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FINE-GRAINED SEDIMENTS: DEEP WATER PROCESSES AND FACIES

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Deep-water fine-grained sediments; history, methodology and terminology

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SUMMARY: To introduce this collection of papers presented at an international research workshop in Halifax, Canada (1982), we highlight briefly three aspects of deep-water fine-grained sediments that are alluded to throughout the volume but never discussed specifically. These are: (a) an historical outline of the research that has made both possible and necessary the workshop and the volume; (b) a review of the methodology currently used in the study of fine-grained sediments; and (c) an assessment of the state of terminology as applied to this class of rocks.

History

The development of knowledge concerning fine-grained sediments in deep water has been closely related to the history of both sedimentology and oceanography, and their interpretation has evolved along with the science of geology as a whole. Major advances within each of these disciplines have, on the one hand, improved our understanding of fine-grained sediments, while on the other hand have acted as significant obstacles to progress in the years immediately following each breakthrough. It is as Kuhn (1970) suggested in his theory of scientific revolutions: the establishment of a paradigm *both* advances an area of study *and* leads to a period of blinkered normal science that serves to elaborate the paradigm but to digress little from it. We can illustrate this with several examples (Fig. 1).

Pelagic sediments

The systematic study of deep-sea sediments and the birth of modern oceanography began with the voyage of HMS Challenger (1872–1876) which established the general morphology of the oceans and the types of sediments they contained. The report on *Deep-Sea Deposits* by Murray & Renard (1891), which documented the calcareous and siliceous pelagic oozes, their microflora and microfauna, the pelagic red clays, and deep marine ferromanganese deposits became the cornerstone of deep-sea sedimentology for over half a century.

Although a major advance over previous knowledge, this new paradigm held that only pelagic clays and biogenic oozes were found in the deep sea and that all coarser-grained clastics were restricted to shallow water or continental environments. It also dismissed any suggestion that rocks now exposed on land were comparable with deep-ocean pelagic sediments. This, therefore, had two main restricting effects on the study of ancient rocks: (a) clastic sediments, other than red clays, were not considered as deep-water; and (b) the interpretation of chalks, cherts and limestones was thrown into confusion. The growing body of evidence that invoked a deep water origin for thick flysch successions (e.g. Lesley 1892; Natland 1933; Bailey 1936; Pettijohn 1943) was held at bay for many years. Similarly, the Alpine geologists who claimed deep-water pelagic successions (e.g. Suess 1875; Fuchs 1877; Steinmann 1905; Heim 1924) and equivalent interpretation in other parts of the world (e.g. Hinde 1890; Molengraaf 1922), had to bide their time before being more generally accepted.

Systematic sedimentology

If Murray & Renard were pioneers of modern oceanography, so Sorby was the father of sedimentology as we know it today. As early as 1861, even prior to the Challenger expedition, he had equated the English Chalk with deep-sea coccolith ooze based on the first reports of coccoliths from Atlantic sediments by Huxley (1858). His paper early in the 20th century (Sorby 1908), *On the application of quantitative methods to the study of the structure and history of rocks*, was equally far ahead of his time and extremely perceptive about fine-grained sediments.

> 'Possibly many may think that the deposition and consolidation of fine-grained mud must be a very simple matter, and the results of little interest. However, when carefully studied . . . it is soon found to be so complex a question, and the results dependent on so many variable conditions, that one might feel inclined to abandon the inquiry, were it not that so much of the history of our rocks appears to be written in this language.'
>
> H.C. Sorby (1908).

