

## Canada's Distinguished Record of Sedimentary Geology

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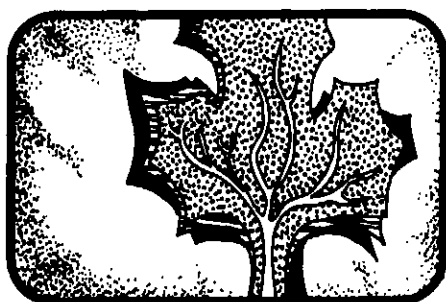
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### Résumé de l'article

En 1947, la découverte du champ pétro-lifère de Leduc a marqué le début d'un important programme de recherche en sédimentologie sur les milieux récifaux et qui a porté la communauté scientifique canadienne à l'avant-scène des recherches dans ce domaine. Dans les années 60, d'importantes découvertes étaient faites en sédimentologie des élastiques et traitant en particulier des structures et des textures des couches sédimentaires, ainsi que des courants de turbidité. L'essor de l'industrie pétro-lière a contribué à faire de la sédimentologie une importante sous-discipline dans la communauté des géologues professionnels au Canada. L'apport scientifique le plus important de ce pays a eu pour objet l'étude des faciès et des milieux sédimentaires. Les découvertes dans ces domaines ont constitué la majeure partie de la matière traitée dans les trois éditions des célèbres manuels de l'AGC sur les modèles de faciès, manuels qui se sont vendus à près de 70 000 copies depuis 1979.

Les sédimentologues canadiens ont également contribué de manière importante à l'étude des séquences stratigraphiques, domaine toujours en développement de nos jours. Cela dit, la restructuration à la baisse des universités mettra fin à cette ère de grandes productions et, à l'avenir, il est probable que les travaux se feront dans d'autres domaines de la géologie, particulièrement dans le domaine des études environnementales.

# ARTICLES



## Canada's Distinguished Record of Sedimentary Geology<sup>1</sup>

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### SUMMARY

The Leduc oil discovery in 1947 started a major research program in reef sedimentology that established Canadian science in the forefront, while in the area of clastic sedimentology, important developments in the study of bedforms and turbidity currents were made in the 1960s.

The growth of the petroleum industry helped to establish sedimentology as a

<sup>1</sup> This is the second paper to be published in *Geoscience Canada* from the 50th Anniversary Symposium "The Impact of Canadian Geoscience over the Last 50 Years," organized by Alan Morgan and held at the 1997 GAC-MAC Annual Meeting in Ottawa. The first paper published from this symposium was that by Jim Monger on plate tectonics and the northern cordillera (*Geoscience Canada*, v. 24, p. 189-198). We are hoping to publish several more papers from this landmark symposium: contributors to the symposium take note.

R.W. Macqueen, Editor.

major subdiscipline among professional geologists in Canada. The most significant scientific contributions in this country have been in the area of facies studies and analysis of depositional environments. Developments in this area have formed much of the basis for the three editions of the highly successful GAC *Facies Models* book, that has sold nearly 70,000 copies since 1979.

Canadian sedimentologists have also made significant contributions to the study of sequence stratigraphy, a field that is still growing. However, downsizing of universities is bringing an era of achievement to an end, and future developments are likely to be in different areas of geology, particularly environmental studies.

### RÉSUMÉ

En 1947, la découverte du champ pétrolier de Leduc a marqué le début d'un important programme de recherche en sédimentologie sur les milieux récifaux et qui a porté la communauté scientifique canadienne à l'avant-scène des recherches dans ce domaine. Dans les années 60, d'importantes découvertes étaient faites en sédimentologie des clastiques et traitant en particulier des structures et des textures des couches sédimentaires, ainsi que des courants de turbidité. L'essor de l'industrie pétrolière a contribué à faire de la sédimentologie une importante sous-discipline dans la communauté des géologues professionnels au Canada. L'apport scientifique le plus important de ce pays a eu pour objet l'étude des faciès et des milieux sédimentaires. Les découvertes dans ces domaines ont constitué la majeure partie de la matière traitée dans les trois éditions des célèbres manuels de l'AGC sur les modèles de faciès, manuels qui se sont vendus à près de 70 000 copies depuis 1979.

Les sédimentologues canadiens ont également contribué de manière importante à l'étude des séquences stratigraphiques, domaine toujours en développement de nos jours. Cela dit, la restructuration à la baisse des universités mettra fin à cette ère de grandes productions et, à l'avenir, il est probable que les travaux se feront dans d'autres domaines de la géologie, particulièrement dans le domaine des études environnementales.

### INTRODUCTION

Sedimentology may be defined as the study of natural sediments and the processes by which they form. While such a study is of intrinsic interest it is of considerable practical importance because of the resources contained in sediments, particularly petroleum, coal, economically important evaporite deposits, certain classes of metal ore, and water. Canada contains significant reserves of all these types of deposit, and that is probably why physical sedimentology has become an important subject of study in Canadian research laboratories, particularly in universities.

The exploration for and exploitation of petroleum is undoubtedly more dependent on a knowledge of sedimentology than is the extraction of any of the other classes of economic deposit, and so it is probably not surprising that the discovery of significant petroleum reserves in Alberta was followed by a marked increase in the number of professionals engaged in sedimentological research in Canada, both in the oil industry itself and in university departments. By far the most important event in this regard was the discovery of oil in a Devonian stromatoporoid reef at the Leduc 1 well near Edmonton in 1947, the year the GAC was founded, and the beginning of the period covered by this

paper.

This paper deals primarily with the area of facies and sedimentary environments, and the contributions these have made to the study of stratigraphy and basin analysis. I have not attempted to deal with the field of chemical sedimentology, including the study of diagenesis, in which Canadians have certainly made notable contributions.

A short but definitive history of sedimentology was published by Middleton (1978), a Canadian sedimentologist to whose career I return later. According to this account, the history of sedimentology can be divided into five periods, beginning with the rise of "actualism" or "uniformitarianism" in the early 19th century. We are concerned in this paper primarily with the final period, which Middleton suggests began in about 1950. Prior to this period, particularly in Canada, it would have been difficult to distinguish sedimentology from its sister discipline stratigraphy. Most of the work on Canadian sediments being carried out until the 1950s, and much of it in subsequent years, is more appropriately classified as descriptive stratigraphy, with little in the nature of sedimentological data or interpretation.

Middleton's final, modern period corresponds to the rise of the actualistic process-response model, or facies model. Canadian sedimentologists have made notable contributions in this field, and in many cases can claim to be among the world leaders. The concept of "facies" was well understood by the end of the 19th century, as documented by Middleton (1973, 1978), but the idea of the facies model as a universal, unifying concept did not develop until late in the 1950s. A significant discussion about the concept of the facies model took place among a small group of sedimentologists at the Illinois State Geological Survey in November 1958 (Potter, 1959). No Canadians are listed as being among the participants in this discussion, but undoubtedly informal discussion was spreading the ideas widely. At this time, important work on the geology of reefs was underway in Canada, triggered by the Leduc discoveries and stimulated by the presence of spectacular outcrops of the producing units in the nearby Rocky Mountains. Much of what we now know about reef geology goes back to this early work, which constitutes the first significant body of sedimentological research in Canada.

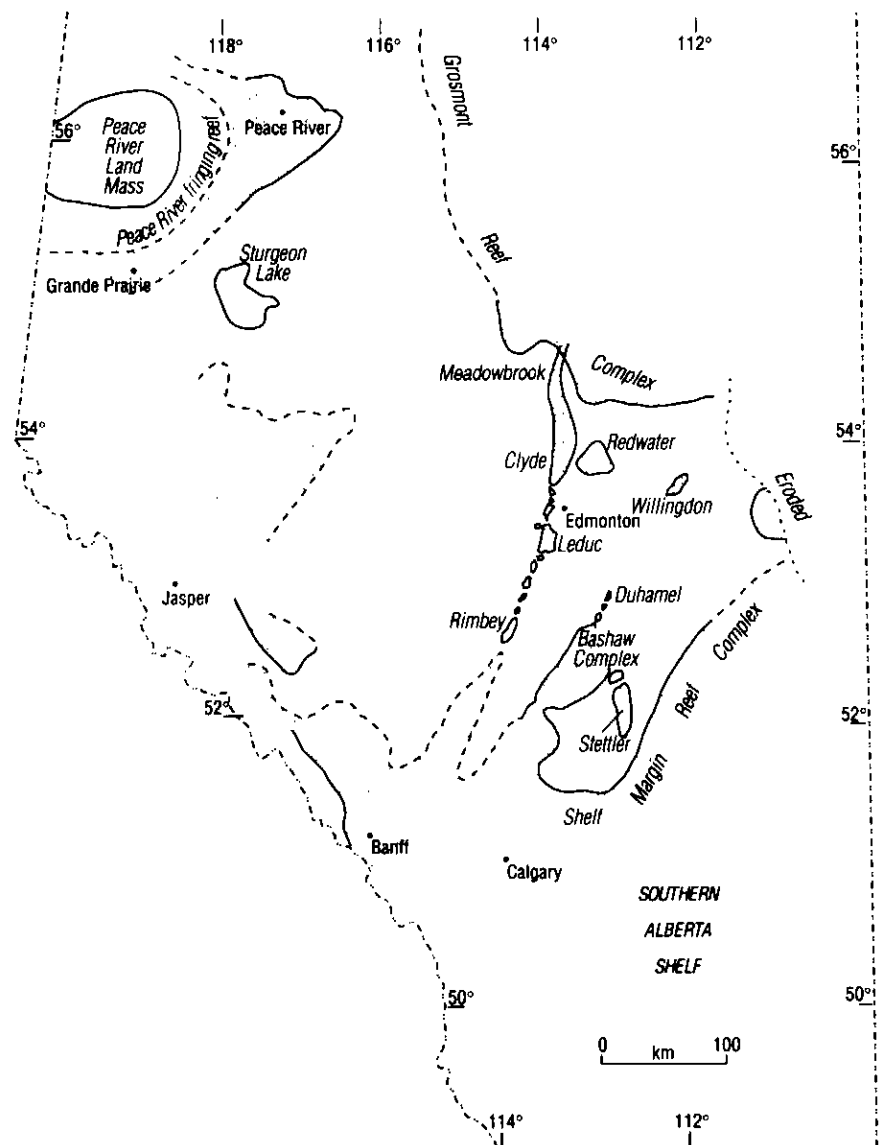
Many other achievements in Canadian sedimentology also undoubtedly reflect the presence of large-scale outcrops in such regions as the Rocky Mountains and the Canadian Arctic Islands, together with the extensive subsurface well and core record of the Western Canada Sedimentary Basin curated at the laboratory of the Alberta Energy and Utilities Board and the Geological Survey of Canada in Calgary.

