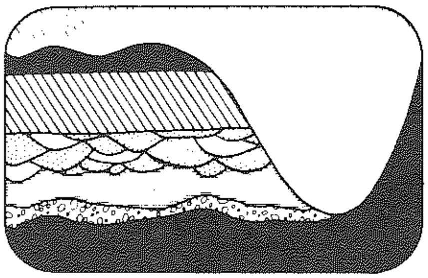

General Introduction: Facies, Facies Sequences and Facies Models

ROGER G. WALKER
Department of Geology
McMaster University
Hamilton, Ontario L8S 4M1

INTRODUCTION

In this paper, I will comment briefly on three concepts – facies, facies sequence and facies models. The intent is to simplify and de-mystify, and hence return some meaning to those misused terms, "facies", and "model". The first part of the bibliography, "basic sources of information", lists with annotations the major texts and monographs on sedimentary environments and facies.

FACIES

The term "facies" was introduced into geology by Nicholaus Steno (1669). It meant the entire aspect of a part of the earth's surface during a certain interval of geological time (Teichert, 1958). The word itself is derived from the latin *facia* or *facies*, implying the external appearance, or look of something. The modern usage was introduced by Gressly (1838), who used the term to imply the sum total of the lithological and paleontological aspects of a stratigraphic unit. Translations of Gressly's extended definition are given by Teichert (1958) and Middleton (1978).

Unfortunately, the term has been used in many different ways since 1838. In particular, arguments have focussed on: 1) whether the term implies an abstract set of characteristics, as opposed to the rock body itself; 2) whether the term should refer only to "areally restricted parts of a designated stratigraphic unit" (Moore, 1949), or also to stratigraphically unconfined rock bodies (as originally used by Gressly and other European workers); and 3) whether the term should be purely descriptive (e.g., "black mudstone facies") or also interpretive (e.g., "fluvial facies").

Succinct discussions of these problems have been given by Middleton (1978) and Reading (1978) – I will use the term in a concrete sense rather than abstractly implying only a set of characteristics, and will use it in a stratigraphically unconfined way. Middleton (1978) has also given the most useful modern working definition of the term, noting that:

> "the more common (modern) usage is exemplified by de Raaf *et al.* (1965) who subdivided a group of three formations into a cyclical repetition of a number of facies distinguished by "lithological, structural and organic aspects detectable in the field". The facies may be given informal designations ("Facies A", etc.) or brief descriptive designations (e.g., "laminated siltstone facies") and it is understood that they are units that will ultimately be given an environmental interpretation; but the facies definition is itself quite objective and based on the total field aspect of the rocks themselves... The key to the interpretation of facies is to combine observations made on their spatial relations and internal characteristics (lithology and sedimentary structures) with comparative information from other well-studied stratigraphic units, and particularly from studies of modern sedimentary environments."

DEFINING FACIES

Many problems concerning the interpretation of depositional environments can be handled without the formal definition of facies. Where the method is invaluable is in stratigraphic sequences where apparently similar facies are repeated many times over (de Raaf *et al.*, 1965; Cant and Walker, 1976).

Subdivision of a rock body into constituent facies (or units of similar *aspect*) is essentially a classification procedure, and the *degree* of subdivision must first and foremost be governed by the *objectives of the study*. If the objective is the routine description and interpretation of a particular stratigraphic unit, a fairly broad facies subdivision may suffice. However, if the objective is more detailed, perhaps the refinement of an existing facies model or the establishment of an entirely new model, then facies subdivision in the field will almost certainly be more detailed.

The *scale of subdivision* is dependent not only upon one's objectives, but on the time available, and the abundance of physical and biological structures in the rocks. A thick sequence of massive mudstones will be difficult to subdivide into facies, but a similar thickness of interbedded sandstones and shales (with abundant and varied examples of ripples, cross bedding and trace fossils) might be subdivisible into a large number of distinct facies. As a general rule, I would advocate erring on the side of oversubdividing in the field – facies can always be recombined in the laboratory, but a crude field subdivision cannot be refined in the lab.

Subdivision of a body of rock into facies ideally should not be attempted until one is thoroughly familiar with the rock body. Only then will it be apparent how much variability there is, and how many different facies must be defined to describe the unit. In the field, most facies studies have relied on distinctive combinations of sedimentary and organic structures (e.g., de Raaf *et al.*, 1965; Williams and Rust, 1969; Cant and Walker, 1976). Statistical methods can also be used to define facies, especially where there is considerable agreement among workers as to the important quantifiable, descriptive parameters. In carbonate rocks, percentages of different organic constituents, and percentages of micrite and/or sparry calcite have been used as input to cluster and factor analyses, with the resulting groupings of samples (in Q mode) being interpreted as facies (Imbrie and Purdy, 1962; Klovan, 1964; Harbaugh and Demirmen, 1964; see also Chapter 7 of the book by Harbaugh and Merriam, 1968, on Computer Applications in Stratigraphic Analysis - Classification Systems). Unfortunately, statistical methods are unsuited to clastic rocks, where most of the important information (sedimentary and biological structures) cannot readily be quantified. Readers unfamiliar with the process of subdividing rock bodies into facies