It is not entirely clear why his plea for systematic sedimentology was not taken up by students of

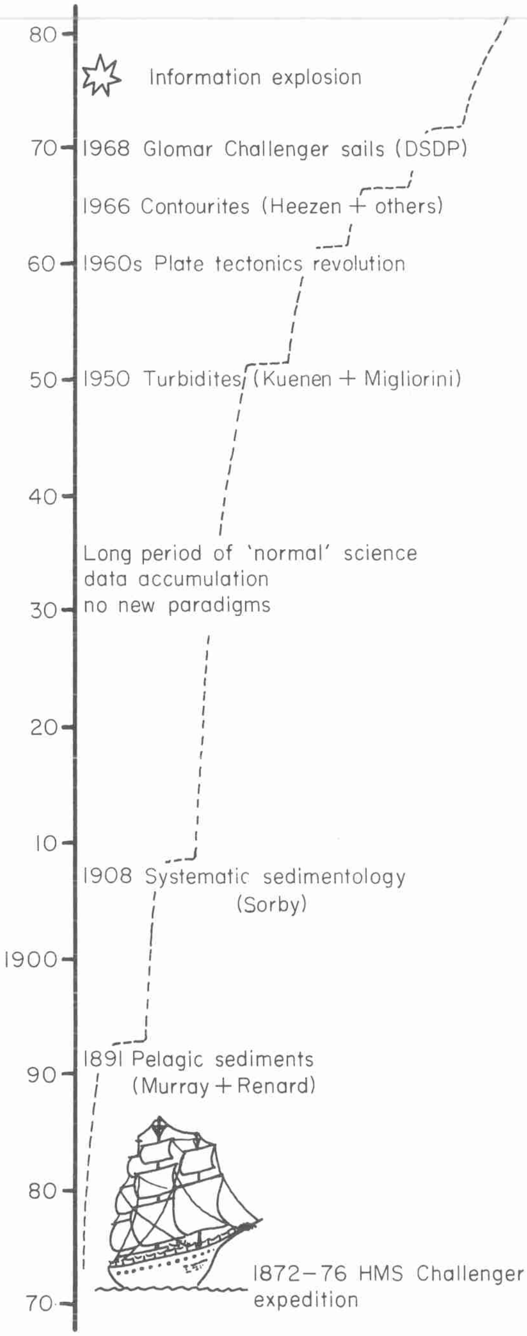


FIG. 1. Historical sketch showing the main concepts that have advanced our understanding of deep-sea fine-grained sediments. The dashed line indicates the stepped increase in our level of understanding, as each new concept (or paradigm) leads both to a significant advance and to period or relative standstill.

shales for so long. Perhaps the rigorous scientific approach was difficult to apply to the finer-grained rocks, or perhaps the methodology was lacking. There were, however, some notable exceptions: Heim's (1924) classic work on Alpine sediments; Archanquelsky's (1927) little known study of Black Sea sediments which he likened to the argillaceous fill of geosynclines; and Ruedemann's (1935) discussion of the ecology and sedimentology of Palaeozoic black shales in the Appalachians.

Turbidite revolution

Walker (1973) has documented the four lines of research that effected the mid-20th century revolution in our thinking about deep-sea sediments. These were: (a) the recovery of varied sediment types other than pelagites on a number of European and American oceanographic expeditions in the first half of the century (e.g. Böggild 1916; Andree 1920; Shepard 1932, 1948; Stocks 1933; Bramlette & Bradley 1940; Arrhenius 1950); (b) the persuasive evidence presented by Daly (1936) and Johnson (1938) suggesting that sediment-laden density currents had excavated submarine canyons as they flowed downslope; (c) a series of flume experiments on both dilute and high-density flows carried out by Kuenen (1937, 1950); and (d) numerous observations of graded sand beds in probable deep-water successions on land (e.g. Natland 1933; Migliorini, 1946). The classic paper *Turbidity currents as a cause of graded bedding* (Kuenen & Migliorini 1950) became the manifesto of the revolution, and stimulated an intense period of systematic field, laboratory and oceanographic studies.