#### LEDUC AND THE BIRTH OF CARBONATE SEDIMENTOLOGY IN CANADA

Petroleum had been discovered at Turner Valley in the foothills of the Rocky Mountains south of Calgary in 1914,

and at Norman Wells in the Northwest Territories in 1920, but these were minor finds compared to the Leduc discovery (Hilborn, 1968; Petroleum Communication Foundation, 1993). Imperial Oil Limited (a subsidiary of the company that is now Exxon) had drilled 130 dry holes across western Canada prior to this discovery, but the Leduc discovery started a long string of successes by the industry that continues to this day, and has established Alberta as one of the world's major petroleum producing regions. Figure 1 is an early map of the distribution of reefs as documented by the first round of exploration work.

Three names stand out as major contributors to sedimentology at this time,



**Figure 1** The distribution of upper Devonian reefs in Alberta, synthesized from surface and subsurface data after about a decade of petroleum exploration work. Adapted by Klovan (1964) from a large-scale map by Belyea (1960); redrawn with permission.

John Andrichuk, Ralph Edie and Frank Beales. They can lay claim to being Canada's first sedimentologists. Andrichuk and Edie established a consulting company in the 1950s at which they still work, and Frank Beales was Canada's first academic sedimentologist, at the University of Toronto, from which he retired in 1984. (He was first appointed to McMaster University in 1947, and moved to Toronto in 1951).

Andrichuk's landmark contribution to Canadian sedimentology (Andrichuk, 1958) was a lengthy paper detailing the sedimentary geology of Upper Devonian reefs in three areas of Alberta — Leduc, Stettler and Redwater — on the basis of data from 128 wells: a similar number to that in many partly explored offshore frontier areas at the present day. The petrographic terminology for carbonates currently in use had not been developed at that time, and Andrichuk used such terms as calcarenite and calcilutite, with modifiers such as bioclastic and oolitic. There is a debate in the paper regarding the appropriateness of the terms reef and bioherm for these Devonian structures, and Andrichuk concluded that the term bioherm is appropriate because of the large vertical dimensions of the structures. Much of the paper consists of detailed stratigraphic documentation of the reef and inter-reef deposits, based on the detailed facies observations of the reef sediments. Many detailed comparisons are made to the conditions of sedimentation and the facies distributions in modern Pacific and Caribbean reefs, drawing on the work of P.E. Cloud, K.O. Emery, R.N. Ginsburg, L.V. Illing, H.S. Ladd, N.D. Newell, and J.K. Rigby, and even going back to Charles Darwin's classic 1897 treatise. None of this

work was Canadian, but the Alberta reef studies were to place Canadian carbonate sedimentology firmly in the "world class" status (it is difficult to avoid this overworked phrase) by the late 1950s.

Based on the comparative work in modern reefs Andrichuk (1958) was able to recognize and interpret significant facies differentiation in the Alberta reefs, and their primary depositional controls, including depth zonation, ocean currents, salinity variations within the back-reef lagoon, differences between windward and leeward reef margins, and different types of overall reef geometry.

This important paper concludes with a lengthy section entitled "facies approach to reef exploration," in which Andrichuk drew together the many lithofacies and biofacies observations that can be used to point to reef architecture. These observations are summarized in the concluding diagram in his paper, which is reproduced here as Figure 2. Application of these ideas to the exploration for oil in Mississippian limestones in Saskatchewan is discussed briefly in a companion paper to that of Andrichuk, by his long-time partner Edie (1958).

The use of modern analogues as a basis for interpretation of the ancient record is one of the foundations of actualistic or uniformitarian sedimentology. Nowhere is this idea more clearly encapsulated than in one of Beales' first important papers, entitled "Ancient sediments of Bahaman type," in which Beales proposed the new term "*bahamite* ... for the granular limestones that closely resemble the present deposits of the interior of the Bahama Banks ..." (Beales, 1958). These ideas, and the words "Bahaman type" were first used by Beales in an earlier paper

detailed the facies of the Devonian Palliser Formation of southwest Alberta (Beales, 1956). Here Beales suggested comparisons between the mode of formation of the Devonian limestones and those occurring on the modern Florida margin, and proposed the term "Palliser banks" for the paleogeographic setting of the Palliser limestones.

The opening statement in the 1958 paper reads "Ancient limestones of Bahaman type are much more common in the geological column than appears from references to them in the literature." Beales challenged the prevailing opinion that most limestones are clastic, derived by the "attrition and accumulation of fragments of pre-existing limestones." He drew close comparisons between many of the features of the ancient Paleozoic limestones of Alberta and central Canada and the modern sediments accumulating in the interior of the Bahama Banks, making extensive use of the new work on the Bahaman deposits by Illing (1954), in which it is demonstrated that biochemical precipitation is the most significant mode of generation of carbonate particles. Limestones that Beales classified as *bahamites* ranged widely in grain size, and included oolitic, grapestone and pelletal facies, together with bioclastic limestones generated by contemporaneous fragmentation of skeletal material.

Although the term *bahamite* did not survive, the ideas developed by Beales in that paper did, and have become part of the foundation of modern carbonate sedimentology.

In the third of Beales' important early papers (Beales, 1961) he noted that the work started on the modern Bahaman and Florida platforms by Illing, Newell, Ginsburg and Lowenstam was leading to an "explosive" development in ideas about shallow-marine carbonate sedimentation. Beales pointed to the importance of such studies in understanding the distribution of petroleum and certain metal ores hosted in carbonate sediments, and summarized some of the difficulties in applying the ideas, including the rapid lateral facies changes that inhibited stratigraphic correlation in the subsurface, and the vastly greater scale of many ancient cratonic and platform-margin carbonate deposits relative to the available modern analogues. Beales called for integrated structural, stratigraphic and sedimentologic stud-

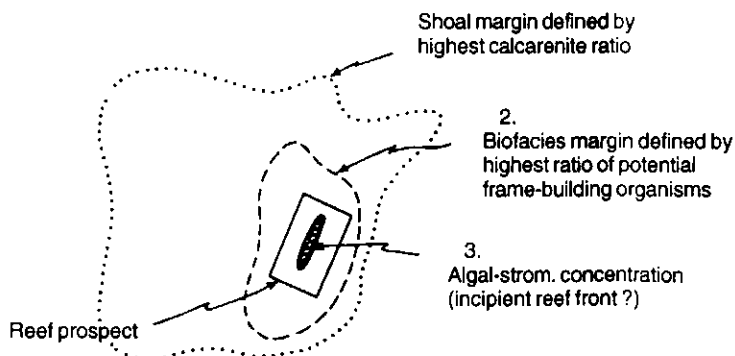


Figure 2 "Hypothetical example of procedure for delineating reef prospect" (from Andrichuk, 1958, Fig. 34), showing the use of lithofacies and biofacies data from exploration wells in the prediction of reef locations. Reproduced with permission.

ies, including detailed petrographic analysis of limestone facies, and cited several examples of such analyses in the development of useable case studies.

Beales was at pains to point out the economic implications of sedimentological studies of carbonates, particularly with regard to the porosity and permeability characteristics of limestones and dolomites, and the implications this had for fluid movement. His research led to some breakthroughs in later years regarding Mississippi Valley-type lead-zinc mineralization in carbonates, which came to be regarded as a process akin in many ways to hydrocarbon expulsion, migration and trapping (Jackson and Beales, 1967; Beales, 1975). Ultimately this intellectual path has led directly to the modern work on sediment-hosted lead and zinc deposits that we now know are forming in deep-marine rift systems (*e.g.*, Goodfellow *et al.*, 1993).

This early phase of carbonate research, that established the importance of Canadian ancient reef studies, was brought to a crescendo by the detailed