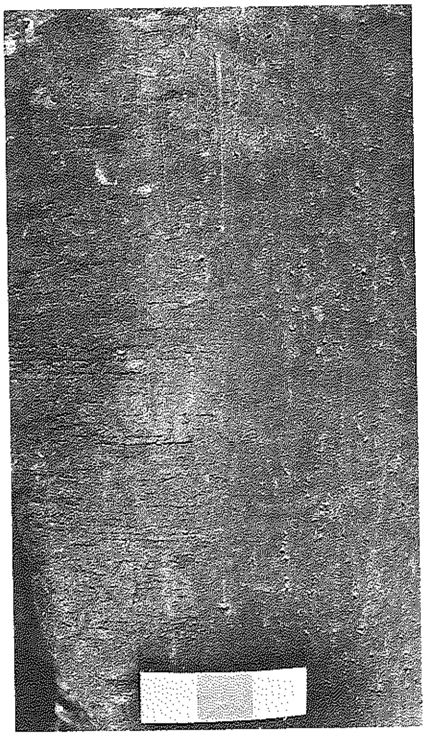

Figure 1
Cardium Formation, facies 1 massive dark mudstones (from Walker, 1983). For comparison with Figures 2, 3 and 4, note absence of silty or sandy laminae, and absence of recognizable burrow forms. Core from well 10-33-34-6W5, 7851 feet (2293.0 m), Caroline Field, Alberta. Scale in cm.

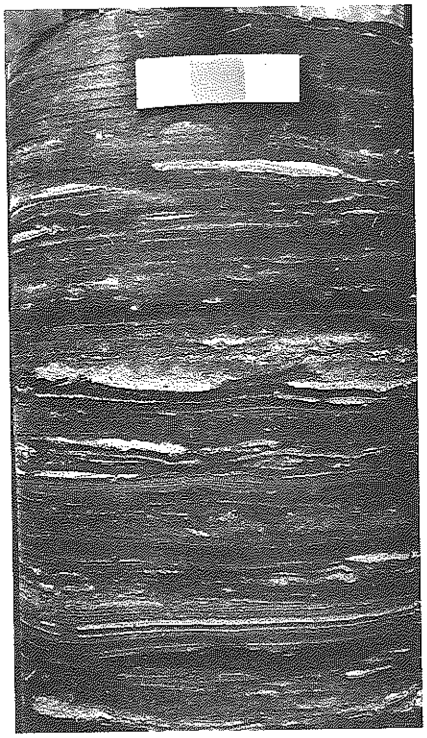

Figure 2
Cardium Formation, facies 2 laminated dark mudstones (from Walker, 1983). Note presence of sharp-based, delicately laminated silty layers (absent in Fig. 1), which are not pervasively bioturbated (compare with Fig. 3). Core from well 8-25-34-5W5, 2098.4 m, between Caroline and Garrington Fields, Alberta. Scale in cm.

Figure 3
Cardium Formation, facies 4 pervasively bioturbated muddy sandstones (from Walker, 1983). Note total bioturbation of silty and sandy layers (compare with Fig. 2), and presence of a few distinct burrow forms - these are better developed in Figure 4. Core from well 10-17-34-7W5, 8390 feet (2557.3 m), between Caroline and Ricinus Fields, Alberta. Scale in cm.

should consult the papers listed in the annotated bibliography, to see how the general principles briefly discussed here can be applied in practise. As one brief example, consider the mudstones and siltstones shown in Figures 1 to 4 from the Upper Cretaceous Cardium Formation of Alberta (Walker, 1983). If one's objective is a detailed study of the hydrocarbon-bearing Cardium sandstones, the examples in Figures 1 to 4 could probably be lumped together as "mudstone or siltstone". But there are clear descriptive differences, involving presence of silty laminations, degree of general bioturbation, and preservation of specific burrow forms. It has turned out that mudstones of Figure 1 only overlie the Cardium "B sand", and mudstones of Figure 2 only overlie the "A sand". Detailed facies subdivision thus happened to define two regional marker horizons (Walker, 1983), which lumping all the mudstones together would not have done.

FACIES SEQUENCE

It was pointed out by Middleton (1978) that "it is understood that (facies) will ultimately be given an environmental interpretation". However, many, if not most, facies defined in the field have ambiguous interpretations – a cross-bedded sandstone facies, for example, could be formed in a meandering or braided river, a tidal channel, an offshore area dominated by alongshore currents, or on an open shelf dominated by tidal currents. Many facies defined in