However, attention became focused on the sandstones and coarser-grained sediments to the detriment of the finer-grained material. Much of the interbedded mudstone was dismissed as 'background', 'ubiquitous' hemipelagic sediment. This has been more true of carbonate turbidites and the interbedded calcilutites which are still largely considered pelagic. The Bouma (1962) standard structural sequence for sandy turbidites has stood for a long time as *the* sequence for turbidites, although it is clearly unsatisfactory for resedimented muds and silts or for fine-grained biogenics. This neglect of fine-grained turbidites was largely a consequence of the 1950s concepts of turbidity current dynamics. Although evidence for deposition of mud beds from turbidity currents was recognized (Dzulynski & Kinle 1957) it was thought that little clay could settle out except at velocities that would give only very dilute turbidity currents, so that the deposit would be very thin (Dzulynski *et al.*

1959). Clay deposition was believed to require velocities of less than 1 cm/sec. The observational evidence for deposition of clay from typical turbidity currents could be explained by deposition as faecal pellets or shale chips, ponding, or repeated small turbidity currents (Dzulynski *et al.* 1959).

In the 1960s, it became clear that clay could be deposited from suspension at velocities at which silt and fine sand could be transported (Einstein & Krone 1962), and increasing investigation of core samples clearly demonstrated that thick turbidite muds were a common deep-sea facies (van Straaten 1967; Hesse 1975).

Modern sedimentology

The turbidite revolution also heralded the development of the modern science of sedimentology. Sedimentary structures were recognized as indicators not just of way-up in folded strata, but more importantly of processes (which could be quantified) and hence sedimentation facies and environments (Middleton 1965). Analysis of the sequence of sedimentation facies in a stratigraphic succession, enunciated in the last part of the nineteenth century by Walther (1893), was developed into a standard tool (de Raaf *et al.* 1965). These two techniques lead to the development of the facies model approach (Walker 1976). At the same time, the principles of carbonate rock classification developed by Folk (1959) provided the foundation for a major expansion of understanding of carbonate rock sedimentology accompanied by major investigations of modern shallow-water carbonate environments of Florida, the Bahamas and the Persian Gulf (Folk 1973).

Plate tectonics

The major upheaval in geology that culminated in the early 1960s ideas of sea floor spreading and plate tectonics (Hess 1960; Dietz 1961; Runcorn 1962; Vine & Matthews 1963), had repercussions throughout the discipline. It finally sanctioned the idea that deep oceanic pelagic sediments may be found high up in mountain ranges, and threw new light on our interpretations of the very thick and largely fine-grained fill of geosynclines. It also spawned new major scientific investigation of the ocean basins and their sediments. However, even these undoubtedly profound advances had their drawbacks. In particular, scientific attention and effort was directed towards the large-scale picture, the placing of giant pieces in a new jigsaw puzzle, and this necessarily detracted from detailed sedimentology.

Contourites

Only a decade after the explosion of research on turbidites many sedimentologists were beginning to see flaws in this undoubtedly elegant paradigm. Land geologists repeatedly described examples of 'turbidite' sequences having orthogonal palaeocurrent directions, even from bottom to top of the same bed (e.g. Kelling 1958; Craig & Walton 1962; Ballance 1964; Klein 1966). Marine geologists were documenting many other kinds of evidence that indicated an important role for bottom currents flowing alongslope in deep water (e.g. Heezen 1959; Heezen & Johnson 1963; Hubert 1964). Finally, it was the compilation of evidence by Heezen *et al.* (1966) on *Shaping of the continental rise by deep geostrophic contour currents* that caught the imagination of many more geologists. Stow & Lovell (1979) suggested that this paper marked the beginning of a revolution in sedimentology comparable to the turbidite revolution.

Important though this paradigm has been in adding a new dimension to our understanding of deep-sea processes and fine-grained facies, it has nevertheless proved an obstacle to progress in two respects: (a) research focused initially on sandy contourites and largely ignores muddy contourites, although the latter now appear volumetrically more significant; and (b) many authors apparently jumped onto the contourite bandwagon without a clear appreciation of just how to recognize a contourite, modern or ancient, and hence many erroneous interpretations have been published.

