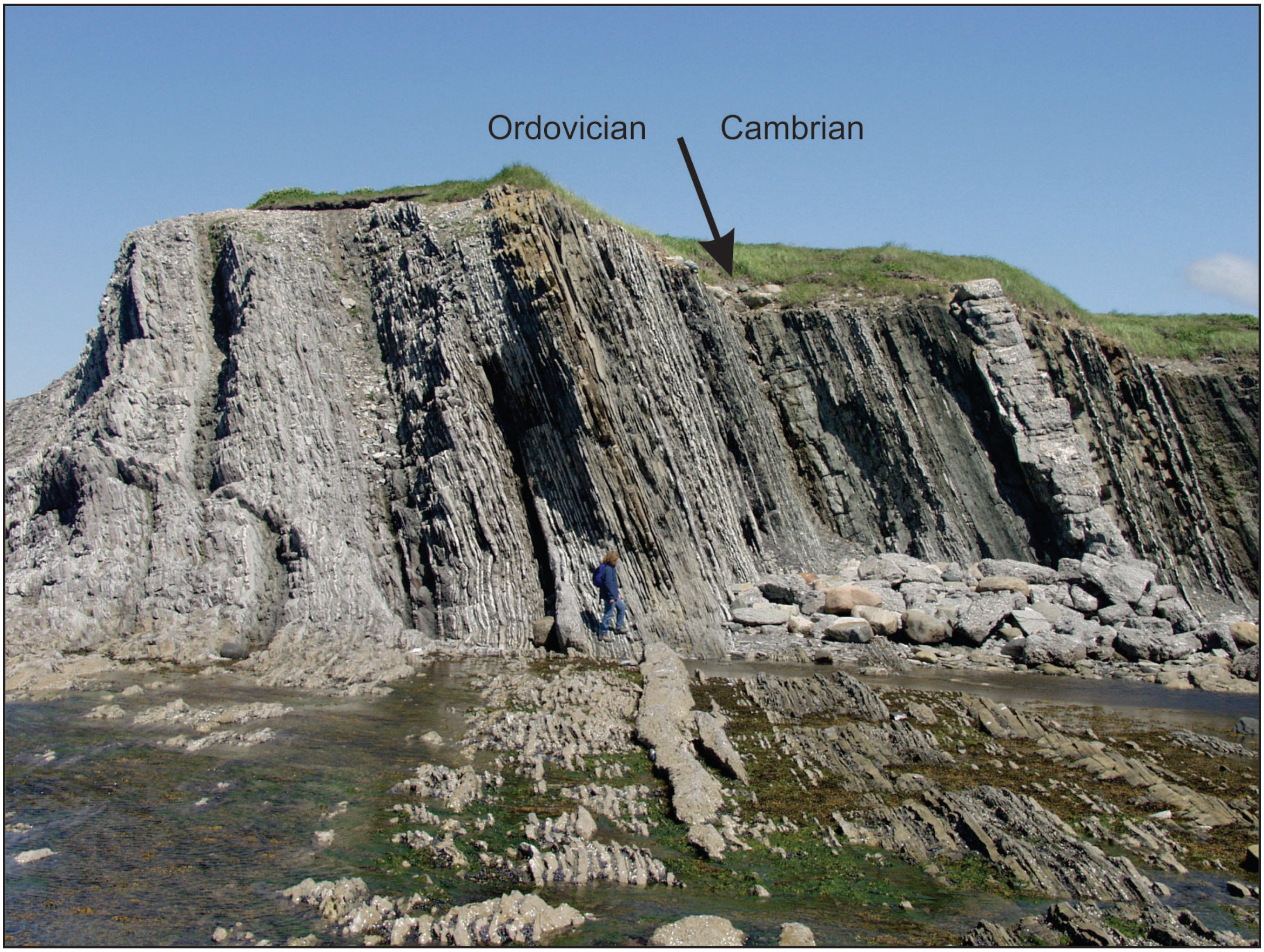

Figure 2. The Global Stratigraphic Section and Point (GSSP) for the Cambrian–Ordovician boundary at Green Point, Gros Morne National Park, Newfoundland.

particles. Careful studies of fine-scale sedimentary structures commonly reveal a complexity of bedforms showing that mud floccules may be moved by tidal and other currents, with some units deposited by wave or storm activity over time periods of hours to days (e.g. Plint et al. 2012; Schieber et al. 2013).

Another example of the importance of modern stratigraphic research is the type of succession illustrated in Figure 5. These interbedded sandstone and shale layers contain clear evidence of shallow marine sedimentation in the form of sedimentary structures, fossil content and trace fossils. We now know that deposits of this type are replete with hiatuses, and that as little as 10% of the elapsed time embodied in this section may be actually represented by sediment. Bedding planes at facies contacts, such as those visible in Figure 5, may represent tens to hundreds of thousands of years of elapsed time (Miall 2015). Detailed stratigraphic reconstructions and subsurface studies using well data and reflection seismic methods demonstrate that many deposits of this type develop by lateral accretion of low-angle clinoform slopes on basin margins (e.g. Johannessen and Steel 2005; Plint et al. 2009). Much of the elapsed time is represented by the lateral growth of the clinoforms. Exposures of the top surface of a clinoform are surfaces of sediment bypass, which explains the lengthy hiatuses at some key bedding contacts. How can we distinguish the bounding surfaces of clinoforms from the bedding planes that result from short-term autogenic changes in shallow marine sedimentary processes?

A brief mention may also be made here of three longstanding controversies in sedimentary geology, solutions to which were arrived at by the application of modern tools of sedimentology and basin analysis.

1) The term ‘till’ has long been applied to the coarse, poorly-sorted, boulder-rich deposits laid down by continental glaciers. In the ancient record, many deposits of this type have been termed till, the glacial origin of which is apparently supported by the presence of such glacial indicators as striated pavements and dropstones, and this has generated a false impression of the importance of continental glaciation. However, modern facies analysis observations demonstrate that many, if not most such deposits in the ancient record were laid down by sediment gravity flows in subaqueous settings (e.g. McMechan 2000). The detritus may be glacigenic, as indicated by associated dropstone facies, the presence of striated pavements, etc., but the final depositional process was one of sub-

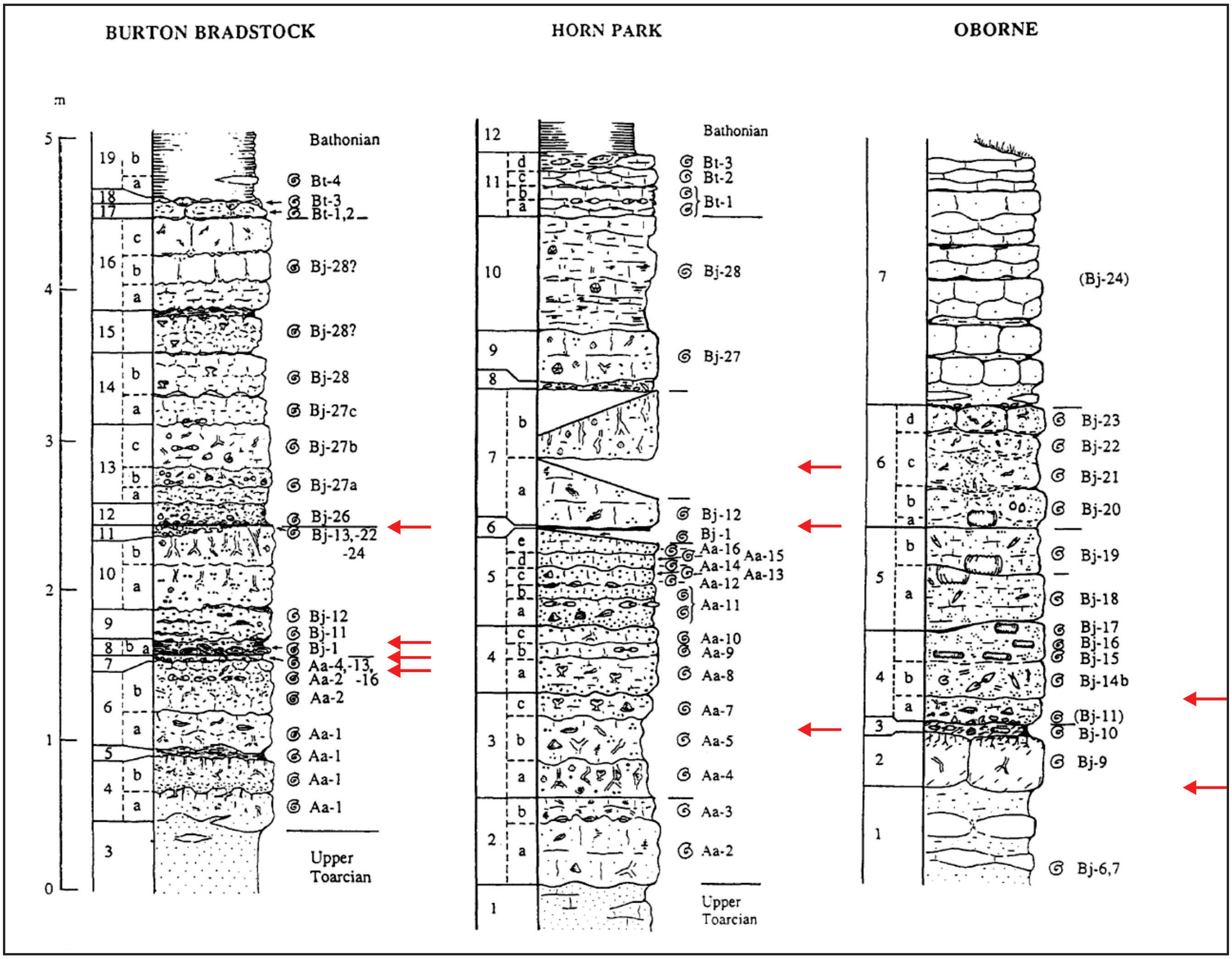

Figure 3. Examples of the sections through the Inferior Oolite (Middle Jurassic) of southern England, showing the numbered ammonite faunas and the bedding surfaces identified as hiatuses (red arrows) (adapted from Callomon 1995).

aqueous reworking. Clast fabrics, the presence of graded bedding, and an association with thick units of marine or lacustrine mudrocks (with or without dropstones) are the key indicators. Till *sensu stricto*, deposited in continental settings, has a low preservation potential and is rare in the rock record. The non-genetic term 'diamict' (termed diamictite when lithified), is preferred. Very similar rocks may occur in non-glacial volcaniclastic settings (Eyles et al. 1983).

2) The Snowball Earth hypothesis holds that during the Neoproterozoic the Earth passed through a period when it became largely or entirely frozen (Hoffman et al. 1998). The evidence consists of widely dispersed suites of coarse conglomeratic deposits interpreted as glacigenic in origin, and the hypothesis is apparently supported by the carbon isotope geochemistry of the successions. All the conglomerate deposits were thought to be of the same age, indicating a simultaneous, Earth-wide freeze-up. However, careful sedimentological and chronostratigraphic analysis of the worldwide occurrences of these rocks indicates that there was more than one Neoproterozoic glacial episode, that many of the deposits are reworked submarine sediment–gravity flow deposits containing ample evidence of active marine currents and of a hydrological cycle inconsistent with a frozen Earth, and that some are entirely volcaniclastic in origin, indicating no relationship whatever to glaciation (Eyles and Januszczak 2004; Allen and Etienne 2008).

3) The important early publications that set out the new techniques of seismic stratigraphy contained the hypothesis that the cycles of change in accommodation that lead to the accumulation of stratigraphic sequences are caused largely or entirely by eustatic changes in sea level on 10^6–10^7 time scale (Vail et al. 1977). However, subsequent re-examination of many sequence assemblages has, in many instances, revealed indisputable evidence of local or regional tectonic control, and it has been argued that for most of the geological record, chronostratigraphic evidence has not been adequate to demonstrate the global synchroneity of the sequences that would be a necessary attribute of sequences that are of eustatic origin (Miall and Miall 2001). Modern studies using the refined methods described in this paper are suggesting a quite

Figure 4. Thin-bedded turbidites, Annot, France.

different idea: the importance of high-frequency orbital climatic and/or glacioeustatic control of parts of the ancient rock record on a 10^4–10^5-year time scale (Hilgen et al. 2015).

As these examples have demonstrated, only the application of all available modern tools of sedimentary geology, including facies analysis, sequence stratigraphy and chronostratigraphy, has yielded the interpretations presented here.

The eminent stratigrapher, P.D. Krynine is reputed to have said, in 1941, "Stratigraphy can be defined as the complete triumph of terminology over facts and common sense." But what has just been described here is not the stratigraphy that Krynine knew.

DEDUCTIVE MODELS AND HYPOTHESES IN STRATIGRAPHY

The modern science of stratigraphy – what I termed 'sophisticated stratigraphy' in a recent review (Miall 2013) – operates by the dynamic interplay between an array of deductive models and hypotheses which express our understanding of the operation of earth system science in the sedimentary realm. Most of these are qualitative, in the sense that they depend on descriptive data, but all are characterized by rigour in the protocols for field data collection, description and processing. Among the more important hypotheses and models are:

- The law of superposition of strata
- The principle of faunal succession
- Walther's Law
- The concept of facies
- Flow regime concept
- Cyclic sedimentation
- Facies models
- Autogenic and allogenic processes and the relationships between them
- The inductive foundation of Global Stratigraphic Sections and Points as the basis of chronostratigraphy
- Concept of accommodation
- Sequence stratigraphy
- Quantitative basin models
- Orbital forcing, cyclostratigraphy and astrochronology

The first eight in this list are amongst the most important components of **sedimentology** a science that did not exist in its modern form until the 1960s. **Chronostratigraphy** is one of the oldest components of stratigraphy, based in the first instance on the discoveries about the successions of rock types and fossil faunas that William Smith used in the construction of the first ever geological map (Smith 1815), discoveries that were studied intensively during the nineteenth century, leading to significant developments in the field of **biostratigraphy**.

Figure 5. Shallow-marine Cretaceous strata at the WAC Bennett dam, near Fort St. John, British Columbia.

Chronostratigraphy has evolved into a highly precise science with the development of an array of dating methods and field procedures. It was the evolution of **sequence stratigraphy** in the 1990s that began to bring all of this together into the modern dynamic science which stratigraphy now represents.

THE EVOLUTION OF MODERN STRATIGRAPHY

Beginnings (Nineteenth Century)

I do not deal here with the work of Steno, Hutton, Lyell and others, from whom came the concepts of uniformitarianism. This history has been amply covered elsewhere.

Middleton (2005) divided the history of sedimentology into six periods or stages. The first stage ended about 1830 with the publication of Lyell's (1830–1833) master work that led to the general acceptance of **uniformitarianism**, or **actualism**, as the basis for geology. What follows in this paper falls into his second period. The subsequent discussion does not adhere to his subdivision into 'periods' because I focus on specific themes which overlapped in time.

Two key early developments were the recognition of the concept of **facies** (Gressly 1838), and the establishment of **Walther's Law** (Walther 1893–1894). Teichert (1958), Middleton (1973) and Woodford (1973) reviewed the history and use of the concepts in light of contemporary ideas. Note the dates of these papers (1958, 1973), in light of the stages of development summarized below, because they help to explain the chronological evolution of modern stratigraphic thought and theory. Walther's Law is discussed further below.

Developments in biostratigraphy were enormously important in establishing some of the basic ideas about stratal succession, relative ages, and correlation. The evolution of the concepts of zone and stage are discussed in detail elsewhere (Hancock 1977; Miall 2004), topics that are not repeated here. Stratigraphic paleontology was a central theme of stratigraphy until relatively recent times. In fact, the first professional society in the field of sedimentary geology, the *Society of Economic Paleontologists and Mineralogists*, founded in Tulsa in 1931, emphasized this fact in the title of the society. Paleontology and mineralogy were important elements of petroleum geology and basin analysis until the seismic revolution of the 1970s, mainly because of their use in the identification and correlation of rock units in petroleum-bearing basins.

Cyclic Sedimentation (1932–1968)

Implicit in the early work on facies and on Walther's Law is the concept of recurrence of certain environments and their deposits. The idea of cyclicity became explicit with the study of the Carboniferous deposits of the US mid-continent in the early 1930s, which consist of repetitions of a coal-bearing, clastic–carbonate succession. These came to be called **cyclothems**. Wanless and Weller (1932, p. 1003) are credited with the original definition of this term:

> *The word "cyclothem" is therefore proposed to designate a series of beds deposited during a single sedimentary cycle of the type that prevailed during the Pennsylvanian period.*

Shepard and Wanless (1935) and Wanless and Shepard (1936) subsequently attributed the cyclicity to cycles of glacioeustatic sea-level change, an explanation that has never been challenged.

The beginnings of an understanding of the significance of the lithofacies signatures of common environmental settings is implicit in the paper by Nanz (1954), where coarsening- and fining-upward trends extracted from some modern sedimentary environments in Texas are presented. There is no discussion of repetitiveness or cyclicity in this paper, but the work was clearly foundational for the very important papers by Nanz's Shell colleagues that followed less than a decade later (see below).

Duff and Walton (1962) demonstrated that the cyclothem concept had become very popular by the early 1960s. For example, J.R.L. Allen, who is credited as one of the two originators of the meandering river point-bar model for fluvial deposits, used the term cyclothem for cycles in the Old Red

Sandstone in his first papers on these deposits (Allen 1962, 1964). Duff and Walton (1962) addressed the widespread use (and misuse) of the term cyclothem, and discussed such related concepts as modal cycle, ideal cycle, idealized cycle, and theoretical cycle, the differences between cyclicity, rhythmicity and repetition, and the possible value of statistical methods for refining cyclic concepts. They speculated about the possibility of repeated delta-lobe migration as a cause of cyclicity, in contrast to the prevailing interpretation of the cycles as the product of sea-level change.

With Carboniferous coal-bearing deposits as the focus, two edited compilations dealing with cyclic sedimentation made essential contributions to the birth of modern sedimentology at about this time. Merriam (1964), based in Kansas, provided a focus on the US mid-continent deposits, while Duff et al. (1967) dealt at length with European examples. The Kansas publication included a study of cyclic mechanisms by Beerbower (1964) that introduced the concepts of **autocyclic** and **allocyclic** processes. Autocyclic processes refer to the processes that lead to the natural redistribution of energy and sediment within a depositional system (e.g. meander migration, shoreline progradation) — the preference is now to use the term **autogenic** because the processes are not always truly cyclic — whereas **allocyclic** (**allogenic**) processes are those generated outside the sedimentary system by changes in discharge, load, and slope. Beerbower (1964) was dealing specifically with alluvial deposits in this paper, but his two terms have subsequently found universal application for other environments and their deposits. The term **allogenic** is now used to refer to processes external to a sedimentary basin, including eustasy, tectonism and climate change.

Another important contribution at this time was that by Visher (1965). The purpose of his paper was to build on the ideas contained in Walther's Law to highlight the importance of the vertical profile in environmental interpretation. He provided detailed descriptions of the profiles for six clastic environments, regressive marine, fluvial (channel or valley-fill), lacustrine, deltaic, transgressive marine, and bathyal-abyssal, drawing on both modern settings and ancient examples. This was, therefore, one of the first comprehensive attempts to apply the principles of actualism (uniformitarianism) to sedimentological interpretations. Interestingly (and this highlights one of the arguments of this paper that some ideas develop as separate lines of research, which take time to come together), Visher's paper makes no reference to what are now the classic papers on Bouma's turbidite model (Bouma 1962), or Allen's (1964, 1965) work on alluvial deposits, which include his block diagram of a fluvial point-bar. However, Beerbower's (1964) description of autocyclicity and Duff and Walton's (1962) speculation about deltaic processes (neither of which are referenced by Visher) indicate the beginnings of what shortly became a flood of new work providing the basis for the facies model revolution. Early applications of these ideas to the interpretation of the subsurface are exemplified by Berg's (1968) study of an interpreted point-bar complex constituting a reservoir unit in Wyoming.

Basin Analysis and the Big Picture (1948–1977)

Driven in large measure by the needs of the petroleum industry to understand subsurface stratigraphic successions, geologists devised a number of ways to explore the broader origins of a basin fill and understand its paleogeographic evolution. Until the plate-tectonics revolution of the 1970s, basins were interpreted in terms of the **geosyncline theory**, which reached its full expression in this period with the definition of a range of classes based on structural and stratigraphic attributes (Kay 1951), many of which, as the plate-tectonics paradigm subsequently revealed, had little to do with the actual dynamics of continental crust.

Whereas the facies model revolution of the 1970s dealt with sedimentology on the relatively small scale of individual depositional systems (rivers, deltas, submarine fans, reefs, etc.), paleogeographic reconstruction for industry meant attempting to understand entire basins. Provenance studies based on detrital petrography were central to this work, hence the title of the first specialized journal in this field, the *Journal of Sedimentary Petrology*, founded in 1931. Isopachs revealed broad subsidence patterns, and (for outcrop work) regional paleocurrent studies confirmed regional transport patterns, even in the absence of the understanding of the hydraulics of sedimentary structures that came later with the development of the flow regime concept. Krumbein (1948) pioneered the generation of lithofacies maps based on such indices as a clastic–carbonate ratio. Dapples et al. (1948) demonstrated how these maps could be used to deduce tectonic controls in a basin. The subject of stratigraphy meant classical lithostratigraphy. The books and reviews by Pettijohn (1949, 1962; Potter and Pettijohn 1963), and Krumbein and Sloss (1951), and Levorsen's (1954) textbook on petroleum geology exemplify this approach.