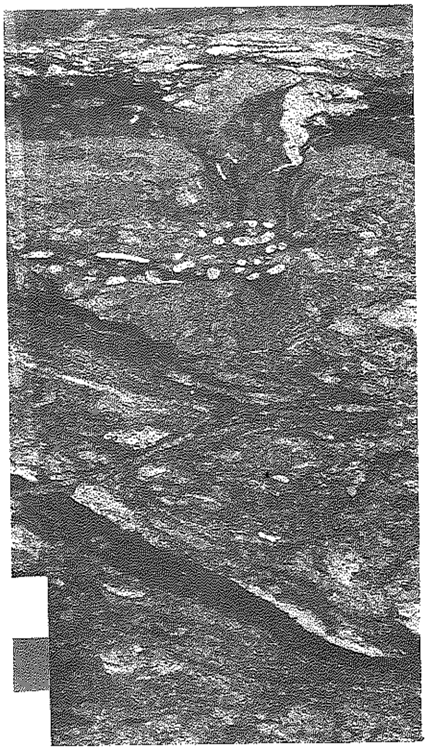

Figure 4 ▶
Cardium Formation, facies 5 bioturbated sandstones (from Walker, 1983). Note excellent development of burrow forms (compare with Figure 3), including prominent Z-shaped Zoophycos burrow, and small vertical tube at top (Conichnus conicus), with later burrowing by Chondrites (white circles/ovals). Core from well 10-20-37-7W5, 2294.1 m, between Caroline and Garrington Fields, Alberta. Scale in cm.

the field may at first suggest no interpretation at all. The key to interpretation is to analyze all of the facies communally, in context. The sequence in which they occur thus contributes as much information as the facies themselves.

The relationship between depositional environments in space, and the resulting stratigraphic sequences developed through time as a result of transgressions and regressions, was first emphasized by Johannes Walther, in his Law of the Correlation of Facies (Walther, 1894, p. 979 — see Middleton, 1973). Walther stated that "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". Careful application of the law, therefore, suggests that in a vertical sequence, a *gradational* transition from one facies to another implies that the two facies represent environments that once were adjacent laterally. The dangers of applying the Law in a gross way to stratigraphic sequences with cyclic repetitions of facies have been emphasized by Middleton (1973, p. 983).

The importance of clearly defining gradational facies boundaries in vertical section as opposed to sharp or erosive boundaries, has been emphasized by de Raaf *et al.* (1965) and Reading (1978, p. 5). If boundaries are sharp or erosional, there is no way of knowing whether two vertically adjacent facies represent environments that once were laterally adjacent. Indeed, sharp breaks between facies, especially if marked by thin bioturbated horizons implying non-deposition (Fig. 5), may signify fundamental changes in depositional environment and the beginnings of new cycles of sedimentation (see de Raaf *et al.*, 1965, and Walker and Harms, 1971, for examples of sharp facies relationships accompanied by bioturbation).

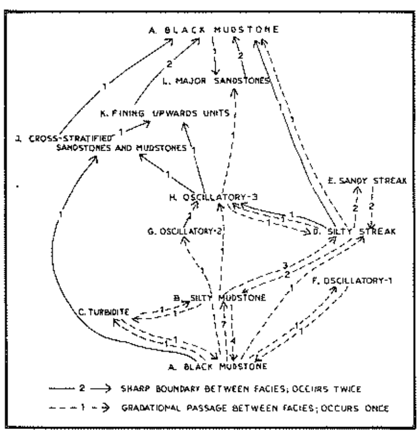

Figure 5
Facies relationship diagram for Carboniferous Abbotsham Formation, North Devon, England. Arrows show nature of transitions, and numbers indicate observed numbers of transitions. This is the first published facies relationship diagram. From de Raaf et al., *1965.*

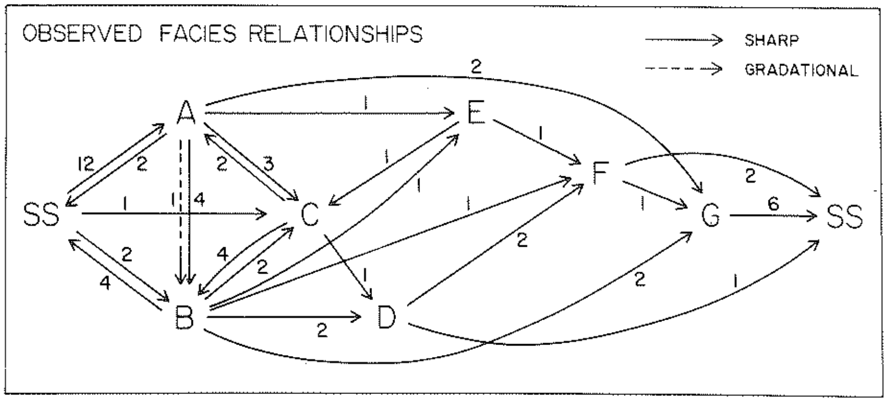

Figure 6
Facies relationship diagram for Battery Point section shown in Figure 8. Numbers indicate the observed number of facies transitions. From Cant and Walker, 1976.

The first formal documentation of the quantitative relationships between facies was published by de Raaf *et al.* (1965; Fig. 5) in a diagram resembling the web of a demented spider. Note that sharp and gradational boundaries have been carefully distinguished. Note also that there are two "spurs" off the main trend of the web (black mudstone to oscillatory 1, and silty streak to sandy streak). These spurs imply that for the purposes of facies transitions, the facies at the end of the spur is completely contained within another facies (e.g., sandy streak within silty streak). This in turn suggests that facies were oversubdivided in the field, and that (for example) sandy streak is a subset of silty streak and could be combined with silty streak for interpretive purposes.