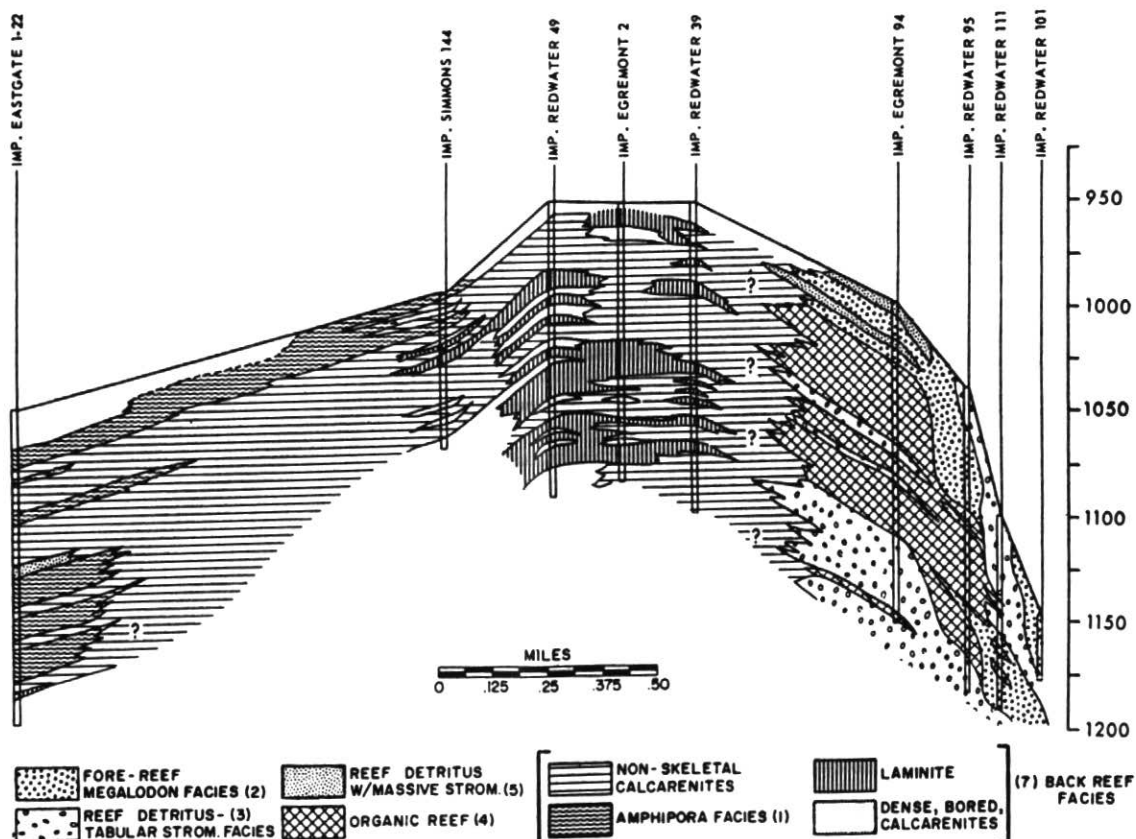
facies analysis of the Redwater reef complex near Edmonton, by Klován (1964). The Redwater reef is far less dolomitized than other major reef bodies in the subsurface of Alberta that had been discovered up to that time, and it had been extensively cored, providing a wealth of stratigraphically controlled facies data. Klován's study was sponsored by Imperial Oil, but was completed as a Ph.D. at Columbia University, supervised by J. Imbrie and N.D. Newell. This study was probably the most detailed stratigraphic analysis of an ancient reef that had been undertaken at that time, and several diagrams from Klován's paper have appeared in many subsequent textbooks to illustrate reef geometry and facies composition (*e.g.*, Fig. 3). Among other contributions, this paper contains a detailed discussion of the meaning and usage of such terms as reef and bioherm in the context of the ancient record, and considerable documentation of the biofacies and interpreted paleoecology of Devonian reef-building organisms.

## THE TRANSPORT AND DEPOSITION OF CLASTIC SEDIMENTS

### Introduction

In the 1960s much progress was made in the development of our understanding of traction currents and turbidity currents and the structures and textures they impart to clastic sediments. In turn, the realization that such structures and textures enabled predictions to be made regarding depositional processes provided the critical foundation upon which actualistic facies models could be built.

Sorby (1859) was the first to realize that the scale and geometry of hydraulic sedimentary structures such as ripples and crossbedding in sandstone relate in a systematic way to hydraulic conditions during bedform generation under the influence of traction currents (Allen, 1963). Progress in developing this concept was slow, however, and it was not until extensive experimental work was undertaken by hydraulic engineers in the United States during the



**Figure 3** A composite cross-section of the Upper Redwater Reef complex of Alberta, illustrating the reef and related facies in correct structural relationships (Klován, 1964, fig. 11). [p. 55] Reproduced with permission.

1950s and early 1960s that empirical data and theoretical work became systematic and comprehensive.

Turbidity currents, one of the most important variants in the general class of transport mechanisms termed sediment-gravity flows, had been observed in Swiss lakes and in Lake Mead, behind the Hoover Dam, in the 1930s (Gorsline and Bourgeois, 1978), but not until critical experimental work was carried out by Kuenen and Migliorini (1950) was the geological significance of this process fully realized. Major Canadian contributions in this field included additional critical experimental work on sediment mechanics of turbidity currents and substantial contributions to the development of ideas about turbidite facies and deep-water turbidite depositional systems.

#### **Bedforms and the Flow-regime Concept**

The major Canadian contribution to this body of work and, in particular, to the development of its geological applications, is credited to G.V. (Gerrard) Middleton who, in 1964, was handed the responsibility of organizing a symposium of the Research Committee of the Society of Economic Paleontologists and Mineralogists to be held in Toronto on the subject of "Primary sedimentary structures and their hydrodynamic interpretation." Middleton arrived at McMaster University in 1955 after a year working for the California Standard Oil Company in Calgary on carbonate sedimentology and stratigraphy. His distinguished career is briefly summarized in an introduction to a symposium held in his honour, in *Geoscience Canada* (1997, v. 24, p. 2), and many of his contributions are discussed below.

The publication that emerged from the 1964 research symposium (Middleton, 1965) immediately became the standard work in the field, and is still required reading for serious students of the topic. The "Canadian" content of this book is limited to Middleton's co-authored summary of the principles of hydraulics that are pertinent to the formation of hydraulic sedimentary structures (Briggs and Middleton, 1965). Far more important is the fact that this book introduced to geologists the wealth of experimental data that had been accumulating in the realm of hydraulic engineering, and its application to the interpretation of hydraulic sedimentary struc-

tures in natural systems (in this book primarily those in fluvial deposits and shallow-marine carbonate sands). As noted by Middleton in his introduction to the volume, an understanding of the origins of hydraulic sedimentary structures is of value for the interpretation of paleocurrent patterns and of structural attitude ("way-up") in deformed strata, and as an aid in environmental and paleogeographic reconstruction. In fact, the development of actualistic process-response models for clastic sediments could not have proceeded without the development of this essential body of data and theory. Middleton noted the confusion in terminology that existed at the time, and offered a glossary for the uninitiated.

Another useful contribution that appeared at about this time was the classification of ripples and ripple-drift cross-lamination by Jopling and Walker (1968). This paper was begun while both authors were working in the United States, but both took up appointments in Canada before it was published, and both subsequently contributed significantly to the development of Canadian sedimentology.

An important new type of hydraulic sedimentary structure that was recognized in the mid 1970s is *hummocky cross-stratification* (HCS). This term was first proposed in a SEPM Short Course, at which Roger Walker was one of the lecturers (Harms *et al.*, 1975). Walker and his students later played an important role in establishing the importance of the structure in the geological record and contributing to an understanding of its origins by their work in a variety of Mesozoic units in Alberta (the paper by Hamblin and Walker, 1979, was the first). The history of HCS is an interesting example of a geological feature that geologists had been seeing without observing for many years, until it was given a name and an interpretation, and its particular significance was recognized. In the early 1980s Walker turned to Alberta units such as the Cardium and Viking sands in part to explore the geological setting and origins of HCS. The Cardium Sand is full of HCS, but its significance was obscure. An excellent example of the art of facies analysis as applied to the Cardium Sand had been published by two Calgary petroleum geologists in 1969 (Michaelis and Dixon, 1969), in which HCS, hitherto unrecognized, is described. Michaelis and

Dixon correctly deduced that the structure is produced by storm waves, but the exact mechanism remained obscure, and they were denied their shot at posterity by failing to make that important Canadian step of giving the structure its own name and distinctive code. HCS and the Cardium Sand played an important role in the development of a distinctive Canadian theme in sequence stratigraphy a few years later, as documented below.

#### **Sediment-gravity Flows**

One of the most important developments in the application of the turbidity-current concept to the interpretation of the sedimentary record was made by the Dutch geologist Arnold Bouma, who carried out his doctoral research on the "flysch" deposits of Switzerland, and published what rapidly became a classic study in which the so-called "Bouma sequence" was established (Bouma, 1962). At about the same time, Gerrard Middleton was beginning his life-long interest in sediment mechanics. His interest in turbidites developed in the early 1960s, although he stated that he was influenced by a seminar by Kuenen that he attended while a graduate student in London between 1952 and 1954 (pers. com., 1996). Middleton's major contributions to this field consist of a series of five papers (Middleton, 1962, 1966a,b,c, 1967), the last three representing the outcome of a series of experiments conducted in a flume of his own design at the California Institute of Technology. Middleton was able to expand existing knowledge of the shape and internal dynamics of turbidity currents (Fig. 4), and to determine with some quantitative rigor the conditions under which various types of graded bedding develop.

In later work, Middleton was to provide valuable syntheses of research on other types of sediment-gravity flow, resulting in a very useful classification in which sediment-support and transport mechanisms, the conditions under which they occur, and the facies criteria by which they may be recognized, were clearly set out (Middleton and Hampton, 1973, 1976). He also provided a valuable commentary on the development of our knowledge of the hydraulic interpretation of sedimentary structures a decade after his Toronto symposium (Middleton, 1977), and began a long-standing co-operation with

the Massachusetts Institute of Technology sedimentologist John Southard in the teaching of principles of sediment mechanics for sedimentologists (Middleton and Southard, 1977).

Although it came somewhat later than the period dealt with here, a symposium at the Sedimentology Congress in Hamilton in 1982 continued what could now, perhaps, be claimed as a Canadian tradition of specialization in the study of sediment-gravity flows. The topic of the symposium was "Rudites formed by unidirectional flow;" it was organized by E.H. Koster and R.J. Steel. The subsequent proceedings volume (Koster and Steel, 1984) stands out as a benchmark work in its field. It contains many papers describing debris flow deposits and other coarse-grained mass-flow deposits in Canada and elsewhere.

#### THE PROFESSIONALIZATION OF SEDIMENTOLOGY FROM THE 1950s TO THE 1970s

Universities underwent a major expansion in the 1960s. It had been traditional for the best Canadian students to carry out their graduate work in the United States (Stearn, 1968), but this practice became less popular in the 1960s because of this expansion of Canadian schools. Most of the senior academic Canadian sedimentologists who are now approaching the end of successful careers were hired during this period, including Roger Walker (McMaster University), Brian Rust (University of Ottawa), Al Donaldson (Carleton University), Reinhardt Hesse and Eric Mountjoy (McGill University), and Jean Lajoie (Université de Montréal).

Likewise, the expansion of the petroleum industry during the 1950s and 1960s was remarkable. Geologists poured into Canada from around the world, and an impressive international cadre of specialists built a highly competitive industry from scratch. Sedimentology and sedimentologists were very much part of this expansion, and the science owes much to individuals such as Andy Baillie, Perry Glaister, Monti Lerand, Eric Michaelis, Peter Fitzgerald Moore, Hans Nelson, Volkmar Schmidt, Monzer Shawa, and others, who carried out much excellent stratigraphic and sedimentologic work, much of it never published, and also helped to train generations of geologists for the industry. Perusal of the *Bulletin of Canadian Petroleum Geology* for this period re-

veals paper after paper constituting important building blocks in the edifice of knowledge about the Western Canada Sedimentary Basin, and the beginnings of knowledge about the Canadian frontier areas, mainly by individuals such as these working in industry and at the Geological Survey of Canada (GSC).