However, some interesting new ideas that we would now classify under the headings of basin architecture, accommodation and sequence stacking patterns began to emerge, although little of this work was widely used at the time, it being only from the perspective of modern sequence methods that we can look back and see how a few individuals were ahead of their times. Rich (1951) described what we would now term the continental shelf, the continental slope and the deep basin as the **undaform**, **clinoform**, and **fondoform**, respectively, and provided descriptions of the processes and resulting sedimentary facies to be expected in each setting. The only one of his terms to survive is **clinoform**, although now it is used as a general term for deposits exhibiting a significant depositional dip (e.g. prograding continental slopes and deltas), rather than as a term for a depositional environment. Van Siclen (1958) examined the late Paleozoic cyclothems where they tip over the southern continental margin which, at that time, lay within what is now central Texas. His work includes a diagram of the stratigraphic response of a continental margin to sea-level change and variations in sediment supply that is very similar to present-day sequence models. Oliver and Cowper (1963, 1965) may have been the first to specifically identify 'clino' beds in the subsurface using Rich's concepts in a stratigraphic reconstruction based on petrophysical log correlation. Curray (1964) was among the first to recognize the importance of the relationships between sea level and sediment supply. He noted that fluvial and strandplain aggradation and shoreface retreat predominate under conditions of rising sea level and low sediment supply, whereas river entrenchment and deltaic progradation predominate under conditions of falling sea level and high sediment supply. Curtis (1970) carried these ideas further, illustrating the effects of variations in the balance between subsidence and sediment supply as controls on the stacking patterns of deltas, concepts that are now encapsulated by the terms **progradation**, **aggradation** and **retrogradation**. Frazier (1974) subdivided the Mississippi deltaic successions into **transgressive**, **progradational**, and **aggradational** phases, and discussed autogenic (delta switching) and glacioeustatic sedimentary controls.

Perhaps it is because Texas specializes in bigness; this may be the explanation why some critical concepts concerning large-scale sedimentological environments were first developed there. The location of petroleum research laboratories, such as that of Shell Oil in Texas (referred to below) may also have been very influential. I refer to the concept of the **depositional system**, the concept that takes sedimentological analysis beyond the shoreface or the river meander or the reef talus slope to an analysis that encompasses entire systems. Fisk's (1944) work on the lower Mississippi valley and delta is an early example of this approach, but it was the later work of William L. Fisher that better exemplifies this next step and was more influential. The work he and his colleagues carried out on the deltas and other depositional systems of the Texas coast (Fisher et al. 1969, 1972) established a whole different scale of operation. Application of current subsurface stratigraphic methods to part of the Eocene section of the Gulf Coast (Fisher and McGowen 1967) demonstrated that existing rivers and deltas along a huge swath of the Gulf Coast had occupied essentially the same map locations for about 40 million years. The depositional systems approach provided the foundation for the **systems tracts** that became a critical part of sequence stratigraphy twenty years later. Lastly, in a paper that appears in the famous memoir that introduced seismic stratigraphy to the geological community (Payton 1977), Brown and Fisher (1977) summarized the ideas of this important group of stratigraphers at the Bureau of Economic Geology (at the University of Texas) and helped to bridge the intellectual next step from large-scale sedimentology to sequence stratigraphy.

The Meaning of 'Facies' (1949–1973)

The concept of **facies** and the importance of **Walther's Law** were well understood and used in continental Europe during the nineteenth century, according to Teichert (1958), but did not become widely used in the English-speaking world until the 1930s.

On November 11th 1948 a conference was organized by the Geological Society of America in New York to discuss "Sedimentary facies in geologic history." This was a landmark event, the outcome of which was a Geological Society of America Memoir (Longwell 1949) that marked the beginnings of several important developments. The memoir begins with a lengthy paper by Moore (1949) which set the scene by describing and illustrating, with the use of a block diagram, the various facies present within a modern carbonate reef complex in Java, from which he derived this definition:

> *Sedimentary facies are areally segregated parts of different nature belonging to any genetically related body of sedimentary deposits.*

The paper includes numerous examples of complex stratigraphic relationships from the Phanerozoic record of the United States, illustrating the inter-tonguing of facies of a wide range of environments. Moore's paper also includes an interpretation of the cyclicity exhibited by the cyclothems of the mid-continent, accompanied by a diagram showing how different facies develop as a result of repeated transgression and regression. Other papers by E.D. McKee, E.M. Spieker, and others, provide many other examples of complex stratigraphy, indicating that by this time there was a sophisticated understanding of the diachronous nature of facies in the stratigraphic record, and its control by sea-level change. The concluding contribution in this memoir is a lengthy paper by Sloss et al. (1949) in which the concept of the **sequence** is first described.

A decade later, Teichert (1958, p. 2719), working from Gressly's original discussion, explained the derivation of the term facies:

> *Facies is a Latin word meaning face, figure, appearance, aspect, look, condition. It signifies not so much a concrete thing, as an abstract idea. The word was introduced into geological literature by Nicolaus Steno (1669, p. 68–75) for the entire aspect of a part of the earth's surface during a certain interval of geologic time.*

In his abstract, Teichert (1958, p. 2718) provided this succinct definition:

> [Facies means] *the sum of lithologic and paleontologic characteristics of a sedimentary rock from which its origin and the environment of its formation may be inferred.*

Teichert (1958) asserted that the concept of **facies associations** and the importance of **vertical facies successions** were well understood by nineteenth-century European geologists.

Interest in the work of the founders of modern sedimentology was renewed in the 1960s, with the new developments in the study of modern sediments, structures and environments. Woodford (1973, p. 3737) translated Gressly's (1838) 'second law' as follows:

> *Facies of the same petrographic and geologic nature assume, in different formations, very similar paleontologic characteristics and even succeed each other generally across a more or less numerous series of formations lying one upon the other.*

Middleton (1973, p. 981) provided a translation of Walther's methodology from the original German. Walther referred to it as '**ontology**' (**actualism**, or **uniformitarianism**, in modern usage) as follows:

> *It consists in trying to investigate the events of the past through modern phenomena. From being (existence), we explain becoming (genesis).*

Middleton's (1973, p. 982) translation of Walther's original statement of his Law is as follows:

> *The various deposits of the same facies-area and similarly the sum of the rocks of different facies-areas are formed beside each other in space, though in a cross-section we see them lying on top of each other. … it is a basic statement of far-reaching significance that only those facies and facies-areas can be superimposed primarily which can be observed beside each other at the present time.*

Middleton (1973, p. 980) suggested that "Walther must be named with Sorby, Gilbert, Grabau, and a few others, as one of the founders of the modern sciences of sedimentology and paleoecology," although he pointed out that whereas Walther's work was cited and acknowledged in much of the pioneer work in the early 20th century, in the first modern treatment of the subject of facies (Longwell 1949) there was no explicit mention of Walther or his Law. He had a much greater influence in Russia, where facies studies were termed '**comparative lithology**.'

Fluid Hydraulics and Sedimentary Structures (1953–1976)

A key step in the development of modern sedimentology was the emergence of the idea that sedimentary structures represent measurable and repeatable physical processes, and that they therefore provide information on depositional environments and processes. Early work on the subject included the observations by Sorby (1859, 1908) and Gilbert (1884, 1899) on sedimentary structures, and Gilbert's experimental work (Gilbert 1914). Sorby (1852) was the first to recognize the utility of crossbedding for determining current directions. However, as Allen (1993) pointed out, it was not until the appearance of the synthesis by Potter and Pettijohn (1963) that the richness and significance of the preserved record caught the general attention of sedimentary geologists.

A necessary first step towards a modern study of sedimentary structures is accurate description and classification. McKee and Weir (1953) made an important contribution in this direction, with their description of the scales of structures, their internal architecture and bounding surfaces. It is in this paper that the familiar terms **planar**- and **trough-cross-stratification** first appear. A decade later, a comprehensive classification by Allen (1963a) introduced a set of Greek letters for different types of crossbedding, a system that was widely used for some time. Several illustrated atlases of sedimentary structures also appeared during this period (Pettijohn and Potter 1964; Conybeare and Crook 1968), indicating that sedimentary geologists were coming to grips with the full range of preserved and observable structures.

By the 1950s, sedimentary geologists had become more widely aware of the directional information contained in sedimentary structures, and some pioneering studies of what came to be known as **paleocurrent analysis** were being performed. For example, Reiche (1938) analyzed eolian crossbedding, Stokes (1945) studied primary current lineation in fluvial sandstone, and several authors were dealing with grain and clast orientation (e.g. Krumbein 1939). Pettijohn (1962) provided an overview of the subject, with many examples of the different techniques for analysis and data display that were then in use. Curray (1956) published what became the standard work on the statistical treatment of paleocurrent data.

Meanwhile, several pioneers were attempting to make sedimentary structures in the laboratory, in part as a means to understand the sedimentary record. There was also an interest in understanding fluid hydraulics from an engineering perspective, to aid in the construction of marine facilities, such as bridges and breakwaters. Kuenen and Migliorini (1950), in a classic paper, brought together flume experiments and observations of the ancient record to demonstrate that graded bedding could be generated by turbidity currents. As with many such contributions, it had been preceded by observations and suggestions by many other authors, but this was the paper that brought these observations together into the comprehensive synthesis that made it the benchmark contribution that it became. The term **turbidite** was subsequently coined by Kuenen (1957). McKee (1957), following his many years observing cross-stratification in outcrop, particularly in fluvial and eolian deposits in the Colorado Plateau area, experimented with the formation of cross-stratification by traction currents in a flume.

The critical theoretical breakthrough at this time was the series of flume experiments carried out by the US Geological Survey to study sediment transport and the generation of bedforms. This resulted in the definition of the **flow regime concept**, and the recognition of **lower** and **upper flow regimes** based on flow characteristics (particularly the structure of turbulence), sediment load and resulting bedforms (Simons and Richardson 1961). At this time, Allen (1963b) reviewed the observational work of Sorby and made one of the first attempts to interpret sedimentary structures in terms of flow regimes. However, the most important next step was a symposium organized by Middleton (1965), which brought together current field and experimental studies in a set of papers that firmly established flow regime concepts as a basic tool for understanding the formation of hydraulic sedimentary structures formed by traction currents as preserved in the rock record.

Middleton (1966a, b, 1967) extended the work of Kuenen with further experiments on turbidity currents and the origins of graded bedding, work that was ultimately to lead to a significant new classification of sediment gravity flows, of which it was now apparent that turbidity currents were only one type (Middleton and Hampton 1976). Reference is made in the first of these papers to field observations of turbidites by Roger G. Walker (1965), a reference which marks the beginning of a significant professional collaboration, to which I return later.

Walker's (1967, 1973) field experience with turbidites led to a proposal for the calculation of an index of the proximal-to-distal changes that occur down-flow within a turbidite. This marked an attempt at an increasingly quantitative approach to the study of sedimentary structures, although this index was not to survive an increasing knowledge of the complexities of the submarine fan environment within which most turbidites are deposited.

The important new developments in this field were well summarized in a short course, organized by the Society for Sedimentary Geologists, the manual for which provides an excellent review of the state of knowledge at this time (Harms et al. 1975). This review contains the first description and definition of hummocky cross-stratification (HCS), and the recognition of this structure as a key indicator of combined-flow (unimodal and oscillatory) storm sedimentation.

Early Studies of Modern Environments (1954–1972)

As noted above, references to modern depositional settings appear in much of the early stratigraphic literature, but in the 1950s studies of 'the modern' became more focused. Much of this was due to the recognition by some oil companies of the value of understanding the primary origins of petroleum-bearing rocks. A leader in this field was the research team at Shell Development Company.

Some of the earliest of these studies of modern environments were carried out in carbonate environments, including the work of Illing (1954), and Newell and Rigby (1957) on the Great Bahamas Bank, and Ginsburg and Lowenstam (1958) on the Florida platform. This, and other work on ancient carbonate deposits (referred to below), led to two approaches to the classification of carbonate rocks (Folk 1962; Dunham 1962) that are still used today. In fact, these two papers (which appeared in the same SEPM Special Publication) are among the most important of the 'classic' papers mentioned in this paper, because of their long survival. Later studies of the Bahamas and Florida by Purdy (1963a, b) and Ball (1967) contributed much to the subsequent growth of facies models for carbonate platforms and reefs.

The other outstanding set of classic works consists of the research on the Texas coastal plain by Bernard, Leblanc and their colleagues at Shell, building on the preliminary work of Nanz (1954). The first facies model for barrier islands emerged from the work of these individuals on Galveston Island (Bernard et al. 1959, 1962). The point-bar model for meandering rivers is also attributed to this group, based on their studies of the Brazos River (Bernard et al. 1962; Bernard and Major 1963).

The Mississippi River and Delta is one of the largest of modern fluvial–delta systems, and its location in the centre of one of the most important, well-populated, industrial and tourist regions of the United States, in a petroleum province that generates a quarter of the US domestic supply, has led to intensive environmental and geological studies. The stratigraphic significance and complexity of the deposits of this system were first brought to geologists' attention by the detailed work of Fisk (1944). From the point of view of the growth of sedimentology the studies of Frazier (1967) were more significant, providing architectural block diagrams that illustrated the growth of distributaries in a river-dominated delta. Later studies by Fisher et al. (1969, 1972) broadened the scope of delta studies to other regions of the Texas coast and to other deltas worldwide, providing an essential basis for the subsequent development of formal delta facies models. Shepard et al. (1960) edited a collection of broader studies of the Gulf Coast.

Exploration methods for the continental shelf and deep oceans were primitive, until the introduction of side-scan sonar methods and improvements in navigation. The GLORIA sonar system was developed in 1970, but did not receive widespread use for geological purposes until it was adopted by the US Geological Survey in 1984 at the commencement of a program to map the newly established US Exclusive Economic Zone. The Deep Sea Drilling Project (DSDP) began in 1968. Extensive use of seismic stratigraphic techniques had to await the developments taking place in Shell, Exxon and BP, as noted below (in particular, the work of Vail et al. 1977). Sedimentological studies of the continental shelves and slopes, and the deep basin were being carried out at this time, but the main breakthroughs in sedimentological analysis came from studies of the ancient sedimentary record, and are referred to below.

Facies Model Concept (1959–2010)

By the late 1950s a key idea was emerging that environments could be categorized into a limited number of depositional configurations, which are amenable to basic descriptive summaries. The first explicit use of the term '**facies model**' was in a conference report by Potter (1959, p. 1292). He opened the report with the following words:

> *A discussion concerning sedimentary rocks was held at the Illinois State Geological Survey on 4-5 Nov. 1958, for the purpose of pooling the knowledge and experience of the group concerning three topics: the existence and number of sedimentary associations; the possibility of establishing a model for each association that would emphasize the areal distribution of lithologic units within it; and the exploration of the spatial and sequential relations between the associations.*

Later, on the same page, this definition is provided:

> *A facies model was defined as the distribution pattern or arrangement of lithologic units within any given association. In the early stages of geological exploration, the function of the model is to improve prediction of the distribution of lithologic types.*

Note that the essential basis for a facies model is the recognition of a distinctive **facies association**. Much work to identify these associations now ensued.

A mention should be made here of the term **process-response model**. This term has sometimes been used with essentially the same meaning as facies model. Whitten's (1964, p. 455) discussion of this term quoted from Krumbein and Sloss (1963, p. 501), who:

> *suggested that in the search for "... generalizing principles it is a useful philosophical device to recognize models – actual or conceptual frameworks to which observations are referred as an aid in identification and as a basis for prediction."*

The journal *Sedimentology* was founded by the International Association of Sedimentologists (IAS) in 1962. The editor was Aart Brouwer from the University of Leyden in the Netherlands, representing what had become a strong Dutch school of sedimentological studies. All the early work on tidal flat sedimentation emerged from this school (e.g. Van Straaten 1954). The then President of the IAS, the American marine geologist Francis Shepard said this, in the preface on p. 1 of v. 1 of the new journal:

> *As this is written, there appear to be several primary purposes in sedimentological studies. One is to relate more completely the present day sediments to ancient sedimentary rocks. Although much has been done in this field recently, there are numerous types of sedimentary rocks for which no equivalent has yet been found in the sediments of today and some correlations need careful reexamination to see if they are correctly interpreted. Another need is for more careful study of sedimentary structures that are often obscured both in old and recent sediments. These structures can be very useful in interpreting paleoclimates and conditions of deposition of ancient sediments. A third important field to investigate is the geochemistry of sediments. Some of the early indications from the chemical nature of sediments have proven misleading and are in need of further study to explain apparent anomalies. Fourth, the rates of sedimentation can be given much more study with all of the new radioactive counting methods.*

In an introductory assessment of sedimentary studies immediately following the preface, editor Brouwer (1962, p. 2–3) reviewed the early history and origins of the separate discipline now called **Sedimentology**:

> *Essential parts are derived from sedimentary petrography,*

others from stratigraphy and still others have a purely palaeontological source. Perhaps stratigraphy takes a more or less central position, and many definitions recently given of stratigraphy (Hedberg 1948; Weller 1960; and others) seem to include nearly all of sedimentology, at least of ancient rocks. This is quite understandable, as sedimentary rocks are the stratigrapher's natural environment. Three modem textbooks, whose scope is mainly sedimentological, have "stratigraphy" in their title (Krumbein and Sloss 1951; Dunbar and Rodgers 1957; Weller 1960).

The reference to sedimentary petrography should be noted here. The first journal to deal specifically with sedimentological topics, the *Journal of Sedimentary Petrology*, was founded in 1931, and initially dealt exclusively with petrographic studies, including studies of detrital composition and provenance, and diagenesis. The scope of the journal gradually widened, and the name was changed to the *Journal of Sedimentary Research* in 1994. According to Gerard V. Middleton (2005) the term **Sedimentology** was coined by A.C. Trowbridge in 1925 and first used in print by Waddell in (1933), but did not come into common usage until the 1950s.

Now began a focused program to identify specific lithofacies and lithofacies associations by direct comparison between modern sediments and the preserved record. The comparison went both ways, determined in large measure by the initial interests of the researcher. One of the first of these studies was that by Beales (1958, p. 1846) who proposed the term **bahamite** for "the granular limestone that closely resembles the present deposits of the interior of the Bahamas Banks described by Illing (1954)." Although this new term did not become part of the sedimentological lexicon, the methods pioneered by Beales and his colleagues were about to become part of the mainstream.

Two classic studies appeared in the early 1960s, Bouma's (1962) turbidite model and Allen's (1964) point-bar model for meandering river deposits. Both are concerned primarily with interpretation of the rock record, but make extensive reference to deposits and structures forming at the present day.

There appeared a flood of new work during the 1960s and 1970s making use of the new facies model concepts. Potter (1967) reviewed sandstone environments. He stated (Potter 1967, p. 360):

The facies-model concept with its emphasis on the existence of relatively few recurring models represents cause-and-effect "deterministic geology"– an approach that attempts to relate distribution and orientation of sand bodies in a basin to measurable, causal factors.

However, much of Potter's discussion dealt with grain size and other petrographic issues, and discussions about the shape and orientation of sand bodies (of importance for stratigraphic trap prospecting) rather than facies modeling, as this term has come to be understood.

An edited compilation that appeared in the middle of this period (Rigby and Hamblin 1972) provides another good snapshot of the state of sedimentology at this time. It opens with a brief review of the topic of 'environmental indicators' by H.R. Gould and this is followed by a classification of sedimentary environments by E.J. Crosby, and by eleven chapters providing details of seven depositional environments (three chapters on alluvial sediments and one discussing the use of trace fossils). There were also several important new textbooks published during this period (e.g. Blatt et al. 1972; Reineck and Singh 1973; Wilson 1975; Friedman and Sanders 1978; Reading 1978). That by Blatt et al (1972) contains the first summary of depositional environments specifically focused on the concept of the facies model (and using that term in the chapter heading).

The critical contribution at this time was the development by Walker (1976) of a formal, theoretical description of the concept of the facies model and its value as a summary and a predictor. Central to this work was a new concept that environments could be characterized by a discrete and limited number of specific facies states. Drawing on Middleton's (1973) restatement of Walther's Law, Walker emphasized the importance of the vertical succession of facies, and introduced the **facies relationship diagram**, a semi-quantitative expression of the range of vertical transitions revealed by careful vertical measurement of a stratigraphic succession. Reference was made to a detailed study of de Raaf et al. (1965), which was the first to employ the concept of facies states and the use of a facies relationship diagram. Another study of vertical facies relationships at this time was that by Miall (1973) using the basic concepts of Markov chain analysis.

Walker's (1976, figure 4) diagram summarizing the construction of a facies model as a process of 'distilling away the local variability' to arrive at the 'pure essence of environmental summary' has been much reproduced.

Walker's (1976) paper appeared first in this journal, *Geoscience Canada* (founded and edited by his colleague at McMaster University, Gerard Middleton), and was intended as the introductory paper in a series of invited articles written mainly by Canadian sedimentologists dealing with specific environments and facies models. The series was later published as a stand-alone volume (Walker 1979) which became a best-seller and subsequently, under changing editorships, went into four editions (Walker 1984, Walker and James 1992; James and Dalrymple 2010). Its success was due in large measure to the concise nature of the descriptions, the elegant diagrams, and the emphasis on the nature of the vertical profile, making this a very practical approach for undergraduate teaching and for work with well logs and cores. A close competitor was the edited volume compiled by Reading (1978), a book written at a more advanced, graduate to professional level by him and some of his graduate students at the University of Oxford. This book went into two later editions (1986, 1996).

Among the other widely used facies models that appeared in the *Geoscience Canada* series (and subsequently in Walker 1979) was a treatment of continental shelf sedimentation highlighting the rock record of hummocky cross-stratification, and a simple and elegant model for submarine fans based almost entirely on ancient fan deposits in California and Italy. In this book, carbonate facies models were compiled and co-authored by Noel P. James, who became a co-editor of later editions. **Ichnology**, the study of trace fossils, evolved into an enormously valuable subsurface facies analysis tool, allowing detailed analysis of sedimentary environments in drill core, as well as throwing much useful light on the significance of stratal surfaces, with the preservation of evidence of non-deposition and early lithification (Frey and Pemberton 1984; McEachern et al. 2010).