The spider's web is now termed a "facies relationship diagram" - examples are shown in Figures 5 and 6. As geologists have become more concerned with facies transitions, they have sought methods for simplifying the facies relationship diagram to remove the "noise". In essence, methods have involved converting the *numbers* of transitions (Figs. 5 and 6) to observed *probabilities* of transitions (see Walker, 1979, Fig. 2). The observed probabilities are then compared with the probabilities that would apply if all the transitions between facies were *random*. It has been argued that those transitions which occur a lot more commonly than random must have some geological significance.

The problem is to derive a matrix of random probabilities. The method used by Selley (1970), Miall (1973), Cant and Walker (1976) and Walker (1979) is statistically incorrect. In the field, it is assumed that one cannot recognize a transition from one facies to itself. Consequently, a matrix of transition probabilities must have "structurally empty cells" along its main diagonal, where the transition from, say, facies A to facies A cannot be recognized in the field and therefore appears in the matrix as zero. However, Carr (1982) has pointed out that "zeros cannot result from a simple independent random process". Consequently, methods for deriving a random matrix based on absolute facies abundances (as explained by Walker, 1979, in the first edition of *Facies Models)* are incorrect.

There is not space here to explain the more complex methods of Markov chain analysis that must now be used, and the reader is referred to the work of Carr (1982) and Powers and Easterling (1982). Another problem of the "old" method, which involved substracting the random probabilities from observed probabilities, was that there was no way of evaluating the differences statistically. This aspect of facies analysis has been improved by Harper (1984) and is explained in "Improved Methods of Facies Sequence Analysis" (this volume). It applies to entries in the

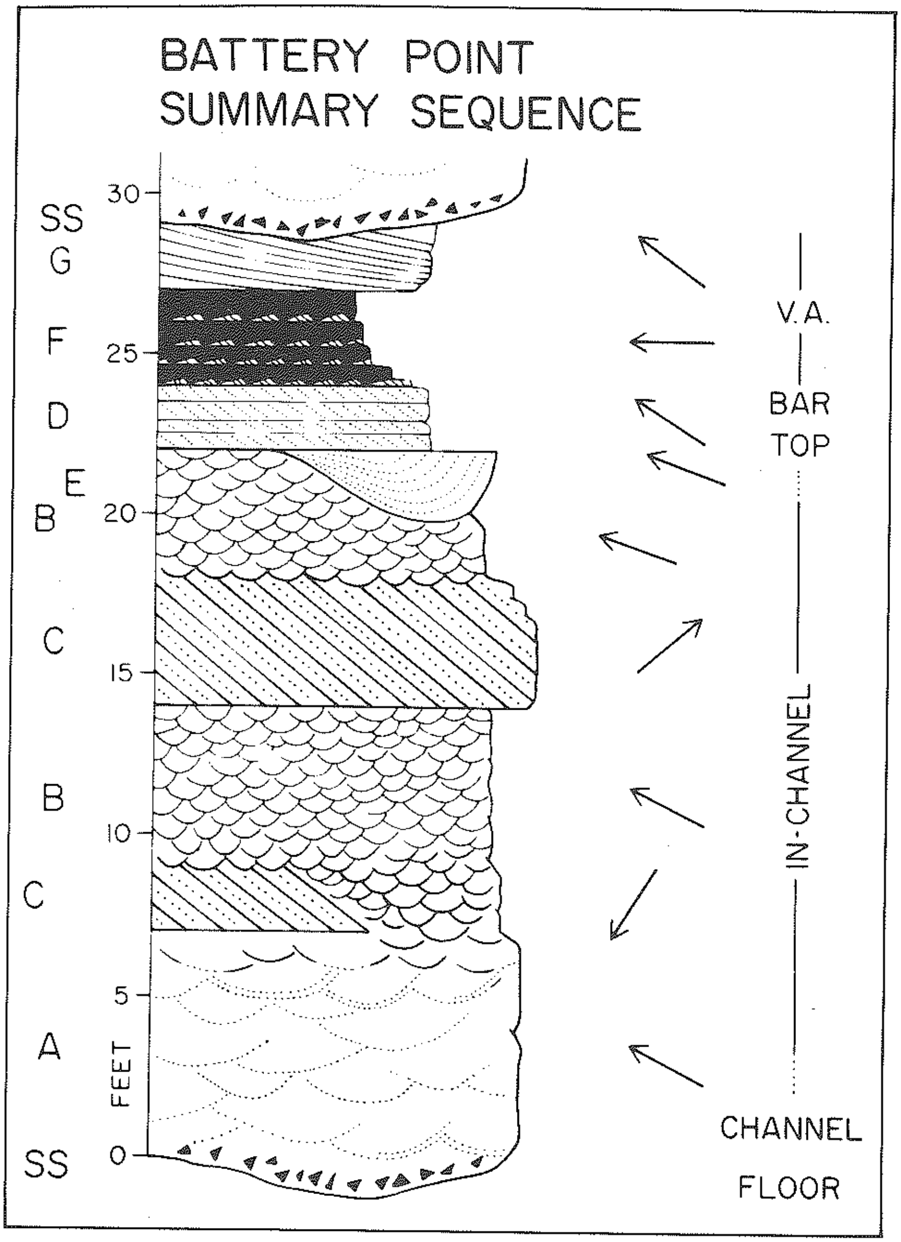

Figure 7
Summary facies sequence expressed as a vertical section. This has the advantage of visual appeal, and allows the facies to be drawn to their observed average thickness. Battery Point Formation, Quebec. From Cant and Walker, 1976.

observed-minus-random matrix that are different from zero, and assumes that a statistically valid random matrix has been derived.