Information explosion

In 1968, nearly 100 years after HMS Challenger set sail, the Glomar Challenger drillship put to sea at the beginning of what was to become the modern equivalent of that historic voyage. By the end of this international scientific mission (late 1983) nearly 100 separate legs of the expedition had been completed and over 600 holes drilled into the deep ocean floor. At the same time, many extensive national marine programmes have ventured into the deep sea; wide-ranging international, national and individual work has been carried out on land; and an enormous amount of geological data has been obtained in the search for hydrocarbons.

Moreover, fine-grained sedimentology no longer takes the back seat. Research has included the muddy turbidites and contourites, hemipelagites, and fine biogenic oozes, red clays and black shales; the processes and controls on the dispersion and deposition of these facies; their micro-characteristics and physical properties; the compaction, disgenesis and association with both hydrocarbon generation and metallic ores.

Clearly, it is difficult to assess the historical significance of such research and, similarly, difficult to see where we are being short-sighted or blinkered by new paradigms. One factor that mitigates against progress is the sheer volume of data now available, mostly undigested and not assimilated into the mainstream of knowledge. It is this information explosion that has made it necessary to focus our attention so narrowly for this workshop and volume in the hope that it may thus be able to contribute a little towards the synthesis and understanding of one small class of rocks.

Methodology

Part of the reason that the study of fine-grained sediments has for so long lagged behind that of coarser-grained rocks is related to methodology. Although the approach and techniques are largely the same, there are certain problems unique to the fine end of the grain-size spectrum. These include: (a) the resolution of the individual particles, often less than 5 μm in diameter, requires high-powered instrumentation and routine use of electron microscopy; (b) fine-grained rocks cannot be adequately characterized in the field or from cores: laboratory-based analyses are imperative; (c) because clays flocculate, textural analysis cannot be easily used to infer hydrodynamic processes (in contrast to sands); and (d) the dramatic post-depositional changes suffered by clays and fine biogenic material often make it extremely difficult to reconstruct the sediment characteristics at the time of deposition.

However, these problems are by no means insurmountable. Many standard techniques are now successfully applied to fine-grained sediments, and new methods or refinements continually being developed. Coulter counters are routinely used for grain-size analysis, scanning electron microscopy for fabric, structure and composition, X-ray diffraction and X-ray fluorescence for mineralogy and geochemistry, CHN analysis for organic carbon determination, induction magnetometers for measuring the anisotropy of magnetic susceptibility, and X-radiography for study of sedimentary structures. In order to fully understand and accurately interpret a given sedimentary succession, it is important that the study be approached from many directions, at different scales of operation and employing a wide range of methods. For fine-grained sediments in particular, it is crucial that field examination is combined with laboratory analysis.

Perhaps the best general approach to use is that described by Potter *et al.* (1980) as the 'Question Set Approach'. They developed a series of questions for the study of shale (mudrock) successions, that help to lead the investigator through the required series of techniques and analyses at the micro, meso and macro scales. We have reproduced their Question Set below (Table 1). Clearly, each particular study might require a modified question set, especially studies of fine-grained biogenic sediments, for example. In addition, many investigators might choose to study in greater detail just one aspect of the whole (e.g. clay fabric, sediment grain-size, etc) but it is nevertheless useful to see where this micro-study fits into the overall picture.

Clearly, we do not intend to describe all the variety of methods used in this short introduction. Instead we list below (Table 2) the main source books on methodology with a brief comment on their relevance to the study of fine-grained sediments.

Terminology

Fine-grained sediments are those rocks, both hard and soft, biogenic and clastic, that have a dominant grain size in the clay or silt grades (i.e. over $50\% < 63\ \mu$m). *Deep-water* implies anything below wave base (say about 50m) and so includes the deeper shelf areas, shelf basins and deep lakes as well as the open ocean basins and marginal seas. Most of the papers in this volume, however, are concerned with sediments deposited at oceanic depths greater than about 200m.