By the mid-1970s the stage was set for Sedimentology to flourish. The Walker (1979) *Facies Models* volume, and Reading's (1978) textbook were enormously influential. However, through the 1980s sedimentology remained largely isolated from the 'big-picture' concepts that were emerging from the plate-tectonics revolution, and developments in seismic stratigraphy. These I discuss below. Textbooks that appeared during this period (e.g. Miall 1984; Matthews 1984; Boggs 1987) deal with all these topics essentially in isolation, as separate chapters with little cross-referencing. As I argue below, it took the maturing of sequence stratigraphy to bring these topics together into what we may now term sophisticated stratigraphy.

The Impact of the Plate-Tectonics Revolution on Basin Studies (1959–1988)

The plate-tectonics revolution explained where and why basins form, provided a quantitative basis for their subsidence and uplift behaviour, and elucidated the relationships between sedimentation and tectonics. As far as sedimentary geology is concerned, the revolution was not complete until the mid-1970s, when the re-classification of basins in terms of their plate tectonic setting reached maturity. However, some important preliminary studies pointed the way.

Bally (1989, p. 397–398) noted the work of Drake et al. (1959) "who first tried to reconcile modern geophysical–oceanographic observations with the geosynclinal concept" and that of Dietz (1963) and Dietz and Holden (1974) who were the first to equate Kay's 'miogeosyncline' with the plate tectonic concept of an Atlantic-type passive continental margin. Mitchell and Reading (1969) made one of the first attempts to reinterpret the old tectono-stratigraphic concepts of **flysch** and **molasse** in terms of the new plate tectonics.

But it was John Bird and John Dewey, in two papers published in 1970, who completely revolutionized our understanding of the origins of sedimentary basins (and much of the rest of geology) with reference to the geology of the Appalachian orogen, in particular, that portion of it exposed throughout the island of Newfoundland (Bird and Dewey 1970; Dewey and Bird 1970). Dickinson (1971) made reference to all of this work in his own first pass at relating sedimentary basins to plate tectonics.

These breakthroughs of the 1970s initiated a worldwide explosion of studies of basins and tectonic belts exploring the new plate tectonic concepts. Through the 1970s, a series of books and papers was published containing the results (Dickinson 1974; Dott and Shaver 1974; Burk and Drake 1974; Strangway 1980; Miall 1980, 1984). One of the more important of these contributions was a paper by Dickinson (1974) which constituted the first comprehensive attempt to classify sedimentary basins of all types in terms of their plate tectonic settings. This paper was particularly notable for the extensive treatment of arc-related basins, and was followed up by a more detailed paper on this subject (Dickinson and Seely 1979) that remained the standard work on the subject for many years. This latter work was based in part on the recognition of a series of arc-related sedimentary basins within the Cordillera (Dickinson 1976), especially the Great Valley basin of California, which has long served as a type example of a forearc basin (e.g. Ingersoll 1978a, b, 1979).

Miall (1984, p. 367) argued that, by the application of judicious simplification and by skillful synthesis we can systematize the descriptions of depositional systems (their facies assemblages and architecture), structural geology, petrology, and plate tectonic setting into a series of **basin models**, for the purpose of interpreting modern and ancient sedimentary basins. Dickinson (1980, 1981) used the term **petrotectonic assemblages** with the same meaning. These basin models are then a powerful tool for interpreting regional plate tectonic history.

Another important era in the field of basin analysis was initiated by the development of quantitative, geophysically based models of crustal subsidence, commencing in the late 1970s. The importance of these models to the development of stratigraphy was that they provided the basis for the development of quantitative models of subsidence and accommodation generation that greatly improved our understanding of large-scale basin architectures. The main breakthrough in the development of a modern extensional margin basin model was made by McKenzie (1978), based in part on his studies of the subsidence of the Aegean Sea. This classic paper introduced the concept of crustal stretching and thinning during the initial sea-floor spreading event, and showed quantitatively how this could account for the subsidence history of Atlantic-type margins. Many of the important early tests of this model were carried out on the Atlantic margin of the United States. Stratigraphic data were obtained from ten Continental Offshore Stratigraphic Test (COST) wells drilled on the continental shelf off New England between 1976 and 1982, and led to the development of formal backstripping procedures (Watts and Ryan 1976; Steckler and Watts 1978; Watts 1989) and to simple computer graphic models of subsiding margins (Watts 1981) that were very useful in illustrating the development of the basic architecture of Atlantic-type margins. Dewey (1982) emphasized their simple two-stage development: the early phase of rifting, typically capped by a regional unconformity, followed by a thermal relaxation phase which generates a distinctive pattern of long-term onlap of the basement.

An important modification of the McKenzie model was to recognize the importance of simple shear during continental extension, as expressed by through-going extensional crustal detachment faults (Wernicke 1985). This style of crustal extension was first recognized in the Basin and Range Province of Nevada, and was suggested by preliminary seismic data from the facing continental margins of Iberia and the Grand Banks of Newfoundland (Tankard and Welsink 1987). The North Sea basin is the best studied rift basin, and has provided many insights regarding subsidence styles and structural geology (White and McKenzie 1988).

Turning to the other major class of sedimentary basins, those formed by flexural loading of the crust, it was Barrell (1917, p. 787) who was the first to realize that "the thick non-marine strata of the Gangetic plains accumulated in space made available by subsidence of the Indian crust beneath the mass of thrust plates of the Himalayan Range" (Jordan 1995, p. 334). Price (1973) revived the concept of regional isostatic subsidence beneath the supracrustal load of a fold–thrust belt that generates the marginal moat we now term a foreland basin (a term introduced by Dickinson 1974), based on his work in the southern Canadian Cordillera. Beaumont (1981) and Jordan (1981) were the first to propose quantitative flexural models for foreland basins, constraining the models with detailed knowledge of the structure and stratigraphy of the studied basins. It is clear that the crust must have mechanical strength for a wide foredeep, such as the Alberta Basin or the Himalayan foreland basin, to be created. The classic architecture of a foreland basin is defined by the isopachs of the sediment fill, which is that of an asymmetric lozenge, with a depocentre adjacent to the location of the crustal load, tapering along strike and also thinning gradually away from the orogen towards the craton.

Two major developments contributed to our current understanding of these basins. Firstly, exploration drilling and reflection seismic data led to an understanding of the structure and dynamics of the fold–thrust belts that border foreland basins and, during uplift, provide much of their sediment. Secondly, a growing knowledge of crustal properties permitted the development of quantitative models relating crustal loading, subsidence, and sedimentation. A significant development during the 1960s and 1970s was the elucidation of the structure of the fold–thrust belts that flank many orogenic uplifts and clearly served as the source for the clastic wedges referred to above. McConnell (1887) was one of the first to emphasize the importance of thrust faulting and crustal shortening in the formation of fold–thrust belts, based on his work in the Rocky Mountains of Alberta. As noted by Berg (1962), the mapping of faults in the Rocky Mountains of the United States and their interpretation in terms of overthrusting became routine in the 1930s. However, as his paper demonstrates, seismic and drilling data available in the early 1960s provided only very limited information about the deep structure of thrust belts. The release of seismic exploration data from the southern Rocky Mountains of Canada by Shell Canada led to a landmark study by Bally et al. (1966) and set the stage for modern structural analyses of fold–thrust belts. A series of papers by Chevron geologist Clinton Dahlstrom, concluding with a major work in 1970, laid out the major theoretical principles for the understanding of the thrust faulting mechanism (Dahlstrom 1970).

The final piece of the puzzle was to explain accommodation generation and the occurrence or regional tilts and gentle angular unconformities on cratons hundreds of kilometres from plate margins — the phenomenon termed **epeirogeny**. Modeling of mantle processes indicated the presence of convection currents that caused heating and uplift or cooling and subsidence of the crust. Gurnis (1988, 1990, 1992) termed this **dynamic topography**. Cloetingh (1988) described the process of **intraplate stress** (also termed **in-plane stress**) whereby horizontal stresses exerted on plates, such as the outward-directed compressive stress from sea-floor spreading centres ('ridge push'), may be expressed as intraplate earthquakes that cumulatively develop faults and long-wavelength folds.

Unconformities and the Issue of Time in Stratigraphy (1909–1970)

Although some of the ideas discussed in this section have been around for many years, the issue of time in stratigraphy did not begin to have a major influence on the science until Ager's work in the 1970s, and it was not until the full flowering of sequence stratigraphy in the 1990s that such contributions as Barrell's accommodation diagram and Wheeler's chronostratigraphic charts (both discussed below) were fully integrated into the science of stratigraphy.

The science of geology began with James Hutton's observations in and around Scotland in the late eighteenth century. His discovery of the angular Silurian–Devonian unconformity at Siccar Point on the coast of southeast Scotland gave rise to Playfair's (1802) famous remark about the "abyss of time."

A predominant strand in geological work during the nineteenth and early twentieth centuries was the gradual documentation of the lithostratigraphy and biostratigraphy of sedimentary basins worldwide. As documented elsewhere (Berry 1968, 1987; Hancock 1977; Conkin and Conkin 1984; Miall 2004), some remarkably refined zonation schemes resulted from this work, and stratigraphic terminology and methods gradually evolved to facilitate description and classification, but until the development of radioisotopic dating by Ernest Rutherford and Arthur Holmes (Holmes' first book on the geological time scale was published in 1913) the development of a quantitative understanding of earth processes was limited (I do not discuss the early evolution of biostratigraphic concepts here. See the references cited above).

Geological mapping and research in North America during the 'frontier' period is usefully summarized by Blackwelder (1909), who discussed the various types of sedimentary break (angular versus structurally conformable) and the duration of the missing time that they represented. His paper contained what is probably the first chronostratigraphic chart for the interior (cratonic) stratigraphy of North America, showing what was then known about the extent of the major Phanerozoic stratigraphic units on this continent and the unconformities that separate them.

In a paper that was remarkably ahead of its time, Barrell (1917, p. 747–748) set out what we now refer to as the concept of **accommodation**:

> *In all stratigraphic measures of time, so far as the writer is aware, the rate of deposition of a sedimentary series has been previously regarded as dependent on the type of sediment, whether sandstone, shale, or limestone, combined with the present rate of supply of such sediment to regions of deposition. Here is developed an opposite view: that the deposition of nearly all sediments occurs just below the local baselevel, represented by wave base or river flood level, and is dependent on upward oscillations of baselevel or downward oscillations of the bottom, either of which makes room for sediments below baselevel. According to this control, the rate of vertical thickening is something less than the rate of supply, and the balance is carried farther by the agents of transportation.*

Barrell (1917) was probably the first to understand the relationships among sedimentation, preservation, and accommodation. He constructed a diagram showing the "Sedimentary Record made by Harmonic Oscillation in Baselevel" (Barrell 1917, p. 796) that is remarkably similar to diagrams that have appeared in some of the Exxon sequence model publications since the 1980s (e.g. Van Wagoner et al. 1990, figure 39). It shows that when long-term and short-term curves of sea-level change are combined, the oscillations of base level provide only limited time periods when base-level is rising and sediments can accumulate. In his diagram "Only one-sixth of time is recorded" by sediments (Barrell 1917, p. 797). This remarkable diagram 1) anticipated Jervey's (1988) ideas about sedimentary accommodation that became fundamental to models of sequence stratigraphy, 2) also anticipated Ager's (1981, 1993) point that the sedimentary record is "more gap than record," and 3) constitutes the first systematic exploration of the problem of preservation potential.

During the early part of the twentieth century there was much theorizing about the forces at work within the Earth to form mountain ranges and sedimentary basins. This is summarized elsewhere (e.g. Miall 2004) and not dealt with here, because ultimately it did not contribute much to the development of modern stratigraphy. However, the practical work of petroleum exploration did make a difference. The distinguished petroleum geologist A.I. Levorsen was one of the first to describe in detail some examples of the 'natural groupings of strata on the North American craton:'

> *A second principle of geology which has a wide application to petroleum geology is the concept of successive layers of geology in the earth, each separated by an unconformity. They are present in most of the sedimentary regions of the United States and will probably be found to prevail the world over (Levorsen 1943, p. 907).*

This principle appears to have been arrived at on the basis of practical experience in the field rather than on the basis of theoretical model building. These unconformity-bounded successions, which are now commonly called '**Sloss sequences**,' for reasons which we mention below, are tens to hundreds of metres thick and, we now know, represent tens to hundreds of millions of years of geologic time. They are therefore of a larger order of magnitude than the cyclothems. Levorsen did not directly credit Grabau, Ulrich, or any of the other contemporary theorists who were at work during this period (see Miall 2004), nor did he cite the description of unconformity-bounded 'rock systems' by Blackwelder (1909). Knowledge of these seems to have been simply taken for granted.

The symposium on "Sedimentary facies in geologic history" referred to above contained a lengthy treatment of facies variability in the Paleozoic rocks of the cratonic interior of the United States by Sloss et al. (1949). In this paper much use is made of isopachs and lithofacies maps using Krumbein's (1948) concepts of clastic ratios and sand-shale ratios. The work revealed to the authors the contradictions inherent in current classifications of rock units in North America according to standard geologic time units. The use of the standard time scale (Cambrian, Ordovician, etc.) as a basis for mapping, obscured the fact that the major sedimentary breaks within the succession commonly did not occur at the divisions provided by the time scale, and so they set out to establish 'operational units' for mapping purposes. Thus were born the first **sequences** for the North American interior: the Sauk, Tippecanoe, Kaskaskia and Absaroka.

The Sloss et al. (1949) paper in the symposium volume (Longwell 1949) is followed by nearly 50 pages of published discussion by many of the leading American geologists of the day, in which the issues raised by detailed mapping and the concepts and classifications available at the time for their systematization were fully discussed. This broader discussion is dealt with at length elsewhere (Miall 2004; Miall 2010, Chap. 1). For the purpose of this review, the importance of the Sloss et al. (1949) paper and the wider discussion of sedimentary facies contained in the other papers is that it clearly confirmed, at the time of publication, the need for a systematic differentiation of descriptive terminologies for 'time' and for the 'rocks.' This had been provided by Schenk and Muller (1941), who proposed the following codification of stratigraphic terminology:

Time division (for abstract concept of time)	Time-stratigraphic division (for rock classification)
Era	-
Period	System
Epoch	Series
Age	Stage
Phase	Zone

Harry E. Wheeler (Wheeler 1958, p. 1050) argued that a time-rock (chronostratigraphic) unit could not be both a 'material rock unit' and one whose boundaries could be extended from the type section as isochronous surfaces, because such isochronous surfaces would in many localities be represented by an unconformity. Wheeler developed the concept of the chronostratigraphic cross-section, in which the vertical dimension in a stratigraphic cross-section is drawn with a time scale instead of a thickness scale. In this way, time gaps (unconformities) become readily apparent, and the nature of time correlation may be accurately indicated. Such diagrams have come to be termed '**Wheeler plots**.' Wheeler cited with approval the early work of Sloss and his colleagues, referred to in more detail below:

> As a tangible framework on which to hang pertinent faunal and lithic data, the *sequence* of Sloss, Krumbein and Dapples (1949, pp. 110-11) generally fulfills these requirements. Paraphrasing these authors' discussion, a *sequence comprises an assemblage of strata exhibiting similar responses to similar tectonic environments over wide areas, separated by objective horizons without specific time significance* (Wheeler 1958, p. 1050; italics as in original).

Sequences came later to be called simply '**unconformity-bounded units**.'

Wheeler's (1958) methods are now universally accepted, although in practice they are still rarely applied. Ager (1973) is famous for his remark that "the sedimentary record is more gap than record." In a later book he expanded on the theme of gaps. Following a description of the major unconformities in the record at the Grand Canyon, he said, (Ager 1993, p. 14):

> *We talk about such obvious breaks, but there are also gaps on a much smaller scale, which may add up to vastly more unrecorded time. Every bedding plane is, in effect, an unconformity. It may seem paradoxical, but to me the gaps probably cover most of earth history, not the dirt that happened to accumulate in the moments between. It was during the breaks that most events probably occurred.*

Dott (1983, 1996) similarly warned about the episodic nature of sedimentation. However, as discussed elsewhere (Miall 2015), stratigraphers are still not dealing fully with the issue of time and its representation in the rock record.

The evolution of chronostratigraphic methods and the increasing accuracy and precision with which sedimentary rocks can be dated is discussed in detail elsewhere (Miall 2004; Miall 2010, Chap. 14). A landmark in the development of modern stratigraphy was the adoption in the 1970s of the GSSP principle for the fixing of major chronostratigraphic boundaries. GSSP stands for **Global Stratigraphic Sections**

and Points, and is a system for identifying outcrop sections that are accepted by the international community as marking the boundaries of stages and series (McLaren 1970).

Sequences and Seismic Stratigraphy (1963–1977)

Building on his earlier work (Sloss et al. 1949), further analysis by Sloss (1963) added two more sequences of Mesozoic–Cenozoic age to the North American suite (Zuni, Tejas) and firmly established the concept of the large-scale control of cratonic stratigraphy by cycles of sea-level change lasting tens of millions of years. In later work, Sloss (1972) demonstrated a crude correlation of these sequences with a similar stratigraphy on the Russian Platform, thereby confirming that global sea-level cycles constituted a major sedimentary control. However, Sloss, unlike his student Peter Vail, was never convinced that global eustasy told the entire story (Sloss 1988, 1991). In his 1963 paper Sloss included a pair of diagrammatic cross-sections of the Sauk and Tippecanoe sequence across the cratonic interior of North America that clearly indicated an angular unconformity between the two sequences, a relationship that could only have been developed as a result of broad warping of the craton before deposition of the Tippecanoe sediments.

Ross (1991) pointed out that all the essential ideas that form the basis for modern sequence stratigraphy were in place by the 1960s. The concept of repetitive episodes of deposition separated by regional unconformities was developed by Wheeler and Sloss in the 1940s and 1950s. The concept of the 'ideal' or 'model' sequence had been developed for the mid-continent cyclothems in the 1930s. The hypothesis of glacioeustasy was also widely discussed at that time. Van Siclen (1958) provided a diagram of the stratigraphic response of a continental margin to sea-level change and variations in sediment supply that is very similar to present-day sequence models. An important symposium on cyclic sedimentation convened by the Kansas Geological Survey marks a major milestone in the progress of research in this area (Merriam 1964); yet the subject did not 'catch on.' There are probably two main reasons for this. Firstly, during the 1960s and 1970s sedimentologists were preoccupied mainly by autogenic processes and the process-response model, and by the implications of plate tectonics for large-scale basin architecture. Secondly, geologists lacked the right kind of data. It was not until the advent of high-quality seismic reflection data in the 1970s, and the development of the interpretive skills required to exploit these data, that the value and importance of sequence concepts became widely appreciated. Shell, British Petroleum, and Exxon were all actively developing these skills in their research and development laboratories in the 1970s. The first published use of the term '**seismic stratigraphy**' was in a paper by Fisher et al. (1973) describing a subsurface succession in Brazil (the term appeared in the Portuguese language as 'estratigrafia sismica'). Peter Vail, working with Exxon, was the first to present his ideas in the English-speaking world, at the 1974 annual meeting of the Geological Society of America, but it was his presentation the following year at the American Association of Petroleum Geologists (Vail 1975) that caught the attention of the petroleum geology community. This was the beginning of the modern revolution in the science of stratigraphy.

The key idea that Vail and his colleagues proposed was that large-scale stratigraphic architecture could be reconstructed from reflection seismic records. Their publication of Memoir 26 of the American Association of Petroleum Geologists (Vail et al. 1977) was one of the major landmark events in the development of modern stratigraphy. Vail had learned about sequences from his graduate supervisor, Larry Sloss, and added to these his own ideas about global sea-level change (eustasy) as the major allogenic control of sequence development. The debate about global eustasy was long and controversial, and has been amply aired elsewhere (see Miall 2010). However, what emerged from the debate was the critical importance of the 'big-picture' in stratigraphic reconstruction, and the predictive value of sequence models. Having once seen a seismic record interpreted in terms of seismic stratigraphy, with its emphasis on seismic terminations and regional unconformities, and the common occurrence of clinoform architectures, old concepts of 'layer-cake' stratigraphy were dead forever.

It also seems likely that, working in the Gulf Coast, Vail learned from the 'big-picture' stratigraphers at the Bureau of Economic Geology. The regional view exemplified by work such as the Texas atlas (Fisher et al. 1972) and the seismic interpretation that these individuals were already working on, and which eventually appeared in the same AAPG Memoir (Brown and Fisher 1977) were very influential in helping sedimentary geologists understand the large-scale setting and tectonic influences on sedimentary basins at the very time that geophysical basin models were providing the quantitative basis for the plate tectonic interpretations of these basins.

Peter Vail has come to be called the 'Father' of sequence stratigraphy, while his graduate supervisor, Larry Sloss, has posthumously earned the title of the 'Grandfather' of sequence stratigraphy.

Architectural Elements: Sedimentology in Two and Three Dimensions (1983–1990)

Lithofacies maps and isopachs, and the reconstruction of regional paleocurrent patterns had become standard tools of the sedimentary geologist (or basin analyst) by the 1970s (the second edition of the Potter and Pettijohn book *Paleocurrents and basin analysis* was published in 1977), but they often failed to capture the fine detail of sedimentary processes that were by now emerging from facies studies. As Miall (1984, Sect. 5.3) pointed out, these mapping methods tended to produce generalizations that did not always reflect the rapidly shifting patterns of depositional systems that could now be reconstructed from detailed sedimentological study of outcrops, well records and cores.

There was a scale mismatch. Lithofacies maps typically dealt with large map areas (tens to hundreds of kilometres across) and sections tens of metres thick, grouping together depositional systems that may have undergone rapid paleogeographic change, thus obscuring local detail. Facies studies at this time (the 1970s to early 1980s) were one-dimensional, focusing on the vertical profile in drill records or outcrops (typically a few metres to tens of metres high). What was clearly needed were the tools to put the observations together. Three-dimensional sedimentological studies provided part of the answer, particularly for outcrop analysis, and sequence studies focused on the larger picture.