Using Battery Point data from Cant and Walker (1976), Harper ("Improved Methods of Facies Sequence Analysis", this volume) has produced a set of facies transitions where the null hypothesis that the transitions occurred at random can be rejected at a given level of significance. For most of the transitions, that level of significance is less than 0.1 (Harper, this volume, Fig. 1); for E to F, and F to SS the level of significance must be set at 0.13 in order to reject the null hypothesis.

Harper's Figure 1 can be regarded as a simplified facies relationship diagram, or a "distillation" of the Battery Point data. Geologists are most accustomed to seeing transitions of this type expressed as a vertical stratigraphic sequence, and one version of the Battery Point data is shown in Figure 7. This is the original Cant and Walker (1976) version, and has *not* been corrected for the statistical problems discussed above. It should be compared with the raw Battery Point data (Figure 6) and with Harper's simplified facies relationship diagram (Figure 1 of "Improved Methods of Facies Sequence Analysis", this volume). Clearly, the transitions included in a "summary diagram" will depend on the arbitrarily set level of significance that one accepts. By gradually relaxing the level from, say, 0.1 to 0.2, one can attempt to evaluate the *geological* significance of the transitions judged to be different from random. The problems of statistical versus geological significance have been examined in the discussion of Selley's paper (1970, p. 575-581).

The columnar method of presenting the data shows not only the facies *sequence* but also the mean *thickness* of each facies (calculated from the raw data). This is one way in which data can be "distilled" into summary sequences, or "models", as discussed below.

It is now important to distinguish between a single facies sequence, and repeated sequences (or cycles). The summary sequence diagram in Figure 7, with the suggested basic interpretations, established the probably fluvial origin of the Battery Point Sandstone. The scoured surface SS can then be interpreted as the fundamental boundary between cycles, and hence individual cycles can be defined on the original complete stratigraphic section (Fig. 8). Using the summary stratigraphic sequence (Fig. 7) as an idealization of all of the Battery Point sequences (Fig. 8), each individual cycle can be compared with the summary to identify points in common and points of difference. The reader may do this with the sequences in Figures 7 and 8.

FACIES MODELS

The construction and use of facies models continues to be one of the most active areas in the general field of stratigraphy, as is demonstrated by several new books in the field (see bibliography). This emphasis is not new; many of the ideas were embodied in Dunbar and Rodgers' *Principles of Stratigraphy* in 1957, and were based on studies dating back to Gressly and Walther in the 19th Century (Middleton, 1973). Walther (1893, quoted by Middleton, 1973, p. 981) "explained that the most satisfying genetic explanations of ancient phenomena were by analogy with modern