As a discipline grows, so the terminology within that discipline proliferates and confusion is inevitable. However, it is clearly important for improved communication within that discipline, as well as within the earth sciences as a whole (e.g. between sedimentologists and engineers), that a generally-accepted standard terminology is widely used. Fortunately, the state of confusion in the terminology applied to fine-grained sediments is not yet too severe, and so we are able here to propose a degree of standardization. We outline first a purely descriptive terminology for fine-grained sediment classification and description and, second, some of the terms used in the interpretation of deep-water facies.

Descriptive terminology

Classifications of fine-grained sediments have been based most commonly on texture and

TABLE 1. *Question set for study of shale (mudrock) sequence (from Potter et al. 1980)*

Describing outcrops and cores and using wire-line logs

1. Where is the section?
2. What are the major units?
3. What is to be done next?
4. What should be described?
5. What terms should be used in the field for the description of the major lithologic types of shales?
6. How should the observations be recorded?
7. What palaeontologic observations can and should be made in the field?
    a. Relative abundances of different macrofossils?
    b. Is the distribution of macrofossils patchy, uniform, or random? Are they concentrated within beds or on bedding planes?
    c. Are the macrofossils intact and well preserved or fragments and worn? Molds or casts? Recrystallized or replaced?
    d. What functional types of organisms are present? Encrusters, sediment trappers or binders, epifauna, or infauna? Mobile or sessile? Suspension feeders, deposit feeders, scavengers, or predators?
8. What is the gamma-ray profile—what is it good for and how is it obtained?
9. Wire-line logs—what are they and how can they be best used?
10. Why and how to describe cuttings?

Laboratory studies

1. What samples should be selected?
2. What tools and techniques should be used?
3. What sequence of study should be followed?
4. How should the observations be recorded?
5. What components are present, what is their abundance, and what do they all mean (fundamental to the understanding of every rock, the key questions are always the same)?
    a. Large detrital grains, such as quartz, feldspar micas, heavy minerals, and carbonate grains?
    b. Detrital clays?
    c. Authigenic grains, including carbonates (calcite, dolomite, and siderite), quartz, feldspar, zeolites, and the authigenic clays, glauconite, sepiolite, etc.?
        i. How are authigenic minerals recognized in a mudstone or shale? Those formed after deposition either by precipitation in pores or by transformation of original detrital minerals (by solution and replacement).
        ii. Significance?
    d. Mineral cements, such as silica, carbonate, or zeolites?
    e. Floccules?
    f. Pellets and pelaggregates?
    g. Organic particles?
    h. What can be learned from micropalaeontology and palynology?
6. What textural parameters should be measured and what do they mean?
    a. What proportions of clay, silt, and sand?
    b. Percentage of large micas?
    c. Size ranges and modes of diverse detrital grains?
    d. How well oriented are the different components of the shale sediment—the clay minerals, the silt and sand grains commonly found in them—and what significance, if any, does their orientation have for palaeocurrents?
        i. Perfection of framework orientation?
        ii. Silt and sand grains?
    e. Burrowed and/or mottled textures?
    f. Pore geometry—kinds and amounts?
    g. Is there any significance to the shape of shale cuttings?
    h. What can be seen by radiography?
7. What name is to be used and how should the shale be classified now that we know so much about it?
8. The petrographic report: What is the best way to organize the foregoing petrology and texture into a useful, concise, and coherent petrographic report?
9. What can be learned from the study of inorganic geochemistry?
    a. The major elements?
    b. The trace elements?
    c. Exchangeable cations?
    d. Pore-water chemistry?
    e. Stable isotope geochemistry?
10. Organic chemistry?
    a. What are the best indicators of thermal history?
    b. What does the study of palaeobiochemical indicators tell us?

Making a synthesis and basin analysis

1. Where did the mud come from?
2. How was it transported to its final depositional site?
3. At what water depth, sedimentation rate, oxygenation, and toxicity to life was the mud deposited?
4. What has happened to the mud since deposition?

TABLE 2. *Principal texts on methods in sedimentary geology*

BOUMA, A.H. 1969. *Methods for the Study of Sedimentary Structures*. Wiley-Interscience, New York. 446 pp.
Comprehensive for sedimentary structures. Good on X-radiography, graphical presentation, impregnation.