A major milestone during this period was the establishment of the Institute of Sedimentary and Petroleum Geology (ISPG), a division of the Geological Survey of Canada, which opened on a site near the University of Calgary campus in 1967, at the time of the First International Symposium on the Devonian. The symposium was itself a major sedimentological event, of a type for which the Canadian Society of Petroleum Geologists (CSPG) has become well known. However, the GSC had been in operation in Calgary for long before this. Figure 1 is simplified from a detailed original compiled by Belyea (1960). It is an excellent example of the meticulous program of research, synthesis, compilation and publication that has long been characteristic of the Geological Survey of Canada.

The new institute was responsible for mapping and basin analysis studies in the Northwest Territories and the Rocky Mountains of Alberta, and served as the repository for exploration data from the Canadian "federal" lands (NWT and offshore regions). The first Director was the well-known Devonian stratigrapher and paleontologist Digby McLaren, who went on to head the Survey and later served as President of the Royal Society of Canada. Sedimentology, as a research subject distinct from stratigraphy, began slowly at ISPG; however, during the 1970s, such research tools as paleocurrent analysis and the documentation and interpretation of cyclic successions in vertical profiles became a routine part of GSC work, and a be-

ginning was made on the use of seismic stratigraphy in regional basin analysis.

At the end of the 1960s, background papers on the earth sciences in Canada were prepared for a report by the National Advisory Committee on Research in the Geological Sciences, commissioned by the Science Council of Canada (Smith, 1970). These papers provide a fascinating snapshot of the state of the science at the time, and of attitudes toward research and the varying roles of universities, industry and government. A survey of "Geosciences in the petroleum industry" by Landes (1968) is quoted to the effect that

Discovery of oil in a Devonian reef in Alberta in 1947 gave considerable impetus to studies of carbonate rocks and associated evaporite and shale sequences, with emphasis on reef bearing facies. Stratigraphic and facies concepts are used routinely to reconstruct basin framework and depositional environments in ancient carbonate sequences." ... [However] "Despite the large reserves of oil in Cardium sandstones of the Pembina field, sandstones have received less attention than carbonate rocks in the last 15 years.

A report on the status of sedimentology in Canada by Middleton (in Smith, 1970) stated:

Canada, however, has lagged in the development of sedimentology, whether in government, industry or the universities. Only in 1966 was the topic 'sedimentation' considered sufficiently distinct from stratigraphy to be included in the title of the relevant subcommittee of the National Advisory Committee on Research in the Geological Sciences. The Geological Survey of Canada has not laid much stress on sedimentological studies, in spite of the example of a few pioneers, such as E.M. Kindle. In recent years, however, an increasing number of Survey publications have included descriptions and maps of sedimentary structures and detailed microscopic and geochemical studies of sedimentary rocks.

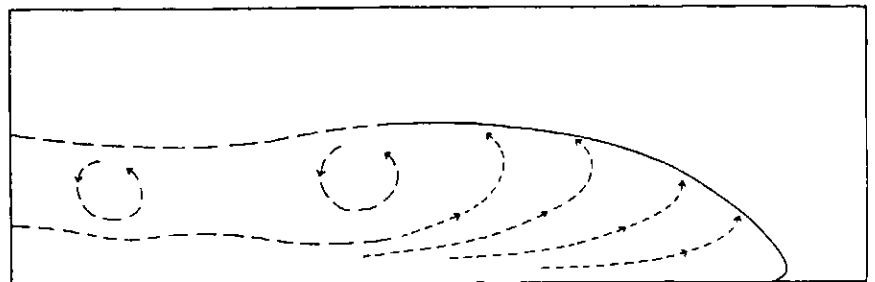


Figure 4 Pattern of flow within a turbidity current, as determined by the experimental work of Middleton (1966b). Reproduced with permission.



The revolution in "process" sedimentology, like many other revolutions in science, took a while to catch on. I still have the reading lists and course notes from a graduate course in sedimentology given by Brian Rust at the University of Ottawa in 1965-1966. Most of the course was designed around petrology; very few process-oriented papers were in the list, and this aspect of sedimentology was not emphasized. For example, one of J.R.L. Allen's first papers on the origins of the Old Red Sandstone, work that was to become part of a classic series of papers on fluvial processes over the next few years, was included under the heading "Arkoses" in a reading list that focused on the petrographic variations between major classes of sandstone.

Sedimentary processes and facies models are assigned limited space in an important textbook, co-authored by Middleton, that represents the state of sedimentology as it was in the early 1970s (Blatt *et al.*, 1972; a second edition appeared in 1980). However, the physics and chemistry of sedimentation are the primary focus of this book.

Important work in marine geology has been carried out at the Geological Survey's regional offices at Patricia Bay on Vancouver Island, and at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia. Brian Bornhold, David Piper and David Prior stand out as individuals energetically engaged in applying the new tools of marine geology (side-scan sonar, high-resolution reflection seismic, precision navigation and bottom coring) to elucidate the sedimentological processes sculpting Canada's continental margins. Amongst the most spectacular of such processes was the great 1929 turbidity current, triggered by an earthquake on the Grand Banks of Newfoundland. Although the first individuals to recognize the sedimentological significance of this event were not Canadian (Heezen and Ewing, 1952), Piper and his co-workers extensively re-surveyed this flow, and have produced spectacular sonar images and maps of the complex deposits now constituting the Laurentian Fan on the slopes of the Grand Banks. Bornhold and Prior have carried out a considerable amount of research on submarine mass wasting processes and fan-delta sedimentation (references below).

Canada joined the Ocean Drilling Program in 1985 with full membership.

Since that time, Canada has been an active participant in all aspects of the Program. In 1988, Canada reduced its contribution to the Program to two-thirds membership. Between 1994 to 1996 Canada and Australia were one-third partners. Canada presently hosts the AusCan Consortium Secretariat.

#### FACIES MODELS: THE BOOK

This publication by the Geological Association of Canada represents Canadian sedimentology's (and the GAC's) great triumph. It has run to three editions which, among them, have sold nearly 70,000 copies worldwide (Walker, 1979, 1984; Walker and James, 1992). Credit for this success is very largely due to its editors Roger Walker and Noel James.

The book began in 1975 as a series of special articles in *Geoscience Canada* which, at that time, was under the editorship of its founder Gerrard Middleton. The articles were invited by the series editor, Roger Walker, who stated in the Preface to the book that the series was initiated by Middleton partly in response to a suggestion from Eric Dimroth for "brief, well-written, concise articles outlining the techniques of rock interpretation, and the concepts and criteria for regional evaluation [that] would be an enormous help to the general purpose field geologist."

The book has been successful for several reasons: many of the major developments in process-response models were made by Canadian scientists and were reported in summary form in this book; and the book evolved a format, largely of Roger Walker's design, that consisted of straightforward text and bold, simple, illustrations summarizing the key ideas. Several series have also appeared in *Geoscience Canada* following this model with sets of invited papers designed around selected themes. Although successful, none has had the sales success achieved by *Facies Models*.

The process-response model was not invented in Canada. Early models evolved in part from attempts to interpret sedimentary vertical profiles, as expressed in petrophysical logs and cores (*e.g.*, Nanz, 1954), and as exposed in fluvial point bars in the Brazos River, Texas, and beach deposits on Galveston Island (Bernard *et al.*, 1962). Oomkens and Terwindt (1960) independently developed a model for the

lateral accretion of tidal creeks using their observations on Dutch tidal flats, and Allen (1963) adapted this for the interpretation of Devonian fluvial deposits in Britain. Bouma's (1962) turbidite model, although primarily a descriptive concept rather than an interpretive model, also belongs to this group.

Although many important original sedimentological contributions have been made in this country, the particular Canadian contribution to the development of process-response models was to simplify, codify and classify facies and facies models. Early trends in this work were revealed in one of Walker's first papers, based on work carried out while he was a graduate student studying under Harold Reading at Oxford (de Raaf *et al.*, 1965). This paper developed the concept of standard facies and of repeated vertical facies relationships. Walker's ideas were encapsulated in the famous facies model diagram reproduced here as Figure 5. Much of the early work in facies models centered around the idea, based on Walther's Law — which Middleton (1973) brought to modern sedimentologists' attention — that a vertical succession of facies could indicate an original horizontal arrangement of the corresponding depositional environments, an idea that promised to provide a powerful tool for the interpretation of subsurface well and core data. For a time, attempts to analyze vertical profiles using statistical techniques, such as Markov chain analysis, were popular (*e.g.*, Miall, 1973; Cant and Walker, 1976), but these techniques soon reached their limits of usefulness.

The major Canadian contributions to the development of process-response models that are captured in the *Facies Models* book are noted briefly in the following sections. The three editions of the book are referred to as FM1, FM2 and FM3, respectively.

#### FACIES MODELS: CANADIAN CONTRIBUTIONS

##### Fluvial Systems

One of the first modern sedimentological descriptions of a braided river with a coarse-grained bedload was that by Williams and Rust (1969), based on their work on the Donjek River, Yukon. Rust authored one of the two chapters on fluvial environments in FM1 and co-authored the revised version in FM2.



Walker's graduate student, Doug Cant, studied an ancient sandy braided fluvial deposit for his M.Sc. and a modern sandy braided river for his Ph.D., acquiring data that enabled him and Walker to publish important comparative analyses (Cant and Walker, 1976, 1978), and this work constituted the main basis for the other chapter on fluvial deposits in FM1. The ideas that braided fluvial deposits could be cyclic, and that they may be characterized by distinctive paleocurrent patterns, were among the important contributions of this work.

Another important development was the appearance of the model for anastomosed rivers, which was almost single-handedly invented by Derald Smith (1973, 1983) and has since been recognized as a very common fluvial style in the ancient record (see Miall, 1996).