Work on fluvial systems by Allen (1983) and by Ramos and his colleagues (Ramos and Sopeña 1983; Ramos et al. 1986) led the way. These papers focused on large two-dimensional outcrops of complex fluvial deposits and offered classifications of the lithofacies units that described them in two or three dimensions. Picking up on this early work, Miall (1985, 1988a, b) offered a systematized approach that re-stated the lithofacies classification idea in terms of a limited suite of **architectural elements** that, it was proposed, constitute the basic building blocks of fluvial assemblages. One of the strengths of the approach is the ability to relate paleocurrent observations to the fine detail of the channel and bar complexes, revealing whole new insights into the bar construction and preservation processes. Comparable approaches have subsequently been adopted for other depositional environments. The use of photomosaics as base maps for analysing large outcrops has become standard, and there have been technological developments, such as the use of LIDAR methods for outcrop documentation, facilitating the digitization of observations, corrections for scale problems and perspective effects in ground observations, and so on.

Sequence Stratigraphy (1986–1990)

In the decade following the publication of AAPG Memoir 26 (Payton 1977) a wholesale re-evaluation of regional stratigraphy was under way. The significance of this revolution can be exemplified by the first publication that applied the new sequence concepts to an important swath of regional geology, the Cardium Sandstone of Alberta. This loosely defined unit is host to the largest oil field hosted in a clastic reservoir in Canada, the Pembina field, and stratigraphic and sedimentological studies of the unit had been under way since it was discovered in 1953. The Pembina reservoir was difficult to understand. It consists of locally as much as 9 m of wave- and tide-deposited conglomerate accumulated some 200 km from the assumed contemporary shoreline. How did it get there? The new interpretation by Plint et al. (1986) reconstructed from well-logs a set of seven basin-wide surfaces of erosion and transgression, implying cycles of base-level change lasting about 125 ka. The interpretation was controversial, and was subject to intense discussion at the time (Rine et al. 1987), but the interpretation has stood the test of time, and has led to a complete remapping of Alberta basin stratigraphy using the new sequence concepts (Mossop and Shetsen 1994).

Meanwhile, researchers working with seismic data, particularly in the research laboratories of Shell, BP and Exxon, were applying sequence concepts to basins around the world, yielding many insights into stratigraphic architecture and regional basin controls, particularly the importance of tectonism, even though the global-eustasy paradigm remained dominant throughout the 1980s and early 1990s. Several atlases were published at this time, taking advantage of the large atlas format to display reflection seismic cross-sections at large scales (Bally 1987). Even more importantly, in 1988 a second major production by the team at Exxon was published (Wilgus et al. 1988), showing in detail how sequence concepts could incorporate facies analysis and could be applied to outcrop studies. The **systems tract** concept reached a full expression in several key papers in this book (Posamentier and Vail 1988; Posamentier et al. 1988), building on experimental models of Jervey (1988) that essentially reinvented Barrell's (1917) ideas about accommodation and its control on sedimentation, and developed them further in the light of modern facies concepts.

Another important publication from the Exxon team was that by Van Wagoner et al. (1990) which presented the results of several detailed field mapping projects and extended the reach of sequence concepts further, to regional outcrop and subsurface studies. Largely on the basis of these two publications by the Exxon team, the term seismic stratigraphy began to be replaced in common use by the more general term **sequence stratigraphy.**

Reconciling Facies Models with Sequence Stratigraphy (1990)

By the year 1990 a moment of tension had arrived in the evolution of sophisticated stratigraphy. The enormously successful facies model approach, focusing on very detailed local studies, including meticulous analysis of drill cores, had resulted in a proliferation of sedimentological studies and numerous refinements of ideas about how to classify and subdivide sedimentary environments in an ever expanding range of tectonic and climatic settings. Most interpretations dwelt at length on autogenic sedimentary processes. Meanwhile, sequence stratigraphy had introduced an entirely different scale of research, encompassing whole basins, and focusing on allogenic controls, particularly sea-level change. In addition, the architectural element approach to facies studies departed from the clean simplicity of the vertical profile by suggesting multi-dimensional assemblages of sedimentary building blocks in patterns difficult to pin down and classify.

The problems may be exemplified by an examination of a paper by Walker (1990), who was attempting to reconcile his facies model approach to the new concepts and methods. He (Walker 1990, p. 779) complained that the architectural element approach, which treated elements as building blocks that could be assembled in multiple ways (Miall 1985), constituted 'sedimentological anarchy.' Walker (1990) conceded that the proliferation of information about environments and facies associations that had resulted from the explosion of facies studies rendered the simple facies model approach for complex depositional systems (such as submarine fans) inadequate. He referred approvingly to the depositional systems approach exemplified by Fisher and McGowen (1967).

> *Future facies modeling must emphasize these contemporaneous, linked depositional environments, and their response to tectonics and changes of relative sea level. This will combine the strengths of classical facies modeling with the recognition that widely spaced and "distinct" geographic environments (summarized as models) can be rapidly superimposed as part of one transgressive or regressive system (Walker 1990, p. 780).*

Walker (1990, p. 781) also expressed concern regarding the new concepts of sequence stratigraphy, which were becoming popular at this time. He pointed out the ambiguity in some of the definitions (e.g. that of the **parasequence**), the uncertainty with regard to scale, and the lack of clarity in such expressions as 'relatively conformable.' The issue of scale arises with reference to such expressions as 'genetically related' strata. In facies model studies, genetically related implies gradational contacts between lithofacies that are related to each other in the sense implied by Walther's Law. In sequence stratigraphy, genetically related means the deposits formed during a full cycle of base-level change, although, as Walker (1990, p. 784) pointed out, using Galloway's (1989) **genetic stratigraphic sequence model** implies that strata above and below a subaerial erosion surface (the E/T surfaces of Plint et al. 1986), are genetically related, which they are certainly not.

While reluctant to fully embrace the new methods and terminology of sequence stratigraphy, Walker (1990) conceded that the regional patterns and the emphasis on large-scale sedimentary controls that were being revealed by sequence studies were valuable. As a compromise he proposed the adoption of the new system of **allostratigraphy** that had been proposed in 1983 by the North American Commission on Stratigraphic Nomenclature. Allostratigraphy is based on the recognition, mapping and subdivision of unconformity-bounded units. For example, a typical sequence, in the sense implied by Vail et al. (1977) constitutes an alloformation.

The Full Flowering of Modern Sequence-Stratigraphic Methods

When sequence stratigraphy was introduced to the geological community through the landmark publications of the Exxon Group (Payton 1977; Wilgus et al. 1988; Van Wagoner et al. 1990) it came with an overriding hypothesis that eustatic sea-level change was the main driver of changes in accommodation, and hence of sequence architecture. Doubts about the universal applicability of this hypothesis began to emerge in the 1980s, and by the mid-1990s most earth scientists had accepted that other factors, including climate change and regional tectonism may play a key role (Miall 1995). The controversy is described in detail in Miall (2010, Chap. 12).

The realization that many allogenic processes are at work during the accumulation of a basin fill gave renewed impetus to stratigraphic studies, because it became clear that sequence methods, combining the large scale of reflection seismic surveying with the facies scale of the outcrop or drill core, could be very powerful tools for the reconstruction of geologic history, as well as provide much more useful predictive stratigraphic models for petroleum exploration and development. The increasing use of horizontal 'seiscrop' sections (horizontal sections extracted from three-dimensional data volumes) has led to the development of an entirely new discipline, **seismic geomorphology**, which deals with the analysis of ancient depositional systems based on their preserved landscape architecture and three-dimensional construction (Davies et al. 2007; Hart 2013). Furthermore, the debate about global eustasy placed renewed emphasis on the need for accurate global chronostratigraphic correlations in order to test regional and global correlations, and this also encouraged new work in this field.

The flourishing of sequence stratigraphy as a research topic inevitably led to differences of interpretation and even to differences in the methods for defining sequences. For example, Hunt and Tucker (1992) showed how the Exxon sequence model was quite inadequate in dealing with the falling stage of a base-level cycle. Galloway (1989) proposed defining sequence boundaries at the maximum flooding surface rather than the subaerial erosion surface and its basinward correlative conformity. This and other controversies hindered the development of a uniform methodology and common language for dealing with sequences on a formal basis.

Catuneanu (2006), in what has become the standard textbook on sequence stratigraphy addressed these topics and showed how different approaches could be reconciled if care is taken with descriptions and definitions. In a series of papers culminating in a review for *Newsletters on Stratigraphy* he and selected colleagues have been leading the way in the work to gain acceptance for sequence stratigraphy as the appropriate formal basis for modern stratigraphic work (Catuneanu et al. 2009, 2010, 2011). More recently, Steel and Milliken (2013) have provided a very useful documentation of the many incremental additions to our knowledge of siliciclastic facies associations and models and their incorporation into sequence-stratigraphic interpretations.

Modern theoretical and experimental work is making substantial contributions to our understanding of processes of sedimentation and sequence generation. The specially designed experimental facility (eXperimental EarthScape Facility, or XES) described by Paola (2000) and Paola et al. (2001, 2009) is particularly well equipped to explore what Sheets et al. (2002) termed the stratigraphic 'mesoscale,' the time scale of years to thousands of years. Within this time frame, "the depositional pattern shifts from reflecting the short-term flow pattern to reflecting long-term basinal accommodation. Individual events are averaged to produce large-scale stratal patterns" (Sheets et al. 2002, p. 288). At this scale, autogenic processes grade into, or are affected by and modified by allogenic forcing. Muto and Steel (2004) demonstrated that, given steady conditions of discharge and sediment supply, prograding deltas will eventually start to 'autoincise' over the mesoscale time scale. Strong and Paola (2008) explored the evolving nature of valley incision, terrace formation and valley fill, and demonstrated that the valley-floor surface that ultimately is preserved in the geological record during a cycle of base-level change is an erosion surface that never actually existed in its entirety as a topographic surface in its preserved form, because it undergoes continuous modification by erosion or sedimentation until final burial. Kim and Paola (2007) demonstrated that the autogenic process of delta and channel switching may, under the influence of fault movement, develop cyclothem-like cycles over time periods of 10^5 years.

Meanwhile, the research theme centred on facies analysis is by no means complete. Advances in the understanding of processes and environments continue, aided by the experimental work touched on above and by improved observational methods. Three topics merit note: 1) the increasing recognition of the importance of cool water environments for carbonate sedimentation (James and Lukasik 2010), 2) an improved understanding of the development of deep-water turbidite deposits relative to the cycle of sea-level change and sediment delivery patterns, together with a much expanded understanding of the variability and complexity of turbidite systems, due in large measure to developments in marine geology, three-dimensional seismic surveying and large-scale outcrop work (Bouma et al. 1985; Arnott 2010), and 3) the increasing realization that in natural systems mud forms silt- and sand-sized floccules, and most mud is transported and deposited by currents of all kinds. Pelagic settling may be of minor importance as a source of mud deposits (Schieber et al. 2013).

Stratigraphy: The Modern Synthesis

The full flowering of modern stratigraphy represents the amalgamation of the concepts and methods encompassed in all of the separate developments described in the preceding sections. The power of the modern science could not possibly have evolved without the contributions from all of these strands of development. However, for the purpose of education and training, the basic components of modern stratigraphy can be broken down into the following list of seven broad topics. Key references are provided here to some of the main recent reviews and textbooks:

1. Facies analysis methods and facies models (James and Dalrymple 2010).
2. Sequence stratigraphy, concepts, definitions and methods (Catuneanu 2006).
3. Interpretations of the origins of sequences in terms of basin processes (tectonism, eustasy, climate change, etc.) (Miall 2010; Allen and Allen 2013).
4. Basin geodynamics: the origins of basins in terms of plate tectonics and crustal behaviour (Busby and Ingersoll 1995; Miall 1999; Allen and Allen 2013).
5. Modern seismic methods, including seismic geomorphology (Veeken 2007; Davies et al. 2007; Hart 2013).
6. Chronostratigraphy and the Geologic Time Scale (Gradstein et al. 2004, 2012; see also www.stratigraphy.org).
7. Modern formal stratigraphic methods (Salvador 1994). Updated methods at www.stratigraphy.org.

A specialized branch of stratigraphy deals with the Quaternary record. Specialists include archaeologists and anthropologists. Age dating reaches levels of accuracy and precision in the 10^3–10^4-year range, based on dating methods designed specifically for the Recent, including ^{14}C and U–Th radiometric methods, optically stimulated luminescence, cosmogenic radionuclides, and amino-acid geochronometry (http://www.inqua-saccom.org/stratigraphic-guide/geochronometry/).

THE ACHIEVEMENTS OF MODERN STRATIGRAPHY

Two hundred years ago, William Smith gave us the first complete geological map (Smith 1815), and started us on the road to an understanding of Earth's geologic history. Lyell (1830–1833) provided the foundation for the future development of sedimentology, based on the principle of uniformitarianism, and Holmes, beginning a little more than one hundred years ago, began the development of the modern geological time scale (culminating in his first book: Holmes 1913). Barrell (1917) was the first to attempt to synthesize these critical developments, but most of his ideas were forgotten or ignored for decades. The development of the formal principles of stratigraphy, the evolution of sedimentology as a mature discipline, the stimulus provided by seismic stratigraphy, all have been necessary developments in the evolution of the modern synthesis that constitutes the science described in this review. So where have we arrived at today, and what may we predict as possible future developments and outcomes from the application of this science?

High-Resolution Stratigraphy

The current 'best practices' for chronostratigraphic analysis make use of the techniques of High-Resolution Event Stratigraphy, or HiRES. "The cornerstone of HiRES is the integration of every available piece of stratigraphic information into a single set of data that can be cross-correlated and internally calibrated" (Cramer et al. 2015, p. 138). Originally conceived by Kauffman (1986, 1988), the guiding principle is that there are many features of a sedimentary section, beyond biostratigraphy, that may be used to develop tools for correlation and dating. Stratigraphic events, such as storm beds, tephras, and flooding events, may have limited regional extents, but when used in combination across multiple stratigraphic sections and integrated with chemostratigraphic, magnetostratigraphic and other indicators, they may permit highly detailed stratigraphic syntheses to be developed. Figure 6 illustrates the principles involved in the development of an 'integrated event stratigraphy.' The application of this methodology is not necessarily straightforward. Individual events may be diachronous to a greater or lesser degree, particularly first and last occurrence taxon data, reflecting environmental control and migration patterns. For example, for HiRES work in the Paleozoic record, it remains a question whether conodonts or graptolites provide the most chronostratigraphically reliable information (Cramer et al. 2015). Other events, such as storm beds may be very confined in their distribution, and hiatuses of varying duration and extent complicate the record. Chemostratigraphic signatures vary in their diachroneity. Cramer et al. (2015, p. 148–149) suggested that given the long residence time of strontium and the magnitude of the Sr reservoir in the marine environment, the $^{87}Sr/^{86}Sr$ composition of ocean waters should be quite stable over long time scales, whereas the shorter residence time of ^{13}C makes $\delta^{13}C$ a higher-precision chronostratigraphic tool, but one with an imprecision in the $10^{3\text{-}4}$-year range reflecting a mixing time of a few thousand years. For many parts of the Phanerozoic time scale the dates of chronostratigraphic boundaries can now be provided with precision in a range of 10^5 years (e.g. Sadler et al. 2009).

The Modern Geologic Time Scale

A quantum leap forward was achieved by the *International Commission on Stratigraphy* with the publication in 2004 of its updated Geologic Time Scale (GTS2004: Gradstein et al. 2004). Gradstein et al. (2012) subsequently published their own updated version (although this is not an official product of the International Stratigraphic Commission). The 2004 version incorporates numerous new data points, documented with the use of quantitative biostratigraphy, much-improved radiometric dating methods, chemostratigraphy and (for the Neogene) cyclostratigraphy. The new scale (Fig. 7) presents us with unprecedented opportunities for the comparison and calibration of detailed local and regional studies of rates and processes. Paleogene, Mesozoic and most Paleozoic ages are given to the nearest 100,000 years, although for parts of the scale, potential errors of >1 m.y. remain. This scale, like all before it, incorporates numerous revisions of assigned ages. Almost all major chronostratigraphic boundaries in the Mesozoic and Paleozoic have been revised by several million years relative to earlier scales, such as that of Berggren et al. (1995), reflecting new data or changing interpretations of earlier data. There is no sign, yet, that the time scale has finally stabilized, although the incremental changes from one scale to the next do appear to be getting smaller.

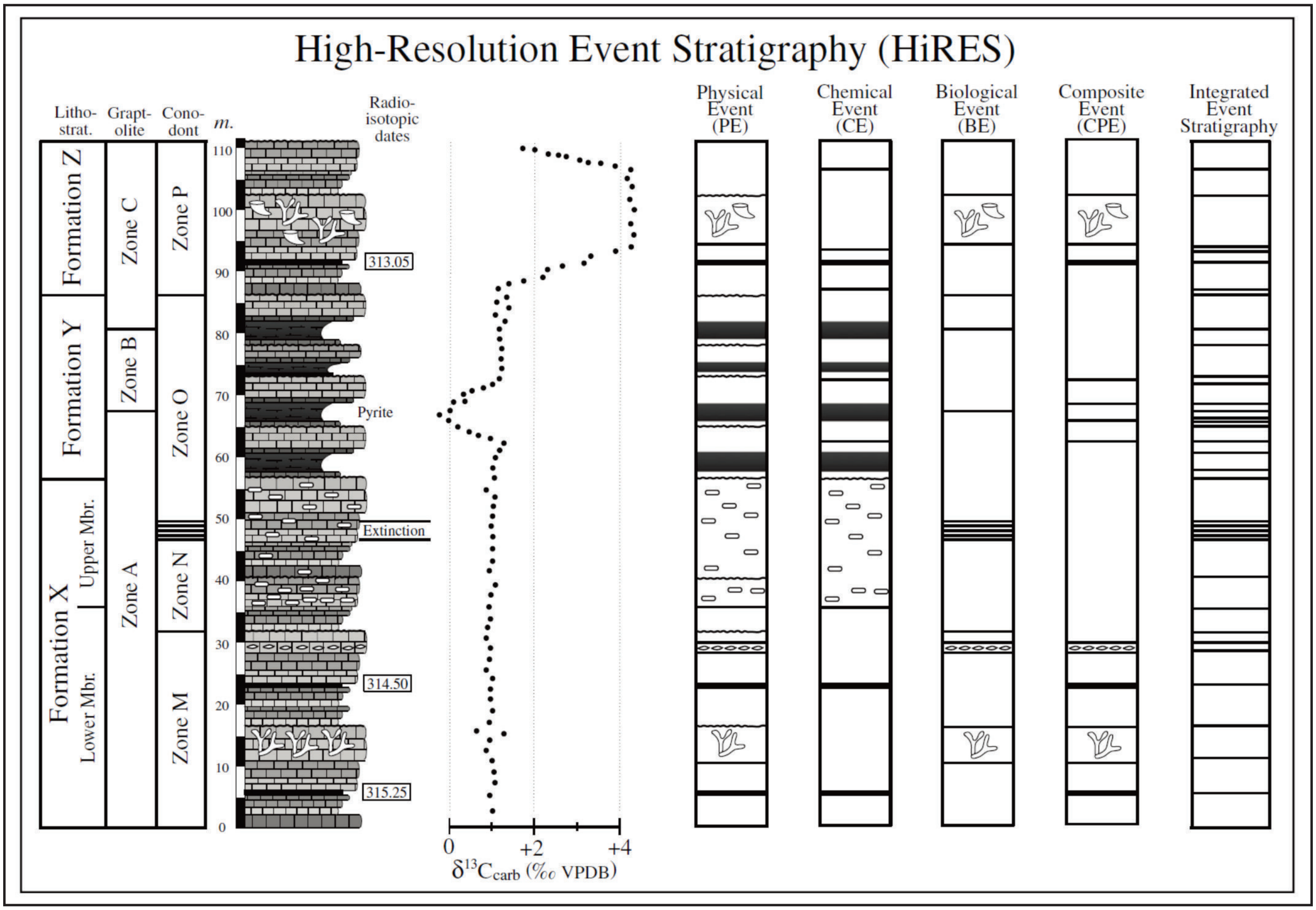

Figure 6. Demonstration of High-Resolution Event Stratigraphy (HiRES) concepts and methods by using a hypothetical stratigraphic section and data (modified from Kauffman 1988). Lithostratigraphic nomenclature, biostratigraphy, lithostratigraphy, biotic events, radioisotopic age determinations, and stable carbon isotope stratigraphy are shown at the left. The five columns shown on the right illustrate the principles of HiRES in which all stratigraphic information is included and a series of 'events' is delimited within the section. All of the chronostratigraphically useful horizons are combined into the integrated event stratigraphy at the far right. In principle, the lithostratigraphic names and biozones at the far left provide a total of 12 discrete horizons for correlation, whereas the integrated event stratigraphy at the far right provides many more potential discrete horizons for correlation and an improved chronostratigraphic resolution (Cramer et al. 2015, their figure 2, p. 139).

Currently finalized global stratotypes for systems, series and stages were identified by Gradstein et al. (2004, 2012) and are posted on the website (www.stratigraphy.org), with references to published documentation, most of which consists of reports in the journal *Episodes* by representatives from boundary working groups. Realistic error estimates are provided for Phanerozoic stages, and range from very small values (10^4-year range) for most of the Cenozoic, the time scale for which is increasingly linked to an astrochronological record, to as much as ± 4 m.y. for several stages between the Middle Jurassic and Early Cretaceous. Figure 8 illustrates the expected error in age estimation through the Phanerozoic, based on information available in 2007. The refinement of the scale expected to accrue from the integration of astrochronology (see next section) into the data base (Fig. 8E) may be regarded as optimistic, but the key workers in this field make a good case for such a development.

Many questions in the earth sciences have at their centre the questions "When did this happen?" and "What were the rates of these processes?" An accurate and high-precision time scale is an essential underpinning to much geological research.

Cyclostratigraphy and Astrochronology

Cyclostratigraphy: The subdiscipline of stratigraphy that deals with the identification, characterization, correlation, and interpretation of cyclic variations in the stratigraphic record.

Astrochronology: The dating of sedimentary units by calibration of the cyclostratigraphic record with astronomically tuned time scales. Accuracy and precision in the 10^4–10^5-year time range may be achievable.