BRINDLEY, G.W. & BROWN, G. (eds) 1980. Crystal structures of clay minerals and their X-ray identification. *Mineral. Soc. Monograph.* No **5.**
The most thorough and up-to-date reference for clay mineralogy and methods.

CARVER, R.E. 1971. *Procedures in Sedimentary Petrology*, Wiley-Interscience, New York. 653 pp.
One of the most comprehensive books on laboratory techniques. Covers sedimentary structures, grain size, grain attributes, and textural, mineralogical and chemical analyses. Lacks many techniques developed over the past 10–15 years.

COMPTON, R.R. 1962. *Manual of Field Geology*. John Wiley, New York. 378 pp.
Early but thorough treatment of what to do in the field.

CONYBEARE, C.E.B. & CROOK, K.A.W. 1968. *Manual of Sedimentary Structures*. Australian Dept. Natl. Development. Bull. Bur. Min. Res. Geol. & Geophys. **102,** 327 pp.
A useful guide to structures in all types of sediments.

FLÜGEL, E. 1982 (english edition), *Microfacies Analysis of Limestones*. Springer-Verlag, New York, Berlin, 633 pp.
Does not detail methods used in the study of limestones at any great length, but has wide-ranging coverage and extensive references.

FOLK, R.E. 1974. *Petrology of Sedimentary Rocks*. Hemphill Pub. Co., Austin, Texas. 159 pp.
General sedimentology text with useful sections and references on methodology.

FREY, R.W., (ed.) 1975. *The Study of Trace Fossils*. Springer-Verlag, New York.
Useful illustrations of trace fossils in sediments.

GRIFFITHS, J.C. 1967. *Scientific Method in the Analysis of Sediments*. McGraw-Hill, New York. 508 pp.
Good on texture, fabric, composition, data processing and statistics.

KUMMEL, B. & RAUP, B. (eds) 1965. *Handbook of Paleontological Techniques*. Freeman & Co., San Francisco. 852 pp.
Still one of the most thorough books on palaeontological techniques.

MULLER, B. 1967. *Methods in Sedimentary Petrology*. Hafner.
Fairly comprehensive, but slightly dated.

PETTIJOHN, F.J. & POTTER, P.E. 1964. *Atlas and Glossary of Primary Sedimentary Structures*, Springer-Verlag, New York. 370 pp.
Well-illustrated guide to structures in all rock types.

POTTER, P.E., MAYNARD, J.B. & PRYOR, W.A. 1980. *Sedimentology of Shale*, Springer-Verlag, New York. 303 pp.
Informative study guide and reference source for shales, including guide and references to methodology.

TUCKER, M.E. (1982). *The Field Description of Sedimentary Rocks*. Open University Press, Milton Keynes, UK and Halsted Press, New York. 112 pp.
A useful field manual covering all sedimentary rock types.

composition and secondarily on fissility, colour, degree of metamorphism and depositional environment. We propose here a twofold division of fine-grained sediments into *mudrocks*, with an implied siliciclastic composition, and, *biogenic mudrocks*, having either a calcareous or siliceous composition (Tables 3 and 4). The term *mudrock* seems more appropriate than *shale* although both are widely used as general class names (e.g. Potter *et al.* 1980). In subdividing the two groups we have tried to use generally-accepted simple terms that can be readily applied in the field and subsequently modified by the appropriate descriptors after laboratory analysis.

The terminology presented in Table 2 is broadly in line with that proposed by many previous authors (e.g. Wentworth 1922; Ingram 1953; Shepard 1954; Dunbar & Rogers 1957; Folk 1968; Picard 1971; Weser 1974; Pettijohn 1975; Blatt *et al.* 1980; Potter *et al.* 1980). It is also commonly used by sedimentologists, marine geologists, engineers and soil scientists. Minor differences that exist between classification systems are mainly concerned with the exact percentage of sand that a mud must contain before it becomes a sandy mud, and so on. We suggest it is better to keep the terms more general in application, so that the textural or compositional contents are estimates rather than strict definitions. Mixtures of sand, silt and clay are commonly displayed graphically on triangular diagrams (Fig. 2).