My contributions to sedimentology have been largely in the fluvial realm, including a review of the braided river depositional environment (Miall, 1977), and the organization of the first international symposium on fluvial sedimentology, in Calgary, that resulted in a major proceedings volume (Miall, 1978). A codification of fluvial lithofacies was developed at that time that has subsequently been much used. A later development was the adaptation of work by Brookfield (see below) and Allen (1983) on three-dimensional sedimentological architecture in an attempt to provide a systematic methodology for the description and classification of fluvial deposits on all observational scales (Miall, 1985, 1988, 1996). This work was summarized in FM3.

**Eolian Systems**

Eolian deposits are not common in Canada, and few researchers have specialized in this field. However, Brookfield (1977), of Guelph University, completed an important project on Permian eolian systems in northern Britain, which led to a significant step forward in eolian studies and is the reason that Brookfield authored the eolian chapters in FM2 and FM3. His contribution was to clarify concepts of a bedform hierarchy in dune systems, and to propose the recognition of a system of bounding surfaces by which this hierarchy could be recognized and mapped. All subsequent workers have used and built on this concept; and, as noted above, it helped to stimulate comparable work in fluvial systems.

**Deltas**

None of the original work on deltaic facies and processes was carried out in Canada. American work, focusing originally on the Mississippi River, has dominated this field, and was the primary reference base for the write-up of deltas in FM1 and FM2. However, in recent years Bhattacharya (1991) and Bhattacharya and Walker (1991) published the results of Bhattacharya's Ph.D. thesis work under Walker that represent a remarkably thorough regional study of the sequence stratigraphy and sedimentation of a major regional subsurface Cretaceous delta system in Alberta. This work forms much of the basis for the deltas chapter in FM3.

**Estuaries**

Early work in this field is primarily Dutch in origin, but sedimentologists in Alberta

began recognizing the characteristic facies in certain Cretaceous units (Rahmani, 1988), and this led to a proposal for the definition and naming of a distinctive class of large-scale cross-bedding called "inclined heterolithic stratification" (IHS) that is a common component of bar deposits in tidal channels and tidally influenced fluvial channels (Thomas *et al.*, 1987). The second international research symposium on "Modern and Ancient Clastic Tidal Deposits" was held in Calgary in 1989, and resulted in a major proceedings volume that highlighted much of the Canadian work in Alberta, the Arctic and elsewhere (Smith *et al.*, 1991).

Estuaries caught the attention of the petroleum geology community in Calgary when it was realized that many producing sandstone reservoirs, particularly in the Lower Cretaceous Mann-

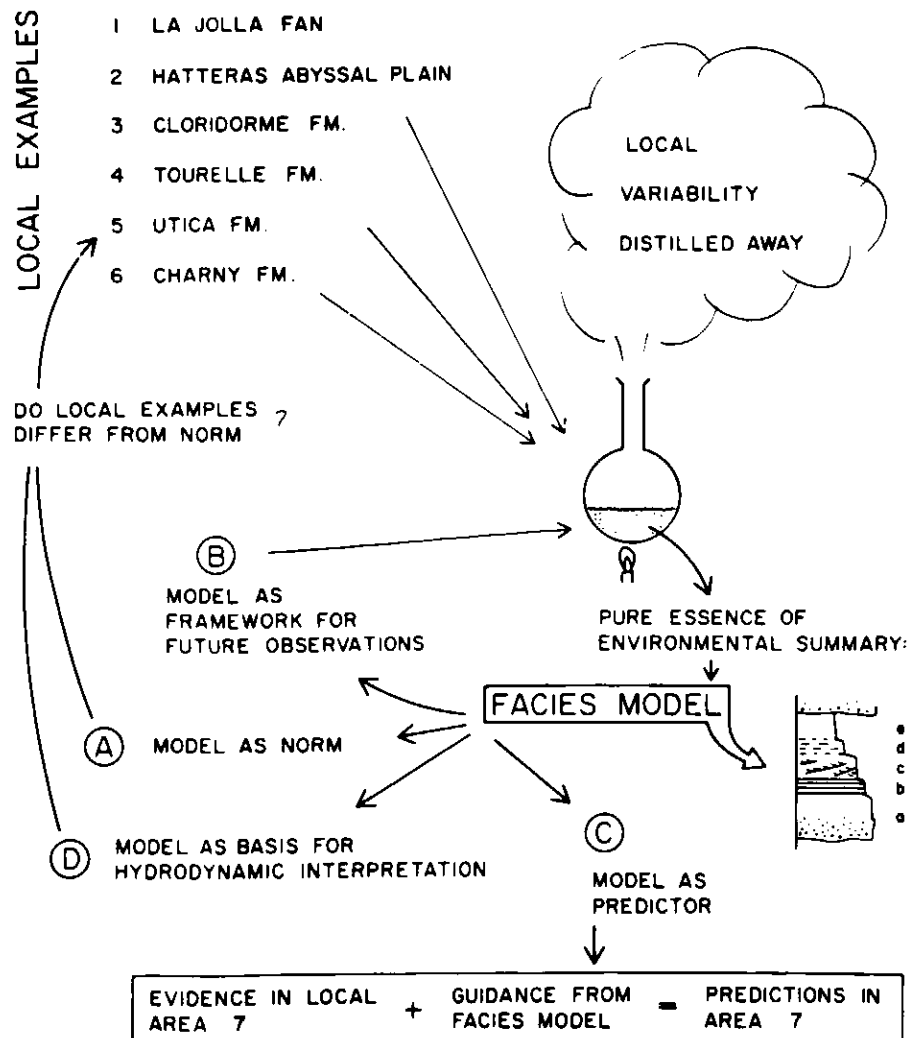


Figure 5 "Distillation of a general facies model from various local examples ...," illustrating the method for the analysis of turbidites. From the first paper in the Facies Models Series (Walker, 1975a). Reproduced with permission.

ville Group, occur in broad linear "channels" and contain evidence of tidal influence during sedimentation. Careful mapping revealed that these channels are deeply incised valleys that form part of regional erosion surfaces, and that they originated as estuaries at the margins of the Western Interior Seaway (e.g., Rosenthal, 1988). This led to a rejuvenation of research into estuarine sedimentation, a theme that had occupied the attention of Gerry Middleton and his student Bob Dalrymple (who carried out his doctoral research on the Bay of Fundy, and is now at Queen's University). The result was new models of estuarine sedimentation (Dalrymple *et al.*, 1992), and a research volume devoted to the sedimentology and petroleum geology of incised valleys (Dalrymple *et al.*, 1994). These relatively recent developments are summarized by Reinson and Dalrymple in separate chapters in FM3.

**Wave-dominated Shelf Deposits**

The story of HCS is told above. It did not form part of the original Facies Models Series in *Geoscience Canada*, but the beginnings of the theory were reported by Walker in FM1. Our ideas about shelf sedimentation were to be

revolutionized by sequence concepts (as reported below), and the summary of this environment in FM3 had to be completely rewritten.

**Deep-sea Depositional Systems**

In the case of deep-marine depositional systems, the step from process to environment was a long one. By the end of the 1960s sedimentologists thought they had learned most of what they needed to know about turbidites, and Walker published several papers on this subject (Walker, 1967, 1970, 1973), including one with the very confident title "Mopping up the turbidite mess" (Walker, 1973). But it was not to be. This early work had focused on the internal facies characteristics of individual turbidite units, including the vertical succession of sedimentary structures and lateral, downcurrent variations in turbidite facies. In a later study Walker (1975b) extended similar ideas regarding facies and proximal-distal variations to conglomeratic sediment-gravity flows, including debris flows. Other field studies, including several graduate theses supervised by Middleton and Walker, were carried out on the Lower Paleozoic "flysch" of the Appalachians, as exposed in the eastern townships of Quebec.

Canadian research on deep-sea turbidite deposits was collected into a book by Lajoie (1970), which provides a good overview of the "state-of-the-art" from this period.

What was not fully realized at that time, as is reflected in these early studies, is that turbidites and debris flows form part of a wide range of complex depositional systems, including what we now call submarine fans. One of the first attempts to bring all these ideas on turbidite facies and depositional systems together was made by Walker and Mutti (1973) for a short course, and the ideas reached their most complete expression in companion papers published by Walker (1978) and Normark (1978). Walker's contribution formed the basis for his summary in FM1.

The FM1 article on turbidites (and Walker, 1978) contains several diagrams that became very well known. Two of them are reproduced here as Figures 6 and 7. These diagrams encapsulate the idea that fans consist of a few distinctive physiographic components that are characterized by predictable facies associations, and that the evolution of these subenvironments, by progradation, aggradation or lateral accretion, generate predictable vertical successions. These diagrams, and the text that accompanied them, are excellent examples of the Canadian methodology at work, that Walker made very much his own. While they readily convey some important basic ideas, and therefore have been very successful as teaching aids, they have also been criticized as simplistic. Of particular importance is the fact that these early ideas were based on rather small modern examples, and more recent marine geological surveys have demonstrated an enormous variability in the scale and architecture of modern fans (e.g., Bouma *et al.*, 1985). Modern work on this topic has been very much influenced by developments in seismic stratigraphy.