Tuning: Adjusting the frequencies, including harmonics, of a complex record preserved in a natural succession to best-fit a predicted astronomical signal.

Croll (1864) and Gilbert (1895) were the first to realize that variations in the Earth's orbital behaviour may affect the amount and distribution of solar radiation received at the Earth's surface, by latitude and by season, and could be the cause of major climate variations. Several classic studies were undertaken to search for orbital frequencies in the rock record, and theoretical work on the distribution of insolation was carried out by the Serbian mathematician Milankovitch (1930, 1941), who showed how orbital oscillations could affect the distribution of solar radiation over the earth's surface. Howev-

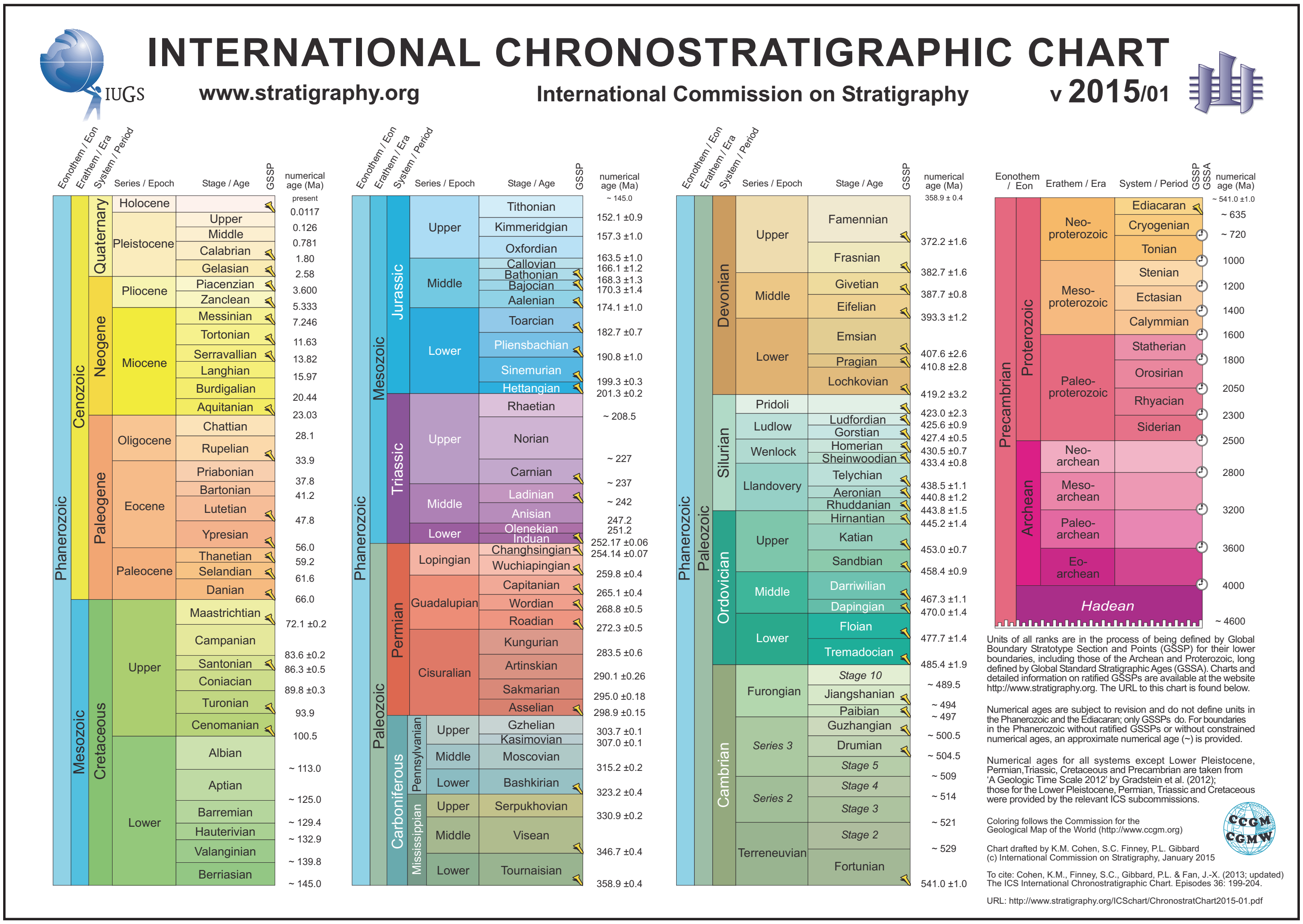

Figure 7. The Geological Time Scale (www.stratigraphy.org). Reproduced by permission © ICS International Commission on Stratigraphy [2015].

er, it was not for some years that the necessary data from the sedimentary record was obtained to support his model. Emiliani (1955) was the first to discover periodicities in the Pleistocene marine isotopic record, and the work by Hays et al. (1976) is regarded by many (e.g. de Boer and Smith 1994) as the definitive study that marked the beginning of a more widespread acceptance of orbital forcing, the so-called **Milankovitch processes**, as a major cause of stratigraphic cyclicity on a 10^4–10^5-year frequency – what is now termed the **Milankovitch band**. The model is now firmly established, particularly since accurate chronostratigraphic dating of marine sediments has led to the documentation of the record of faunal variations and temperature changes in numerous upper Cenozoic sections (Gradstein et al. 2004; Hilgen et al. 2015; see summary in Miall 2010, Sects. 7.2, 11.3). These show remarkably close agreement with the predictions made from astronomical observations. Many high-frequency sequence records are now interpreted in terms of the orbital-forcing model (summaries and reviews in Miall 2010, Chap. 11; Hilgen et al. 2015).

The idea that the preserved orbital record could be used as a kind of 'pacemaker' of Earth history and form the basis for a high-precision time scale has been around for some time (e.g. House 1985). Pioneering studies to establish the astrochronological time scale were led by Fritz Hilgen. A reliable scale was first established for the youngest Cenozoic strata, back to about 5 Ma (Hilgen 1991; Berggren et al. 1995; Hilgen et al. 2006). Over the succeeding decade, astronomically calibrated sections were used to extend the astrochronological time scale back to 14.84 Ma, the base of the Serravallian stage, in the mid-Miocene (www.stratigraphy.org), and research is proceeding to extend the time scale not only to the base of the Cenozoic, but through at least the Mesozoic (Hilgen et al. 2006, 2015; Hinnov and Ogg 2007).

For the older part of the geological record (particularly the Mesozoic and Paleozoic), several studies have now established convincing 'floating' scales for specific stratigraphic intervals; that is, scales that exhibit reliable orbital frequencies, once tuned, but that cannot yet necessarily be precisely correlated to the numerical time scale because of residual imprecisions in numerical dating methods (Hilgen et al. 2015). This project is generating an intense focus on the accuracy and precision of radioisotopic dating methods and the practices of high-resolution stratigraphy, with resulting incremental improvements in the accuracy and precision of the geological time scale (e.g. Sageman et al. 2014).

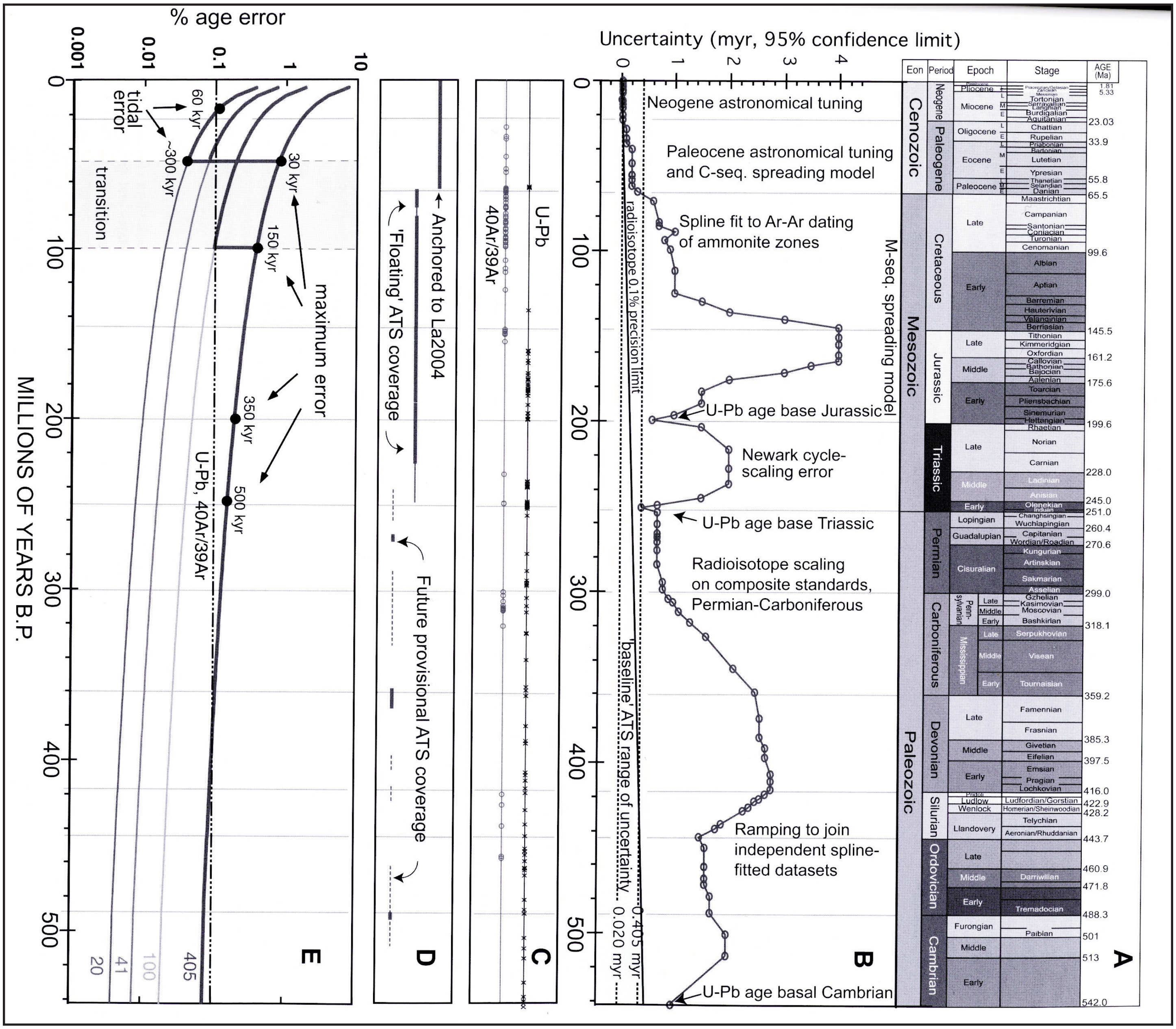

Figure 8. A. The standard divisions of the Phanerozoic International Geologic Time Scale (Gradstein et al. 2004). **B.** Estimated uncertainty (95% confidence level) in the ages of stage boundaries. **C.** Distribution of radiometric ages used in the construction of the time scale. **D.** Documented and potential astrochronological time series. **E.** Estimated error to be expected when the astrochronological time scale through the Phanerozoic is completed and integrated into the International Geologic Time Scale. The curves are labeled according to present-day Milankovitch frequencies. The 405-kyr frequency is the one which cyclostratigraphers are currently retrodicting back into the distant geological past with the greatest confidence (Hilgen et al. 2015; diagram from Hinnov and Ogg 2007).

Sedimentation Rates and Missing Time

Uniformitarianism is still the fundamental principle on which geology is built, but stratigraphers and sedimentologists have long had difficulty reconciling the concept of the uniformity of process over time with the wide range of time scales and rates of processes over which sedimentation takes place. Since the work of Barrell (1917) it has been understood that the sedimentary record is highly fragmentary. In many sedimentary basins as little as 10% of elapsed time may be represented by preserved sediment, when modern measurement of sedimentation rates in present-day environments are taken into account. However, many key concepts in sedimentary geology carry an implication of continuity in the sedimentary record: the practices of stratigraphic classification and correlation, Walther's Law, cyclic sedimentation, facies models, sequence stratigraphy – all are based on the fundamental principle that "the present is the key to the past" and its reverse. In practice, also, we assume that ancient sedimentary records representing much longer intervals than the human time scale ($\geq 10^4$ a) may be reliably compared with observations made over the much shorter time scales accessible to human observation. Questions persist concerning the relevance and significance of transient processes and ephemeral modern deposits to the interpretation of the rock record, given questions about the highly variable preservability of different sedimentary facies. Ager's (1973) remark that the stratigraphic record is "more gap than

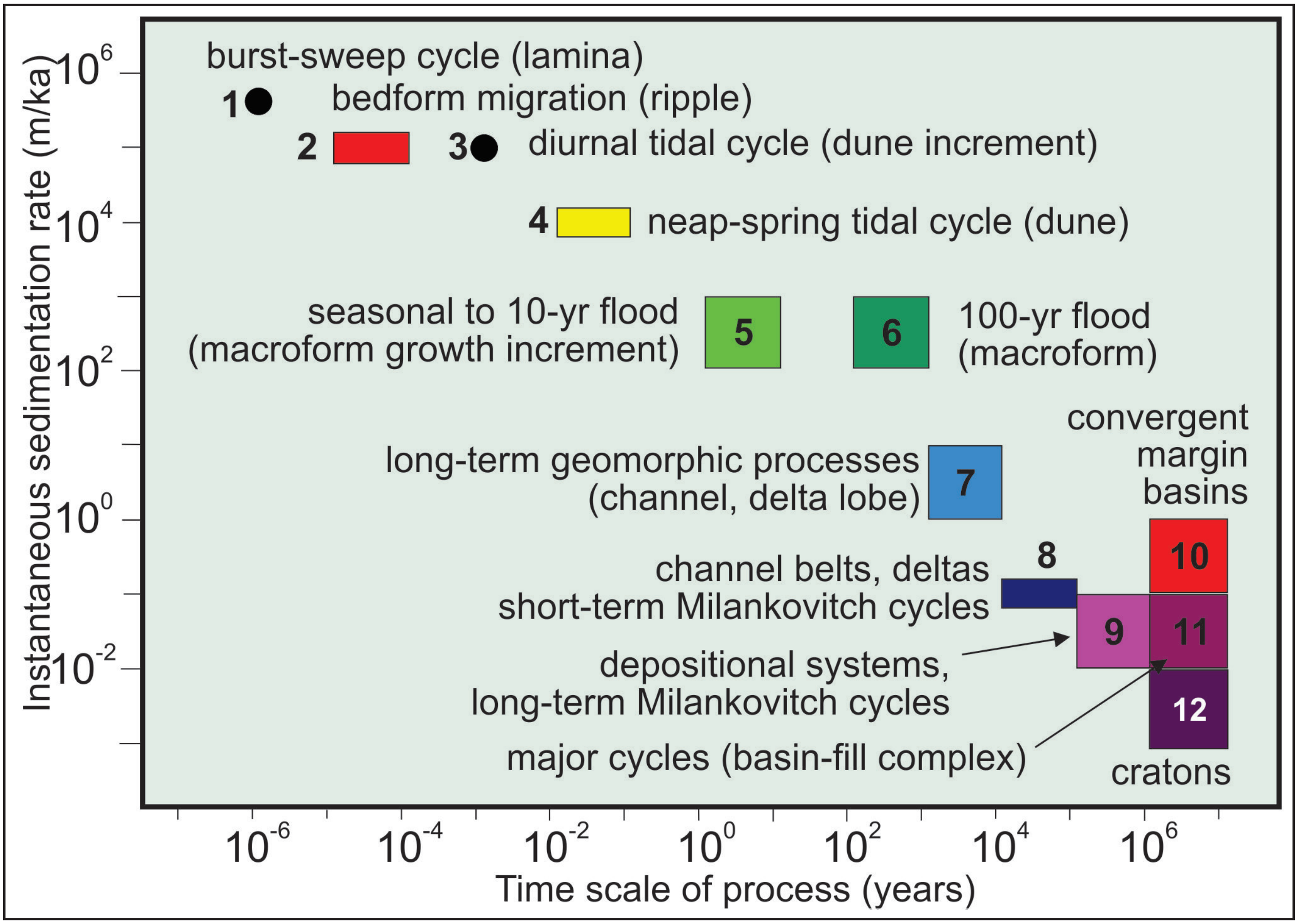

Figure 9. Sedimentation rates and sedimentary processes over time scales spanning 14 orders of magnitude. The numbers associated with each box refer to a Sedimentation Rate Scale described by Miall (2015).

record" is widely cited, but hides a complexity that has yet to be satisfactorily resolved.

It has long been realized that rates of sedimentation measured in modern depositional environments or the ancient record vary in inverse proportion to the time scale over which they are measured. Sadler (1981, 1999) documented this in detail, using 25,000 records of accumulation rates. His synthesis showed that measured sedimentation rates vary by twelve orders of magnitude, from 10^{-4} to 10^{7} m/ka. This huge range of values reflects the range of sedimentation rates at different scales (Fig. 9) and the increasing number and duration of intervals of non-deposition or erosion factored into the measurements as the length of the measured stratigraphic record increases.

Analysis of depositional and erosional processes over the full range of time scales provides insights into long-term geological preservation. At time scales of seconds to months (10^{-1}–10^{-6} years), preservation of individual lithofacies units is essentially random, reflecting autogenic processes, such as diurnal changes in current speed and tidal activity (although topographically lower deposits, such as dune troughs, channel bases, have somewhat higher preservation potential). Packages of strata that survive long enough are subject to the next cycle of preservational processes, such as autogenic channel switching, the '100-year flood,' or storm activity at the 10^{0}–10^{3}-yr time scale. At the 10^{4}–10^{5}-yr time scale, so-called 'high-frequency' geological processes come into play, including orbital forcing of climate and sea level, and local tectonic episodicity. Ultimately, all remaining stratigraphic accumulations are subject to the long-term (10^{6}–10^{7} yr) geological (largely tectonic) controls on basin accommodation (Miall 2015).

An important insight emerging from this analysis has critical implications for the application of uniformitarianist principles. Geological processes interpreted from successions accumulated over the post-glacial period, such as those of the Mississippi and Rhine-Meuse deltas (descriptions and analyses of which comprise substantial contributions to sedimentological literature on fluvial and deltaic systems) can only be used as analogs for interpretations of geological processes up to the 10^{4}-year time scale. The geological record contains many examples of coastal fluvial-deltaic successions spanning millions of years, but a 10^{6}–10^{7}-year record cannot be interpreted simply by 'scaling-up' an analysis carried out on a 10^{4}–10^{5}-year time scale. Firstly, coastal successions, such as those on present day continental margins could be largely eliminated by subaerial erosion during the next glacial cycle of lowered sea level as the geological preservation machine begins to operate over the next longer time scale. Secondly, the time scales implied for sedimentary processes would be wrong. For example, sequence models for fluvial systems, which relate channel stacking behaviour to rates of sedimentary accommodation, are largely based on measurements of rates of sedimentation and channel switching in modern rivers and in post-glacial alluvial valley fills, at time scales no greater than 10^3 years. Applications of these models to the ancient record deal mostly with so-called third-order sequences (durations in the 10^6 yr range) for which calculated accumulation rates are one to three orders of magnitude slower than those on which the sequence models are based (Miall 2014). Colombera et al. (2015) confirmed, by a detailed study of twenty ancient fluvial systems, that there is no relationship between channel-stacking pattern and aggradation rate. It is suggested that the observed changes in channel-stacking patterns that have been observed in the rock record are the product of longer term processes, such as tectonically controlled changes in paleoslope or sediment supply (Miall 2014).

Sequence Stratigraphy as a Key to Earth Processes

The range of sedimentation rates and the durations of hiatuses are fractal-like. They comprise a range of discrete geological processes that control sedimentation, erosion, and long-term preservation. The fractal model provides an elegant basis for integrating our knowledge of sedimentary processes with modern data on varying sedimentation rates and varying scales of hiatuses (Miall 2015). Sequence stratigraphy is essentially a study of the repetitive cycle of accumulation followed by the next gap, at various time scales. The larger, more obvious gaps define for us the major sequences, over a range of time scales. The prominence of particular ranges of accumulation-plus-gap length in the first data sets compiled by Vail et al. (1977) was what led to their establishment of the sequence hierarchy of first-order, second-order, and so on. That this has now been shown to be an incomplete representation of nature (Schlager 2005; Miall 2010) does not alter the fact that there is a limited range of processes that control accumulation. These have fairly well defined rates which, nevertheless, overlap in time to some extent. A review of these sequence-generating mechanisms was compiled by Miall (1995) during a lengthy controversy regarding the importance or otherwise of eustatic sea-level changes as the major controlling mechanism (Dewey and Pitman 1998; Miall and Miall 2001).

Much research into basinal processes has been stimulated directly or indirectly by developments in sequence stratigraphy, and significant advances have been made in the understanding of sedimentary cyclic processes, particularly the geological record of orbital forcing (e.g. de Boer and Smith 1994; Hilgen et al. 2015), and the nature of high-frequency tectonism (e.g. Macdonald 1991; Williams and Dobb 1993).

The Search for Fossil Fuels

The concept of the **petroleum system** has evolved as the essential key to the understanding of how and why fossil fuels accumulate in sedimentary basins. Stratigraphy is at the centre of this enterprise, as noted here:

1. **Source:** The accumulation of plant and animal remains constitute the source of oil, gas and coal. Stratigraphy and sedimentology explain how, where and why.
2. **Maturation:** The generation of fluid oil and gas and the maturation of plant matter into coal are depth- and temperature-dependent, studies of which are the domain of basin analysis.
3. **Migration:** Of oil and gas requires a porosity–permeability plumbing system, which is largely a question of the primary depositional control on lithofacies distribution, with possible subsequent modification by diagenesis and structural deformation.
4. **Reservoir:** The accumulation of oil and gas in discrete pools requires the combination of the three remaining elements of the system. Porous and permeable reservoirs are the product of a range of specific sedimentary processes, such as organic reef growth, the accumulation of clean sands on a beach or in submarine fan complexes at the base of a continental slope (albeit with subsequent diagenetic modification). Much sedimentological research owes its primary motivation to a desire to understand the processes that lead to such accumulations.
5. **Seal:** The converse of a reservoir: a unit that is not porous or permeable.
6. **Trap:** Many petroleum traps are of a type termed **stratigraphic traps**, in which it is the limited extent and configuration of the porous reservoir unit that defines the trap and therefore the pool itself.