Colour, chemical composition or genetic terms can be used as additional descriptors to the basic terms as appropriate (e.g. black shale, uraniferous mudstone). These, and mineralogical terms such as chlorite illite mudstone, are mainly applicable only after detailed laboratory investigations. Spears (1980) notes that the percentage of quartz in mudrocks is generally proportional to the grain-size or siltiness. In ancient well-lithified rocks it is often simpler to estimate quartz-content than grain size directly, particularly by laboratory methods, but the same basic terminology should still be applied. Lewan's (1979) attempt to erect a laboratory classification of very fine-grained sediments is also based on textural

TABLE 3. *Mudrock terminology (after Stow 1981)*

	Mudrock (> 50% less than 63 μm)		
Basic terms			
Unlithified	*Lithified/non-fissile*	*Lithified/fissile*	*Approx. proportions/grain-size*
Silt	Siltstone	Silt-shale	$> \frac{2}{3}$ silt-sized (4–63 μm)
Mud	Mudstone	Mud-shale	silt and clay mixture (< 63 μm)
Clay	Claystone	Clay-shale	$> \frac{2}{3}$ clay-sized (< 4 μm)
Metamorphic terms			
Argillite	slightly metamorphosed/non-fissile		silt and clay mixture
Slate	metamorphosed/fissile		silt and clay mixture
Textural descriptors	*Approx. proportions*		
Silty	$> 10\%$ silt-size		
Muddy	$> 10\%$ silt- or clay-size (applied to non-mudrock sediments)		
Clayey	$> 10\%$ clay size		
Sandy, pebbly, etc	$> 10\%$ sand-size, pebble-size, etc.		
Compositional descriptors	*Approx. proportions*		
Calcareous	$> 10\%$ $CaCO_3$ (foraminiferal, nannofossil, etc)		
Siliceous	$> 10\%$ SiO_2 (diatomaceous, radiolarian, etc)		
Carbonaceous	$> 1\%$ Organic carbon		
Pyritiferous Ferruginous Micaceous and others	Commonly used for contents greater than about 1–5%		

criteria and compositional modifiers. However, his redefinition of mudstone, shale, claystone and marlstone are not very helpful.

Pelite and lutite (pelitic and lutaceous) are synonymous with mudstone (muddy) and are not recommended terms, particularly since pelite is widely used to indicate a metamorphic rock. Siltite for siltstone is also a redundant term. Argillaceous sedimentary rock is more conveniently replaced by mudrock, but argillaceous as a strictly compositional term (meaning rich in clay minerals) is still useful in certain cases.

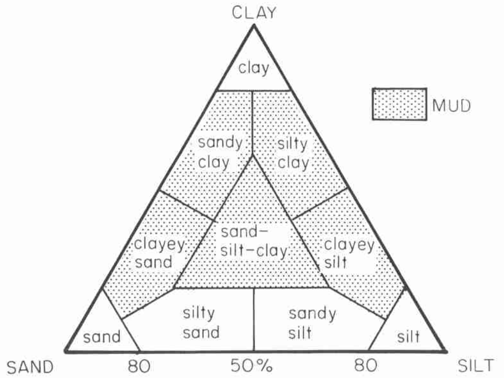


FIG. 2. Terminology for sand-silt-clay sediment admixtures (after Shepard 1954). The shaded area denotes *mud*, a term much used for silt-clay mixtures following Folk (1968).