Much important additional Canadian research carried out at Canada's two marine geology institutes includes side-scan sonar and high-resolution seismic surveys of Canada's continental margins, which have contributed significantly to our understanding of submarine sediment transport processes, and the characteristics of the resulting deposits. Piper's work on the Laurentian Fan has been noted earlier (Piper *et al.*, 1985, 1988). Bornhold and Prior and

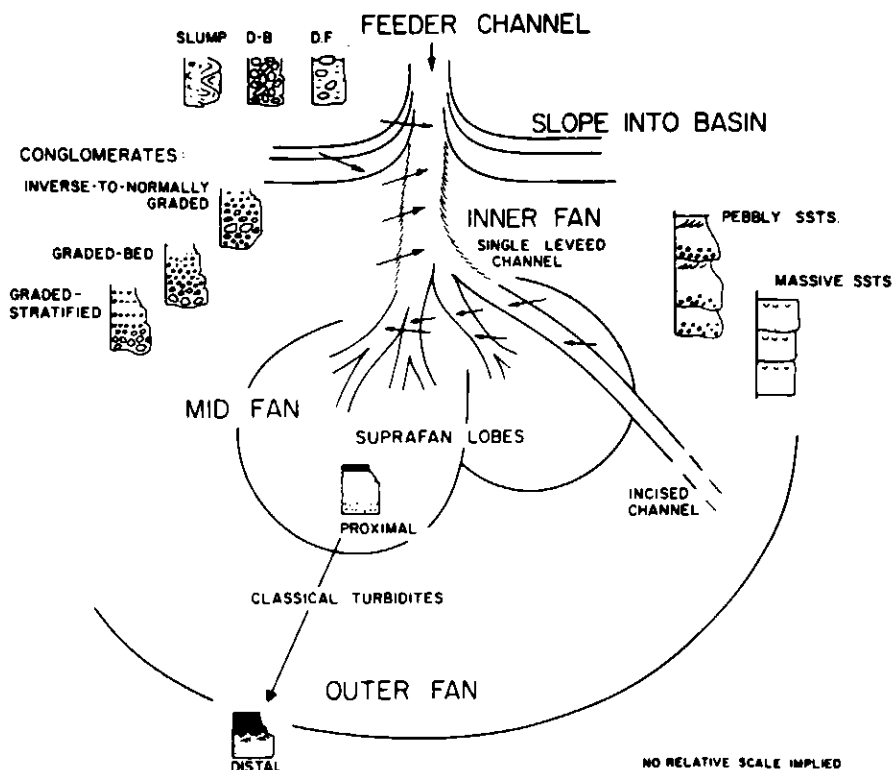


Figure 6 The first attempt at a generalized facies model for submarine fans (Walker, in FM1). Reproduced with permission.

their co-workers have contributed numerous studies of submarine mass-wasting processes and the sedimentology of fan deltas (Prior *et al.*, 1982, 1984; Prior and Bornhold, 1988, 1989, 1990; Coleman and Prior, 1988; Bornhold and Prior, 1990; Hart *et al.*, 1992). Chough and Hesse (1976, and later publications) have described the North Atlantic mid-oceanic channel (NAMOC). A series of marine cruises have mapped out a remarkable system of submarine channels that "drain" the continental slope off Labrador, and channel turbidity-current flow for distances of several thousand kilometres into the centre of the North Atlantic Ocean.

**Glacial Depositional Systems**

Although the Canadian landmass is covered with an immense spread of Late Cenozoic continental glacial deposits, modern sedimentological techniques were not applied to their study for many years. Canadian work by Eyles *et al.* (1983) can claim to be one of the first contributions to change this picture. These authors took the methods of facies classification and vertical-profile analysis and applied them to the study of a range of ancient glacial deposits. Amongst the most interesting of these units is the succession of "tills" and interbedded interglacial deposits that constitute the Scarborough Bluffs section near Toronto — a classic Quaternary section — that were radically reinterpreted by Eyles and Eyles (1983).

One of the more important ideas contained in these papers, and in the summaries written up by Eyles and co-workers for FM2 and FM3, is that most tills are probably not deposited by ice at all, but are subaqueous deposits formed by sediment gravity flows. The non-genetic term diamict is now recommended for all poorly sorted, glacially related, conglomeratic deposits. Eyles also showed in these and other studies that most ancient glacial deposits are glaciomarine, and that the ancient record of continental glaciation is extremely limited, largely due to the low preservation potential of such deposits. More recently, in a masterly overview of the global glacial record, he has forcefully argued for the importance of regional tectonic uplift as a major influence leading to continental-scale cooling and the triggering of continental glaciation (Eyles, 1993).

**Reef Carbonates**

Studies of Western Canadian reefs were reviewed by Klovan (1974) and Davies (1975), and a useful contribution to petrographic nomenclature for organically bound reef facies was made by Embry and Klovan (1971).

In the 1970s reef studies in Canada were picked up by Noel James (*e.g.*, James and Ginsburg, 1979), who quickly became one of the world's leading authorities on carbonate sedimentation in general, and the sedimentology of reefs, in particular. James co-ordinated

all the carbonate sedimentology contributions in FM1, FM2 and FM3 and has co-authored most of them. He contributed a lengthy review of reef sedimentology to a superbly illustrated AAPG memoir on carbonate depositional environments, that remains a landmark study in this field (James, 1983). One of James' most useful contributions has been his studies of the litho- and bio-facies zonation of reefs, particularly the large platform-margin reefs that fringe many modern and ancient continental margins (Fig. 8). He demonstrated how

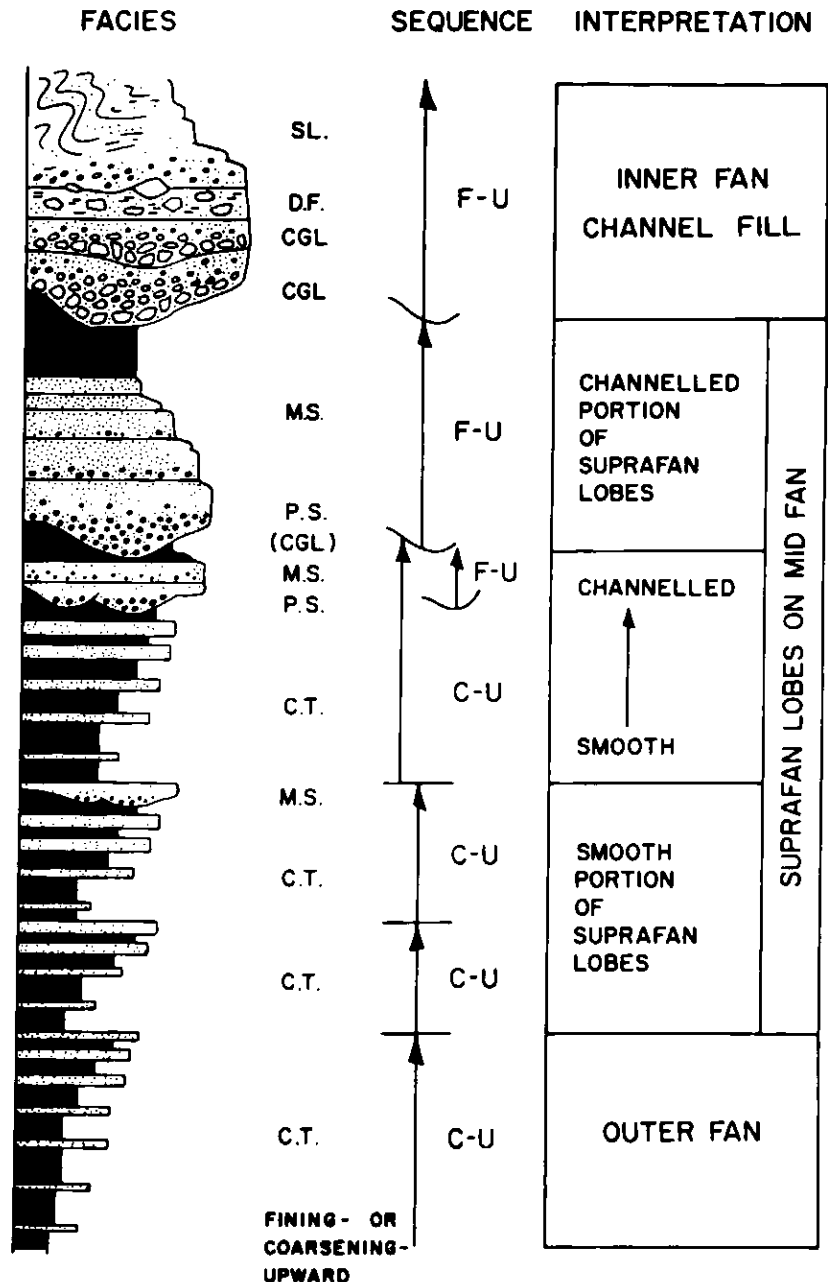


Figure 7 Distillation of ideas about fan aggradation and progradation into a single model vertical profile, focusing on the occurrence of coarsening- and fining-upward successions (Walker, in FM1). Reproduced with permission.

these large reefs evolve through the four stages, "stabilization, colonization, diversification and domination," and documented the evolution in biofacies composition and the variations in reef abundance through geologic time. Like Walker, James has been able to construct some simple, elegant diagrams that capture the essence of basic ideas for use in teaching.

Students and associates of James have contributed to a wide range of innovative studies of reefs, many of which are reported in Geldsetzer *et al.* (1988). These include algal, stromatolitic, stromatolitic and archaeocyathid reefs in the Proterozoic and Cambrian, and stromatoporoid, coral, and rudist reefs in the younger record. One of the first important studies of stromatolites in the modern literature was that by Hoffman (1974), based on his work in the Lower Proterozoic succession spectacularly exposed along the East Arm of Great Slave Lake. Hoffman (1973, 1976) and G.R. Davies (*in Logan et al.*, 1970) contributed to our knowledge of these organic structures by their analysis of the modern stromatolites in Shark Bay, Australia. The work of Mountjoy and his associates on the Miette and Ancient Wall Reef Complexes in Jasper Park is also well known (Mountjoy, 1965, 1967; Mountjoy *et al.*, 1967). Jansa *et al.* (1981, 1993) have documented the Mesozoic carbonate platform and reef deposits in the subsurface of offshore eastern Canada.

**Platform Carbonates**

The cratonic interior of Canada is un-

derlain by vast expanses of platform limestone of Paleozoic age. Studies of these contributed to the reviews of this environment by B. Jones, A. Desrocher, B.R. Pratt, N.P. James and C.A. Cowan, in two chapters in FM3. A particularly important Canadian contribution in this area has been the documentation of carbonate platform sedimentation in cool-water environments, such as the Great Australian Bight (James and Bone, 1991; Boreen and James, 1995). Pratt and James (1986) developed a tidal-flat island model for the metre-scale shoaling-upward peritidal successions that are so common in cratonic carbonates. This is a useful idea that offers an alternative to the progradational and aggradational models of autogenic cycle development.