Unconventional resources, including shale gas, tight oil and oil sands operate under modified petroleum systems. For shale gas and tight oil migration is of negligible significance. These are commonly described as self-sourced resources. The petroleum matures in place and remains there because of very limited porosity and permeability. Stratigraphic methods are no less important in the development of these resources – not all shale units are equally productive, and much may be learned from petrographic and fracture studies.

The techniques that have evolved to maximize discovery success and development efficiency are among the most technically advanced in the geological sciences and have contributed significantly to the evolution of stratigraphy and sedimentology. Three-dimensional reflection seismic methods reach their maximum effectiveness when the user turns to sedimentology, in particular the new field of seismic geomorphology, to interpret reflection patterns. Directional drilling has become a vital engineering tool for the exploitation of many oil and gas reserves, and its greatest efficiency in practice comes when the tool is directed in real time by the application of **geosteering** methods, which employ down-hole geophysics and well-sample data to direct the drill bit through the desired stratigraphic unit.

In all of these cases, describing the configuration of the reservoir, determining its situation within the regional sequence stratigraphy and defining its basinal setting, constitute important elements in the development of a petroleum play. Numerical modeling and graphic visualization of these

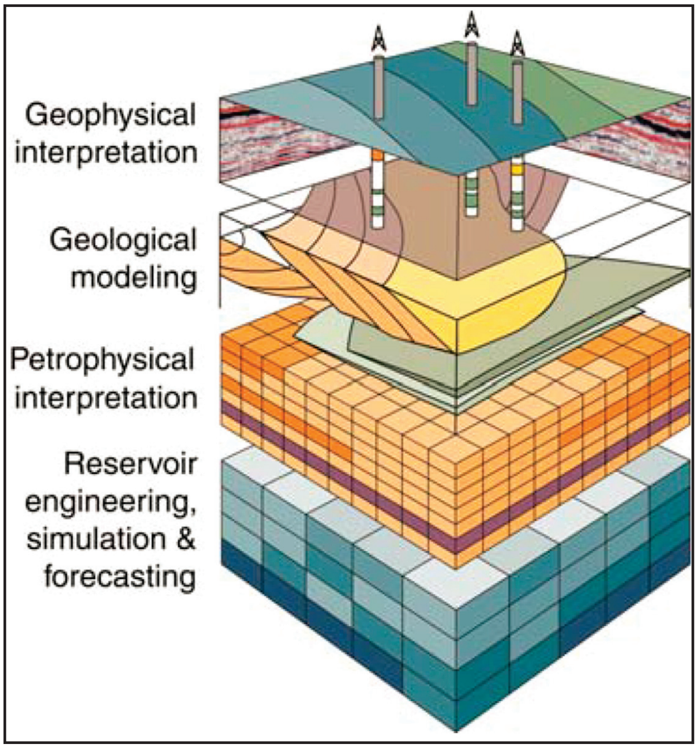

Figure 10. The 3-D modeling process as used in hydrocarbon development. Stratigraphy, as defined in its broadest sense, is essential to the geophysical interpretation and to the geological input into the model (the top two layers). Petrophysical and reservoir engineering interpretations are carried out by statistical sampling and numerical modeling of the stratigraphy, using three-dimensional grid blocks, and it is on the quantitative basis provided by these steps that production programs are designed by the engineers (Bentley and Smith 2008).

elements are essential components of the development process, and require a meticulous attention to the input data from the geological team managing the project (Fig. 10).

CONCLUSIONS

Doyle and Bennett (1998, p. 1) stated that "Stratigraphy is the key to understand the Earth, its materials, structure and past life. It encompasses everything that has happened in the history of the planet." In this statement is the recognition that the stratigraphic history of layered sedimentary rocks preserved on the continents and on the ocean floors constitutes the documented record of Earth history. No other branch of geology can provide this information. Historical geology depends largely on the study of the stratigraphic record. It is from the rocks that we know about the evolution of life, the plate-tectonic development of the earth's crust, and ancient climate changes.

If earth scientists are ever to contribute significantly to the current debate about climate change, their contribution will be to offer a precise record of natural paleoclimatic variability, including the nature of greenhouse and icehouse climates, and such climatic events as the Paleocene–Eocene Thermal Maximum. This natural history should provide a base-line against which to evaluate anthropogenic influences. It is stratigraphy, in its modern complexity, that will provide this base line. Our layers have meaning. These are the files wherein our answers lie.

ACKNOWLEDGEMENTS

Thanks are due to my wife, Charlene, for her more than 46 years of support and encouragement. I thank her, in particular, for her companionship in the field, and for contributing her sociological wisdom to the collaborative work we have done to explore the elements of social construction in the development of the science of Stratigraphy. Thanks are due to Bill Fisher for reviewing the historical sections of this paper. Ron Steel, Martin Gibling and Bob Dalrymple read earlier versions of the paper and provided many useful suggestions.

REFERENCES

Ager, D.V., 1970, On seeing the most rocks: Proceedings of the Geologists' Association, v. 81, p. 421–427, http://dx.doi.org/ 10.1016/s0016-7878(70)80004-9.

Ager, D.V., 1973, The nature of the stratigraphical record: John Wiley, New York, NY, 114 p.

Ager, D.V., 1981, The nature of the stratigraphical record (Second Edition): John Wiley, New York, NY, 122 p.

Ager, D.V., 1993, The new catastrophism: The importance of the rare event in geological history: Cambridge University Press, 231 p.

Allen, J.R.L., 1962, Petrology, origin and deposition of the highest Lower Old Red Sandstone of Shropshire, England: Journal of Sedimentary Petrology (Research), v. 32, p. 657–697, http://dx.doi.org/10.1306/74D70D49-2B21-11D7-8648000102C1865D.

Allen, J.R.L., 1963a, The classification of cross-stratified units. With notes on their origin: Sedimentology, v. 2, p. 93–114, http://dx.doi.org/10.1111/j.1365-3091.1963.tb01204.x.

Allen, J.R.L., 1963b, Henry Clifton Sorby and the sedimentary structures of sands and sandstones in relation to flow conditions: Geologie en Mijnbouw, v. 42, p. 223–228.

Allen, J.R.L., 1964, Studies in fluviatile sedimentation: six cyclothems from the Lower Old Red Sandstone, Anglo-Welsh basin: Sedimentology, v. 3, p. 163–198, http://dx.doi.org/10.1111/j.1365-3091.1964.tb00459.x.

Allen, J.R.L., 1965, A review of the origin and characteristics of recent alluvial sediments: Sedimentology, v. 5, p. 89–191, http://dx.doi.org/10.1111/j.1365-3091.1965.tb01561.x.

Allen, J.R.L., 1983, Studies in fluviatile sedimentation: Bars, bar-complexes and sandstone sheets (low-sinuosity braided streams) in the Brownstones (L. Devonian), Welsh Borders: Sedimentary Geology, v. 33, p. 237–293, http://dx.doi.org/ 10.1016/0037-0738(83)90076-3.

Allen, J.R.L., 1993, Sedimentary structures: Sorby and the last decade: Journal of the Geological Society, v. 150, p. 417–425, http://dx.doi.org/10.1144/ gsjgs.150.3.0417.

Allen, P.A., and Allen, J.R., 2013, Basin analysis: Principles and application to petroleum play assessment: Wiley-Blackwell, Chichester, 619 p.

Allen, P.A., and Etienne, J.L., 2008, Sedimentary challenge to Snowball Earth: Nature Geoscience, v. 1, p. 817–825, http://dx.doi.org/10.1038/ngeo355.

Arnott, R.W.C., 2010, Deep-marine sediments and sedimentary systems, *in* James, N.P., and Dalrymple, R.W., *eds.*, Facies Models 4: GEOtext 6, Geological Association of Canada, St. John's, NL, p. 295–322.

Baker, V.R., 2000, Let Earth Speak, *in* Schneiderman, J., *ed.*, The earth around us: maintaining a livable planet: Freeman, New York, p. 358–367.

Baker, V.R., *ed.*, 2013, Rethinking the fabric of geology: Geological Society of America, Special Papers, v. 502, 185 p., http://dx.doi.org/10.1130/9780813725024.

Ball, M.M., 1967, Carbonate sand bodies of Florida and the Bahamas: Journal of Sedimentary Petrology (Research), v. 37, p. 556–591, http://dx.doi.org/ 10.1306/74D7171C-2B21-11D7-8648000102C1865D.

Bally, A.W., *ed.*, 1987, Atlas of seismic stratigraphy: American Association of Petroleum Geologists Studies in Geology 27, in 3 volumes.

Bally, A.W., 1989, Phanerozoic basins of North America, *in* Bally, A.W., and Palmer, A.R., *eds.*, The geology of North America—an overview: The geology of North America, Geological Society of America, v. A, p. 397–446, http://dx.doi.org/ 10.1130/DNAG-GNA-A.397.

Bally, A.W., Gordy, P.L., and Stewart, G.A., 1966, Structure, seismic data and orogenic evolution of southern Canadian Rockies: Bulletin of Canadian Petroleum Geology, v. 14, p. 337–381.

Barrell, Joseph, 1917, Rhythms and the measurements of geologic time: Geological Society of America Bulletin, v. 28, p. 745–904, http://dx.doi.org/10.1130/ GSAB-28-745.

Beales, F.W., 1958, Ancient sediments of Bahaman type: American Association of Petroleum Geologists, v. 42, p. 1845–1880.

Beaumont, C., 1981, Foreland basins: Geophysical Journal International, v. 65, p. 291–329, http://dx.doi.org/10.1111/j.1365-246X.1981.tb02715.x.

Beerbower, J.R., 1964, Cyclothems and cyclic depositional mechanisms in alluvial

plain sedimentation: Geological Survey of Kansas Bulletin 169, v. 1, p. 31–42.
Bentley, M., and Smith, S., 2008, Scenario-based reservoir modelling: the need for more determinism and less anchoring, *in* Robinson, A., Griffiths, P., Price, S., Hegre, J., and Muggeridge, A., *eds.*, The Future of Geological Modelling in Hydrocarbon Development: Geological Society, London, Special Publications, v. 309, p. 145–159, http://dx.doi.org/10.1144/sp309.11.
Berg, R.R., 1962, Mountain flank thrusting in Rocky Mountain foreland, Wyoming and Colorado: American Association of Petroleum Geologists Bulletin, v. 46, p. 2019–2032.
Berg, R.R., 1968, Point-bar origin of Fall River Sandstone reservoirs, northeastern Wyoming: American Association of Petroleum Geologists Bulletin, v. 52, p. 2116–2122.
Berggren, W.A., Kent, D.V., Aubry, M.-P., and Hardenbol, J., *eds.,* 1995, Geochronology, time scales and global stratigraphic correlation: Society for Sedimentary Geology Special Publication 54, 386 p.
Bernard, H.A., and Major, C.J., 1963, Recent meander belt deposits of the Brazos River: an alluvial "sand" model (Abstract): American Association of Petroleum Geologists Bulletin, v. 47, p. 350.
Bernard, H.A., Major, C.F., Jr., and Parrott, B.S., 1959, The Galveston Barrier Island and environs – a model for predicting reservoir occurrence and trend: Transactions of the Gulf Coast Association of Geological Societies, v. 9, p. 221–224.
Bernard, H.A., Leblanc, R.J., and Major, C.J., 1962, Recent and Pleistocene geology of southeast Texas, *in* Rainwater, E.H., and Zingula, R.P., *eds.*, Geology of the Gulf Coast and central Texas: Geological Society of America, Guidebook for 1962 Annual Meeting, p. 175–224.
Berry, W.B.N., 1968, Growth of prehistoric time scale, based on organic evolution: W.H. Freeman and Co., San Francisco, 158 p.
Berry, W.B.N., 1987, Growth of prehistoric time scale based on organic evolution (Revised Edition): Blackwell Science, Oxford, 202 p.
Bird, J.M., and Dewey, J.F., 1970, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian Orogen: Geological Society of America Bulletin, v. 81, p. 1031–1060, http://dx.doi.org/10.1130/0016-7606(1970)81[1031:LPMTAT]2.0.CO;2.
Blackwelder, E., 1909, The valuation of unconformities: The Journal of Geology, v. 17, p. 289–299, http://dx.doi.org/10.1086/621610.
Blatt, H., Middleton, G.V., and Murray, R.C., 1972, Origin of sedimentary rocks: Prentice-Hall, Englewood Cliffs, NJ, 634 p.
Boggs, S., Jr., 1987, Principles of sedimentology and stratigraphy: Prentice Hall, Englewood Cliffs, NJ, 784 p.
Bouma, A.H., 1962, Sedimentology of some flysch deposits: Elsevier, Amsterdam, 168 p.
Bouma, A.H., Normark, W.R., and Barnes, N.E., *eds*., 1985, Submarine fans and related turbidite systems: Springer-Verlag Inc., Berlin and New York, 351 p., http://dx.doi.org/10.1007/978-1-4612-5114-9.
Brouwer, A., 1962, Past and present in Sedimentology: Sedimentology, v. 1, p. 2–6, http://dx.doi.org/10.1111/j.1365-3091.1962.tb01143.x.
Brown, L.F., Jr., and Fisher, W.L., 1977, Seismic-stratigraphic interpretation of depositional systems: examples from Brazilian rift and pull-apart basins, *in* Payton, C.E., *ed*., Seismic stratigraphy — applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 213–248.
Burk, C.A., and Drake, C.L., *eds*., 1974, The geology of continental margins: Springer-Verlag, New York, 1009 p., http://dx.doi.org/10.1007/978-3-662-01141-6.
Busby, C.J., and Ingersoll, R.V., *eds*., 1995, Tectonics of sedimentary basins: Blackwell Science, Oxford, 579 p.
Callomon, J.H., 1995, Time from fossils: S.S. Buckman and Jurassic high-resolution geochronology, *in* Le Bas, M.J., *ed*., Milestones in Geology: Geological Society, London, Memoirs, v. 16, p. 127–150, http://dx.doi.org/10.1144/gsl.mem.1995.016.01.14.
Catuneanu, O., 2006, Principles of sequence stratigraphy: Elsevier, Amsterdam, 375 p.
Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., and Winker, C., 2009, Toward the standardization of sequence stratigraphy: Earth-Science Reviews, v. 92, p. 1–33, http://dx.doi.org/10.1016/j.earscirev.2008.10.003.
Catuneanu, O., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gianolla, P., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Nummedal, D., Posamentier, H.W., Pratt, B.R,. Shanley, K.W., Steel, R.J., Strasser, A., and Tucker, M.E., 2010, Sequence stratigraphy: common ground after three decades of development: First Break, v. 28, p. 41–54, http://dx.doi.org/10.3997/1365-2397.2010002.
Catuneanu, O., Galloway, W.E., Kendall, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser A., and Tucker, M.E., 2011, Sequence Stratigraphy: Methodology and Nomenclature: Report to ISSC: Newsletters on Stratigraphy, v. 44, p. 173–245, http://dx.doi.org/10.1127/0078-0421/2011/0011.
Cloetingh, S., 1988, Intraplate stresses: A new element in basin analysis, *in* Kleinspehn, K.L., and Paola, C., *eds*., New Perspectives in basin analysis: Springer-Verlag, New York, p. 205–230, http://dx.doi.org/10.1007/978-1-4612-3788-4_10.
Colombera, L., Mountney, N.P., and McCaffrey, W.D., 2015, A meta-study of relationships between fluvial channel-body stacking pattern and aggradation rate: Implications for sequence stratigraphy: Geology, v. 43, p. 283–286, http://dx.doi.org/10.1130/G36385.1.
Conkin, B.M., and Conkin, J.E., *eds*., 1984, Stratigraphy: foundations and concepts: Benchmark Papers in Geology, Van Nostrand Reinhold, New York, 363 p.
Conybeare, C.E.B., and Crook, K.A.W., 1968, Manual of sedimentary structures: Australian Bureau of Mineral Resources, Geology and Geophysics, Bulletin 102, 327 p.
Cramer, B.D., Vandenbroucke, T.R.A., and Ludvigson, G.A., 2015, High-resolution event stratigraphy (HiRES) and the quantification of stratigraphic uncertainty: Silurian examples of the quest for precision in stratigraphy: Earth-Science Reviews, v. 141, p. 136–153, http://dx.doi.org/10.1016/j.earscirev.2014.11.011.
Croll, J., 1864, On the physical cause of the change of climate during geological epochs: Philosophical Magazine, v. 28, p. 435–436.
Curray, J.R., 1956, The analysis of two-dimensional orientation data: The Journal of Geology, v. 64, p. 117–131, http://dx.doi.org/10.1086/626329.
Curray, J.R., 1964, Transgressions and regressions, *in* Miller, R.L., *ed*., Papers in marine geology, Shepard Commemorative volume: MacMillan Press, New York, p. 175–203.
Curtis, D.M., 1970, Miocene deltaic sedimentation, Louisiana Gulf Coast, *in* Morgan, J.P., *ed*., Deltaic sedimentation modern and ancient: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 15, p. 293–308.
Dahlstrom, C.D.A., 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, p. 332–406.
Dapples, E.C., Krumbein, W.C., and Sloss, L.L., 1948, Tectonic control of lithologic associations: American Association of Petroleum Geologists Bulletin, v. 32, p. 1924–1947.
Davies, R.J., Posamentier, H.W., Wood, L.J., and Cartwright, J.A., *eds*., 2007, Seismic geomorphology: applications to hydrocarbon exploration and production: Geological Society, London, Special Publications, v. 277, 274 p., http://dx.doi.org/10.1144/GSL.SP.2007.277.01.16.
de Boer, P.L., and Smith, D.G., *eds*., 1994, Orbital forcing and cyclic sequences: International Association of Sedimentologists Special Publication 19, 559 p.
De Raaf, J.F.M., Reading, H.G., and Walker, R.G., 1965, Cyclic sedimentation in the Lower Westphalian of North Devon, England: Sedimentology, v. 4, p. 1–52, http://dx.doi.org/10.1111/j.1365-3091.1965.tb01282.x.
Dewey, J.F., 1982, Plate tectonics and the evolution of the British Isles: Journal of the Geological Society, v. 139, p. 371–412, http://dx.doi.org/10.1144/gsjgs.139.4.0371.
Dewey, J.F., 1999, Reply when awarded the Wollaston medal: Geological Society, London, 1999 Awards.
Dewey, J.F., and Bird, J.M., 1970, Plate tectonics and geosynclines: Tectonophysics, v. 10, p. 625–638, http://dx.doi.org/10.1016/0040-1951(70)90050-8.
Dewey, J.F., and Pitman, W.C., 1998, Sea-level changes: mechanisms, magnitudes and rates, *in* Pindell, J.L., and Drake, C.L., *eds*., Paleogeographic evolution and non-glacial eustacy, northern South America: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 58, p. 1–16, http://dx.doi.org/10.2110/pec.98.58.0001.
Dickinson, W.R., 1971, Plate tectonic models of geosynclines: Earth and Planetary Science Letters, v. 10, p. 165–174, http://dx.doi.org/10.1016/0012-821X(71)90002-1.
Dickinson, W.R., 1974, Plate tectonics and sedimentation, *in* Dickinson, W.R., *ed*., Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 22, p. 1–27, http://dx.doi.org/10.2110/pec.74.22.0001.
Dickinson, W.R., 1976, Sedimentary basins developed during evolution of Mesozoic–Cenozoic arc-trench system in western North America: Canadian Journal of Earth Sciences, v. 13, p. 1268–1287, http://dx.doi.org/10.1139/e76-129.
Dickinson, W.R., 1980, Plate tectonics and key petrologic associations, *in* Strangway, D.W., *ed*., The continental crust and its mineral deposits: Geological Association of Canada Special Paper 20, p. 341–360.
Dickinson, W.R., 1981, Plate tectonics and the continental margin of California, *in* Ernst, W.G., *ed*., The geotectonic development of California: Prentice-Hall Inc., Englewood Cliffs, NJ, p. 1–28.
Dickinson, W.R., and Seely, D.R., 1979, Structure and stratigraphy of forearc