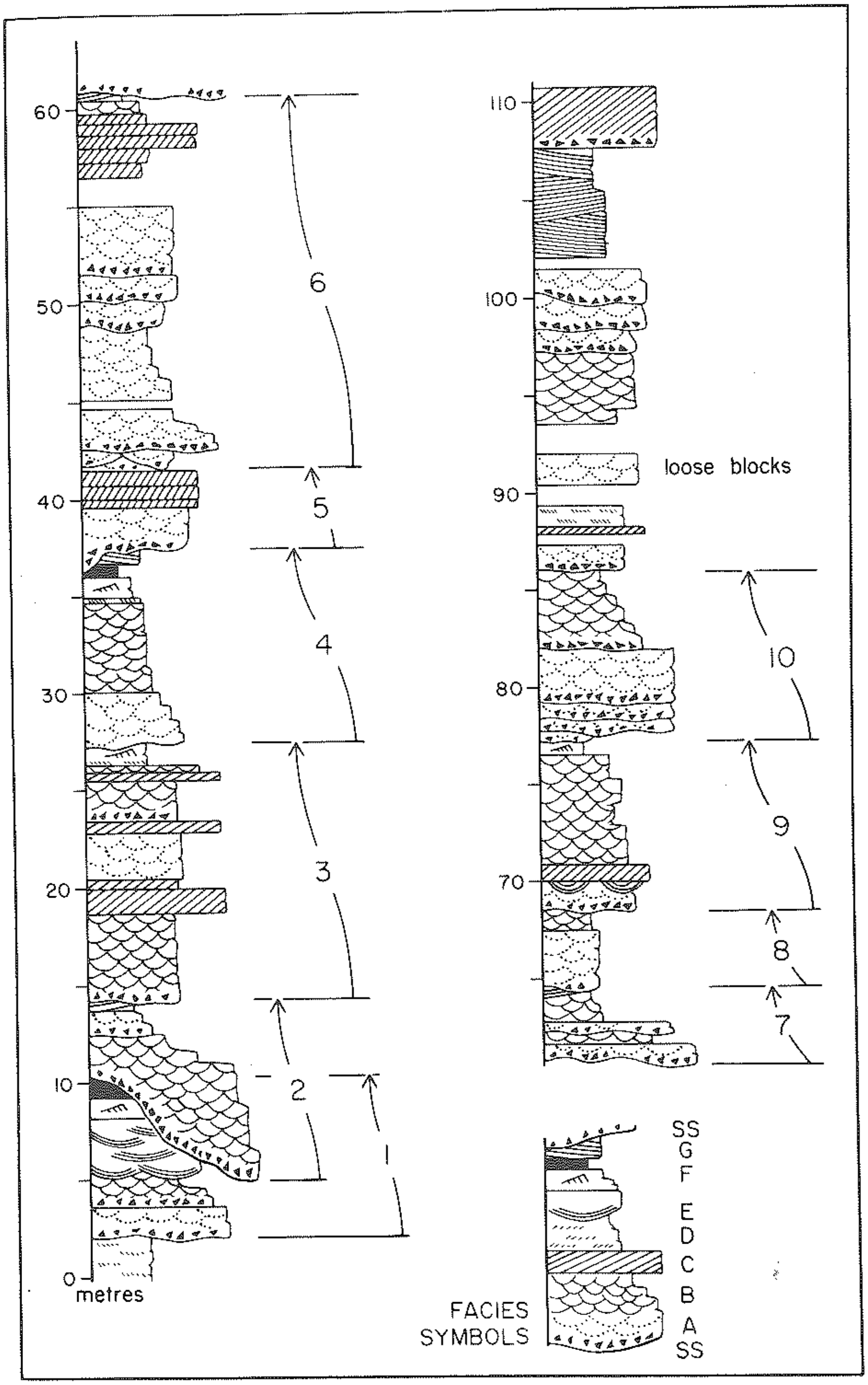

Figure 8
Measured section of the Lower Devonian Battery Point Sandstone near Gaspe, Quebec. Numbers refer to individual channel-fill sequences. From Cant and Walker, 1976.

geological processes". The study of modern environments and processes was termed the "ontological method" by Walther, who observed that "only the ontological method can save us from stratigraphy" (Walther, in Middleton, 1973, p. 883). Facies models similarly link modern and ancient observations into coherent syntheses, and their importance at the present time is due to an increasing need for the models, and a rapidly increasing data base on which the models are formulated.

In this volume, facies models are expressed in several different ways —as idealized sequences of facies, as block diagrams, and as graphs and equations. Examples of all of these are given in "Sandy Fluvial Deposits" (this volume). The term model here has a generality that goes beyond a single study of one formation. The final facies relationship diagram and its stratigraphic section (Fig. 7) are only local summaries, not general models for fluvial deposits. But when the Battery Point facies relationship diagram is compared and contrasted with the facies relationship diagrams from other ancient braided river deposits, and then data from modern braided rivers is incorporated (e.g., Cant, 1978), the points in common between all of these studies begin to assume a generality that can be termed a *model*.

A facies model could thus be defined as a general summary of a specific sedimentary environment, written in terms that make the summary useable in at least four different ways. The basis of the summary consists of many studies of both ancient rocks and recent sediments; the rapidly increasing data base is due at least partly to the large number of recent sediment studies in the last 20 years. The increased need for the models is due to the increasing amount of prediction that geologists are making from a limited local data base. This prediction may concern subsurface sandstone geometry in hydrocarbon reservoirs, the association of mineral deposits with specific sedimentary environments (for example, uraniferous conglomerates), or the movement of modern sand bars in shallow water (Bay of Fundy, tidal power). In all cases, a limited amount of local information plus the guidance of a well-understood facies model results in potentially important predictions about that local environment.

Our aim as geologists is partly to identify different environments in ancient rocks, and also to understand the range of processes that can operate within these environments. We must also be sure of why we want to identify environments in the first place. Is it to provide a name showing that we have thought about the origin of the unit we have mapped ("the Ordovician Cloridorme Formation consists of deep water turbidites"), or is it to provide a framework for further thought? It is the latter – the framework for further thought – that in my mind separates the