**Carbonate Slope and Deep-water Environments**

Canadian contributions in this area have benefited from excellent exposures of spectacular features. Stratigraphic and sedimentologic studies of the Cambrian Burgess Shale of British Columbia, well-known for its unique soft-bodied fauna, revealed that the deposits were formed in the shelter of a contemporaneous deep-water cliff. The geology of this feature was described by McIlreath (1977; see also McIlreath and James in FM1).

The Cow Head Breccia of Newfoundland has always attracted attention because of its unique carbonate facies, faunas and tectonic associations. Studies of the slump deposits and debris flows constituting this unit have been published by Hiscott and James (1985)

and Coniglio (1986).

Spectacular carbonate turbidites, debris sheets and truncation structures were described from the Pennsylvanian-Permian carbonates of the northeastern Sverdrup Basin, Canada, by Davies (1977).

**Evaporites**

The sedimentological understanding of evaporites has developed mainly from studies of ancient deposits such as the Messinian and Zechstein evaporites of Europe, and the modern sabkha flats of the Arabian Gulf. Notable work in Canada has been carried out on the widespread Devonian evaporites of the Western Interior and the Canadian Arctic, by individuals such as G.R. Davies, A.C. Kendall, W.R. Maiklem, G.D. Mosop, and N.C. Wardlaw. Maiklem (1971) was among the first to suggest the mechanism of evaporative draw-down for evaporite genesis, a process that became generally accepted following the discovery and interpretation of the giant Messinian evaporites of the Mediterranean basin. Jansa *et al.* (1980) studied the Triassic evaporite deposits in the subsurface of offshore eastern Canada. Evaporite sedimentology is ably summarized by Kendall (1988; and in FM1, FM2 and FM3).

**The Sedimentology of Trace Fossils**

Trace fossils have been found to be enormously useful as environmental indicators. They are particularly valuable in the study of drill core, because they are typically well-preserved and

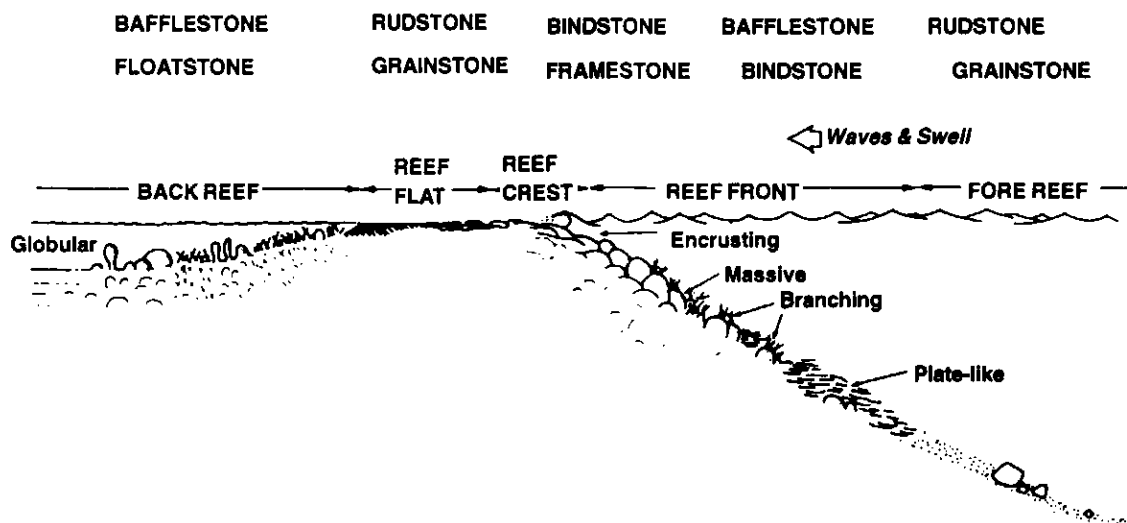


Figure 8 The environmental and facies zonation of marginal reefs (James, in FM1). Reproduced with permission.

easy to study in core. S.G. Pemberton, of the University of Alberta, has carried out an energetic research program in this field for many years, assisted by numerous graduate students. His work has found a particularly widespread application in petroleum exploration studies in Western Canada. He and his associates have authored many publications, including a summary co-authored with R.W. Frey in FM2 and another, with J.A. MacEachern, a former student, now at Simon Fraser University, in FM3.

**DEPOSITIONAL SYSTEMS ANALYSIS IN THE 1960s AND 1970s**

The concept of depositional episodes and the depositional-systems basin-analysis method were developed largely in the Gulf Coast region during the 1960s and 1970s as a means of analyzing and interpreting the immense thicknesses of sediment there that are so rich in oil and gas. In its original form depositional-systems analysis preceded the development of sequence stratigraphy, and therefore the essential element of repeated base-level change is missing from the early work. Nonetheless, the methods provided a powerful tool for regional analysis. Excellent examples of the method emerged from the study of some of Canada's large sedimentary basins. There is no better place to review such studies from this period than in the fifth edition of *Geology and Economic Minerals of Canada*, which was completed in the late 1960s (Douglas, 1970). Here, sedimentological and stratigraphic data have been combined into series of paleogeographic maps for each of the major regions of the country.

A particularly instructive example of depositional-systems analysis is the evolution in thinking about the Middle and Upper Devonian clastic wedge of the Canadian Arctic Islands that took place during the 1970s. This unit consists of up to 5 km of strata extending in the surface and subsurface over an area exceeding 200,000 km<sup>2</sup>. Embry and Klovan (1976) carried out a depositional-systems analysis of these rocks, incorporating new subsurface data that had become available (this was A.F. Embry's Ph.D. thesis). With a few judicious revisions of the GSC's lithostratigraphic nomenclature (Fig. 9) and a unifying concept of the origin of the rocks, the stratigraphy of this major suc-

cession sprang to life. Figure 10 is their generalized cross-section through the clastic wedge, showing it to consist of a prograding fluvial, deltaic, continental slope, and submarine-fan complex. Three periods of progradation were recognized, based on sedimentological and palynological data. Many of the older formation and member names were retained, but their meaning and usefulness are now more readily understood.

**SEQUENCE STRATIGRAPHY**

The foundation of modern sequence stratigraphy is commonly regarded as the paper by Sloss (1963) that describes the six major sequences of the Phanerozoic record of the cratonic interior of North America. Canadian work, particularly in Western Canada, contributed to the development of Sloss's ideas, which were enlarged and expanded in many later publications. The work on the "grand cycles" of the Cambrian record, by Aitken (1966, 1978), belongs in this early period. However, the ideas did not become popular and widely known until Vail and his co-workers (1977) demonstrated how stratigraphic information could be derived from a careful analysis of reflection-seismic records, and the same ideas were applied to outcrop-scale analysis in a pair of landmark papers by Posamentier and Vail (1988) and Posamentier *et al.* (1988). A recent review of sequence stratigraphy was provided by Miall (1997).

The first major Canadian contribution in this field was that by Plint *et al.* (1986), and consisted of a subsurface analysis of the Cardium Sandstone in Alberta. As noted earlier in this paper, the Cardium had attracted attention early in the exploration history of Alberta because it constitutes the reservoir of the first, and still one of the largest, giant, sandstone-hosted oil fields in Alberta, the Pembina field (Michaelis, 1957). It was shown by R.G. Walker to contain abundant HCS, and was studied as an example of shelf sedimentation. However, ideas about Cardium sedimentation changed dramatically with the analysis offered by Plint *et al.* (1986). Up until that time the sandstone shoals and conglomerate lenses that form the major reservoir bodies had been interpreted as "offshore bars," an idea that was never fully satisfactory because of the difficulty in demonstrating a mechanism that could transport coarse debris far out onto a continental shelf (as central Alberta was interpreted to be in the mid-Cretaceous). These ideas about the Cardium Sandstone, and other shelf sandstones of the Western Interior Seaway, formed the main basis for the discussion of shallow-marine sandstones in FM1 and FM2.

The importance of the 1986 study is the breakthrough developed by A.G. Plint, who was a post-doctoral fellow at McMaster University at the time, studying with R. G. Walker. Plint was able to

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Figure 9 Table of stratigraphic nomenclature for the Middle-Upper Devonian clastic wedge of the Canadian Arctic Islands (T&T: Thorsteinsson and Tozer, 1970; Present study: Embry and Klovan, 1976). Reproduced with permission.

demonstrate, by way of meticulous correlation of hundreds of petrophysical logs, that the Cardium, a unit typically less than 100 m thick and representing about 1 m.y. in geological time, consists of up to six superimposed unconformity-bounded units formed as a result of six basin-wide cycles of relative sea-level change (Fig. 11). The conglomerates, in this interpretation, are not some enigmatic shelf-margin deposit, but beach deposits formed initially as fluvial gravels at low stands of sea level, and reworked during the transgression that accompanied the next rise in sea level.

This new idea was a substantial change from earlier interpretations (compare the chapter on shallow-marine shelf sandstones in FM2 with that in FM3), and stimulated considerable debate in the *Bulletin of Canadian Petroleum Geology* at the time (Rine *et al.*, 1987). The main ideas have now been largely accepted, however.

The second important contribution to the study of sequence stratigraphy is also attributed to Plint (1988). He described the seaward-stepping, erosionally based, shoreface sandstones formed as a result of "forced regression" during the falling leg of a sea-level cycle. The documentation of such deposits was important, because falling-stage

deposits had not been described in the early sequence models by Vail, Posamentier, and their co-workers.

Difficulties in developing rigorous definitions of systems tracts, and controversies in defining sequence boundaries, have led several sequence stratigraphers to attempt redefinition of critical sequence concepts. Notable contributions in this area have been made by A.F. Embry whose ideas developed following a detailed surface and subsurface analysis of the 9 km-thick Mesozoic succession of the Sverdrup Basin in the Arctic Islands (Embry, 1988, 1993), and a regional comparison with correlative successions elsewhere in the Arctic (Johannessen and Embry, 1989; Mork *et al.*, 1989). Embry (1993) recommended that sequences be subdivided into only two systems tracts corresponding to their transgressive and regressive portions, and that the sequence boundary be drawn at the surface of transgression, which passes landward, and is virtually contemporaneous with, the surface of subaerial erosion. Sequences so defined are referred to as T-R sequences. Some workers (*e.g.*, Catuneanu *et al.*, 1997) have followed these recommendations, but they have not been generally adopted. In part, this is probably because, where permitted by the

data, it is useful to be able to define other systems tracts (lowstand, highstand, falling-stage). In a later study Embry (1995) elaborated on the types of bounding surface present in sequences, and their use in sequence definition and subdivision. He also offered a new classification of sequences according to their areal extent, and the degree of deformation and the nature of the stratigraphic contrasts at the sequence boundary.