regions: American Association of Petroleum Geologists Bulletin, v. 63, p. 2–31.
Dietz, R.S., 1963, Collapsing continental rises: An actualistic concept of geosynclines and mountain building: The Journal of Geology, v. 71, p. 314–333, http://dx.doi.org/10.1086/626904.
Dietz, R.S., 1994, Earth, sea and sky: Life and times of a journeyman geologist: Annual Review of Earth and Planetary Sciences, v. 22, p. 1–33, http://dx.doi.org/10.1146/annurev.ea.22.050194.000245.
Dietz, R.S., and Holden, J.C., 1974, Collapsing continental rises: actualistic concept of geosynclines—a review, *in* Dott, R.H., Jr., and Shaver, R.H., *eds.*, Modern and ancient geosynclinal sedimentation: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 19, p. 14–25, http://dx.doi.org/10.2110/pec.74.19.0014.
Dott, R.H., Jr., 1983, 1982 SEPM Presidential Address: Episodic sedimentation—how normal is average? How rare is rare? Does it matter?: Journal of Sedimentary Petrology (Research), v. 53, p. 5–23, http://dx.doi.org/10.1306/212F8148-2B24-11D7-8648000102C1865D.
Dott, R.H., Jr., 1996, Episodic event deposits versus stratigraphic sequences—shall the twain never meet?: Sedimentary Geology, v. 104, p. 243–247, http://dx.doi.org/10.1016/0037-0738(95)00131-X.
Dott, R.H., Jr., and Shaver, R.H., *eds.*, 1974, Modern and ancient geosynclinal sedimentation: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 19, 380 p., http://dx.doi.org/10.2110/pec.74.19.0014.
Doyle, P., and Bennett, M.R., *eds.*, 1998, Unlocking the stratigraphical record: John Wiley and Sons, Chichester, 532 p.
Drake, C.L., Ewing, M., and Sutton, G.H., 1959, Continental margins and geosynclines—the east coast of North America north of Cape Hatteras: Physics and Chemistry of the Earth, v. 3, p. 110–198, http://dx.doi.org/10.1016/0079-1946(59)90005-9.
Duff, P.McL.D., and Walton, E.K., 1962, Statistical basis for cyclothems: a quantitative study of the sedimentary succession in the east Pennine Coalfield: Sedimentology, v. 1, p. 235–255, http://dx.doi.org/10.1111/j.1365-3091.1962.tb01149.x.
Duff, P.McL.D., Hallam, A., and Walton, E.K., *eds.,* 1967, Cyclic sedimentation: Developments in Sedimentology, v. 10, Elsevier, Amsterdam, 280 p., http://dx.doi.org/10.1016/S0070-4571(08)70120-1.
Dunbar, C.O., and Rodgers, J., 1957, Principles of Stratigraphy: Wiley, New York, 356 p.
Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture, *in* Ham, W.E., *ed.*, Classification of carbonate rocks: American Association of Petroleum Geologists Memoir 1, p. 108–121.
Emiliani, C., 1955, Pleistocene temperatures: The Journal of Geology, v. 63, p. 538–578, http://dx.doi.org/10.1086/626295.
Eyles, N., and Januszczak, N., 2004, 'Zipper-rift': a tectonic model for Neoproterozoic glaciations during the breakup of Rodinia after 750 Ma: Earth-Science Reviews, v. 65, p. 1–73, http://dx.doi.org/10.1016/S0012-8252(03)00080-1.
Eyles, N., Eyles, C.H., and Miall, A.D., 1983, Lithofacies types and vertical profile models; an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences: Sedimentology, v. 30, p. 393–410, http://dx.doi.org/10.1111/j.1365-3091.1983.tb00679.x.
Fisher, W.L., and McGowen, J.H., 1967, Depositional systems in the Wilcox Group of Texas and their relationship to occurrence of oil and gas: Transactions of the Gulf Coast Association of Geological Societies, v. 17, p. 105–125.
Fisher, W.L., Brown, L.F., Scott, A.J., and McGowen, J.H., 1969, Delta systems in the exploration for oil and gas: Bureau of Economic Geology, University of Texas, 78 p.
Fisher, W.L., McGowen, J.H., Brown, L.F., Jr., and Groat, C.G., 1972, Environmental geologic atlas of the Texas coastal zone — Galveston-Houston area: Bureau of Economic Geology, University of Texas.
Fisher, W.L., Gama, E., and Ojeda, H.A., 1973, Estratigrafia sismica e sistemas deposicionais da Formação Piaçabuçu: Sociedade Brasileira de Geologia, Anai do XXVII Congresso, v. 3, p. 123–133.
Fisk, H.N., 1944, Geological investigations of the alluvial valley of the lower Mississippi River: U.S. Army Corps of Engineers, Mississippi River Commission, Vicksburg, MS, 78 p.
Folk, R.L., 1962, Spectral subdivision of limestone types, *in* Ham, W.E., *ed.*, Classification of carbonate rocks: American Association of Petroleum Geologists Memoir 1, p. 62–84.
Frazier, D.E., 1967, Recent deltaic deposits of the Mississippi River—their development and chronology: Transactions of the Gulf Coast Association of Geological Societies, v. 17, p. 287–315.
Frazier, D.E., 1974, Depositional episodes: their relationship to the Quaternary stratigraphic framework in the northwestern portion of the Gulf Basin: Bureau of Economic Geology, University of Texas at Austin, Geological Circular 74-1, 26 p.
Frey, R.W., and Pemberton, S.G., 1984, Trace fossil facies models, *in* Walker, R.G., *ed.*, Facies models (Second Edition): Geoscience Canada Reprint Series 1, p. 189–207.
Friedman, G.M., and Sanders, J.E., 1978, Principles of Sedimentology: John Wiley and Sons, New York, 791 p.
Galloway, W.E., 1989, Genetic stratigraphic sequences in basin analysis I: Architecture and genesis of flooding-surface bounded depositional units: American Association of Petroleum Geologists Bulletin, v. 73, p. 125–142.
Gilbert, G.K., 1884, Ripple-marks: Science, v. 3, p. 375–376, http://dx.doi.org/10.1126/science.ns-3.60.375-c.
Gilbert, G.K., 1895, Sedimentary measurement of Cretaceous time: The Journal of Geology, v. 3, p. 121–127, http://dx.doi.org/10.1086/607150.
Gilbert, G.K., 1899, Ripple-marks and cross-bedding: Geological Society of America Bulletin, v. 10, p. 135–140, http://dx.doi.org/10.1130/GSAB-10-135.
Gilbert, G.K., 1914, The transportation of debris by running water: U.S. Geological Survey Professional Paper 86, 263 p.
Ginsburg, R.N., and Lowenstam, H.A., 1958, The influence of marine bottom communities on the depositional environment of sediments: The Journal of Geology, v. 66, p. 310–318, http://dx.doi.org/10.1086/626507.
Gradstein, F.M., Ogg, J.G., and Smith, A.G., *eds.*, 2004, A geologic time scale: Cambridge University Press, Cambridge, 610 p.
Gradstein, F.M., Ogg, J.G., Schmitz, M.D., and Ogg, G.M., 2012, The Geologic time scale 2012: Elsevier, Amsterdam, 2 volumes, 1176 p.
Gressly, A., 1838, Observations géologiques sur le Jura Soleurois: Nouveaux Memoires de la Société Helvétique des Sciences. Naturelles, v. 2, p. 1–112.
Gurnis, M., 1988, Large-scale mantle convection and the aggregation and dispersal of supercontinents: Nature, v. 332, p. 695–699, http://dx.doi.org/10.1038/332695a0.
Gurnis, M., 1990, Bounds on global dynamic topography from Phanerozoic flooding of continental platforms: Nature, v. 344, p. 754–756, http://dx.doi.org/10.1038/344754a0.
Gurnis, M., 1992, Long-term controls on eustatic and epeirogenic motions by mantle convection: GSA Today, v. 2, p. 141–157.
Hallam, A., 1989, Great geological controversies (Second Edition): Oxford University Press, Oxford, 244 p.
Hancock, J.M., 1977, The historic development of biostratigraphic correlation, *in* Kauffman, E.G., and Hazel, J.E., *eds.*, Concepts and methods of biostratigraphy: Dowden, Hutchinson and Ross Inc., Stroudsburg, PA, p. 3–22.
Harms, J.C., Southard, J.B., Spearing, D.R., and Walker, R.G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: Society of Economic Paleontologists and Mineralogists Short Course 2, 161 p.
Hart, B.S., 2013, Whither seismic stratigraphy: Interpretation, v. 1, p. SA3–SA20, http://dx.doi.org/10.1190/int-2013-0049.1.
Hays, J.D., Imbrie, J., and Shackleton, N.J., 1976, Variations in the earth's orbit: Pacemaker of the Ice Ages: Science, v. 194, p. 1121–1132, http://dx.doi.org/10.1126/science.194.4270.1121.
Hedberg, H.D., 1948, Time stratigraphic classification of sedimentary rocks: Geological Society of America Bulletin, v. 59, p. 447–462, http://dx.doi.org/10.1130/0016-7606(1948)59[447:TCOSR]2.0.CO;2.
Hilgen, F.J., 1991, Extension of the astronomically calibrated (polarity) time scale to the Miocene/Pliocene boundary: Earth and Planetary Science Letters, v. 107, p. 349–368, http://dx.doi.org/10.1016/0012-821X(91)90082-S.
Hilgen, F.J., Brinkhuis, H., and Zachariasse, W.J., 2006, Unit stratotypes for global stages. The Neogene perspective: Earth-Science Reviews, v. 74, p. 113–125, http://dx.doi.org/10.1016/j.earscirev.2005.09.003.
Hilgen, F.J., Hinnov, L.A., Aziz, H.A., Abels, H.A., Batenburg, S., Bosmans, J.H.C., de Boer, B., Hüsings, S.K., Kuiper, K.F., Lourens, L.J., Rivera, T., Tuenter, E., Van de Wal, R.S.W., Wotzlaw, J.-F., and Zeeden, C., 2015, Stratigraphic continuity and fragmentary sedimentation: the success of cyclostratigraphy as part of integrated stratigraphy, *in* Smith, D.G., Bailey, R.J., Burgess, P.M., and Fraser, A.J*., eds.,* Strata and time: Probing the Gaps in Our Understanding; Geological Society, London, Special Publications, v. 404, p. 157–197, http://dx.doi.org/10.1144/SP404.12.
Hinnov, L.A., and Ogg, J.G., 2007, Cyclostratigraphy and the astronomical time scale: Stratigraphy, v. 4, p. 239–251.
Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P., 1998, A Neoproterozoic snowball Earth: Science, v. 281, p. 1342–1346, http://dx.doi.org/10.1126/science.281.5381.1342.
Holmes, A., 1913, The age of the Earth: Harper, London.
House, M.R., 1985, A new approach to an absolute timescale from measurements of orbital cycles and sedimentary microrhythms: Nature, v. 315, p. 721–725, http://dx.doi.org/10.1038/315721a0.
Hunt, D., and Tucker, M.E., 1992, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall: Sedimentary Geology, v. 81, p. 1–9, http://dx.doi.org/10.1016/0037-0738(92)90052-S.

Illing, L.V., 1954, Bahaman calcareous sands: American Association of Petroleum Geologists, v. 38, p. 1–95.
Ingersoll, R.V., 1978a, Submarine fan facies of the Upper Cretaceous Great Valley Sequence, northern and central California: Sedimentary Geology, v. 21, p. 205–230, http://dx.doi.org/10.1016/0037-0738(78)90009-X.
Ingersoll, R.V., 1978b, Petrofacies and petrologic evolution of the Late Cretaceous fore-arc basin, northern and central California: The Journal of Geology, v. 86, p. 335–352, http://dx.doi.org/10.1086/649695.
Ingersoll, R.V., 1979, Evolution of the Late Cretaceous forearc basin, northern and central California: Geological Society of America Bulletin, v. 90, p. 813–826, http://dx.doi.org/10.1130/0016-7606(1979)90<813:EOTLCF>2.0.CO;2.
James, N.P., and Dalrymple, R.W., *eds*., 2010, Facies Models 4: GEOtext 6: Geological Association of Canada, St. John's, NL, 586 p.
James, N.P., and Lukasik, J., 2010, Cool- and cold-water neritic carbonates, *in* James, N.P., and Dalrymple, R.W., *eds*., Facies Models 4: GEOtext 6: Geological Association of Canada, St. John's, NL, p. 371–420.
Jervey, M.T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expression, *in* Wilgus, C.K., Hastings, B.S., Posamentier, H.W., Van Wagoner, J.C., Ross, C.A., and Kendall, C.G.St.C., *eds*., Sea-level Changes - an integrated approach: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 42, p. 47–69, http://dx.doi.org/10.2110/pec.88.01.0047.
Johannessen, E.P., and Steel, R.J., 2005, Shelf-margin clinoforms and prediction of deepwater sands: Basin Research, v. 17, p. 521–550, http://dx.doi.org/10.1111/j.1365-2117.2005.00278.x.
Jordan, T.E., 1981, Thrust loads and foreland basin evolution, Cretaceous, western United States: American Association of Petroleum Geologists Bulletin, v. 65, p. 2506–2520.
Jordan, T.E., 1995, Retroarc foreland and related basins, *in* Busby, C.J., and Ingersoll, R.V., *eds*., Tectonics of sedimentary basins: Blackwell Science, Oxford, p. 331–362.
Kauffman, E.G., 1986, High-resolution event stratigraphy: regional and global Cretaceous bio-events, *in* Walliser, O.H., *ed.,* Global Bio-events: Lecture Notes on Earth History, v. 8: Springer-Verlag, Berlin, p. 277–335, http://dx.doi.org/10.1007/bfb0010215.
Kauffman, E.G., 1988, Concepts and methods of high-resolution event stratigraphy: Annual Review of Earth and Planetary Sciences, v. 16, p. 605–654, http://dx.doi.org/10.1146/annurev.ea.16.050188.003133.
Kay, M., 1951, North American geosynclines: Geological Society of America Memoirs, v. 48, p. 1–132, http://dx.doi.org/10.1130/mem48-p1.
Kim, W., and Paola, C., 2007, Long-period cyclic sedimentation with constant tectonic forcing in an experimental relay ramp: Geology, v. 35, p. 331–334, http://dx.doi.org/10.1130/G23194A.1.
Krumbein, W.C., 1939, Preferred orientation of pebbles in sedimentary deposits: The Journal of Geology, v. 47, p. 673–706, http://dx.doi.org/10.1086/624827.
Krumbein, W.C., 1948, Lithofacies maps and regional sedimentary-stratigraphic analysis: American Association of Petroleum Geologists, v. 32, p. 1909–1923.
Krumbein, W.C., and Sloss, L.L., 1951, Stratigraphy and Sedimentation: Freeman, San Francisco, 497 p.
Krumbein, W.C., and Sloss, L.L., 1963, Stratigraphy and sedimentation (Second Edition): W.H. Freeman and Co., San Francisco, 660 p.
Kuenen, Ph.H., 1957, Review of Marine Sand-Transporting Mechanisms: Journal of the Alberta Society of Petroleum Geologists, v. 5, No. 4, p. 59–62
Kuenen, Ph.H., and Migliorini, C.I., 1950, Turbidity currents as a cause of graded bedding: The Journal of Geology, v. 58, p. 91–127, http://dx.doi.org/10.1086/625710.
Levorsen, A.I., 1943, Discovery thinking: American Association of Petroleum Geologists Bulletin, v. 27, p. 887–928.
Levorsen, A.I., 1954, Geology of petroleum: W.H. Freeman, San Francisco, 703 p.
Longwell, C.R., *ed*., 1949, Sedimentary facies in geologic history: Geological Society of America Memoirs, v. 39, 172 p., http://dx.doi.org/10.1130/MEM39-pv.
Lyell, C., 1830–1833, Principles of Geology, 3 volumes: John Murray, London (reprinted by Johnson Reprint Corp., New York, 1969).
Macdonald, D.I.M., *ed*., 1991, Sedimentation, tectonics and eustasy: sea-level changes at active margins: International Association of Sedimentologists Special Publication 12, 518 p.
Mackin, J. H., 1963, Rational and empirical methods of investigation in geology, *in* Albritton, C.C., *ed*., The fabric of geology: Freeman, Cooper and Company, San Francisco, p. 135–163.
Matthews, R.K., 1984, Dynamic Stratigraphy (Second Edition): Prentice-Hall, Englewood Cliffs, NJ, 489 p.
McConnell, R.G., 1887, Report of the geological structure of a portion of the Rocky Mountains, accompanied by a section measured near the 51st parallel: Geological Survey of Canada, Annual Report 1886, p. 1D–41D.
McEachern, J.A., Pemberton, S.G., Gingras, M.K., and Bann, K.L., 2010, Ichnology and facies models, *in* James, N.P., and Dalrymple, R.W., *eds*., Facies Models 4: Geotext 6: Geological Association of Canada, St John's, NL, p. 19–58.
McKee, E.D., 1957, Flume experiments on the production of stratification and cross-stratification: Journal of Sedimentary Petrology (Research), v. 27, p. 129–134, http://dx.doi.org/10.1306/74D70678-2B21-11D7-8648000102C1865D.
McKee, E.D., and Weir, G.W., 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geological Society of America Bulletin, v. 64, p. 381–390, http://dx.doi.org/10.1130/0016-7606(1953)64[381:TFSACI]2.0.CO;2.
McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32, http://dx.doi.org/10.1016/0012-821X(78)90071-7.
McLaren, D.J., 1970, Presidential address: time, life and boundaries: Journal of Paleontology, v. 44, p. 801–813.
McMechan, M.E., 2000, Vreeland diamictites – Neoproterozoic glaciogenic slope deposits, Rocky Mountains, northeast British Columbia: Bulletin of Canadian Petroleum Geology, v. 48, p. 246–261, http://dx.doi.org/10.2113/48.3.246.
Merriam, D.F., *ed*., 1964, Symposium on cyclic sedimentation: Kansas Geological Survey Bulletin 169, 636 p.
Miall, A.D., 1973, Markov chain analysis applied to an ancient alluvial plain succession: Sedimentology, v. 20, p. 347–364, http://dx.doi.org/10.1111/j.1365-3091.1973.tb01615.x.
Miall, A.D., *ed*., 1980, Facts and Principles of World Petroleum Occurrence: Canadian Society of Petroleum Geologists Memoir 6, 1003 p.
Miall, A.D., 1984, Principles of sedimentary basin analysis: Springer-Verlag, Berlin, 490 p., http://dx.doi.org/10.1007/978-1-4757-4232-9.
Miall, A.D., 1985, Architectural-element analysis: A new method of facies analysis applied to fluvial deposits: Earth-Science Reviews, v. 22, p. 261–308, http://dx.doi.org/10.1016/0012-8252(85)90001-7.
Miall, A.D., 1988a, Reservoir heterogeneities in fluvial sandstones: lessons from outcrop studies: American Association of Petroleum Geologists Bulletin, v. 72, p. 682–697.
Miall, A.D., 1988b, Facies architecture in clastic sedimentary basins, *in* Kleinspehn, K., and Paola, C., *eds*., New perspectives in basin analysis: Springer-Verlag Inc., New York, p. 67–81, http://dx.doi.org/10.1007/978-1-4612-3788-4_4.
Miall, A.D., 1995, Whither stratigraphy?: Sedimentary Geology, v. 100, p. 5–20, http://dx.doi.org/10.1016/0037-0738(95)00100-X.
Miall, A.D., 1999, Principles of sedimentary basin analysis (Third Edition): Springer-Verlag Inc., New York, 616 p.
Miall, A.D., 2004, Empiricism and model building in stratigraphy: the historical roots of present-day practices. Stratigraphy: American Museum of Natural History, v. 1, p. 3–25.
Miall, A.D., 2010, The geology of stratigraphic sequences (Second Edition): Springer-Verlag, Berlin, 522 p., http://dx.doi.org/10.1007/978-3-642-05027-5.
Miall, A.D., 2013, Sophisticated stratigraphy, *in* Bickford, M.E., *ed*., The web of geological sciences: Advances, impacts and interactions: Geological Society of America Special Papers, v. 500, p. 169–190, http://dx.doi.org/10.1130/2013.2500(05).
Miall, A.D., 2014, Fluvial depositional systems: Springer-Verlag, Berlin 316 p., http://dx.doi.org/10.1007/978-3-319-00666-6.
Miall, A.D., 2015, Updating uniformitarianism: stratigraphy as just a set of 'frozen accidents,' *in* Smith, D.G., Bailey, R.J., Burgess, P.M., and Fraser, A.J., *eds*., Strata and time: Geological Society, London, Special Publications, v. 404, p. 11–36, http://dx.doi.org/10.1144/SP404.4.
Miall, A.D., and Miall, C.E., 2001, Sequence stratigraphy as a scientific enterprise: the evolution and persistence of conflicting paradigms: Earth-Science Reviews, v. 54, p. 321–348, http://dx.doi.org/10.1016/S0012-8252(00)00041-6.
Middleton, G.V., *ed*., 1965, Primary sedimentary structures and their hydrodynamic interpretation: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 12, 265 p.
Middleton, G.V., 1966a, Experiments on density and turbidity currents: I. Motion of the head: Canadian Journal of Earth Sciences, v. 3, p. 523–546, http://dx.doi.org/10.1139/e66-038.
Middleton, G.V., 1966b, Experiments on density and turbidity currents: II. Uniform flow of density currents: Canadian Journal of Earth Sciences, v. 3, p. 627–637, http://dx.doi.org/10.1139/e66-044.
Middleton, G.V., 1967, Experiments on density and turbidity currents: III. Deposition of sediment: Canadian Journal of Earth Sciences, v. 4, p. 475–505, http://dx.doi.org/10.1139/e67-025.
Middleton, G.V., 1973, "Johannes Walther's law of the correlation of facies:" Geological Society of America Bulletin, v. 84, p. 979–988, http://dx.doi.org/10.1130/0016-7606(1973)84<979:JWLOTC>2.0.CO;2.
Middleton, G.V., 2005, Sedimentology, History, *in* Middleton, G.V., *ed*., Encyclopedia of sediments and sedimentary rocks: Springer-Verlag, Berlin, p. 628–635.

Middleton, G.V., and Hampton, M.A., 1976, Subaqueous sediment transport and deposition by sediment gravity flows, *in* Stanley, D.J., and Swift, D.J.P., *eds*., Marine sediment transport and environmental management: Wiley, New York, p. 197–218.

Milankovitch, M., 1930, Mathematische klimalehre und astronomische theorie der klimaschwankungen, *in* Koppen, W., and Geiger, R., *eds*., Handbuch der klimatologie, I (A): Gebruder Borntraeger, Berlin, p. 1–176.

Milankovitch, M., 1941, Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem: Akad. Royale Serbe, v. 133, 633 p.

Mitchell, A.H., and Reading, H.G., 1969, Continental margins, geosynclines and ocean floor spreading: The Journal of Geology, v. 77, p. 629–646, http://dx.doi.org/10.1086/627462.

Moore, R.C., 1949, Meaning of facies, *in* Longwell, C., *ed*., Sedimentary facies in geologic history: Geological Society of America Memoirs, v. 39, p. 1–34, http://dx.doi.org/10.1130/MEM39-p1.

Mossop, G.D., and Shetsen, I., *compilers,* 1994, Geological Atlas of the Western Canada Sedimentary Basin: Canadian Society of Petroleum Geologists, 510 p.