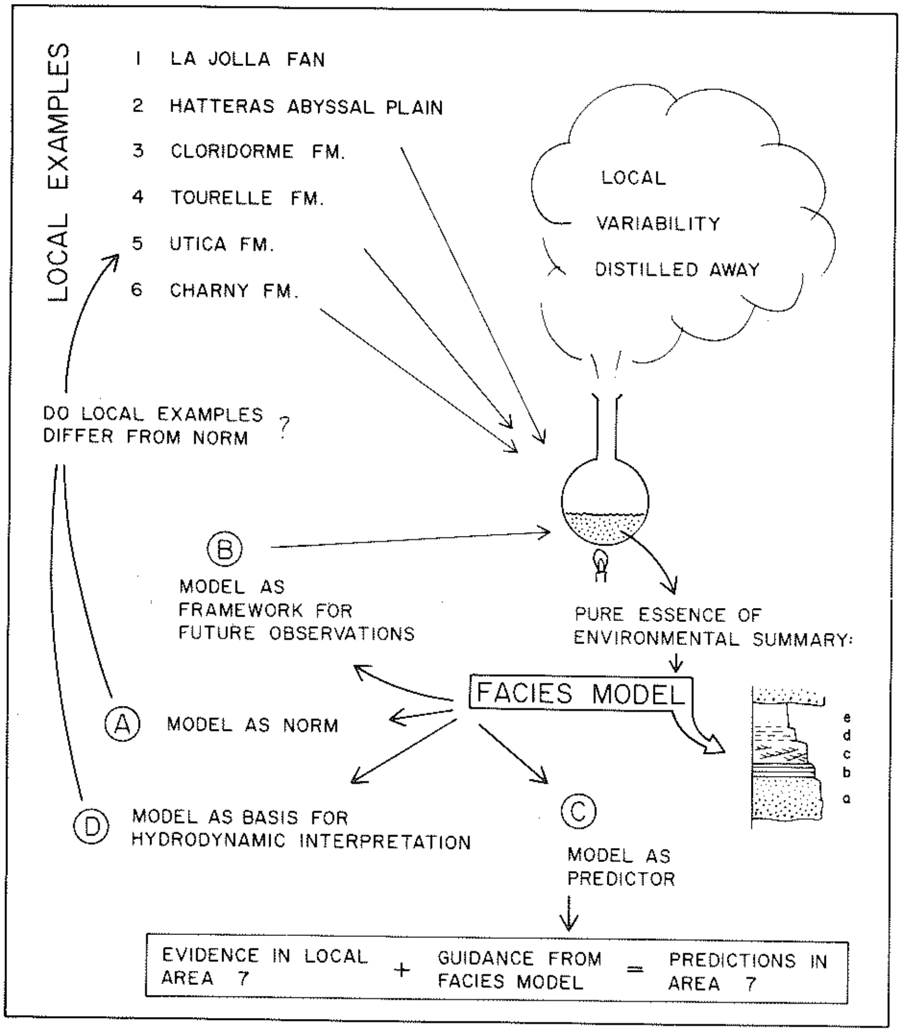

Figure 9
Distillation of a general facies model from various local examples, and its use as a NORM, FRAMEWORK for OBSERVATIONS, PREDICTOR, and BASIS for INTERPRETATION. See text for details.

art of recognizing environments from the art of FACIES ANALYSIS and FACIES MODELLING. The meaning and implication of these two terms will become apparent below.

FACIES MODELS – CONSTRUCTION AND USE

The principles, methods and motives of facies analysis are shown in Figure 9, using turbidites as an example. The principles, of course, apply to all environments. We begin by assuming that if enough modern turbidites can be studied in cores, and if enough ancient turbidites can be studied in the field, we may be able to make some *general* statements about turbidites, rather than statements about only one particular example.

The process of extracting the general information is shown diagramatically in Figure 9, where numbers 1 and 2 represent recent sediment studies (cores from, say, La Jolla fan and Hatteras abyssal plain) and numbers 3 through 6 represent studies of ancient turbidites (for example, the Cloridorme and Tourelle Formations of Gaspe, the Utica Formation at Montmorency Falls, and the Charny Formation around Quebec City). The entire wealth of information on modern and ancient turbidites can then be distilled, boiling away the local details, but distilling and concentrating the important features that they have in common into a general summary of turbidites. If we distill enough individual turbidites, we can end up with a perfect "essence of turbidite" – now called the Bouma model. But what is the essence of any local example and what is its "noise"? Which aspects do we dismiss and which do we extract and consider important? Answering these questions involves experience, judgment, knowledge and argument among sedimentologists, and the answers also involve the ultimate purpose of the environmental synthesis and summary. Some of the different methods for "distilling" the examples will become apparent in the papers in this volume. Facies relationship diagrams could be used if the same facies can be recognized in many different examples. Indeed, "standard" facies classifications have been proposed for turbidite (Mutti and Ricci Lucchi, 1972; Walker, 1978) and braided fluvial (Miall, 1977) environments. More commonly, models are still derived by qualitative comparison and contrast, rather than strict quantitative distillation.

I pointed out earlier that the difference between the summary of an environment and a facies model perhaps depends mainly on the use to which the summary is put. As well as being a summary, a FACIES MODEL must fulfill four other important functions:

1) it must act as a *norm*, for purposes of comparison;
2) it must act as a *framework* and *guide* for future observations;
3) it must act as a *predictor* in new geological situations; and
4) it must act as an integrated *basis for interpretation* of the environment or system that it represents.

Figure 9 has been constructed to illustrate these various functions. Using the example of the turbidite model, the numbers 1 through 6 indicate various local studies of modern and ancient turbidites. There is a constant feedback between examples – in this way the sedimentologist exercises his judgment in defining the features in common and identifying "local irregularities". This is the "distillation" process that allows the environmental summary (that will act as a facies model) to be set up.

Having constructed the facies model, it must act first as a norm (Fig. 9, A) with which individual examples can be compared. Without a norm, we are unable to say whether example 5 of Figure 9 contains any unusual features. In this example, Utica Formation turbidites at Montmorency Falls are very thin, silty, and many beds do not begin with division A of the Bouma model (Fig. 9); they begin with division B or C. Because of the existence of the norm (Bouma model), we can ask questions about example 5 that we could not otherwise have asked, and whole new avenues of productive thought can be opened up this way. Thus there is a constant feedback between a model and its individual examples – the more examples and the more distillation, the better the norm will be, and the more we must be forced into explaining local variations.