One of the concerns with the definitions of systems tracts is that the criteria by which they are defined, including their facies composition and facies architecture, are not necessarily reliable indicators of the condition for which they are named. Leckie and Krystinik (1993) and Leckie (1994) reviewed the Recent history of the east coast of South Island, New Zealand, which is undergoing both active regression and transgression along different parts of the coastline. The conclusions of these studies are that many of our ideas about systems tracts need to be used with considerable caution, taking local conditions into account in each field case.

I have been responsible for another class of critiques of sequence stratigraphy bearing on the famous "Vail curve" or "Exxon global cycle chart." It

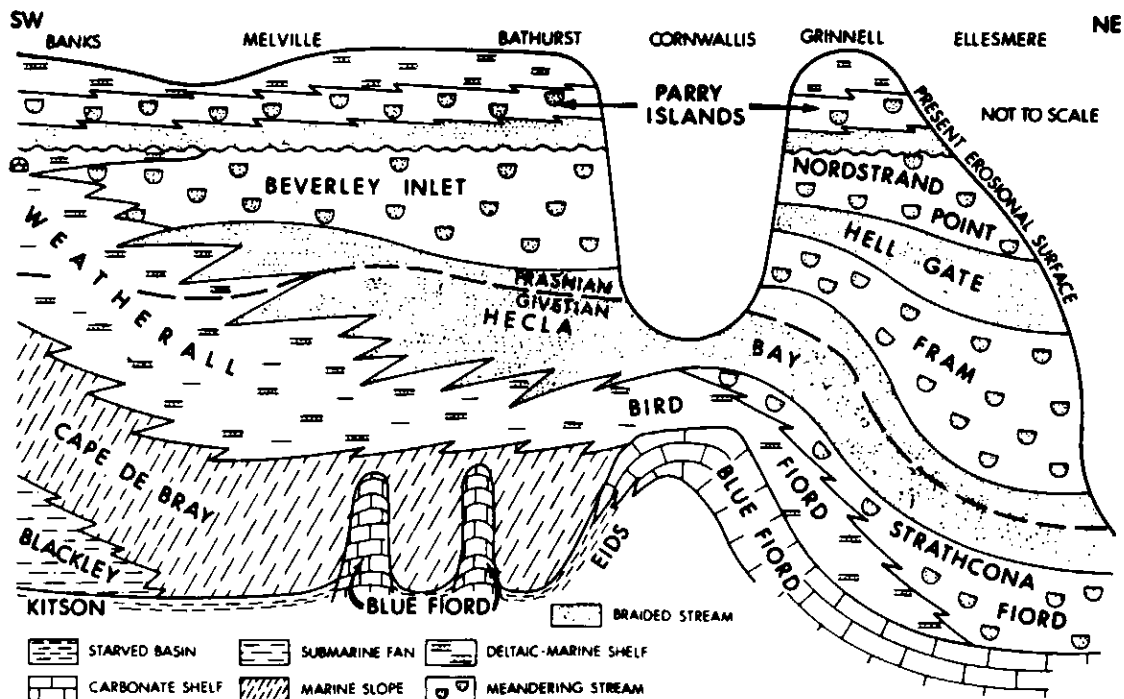


Figure 10 Cross-section through the Middle-Upper Devonian clastic wedge of the Canadian Arctic Islands based on a depositional-systems analysis (Embry and Klovan, 1976). Compare this figure with Figure 11. Reproduced with permission.

had been claimed by the authors of these charts (e.g., Vail *et al.*, 1977), that they provided a new standard of geologic time, with application to global stratigraphic correlation. However, I pointed out that the chronostratigraphic basis for such correlations is inadequate, and that the data on which the charts had been based, have never been published (Miall, 1992, 1994, 1997).

The superb outcrops of the Canadian Rocky Mountains and the immense subsurface data base stored in Calgary have provided an ideal basis for many studies in sequence stratigraphy, and the needs of the petroleum industry have stimulated much practical research in this area. Among the more notable contributions in the field of sequence stratigraphy was the conference held at Calgary in 1988, that led to a major memoir dealing primarily with Canadian sequence stratigraphic studies (James and Leckie, 1988). The Geological Association of Canada has also sponsored a landmark event in the development of sequence stratigraphy, with the NUNA Conference on "High-resolution sequence stratigraphy," held at Banff, with accompanying field trips, organized by Leckie *et al.* (1991). Again in June 1997 the CSPG, this time jointly with the Society for Sedimentary Geology (SEPM), sponsored a major symposium on sequence stratigraphy in Calgary. Larry Sloss, the founder of sequence strati-

graphy, was to be the Honorary Chair of this event, but he passed away shortly before, and in the end the symposium served as a very fitting memorial for his life and career.

### BASIN SUBSIDENCE MODELS

An integral part of any complete, modern sedimentological study is an examination of the large-scale architecture of a sedimentary basin and the controls that determine its subsidence style. Although not a core component of the science of sedimentology (typically classified, in fact, as an aspect of crustal geophysics), the topic of basin subsidence models is mentioned here for the sake of completeness.

Some of the most important early papers exploring the effect of large loads on the crust were written by the Canadian geophysicist Walcott (1970a,b, 1972), who examined the response of the crust to loading by major ice sheets, volcanic edifices and continental-margin sediment wedges. The concepts of crustal flexure that he developed have become an integral part of all subsequent basin models. Later Canadian work in this area has led the field, particularly that carried out at Dalhousie University, under the leadership of Chris Beaumont. Beaumont (1981) developed one of the first quantitative models for the subsidence history of foreland basins, and he and his students and associates (R.

Boutillier, C.E. Keen, J.X. Mitrovica, G.M. Quinlan, G.S. Stockmal) have subsequently contributed many important elaborations to this body of ideas, primarily by the use of numerical modeling and graphical simulation. Johnson and Beaumont (1995) are now bringing basin subsidence models and sedimentology together, with their fascinating study of the interdependence of sediment supply, dispersal patterns, subsidence rates, crustal behaviour, and climate.

### DISCUSSION

The major Canadian contribution to sedimentology has been the full development of the facies model concept and its application to a wide range of depositional environments. This work has been able to take advantage of a superb Canadian outcrop and subsurface data base, especially in the Western Canada sedimentary basin, where much world-class research has been carried out, and has had a world-wide impact through the "Facies Models" volume.

A future review article, decades from now, likely will show that sedimentology has become less important as a focus for petroleum geologists and more a concern of those studying hydrogeology, urban waste disposal, recent climate change, and other topics in environmental geology. May Canadian sedimentologists continue to be world leaders in these new developments.

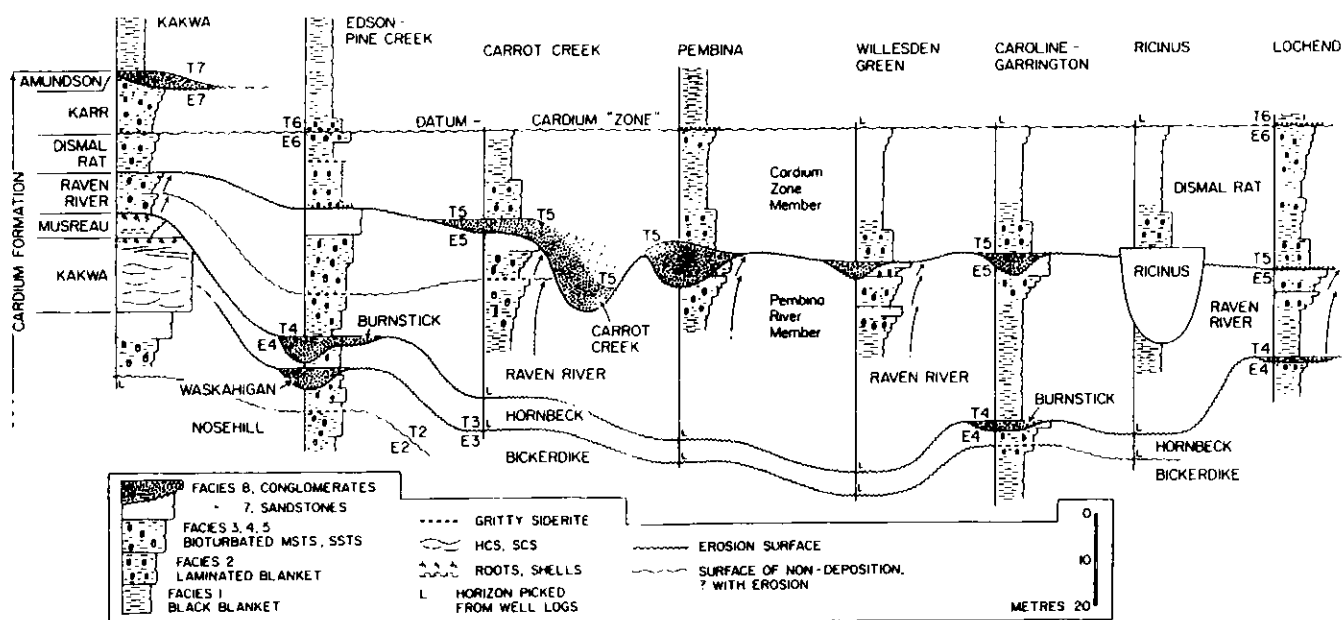


Figure 11 The new synthesis of the Cardium Sandstone, based on sequence concepts (Plint *et al.*, 1986). Reproduced with permission.



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Interested applicants should submit a curriculum vitae, a statement of research and teaching interests and a list of three referees (with addresses, e-mail, telephone and fax numbers) to:

Dr. H. Helmstaedt  
Department of Geological Sciences  
Queen's University  
Kingston, Ontario K7L 3N6

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