Muir Wood, R., 1985, The dark side of the Earth: George Allen and Unwin, 246 p.

Muto, T., and Steel, R.J., 2004, Autogenic response of fluvial deltas to steady sea-level fall: Implications from flume-tank experiments: Geology, v. 32, p. 401–404, http://dx.doi.org/10.1130/G20269.1.

Nanz, R.H., Jr., 1954, Genesis of Oligocene sandstone reservoir, Seeligson field, Jim Wells and Kleberg Counties, Texas: American Association of Petroleum Geologists Bulletin, v. 38, p. 96–117.

Newell, N.D., and Rigby, J.K., 1957, Geological studies on the Great Bahama Bank: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 5, p. 15–72, http://dx.doi.org/10.2110/pec.57.01.0015.

Oliver, T.A., and Cowper, N.W., 1963, Depositional environments of the Ireton Formation, central Alberta: Bulletin of Canadian Petroleum Geology, v. 11, p. 183–202.

Oliver, T.A., and Cowper, N.W., 1965, Depositional environments of Ireton Formation, central Alberta: Bulletin of the American Association of Petroleum Geologists, v. 49, p. 1410–1425.

Paola, C., 2000, Quantitative models of sedimentary basin filling: Sedimentology, v. 47 (S1), p. 121–178, http://dx.doi.org/10.1046/j.1365-3091.2000.00006.x.

Paola, C., Mullin, J., Ellis, C., Mohrig, D.C., Swenson, J.B., Parker, G., Hickson, T., Heller, P.L., Pratson, L., Syvitski, J., Sheets, B., and Strong, N., 2001, Experimental stratigraphy: GSA Today, v. 11, p. 4–9, http://dx.doi.org/10.1130/1052-5173(2001)011<0004:ES>2.0.CO;2.

Paola, C., Straub, K., Mohrig, D., and Reinhardt, L., 2009, The "unreasonable effectiveness" of stratigraphic and geomorphic experiments: Earth-Science Reviews, v. 97, p. 1–43, http://dx.doi.org/10.1016/j.earscirev.2009.05.003.

Payton, C.E., *ed*., 1977, Seismic stratigraphy—applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, 516 p.

Pettijohn, F.J., 1949, Sedimentary rocks: Harper and Bros, New York, 513 p.

Pettijohn, F.J., 1956, In defence of outdoor geology: American Association of Petroleum Geologists Bulletin, v. 40, p. 1455–1461.

Pettijohn, F.J., 1962, Paleocurrents and paleogeography: American Association of Petroleum Geologists Bulletin, v. 46, p. 1468–1493.

Pettijohn, F.J., 1984, Memoirs of an unrepentant field geologist: A candid profile of some geologists and their science, 1921–1981: University of Chicago Press, Chicago, 260 p.

Pettijohn, F.J., and Potter, P.E., 1964, Atlas and glossary of primary sedimentary structures: Springer-Verlag, New York, 370 p., http://dx.doi.org/10.1007/978-3-642-94899-2.

Playfair, J., 1802, Illustrations of the Huttonian theory of the Earth: Dover Publications, (White, G.W., *ed*., 1956), New York, 528 p.

Plint, A.G., Walker, R.G., and Bergman, K.M., 1986, Cardium Formation 6. Stratigraphic framework of the Cardium in subsurface: Bulletin of Canadian Petroleum Geology, v. 34, p. 213–225.

Plint, A.G., Tyagi, A., Hay, M.J., Varban, B.L., Zhang, H., and Roca, X., 2009, Clinoforms, paleobathymetry, and mud dispersal across the Western Canada Cretaceous Foreland Basin: Evidence from the Cenomanian Dunvegan Formation and contiguous strata: Journal of Sedimentary Research, v. 79, p. 144–161, http://dx.doi.org/10.2110/jsr.2009.020.

Plint, A.G., Macquaker, J.H.S., and Varban, B.L., 2012, Bedload transport of mud across a wide, storm-influenced ramp: Cenomanian–Turonian Kaskapau Formation, Western Canada Foreland Basin: Journal of Sedimentary Research , v. 82, p. 801–822, http://dx.doi.org/10.2110/jsr.2012.64.

Posamentier, H.W., and Vail, P.R., 1988, Eustatic controls on clastic deposition II—Sequence and systems tract models, *in* Wilgus, C.K., Hastings, B.S., Posamentier, H.W., Van Wagoner, J.C., Ross, C.A., and Kendall, C.G.St.C., *eds*., Sea-level Changes: an integrated approach: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 42, p. 125–154, http://dx.doi.org/10.2110/pec.88.01.0125.

Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988, Eustatic controls on clastic deposition I—Conceptual framework, *in* Wilgus, C.K., Hastings, B.S., Posamentier, H.W., Van Wagoner, J.C., Ross, C.A., and Kendall, C.G.St.C., *eds.,* Sea-level Changes: an integrated approach: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 42, p. 109–124, http://dx.doi.org/10.2110/pec.88.01.0109.

Potter, P.E., 1959, Facies models conference: Science, (Meetings), v. 129, p. 1292–1294, http:/dx.doi.org/10.1126/science.129.3358.1292.

Potter, P.E., 1967, Sand bodies and sedimentary environments: A review: American Association of Petroleum Geologists Bulletin, v. 51, p. 337–365.

Potter, P.E., and Pettijohn, F.J., 1963, Paleocurrents and basin analysis: Springer-Verlag, Berlin, 296 p., http://dx.doi.org/10.1007/978-3-662-01020-4.

Potter, P.E., and Pettijohn, F.J., 1977, Paleocurrents and basin analysis (Second Edition): Academic Press, San Diego, CA, 296 p., http://dx.doi.org/10.1007/978-3-642-61887-1.

Price, R.A., 1973, Large-scale gravitational flow of supracrustal rocks, southern Canadian Rockies, *in* DeJong, K.A., and Scholten, R.A., *eds*., Gravity and tectonics: John Wiley, New York, p. 491–502.

Purdy, E.G., 1963a, Recent calcium carbonate facies of the Great Bahama Bank. 1. Petrography and Reaction Groups: The Journal of Geology, v. 71, p. 334–355.

Purdy, E.G., 1963b, Recent calcium carbonate facies of the Great Bahama Bank. 2. Sedimentary Facies: The Journal of Geology, v. 71, p. 472–497.

Ramos, A., and Sopeña, A., 1983, Gravel bars in low-sinuosity streams (Permian and Triassic, central Spain), *in* Collinson, J.D., and Lewin, J., *eds*., Modern and ancient fluvial systems: Blackwell Publishing Ltd., Oxford, UK, p. 301–312, http://dx.doi.org/10.1002/9781444303773.ch24.

Ramos, A., Sopeña, A., and Perez-Arlucea, M., 1986, Evolution of Buntsandstein fluvial sedimentation in the northwest Iberian Ranges (central Spain): Journal of Sedimentary Petrology (Research), v. 56, p. 862–875, http://dx.doi.org/10.1306/212F8A6C-2B24-11D7-8648000102C1865D.

Read, H.H., 1952, The geologist as historian, *in* Scientific Objectives: Butterworths, p. 52–67, (reprinted in Proceedings of the Geologists' Association, v. 81, p. 409–420).

Reading, H.G., *ed*., 1978, Sedimentary environments and facies: Blackwell, Oxford, 557 p.

Reading, H.G., *ed*., 1986, Sedimentary environments and facies (Second Edition): Blackwell, Oxford, 615 p.

Reading, H.G., *ed*., 1996, Sedimentary environments: processes, facies and stratigraphy (Third Edition): Blackwell Science, Oxford, 688 p.

Reiche, P., 1938, An analysis of cross-lamination: The Coconino Sandstone: The Journal of Geology, v. 46, p. 905–932, http://dx.doi.org/10.1086/624709.

Reineck, H.E., and Singh, I.B., 1973, Depositional sedimentary environments—with reference to terrigenous clastics: Springer-Verlag, Berlin, 439 p.

Rich, J.L., 1951, Three critical environments of deposition and criteria for recognition of rocks deposited in each of them: Geological Society of America Bulletin, v. 62, p. 1–20, http://dx.doi.org/10.1130/0016-7606(1951)62[1:TCEODA]2.0.CO;2.

Rigby, J.K., and Hamblin, W.K., *eds*., 1972, Recognition of ancient sedimentary environments: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 16, 340 p.

Rine, J.M., Helmold, K.P., Bartlett, G.A., Hayes, B.J.R., Smith, D.G., Plint, A.G., Walker, R.G., and Bergman, K.M., 1987, Cardium Formation 6. Stratigraphic framework of the Cardium in subsurface: Discussions and reply: Bulletin of Canadian Petroleum Geology, v. 35, p. 362–374.

Ross, W.C., 1991, Cyclic stratigraphy, sequence stratigraphy, and stratigraphic modeling from 1964 to 1989: twenty-five years of progress?, *in* Franseen, E.K., Watney, W.L., and Kendall, C.G.St.C., *eds*., Sedimentary modeling: computer simulations and methods for improved parameter definition: Kansas Geological Survey Bulletin 233, p. 3–8.

Sadler, P.M., 1981, Sediment accumulation rates and the completeness of stratigraphic sections: The Journal of Geology, v. 89, p. 569–584, http://dx.doi.org/10.1086/628623.

Sadler, P.M., 1999, The influence of hiatuses on sediment accumulation rates: GeoResearch Forum, v. 5, p. 15–40.

Sadler, P.M., Cooper, R.A., and Melchin, M., 2009, High-resolution, early Paleozoic (Ordovician–Silurian) time scales: Geological Society of America Bulletin, v. 121, p. 887–906, http://dx.doi.org/10.1130/B26357.1.

Sageman, B.B., Singer, B.S., Meyers, S.R., Siewert, S.E., Walaszczyk, I., Condon, D.J., Jicha, B.R., Obradovich, J.D., and Sawyer, D.A., 2014, Integrating $^{40}Ar/^{39}Ar$, U–Pb and astronomical clocks in the Cretaceous Niobrara Formation, Western Interior Basin, USA: Geological Society of America Bulletin, v. 126, p. 956–973, http://dx.doi.org/10.1130/B30929.1.

Salvador, A., *ed*., 1994, International Stratigraphic Guide (Second Edition): International Union of Geological Sciences, Trondheim, Norway, and Geological Society of America, Boulder, Colorado, 214 p.

Schenk, H.G., and Muller, S.W.M., 1941, Stratigraphic terminology: Geological Society of America Bulletin, v. 52, p. 1419–1426, http://dx.doi.org/10.1130/GSAB-52-1419.

Schieber, J., Southard, J.B., Kissling, P., Rossman, B., and Ginsburg, R., 2013, Experimental deposition of carbonate mud from moving suspensions: Importance of flocculation and implications for modern and ancient carbonate mud deposition: Journal of Sedimentary Research, v. 83, p. 1026–1032, http://dx.doi.org/10.2110/jsr.2013.77.

Schlager, W., 2005, Carbonate sedimentology and sequence stratigraphy: SEPM Concepts in Sedimentology and Paleontology, # 8, 200 p.

Sheets, B.A., Hickson, T.A., and Paola, C., 2002, Assembling the stratigraphic record: depositional patterns and time-scales in an experimental alluvial basin: Basin Research, v. 14, p. 287–301, http://dx.doi.org/10.1046/j.1365-2117.2002.00185.x.

Shepard, F.P., and Wanless, H.R., 1935, Permo–Carboniferous coal series related to southern hemisphere glaciation: Science, v. 81, p. 521–522, http://dx.doi.org/10.1126/science.81.2108.521.

Shepard, F.P., Phleger, F.B., and van Andel, T.H., *eds.*, 1960, Recent sediments, northwest Gulf of Mexico: American Association of Petroleum Geologists, 394 p.

Simons, D.B., and Richardson, E.V., 1961, Forms of bed roughness in alluvial channels: American Society of Civil Engineers Proceedings, v. 87, No. HY3, p. 87–105.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, p. 93–114, http://dx.doi.org/10.1130/0016-7606(1963)74[93:SITCIO]2.0.CO;2.

Sloss, L.L., 1972, Synchrony of Phanerozoic sedimentary-tectonic events of the North American craton and the Russian platform: 24th International Geological Congress, Montreal, Section 6, p. 24–32.

Sloss, L.L., 1988, Tectonic evolution of the craton in Phanerozoic time, *in* Sloss, L.L., *ed.*, Sedimentary cover—North American Craton: U.S.: The Geology of North America, Geological Society of America, v. D-2, Boulder, CO, p. 25–51.

Sloss, L.L., 1991, The tectonic factor in sea level change: a countervailing view: Journal of Geophysical Research, v. 96, p. 6609–6617, http://dx.doi.org/10.1029/90JB00840.

Sloss, L.L., Krumbein, W.C., and Dapples, E.C., 1949, Integrated facies analysis; *in* Longwell, C.R., *ed.*, Sedimentary facies in geologic history: Geological Society of America Memoirs, v. 39, p. 91–124, http://dx.doi.org/10.1130/MEM39-p91.

Smith, W., 1815, A memoir to the map and delineation of the strata of England and Wales, with part of Scotland: John Carey, London, 51 p.

Sorby, H.C., 1852, On the oscillation of the currents drifting the sandstone beds of the southeast of Northumberland, and on their general direction in the coal field in the neighbourhood of Edinburgh: Proceedings of the West Yorkshire Geological Society, v. 3, p. 232–240, http://dx.doi.org/10.1144/pygs.3.232.

Sorby, H.C., 1859, On the structures produced by the currents present during the deposition of stratified rocks: The Geologist, v. II, p. 137–147.

Sorby, H.C., 1908, On the application of quantitative methods to the study of the structure and history of rocks: Quarterly Journal of the Geological Society, v. 64, p. 171–233, http://dx.doi.org/10.1144/GSL.JGS.1908.064.01-04.12.

Steckler, M.S., and Watts, A.B., 1978, Subsidence of the Atlantic-type continental margin off New York: Earth and Planetary Science Letters, v. 41, p. 1–13, http://dx.doi.org/10.1016/0012-821X(78)90036-5.

Steel, R.J., and Milliken, K.L., 2013, Major advances in siliciclastic sedimentary geology, 1960–2012, *in* Bickford, M.E., *ed.*, The web of geological sciences: Advances, impacts and interactions: Geological Society of America Special Papers, v. 500, p. 121–167, http://dx.doi.org/10.1130/2013.2500(04).

Steno, Nicolaus, 1669, De Solido intra Solidum naturaliter contento dissertationis prodromus: Florence, 78 p.

Stokes, W.L., 1945, Primary lineation in fluvial sandstones: a criterion of current direction: The Journal of Geology, v. 45, p. 52–54.

Strangway, D.W., *ed.*, 1980, The continental crust and its mineral deposits: Geological Association of Canada Special Paper 20, 804 p.

Strong, N., and Paola, C., 2008, Valleys that never were: Time surfaces versus stratigraphic surfaces: Journal of Sedimentary Research, v. 78, p. 579–593, http://dx.doi.org/10.2110/jsr.2008.059.

Tankard, A.J., and Welsink, H.J., 1987, Extensional tectonics and stratigraphy of Hibernia oil field, Grand Banks, Newfoundland: American Association of Petroleum Geologists Bulletin, v. 71, p. 1210–1232.

Teichert, C., 1958, Concepts of facies: American Association of Petroleum Geologists Bulletin, v. 42, p. 2718–2744.

Torrens, H.S., 2002, Some personal thoughts on stratigraphic precision in the twentieth century, *in* Oldroyd, D.R., *ed.*, The Earth inside and out: Some major contributions to geology in the twentieth century: Geological Society, London, Special Publications, v. 192, p. 251–272, http://dx.doi.org/10.1144/gsl.sp.2002.192.01.14.

Vail, P.R., 1975, Eustatic cycles from seismic data for global stratigraphic analysis (Abstract): American Association of Petroleum Geologists Bulletin, v. 59, p. 2198–2199.

Vail, P.R., Mitchum, R.M., Jr., Todd, R.G., Widmier, J.M., Thompson, S., III, Sangree, J.B., Bubb, J.N., and Hatlelid, W.G., 1977, Seismic stratigraphy and global changes of sea-level, *in* Payton, C.E., *ed.*, Seismic stratigraphy - applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 49–212.

Van Siclen, D.C., 1958, Depositional topography—examples and theory: American Association of Petroleum Geologists Bulletin, v. 42, p. 1897–1913.

Van Straaten, L.M.J.U., 1954, Composition and structure of recent marine sediments in the Netherlands: Leidse Geol. Mededel., v. 19, p. 1–110.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: American Association of Petroleum Geologists, Methods in Exploration Series 7, 55 p.

Veeken, P.C.H., 2007, Seismic stratigraphy, basin analysis and reservoir characterisation. Handbook of Geophysical Exploration, Volume 37: Elsevier, Amsterdam, 509 p.

Visher, G.S., 1965, Use of vertical profile in environmental reconstruction: American Association of Petroleum Geologists Bulletin, v. 49, p. 41–61.

Waddell, H., 1933, Sedimentation and sedimentology: Science, v. 77, p. 536–537, http://dx.doi.org/10.1126/science.77.2005.536.

Walker, R.G., 1965, The origin and significance of the internal sedimentary structures of turbidites: Proceedings of the Yorkshire Geological Society, v. 35, p. 1–32, http://dx.doi.org/10.1144/pygs.35.1.1.

Walker, R.G., 1967, Turbidite sedimentary structures and their relationship to proximal and distal depositional environments: Journal of Sedimentary Petrology (Research), v. 37, p. 25–43, http://dx.doi.org/10.1306/74D71645-2B21-11D7-8648000102C1865D.

Walker, R.G., 1973, Mopping up the turbidite mess, *in* Ginsburg, R.N., *ed.*, Evolving concepts in sedimentology: Johns Hopkins University Press, Baltimore, p. 1–37.

Walker, R.G., 1976, Facies models 1. General Introduction: Geoscience Canada, v. 3, p. 21–24.

Walker, R.G., *ed.*, 1979, Facies models: Geoscience Canada Reprint Series 1, 211 p.

Walker, R.G., *ed.*, 1984, Facies Models (Second Edition): Geoscience Canada Reprint Series 1, 317 p.

Walker, R.G., 1990, Facies modeling and sequence stratigraphy: Journal of Sedimentary Petrology (Research), v. 60, p. 777–786, http://dx.doi.org/10.1306/212F926E-2B24-11D7-8648000102C1865D.

Walker, R.G., and James, N.P., 1992, Facies models: response to sea-level change: Geological Association of Canada, St. John's, NL, 409 p.

Walther, Johannes, 1893–1894, Einleisung in die Geologie alshistorische Wissemchaft: Jena, Verlag von Gustav Fischer, 3 volumes, 1055 p.

Wanless, H.R., and Shepard, F.P., 1936, Sea level and climatic changes related to Late Paleozoic cycles: Geological Society of America Bulletin, v. 47, p. 1177–1206, http://dx.doi.org/10.1130/GSAB-47-1177.

Wanless, H.R., and Weller, J.M., 1932, Correlation and extent of Pennsylvanian cyclothems: Geological Society of America Bulletin, v. 43, p. 1003–1016, http://dx.doi.org/10.1130/GSAB-43-1003.

Watts, A.B., 1981, The U.S. Atlantic margin: subsidence history, crustal structure and thermal evolution: American Association of Petroleum Geologists, Education Course Notes Series #19, Chapter 2, 75 p.

Watts, A.B., 1989, Lithospheric flexure due to prograding sediment loads: implications for the origin of offlap/onlap patterns in sedimentary basins: Basin Research, v. 2, p. 133–144, http://dx.doi.org/10.1111/j.1365-2117.1989.tb00031.x.

Watts, A.B., and Ryan, W.B.F., 1976, Flexure of the lithosphere and continental margin basins: Tectonophysics, v. 36, p. 25–44, http://dx.doi.org/10.1016/0040-1951(76)90004-4.

Weller, J.M., 1960, Stratigraphic Principles and Practice: Harper, New York, 725 p.

Wernicke, B., 1985, Uniform-sense normal simple shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, p. 108–125, http://dx.doi.org/10.1139/e85-009.

Wheeler, H.E., 1958, Time-stratigraphy: American Association of Petroleum Geologists Bulletin, v. 42, p. 1047–1063.

White, N., and McKenzie, D., 1988, Formation of the "steer's head" geometry of sedimentary basins by differential stretching of the crust and mantle: Geology, v. 16, p. 250–253, http://dx.doi.org/10.1130/0091-7613(1988)016<0250:FOTSSH>2.3.CO;2.

Whitten, E.H.T., 1964, Process-response models in geology: Geological Society of America Bulletin, v. 75, p. 455–464, http://dx.doi.org/10.1130/0016-7606(1964)75[455:PMIG]2.0.CO;2.

Wilgus, C.K., Hastings, B.S., Posamentier, H.W., Van Wagoner, J.C., Ross, C.A., and Kendall, C.G.St.C., *eds.*, 1988, Sea-level changes: an integrated approach: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications, v. 42, 407 p., http://dx.doi.org/10.2110/pec.88.42.

Williams, G.D., and Dobb, A., *eds*., 1993, Tectonics and seismic sequence stratigraphy: Geological Society, London, Special Publications, v. 71, 226 p.
Wilson, J.L., 1975, Carbonate facies in geologic history: Springer-Verlag, New York, 471 p., http://dx.doi.org/10.1007/978-1-4612-6383-8.
Wilson, J.T., 1985, Development of ideas about the Canadian Shield: A personal account, *in* Drake, E.T., and Jordan, W.M., *eds*., Geologists and ideas: A History of North American Geology, Geological Society of America Centennial Special Volume 1, p. 143–150, http://dx.doi.org/10.1130/DNAG-CENT-v1.143.
Woodford, A.O., 1973, Johannes Walther's Law of the Correlation of Facies: Discussion: Geological Society of America Bulletin, v. 84, p. 3737–3740, http://dx.doi.org/10.1130/0016-7606(1973)84<3737:JWLOTC>2.0.CO;2.

Received March 2015
Accepted as revised June 2015