The second function of the facies model is to set up a framework for future observations (Fig. 9B). In as much as the model summarizes all the important descriptive features of the system, geologists know that similar information must be recorded when working with a new example. In Figure 9, this would include the detailed characteristics and thicknesses of the five Bouma divisions. Although the framework ensures that this information is recorded wherever possible, it can also act to blind the unwary, who might ignore some evidence because it is not clearly spelled out by the model. This leads to imprecise interpretations, and would cause a freeze on any further improvement of the facies model – hence the feedack arrow (Fig. 9B) implying that all future observations must in turn be distilled to better define the general model.

The third function of a model is to act as a predictor in new geological situations (Fig. 9C). This is hard to illustrate on the small scale of an individual Bouma bed, so let us imagine that we have a generalized facies model for automobiles – four wheels, hood, trunk, doors, etc. The new discovery of an *in situ* radiator by itself might be interesting, but without other information, one might be able to say little more than "nice radiator". With a general model, which ideally expresses the relationship of all the parts of the system, we should be able to predict the rest of the car from the discovery of a radiator. Or we might be able to predict other parts of a submarine fan from one thickening-upward prograding lobe sequence. This is obviously a vitally important aspect of facies modelling, and good surface or subsurface prediction from limited data can save unnecessary exploration guesswork and potentially vast sums of money.

The fourth major function of a facies model is to act as an integrated basis for interpretation (Fig. 9D). Again, it is important to eliminate "noise" before looking for a general interpretation, and hence, there should be feedback between the interpretation and the individual examples (Fig. 9D). This is indicated by the feedback arrow to example 5 (Fig. 9), implying the question "does the interpretation of example 5 differ from the idealized hydrodynamic interpretation?" If there is a difference (and there is), we can again ask questions that could not be asked if we had not used the facies model to formulate a general interpretation. This usage of the facies model is demonstrated particularly well by the Bouma sequence for turbidites, as discussed later in this volume.

The turbidite example of Figure 9 illustrates another point, namely that facies models can exist on different scales. The Bouma sequence for individual turbidite beds is a small scale example, but when turbidites are studied as groups of related beds, the system as a whole is referred to a large scale submarine fan model.

The turbidite/submarine fan example has been discussed above because it is reasonably well understood, and because it illustrates the four functions of a facies model (Fig. 9). Some of the other models discussed in this volume are less well understood – because the environmental summary is weaker, so the functioning of the model is weaker. I emphasize that the construction and functioning of facies models is essentially similar for all environments, and that the turbidite example was discussed above to make the general statements about facies models a little more specific.

Just as there can never be any absolute classification of depositional environments, so there will be differing numbers and types of facies models. As very large scale systems are studied in more detail (e.g., submarine fans), models for sub-components of the system may emerge, such as depositional suprafan lobes, or channel-levee complexes on fans. However, it is probably safest at the moment to emphasize and develop the generality of existing models, rather than encouraging the proliferation of more and more very restricted models. The reason for this suggestion is that given one piece of new information, such as an *in situ* radiator, one might make fairly safe generalizations about automobiles in general. But with many different types of automobile models, one may have problems about assigning the new data to the correct model (is the radiator a Chevrolet or Ford?), and hence run the risk of incorrect predictions. But ultimately, as our understanding improves, subdivision of broad models will be both possible and desirable, as in the case of braided and sandy fluvial models; river-, wave- and tide-dominated deltaic models; and storm- and tide-dominated shallow marine models.

BASIC SOURCES OF INFORMATION

This list is not intended to be complete, but highlights some of the more recent and more important books on depositional environment, facies and facies models. The list is roughly in the order of increasing scope and complexity of coverage of the subject, with Selley as a good place to start, and Reading as the most complete and detailed source.

Selley, R.C., 1970. Ancient sedimentary environments. Ithaca, N.Y., Cornell University Press, 237 p.
Selley introduces the volume as "not a work for the specialist sedimentologist, but an introductory survey for readers with a basic knowledge of geology". The book achieves this end very well – it summarizes, it leans on classical examples, and it very briefly indicates the economic implications (oil, gas, minerals) of some of the environments. This volume is a good place to start.

Blatt, H., Middleton, G.V., and Murray, R.C., 1980. Origin of sedimentary rocks, Second Edition. Englewood Cliffs, N.J., Prentice Hall, 782 p.
Chapter 19, on facies models has been greatly expanded in the second edition, and now summarizes concisely the general principles of facies and facies analysis, and reviews all important depositional environments.

Allen, J.R.L., 1970. Physical processes of sedimentation. New York, American Elsevier, 248 p.
Chapter 11 (p. 439-543) is a review of sand bodies and environments written at a fuller and more technical level than Selley (1970), or Blatt, Middleton and Murray (1980). It considers Alluvial, Deltaic, Estuarine, Tidal Flat, Beach and Barrier, Marine Shelf, Turbidite and Aeolian environments, with separate remarks on sand body prediction. Useful follow-up reading after Selley and Blatt, Middleton and Murray in that order.