The terminology for biogenic mudrocks shown in Table 4 follows closely the various systems in common use (e.g. Gealy *et al.* 1971; Weser 1974; Berger 1974; Davies *et al.* 1977). Dean *et al.* (1984) have proposed that a more formal intermediate category is needed between ooze and mud for mixtures of biogenic material and mud (Fig. 3). They recognized *marl* as a very common and useful term for calcareous biogenic muds and introduced *sarl* for siliceous biogenic muds and *smarl* for mixed calcareous and siliceous biogenic muds. The general term for sediments in this category therefore becomes *arl.*

Descriptors of all kinds (composition, texture, colour, etc.) can then be applied to the basic terms as for the siliciclastic sediments. A single descriptor indicates the dominant component, and a second descriptor (added at the beginning) indicates the second most important component when applied to oozes and muddy oozes (arls).

Further classifications of lithified carbonate rocks, commonly after laboratory analyses, should follow the systems proposed by Folk (1959) or Dunham (1962). The former is based on the type of carbonate particle (ooliths, skeletal grains, pellets) and the type of cement (microcrystalline micrite or macrocrystalline sparry calcite). The latter is concerned more with the relative proportions of matrix and discrete particles. The terms *calcilutite* and *calcisiltite*, together with *calcarenite* and *calcirudite* for coarser-grained carbonates, can be useful when the grain-size of

TABLE 4. *Biogenic mudrock terminology*

	Biogenic mudrock (50% biogenic, 50% less than $63\ \mu m$)	
Basic terms		
Unlithified	*Lithified*	*Approx. proportions*
Ooze	chalk, limestone, diatomite, chert, etc.	$> 2/3$ biogenic
Muddy ooze*	Argillaceous chert, chalk etc.	biogenic/terrigenous mix
Mud	mudstone	$> 2/3$ terrigenous
Descriptors	*Approx. proportions*	
Calcareous	e.g. siliceous ooze, biogenic $SiO_2 > 50\%$	
Siliceous	foraminiferal ooze, forams $> 50\%$	
Foraminiferal	foraminiferal-nannofossil ooze, forams & nannos $> 50\%$ with nannos dominant	
Diatomaceous	diatomaceous muddy ooze, diatoms dominant biogenic component	
Radiolarian etc.	calcareous mud, $30\% > CO_3 > 10\%$	
Carbonaceous	organic carbon $> 1\%$	

* Dean et al (1984) suggest Arl = muddy ooze hence marlstone, sarlstone, smarlstone.

the rock is considered its most important feature as, for example, with resedimented carbonates.

Another area of descriptive terminology in which there is often confusion is that applied to sedimentary structures, and in particular to *lamination* and bedding. The most widely accepted system for stratification thickness is that of Ingram (1954) shown below (Table 5).

Grading can be either *positive* (normal) in which the grain-size decreases upwards, or *negative* (reverse) in which the grain-size increases upwards. This is commonly applied to a single bed or discrete unit. Series of beds that show an overall grain-size change are termed *fining-upward* or *coarsening-upward* sequences, although this usually refers only to the coarser (silt or sand) beds within the sequence. Similarly, *a graded laminated unit* is an interval (commonly 2–20 cm thick) through which discrete silt laminae, separated by a finer-grained mud, show an overall upward decrease in grain-size. The terms massive, homogeneous and structureless are used synonymously to mean an ungraded and featureless sediment.

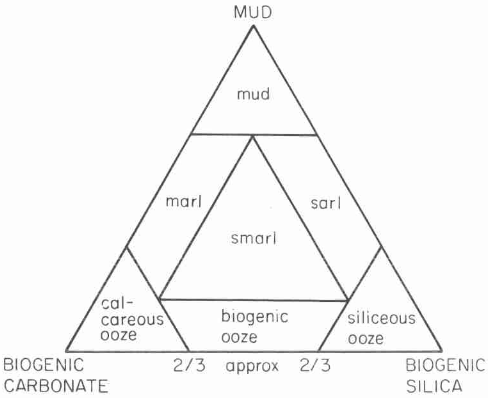


FIG. 3. Terminology for biogenic carbonage, biogenic silica and terrigenous mud mixtures (as proposed by Dean *et al.* 1984).

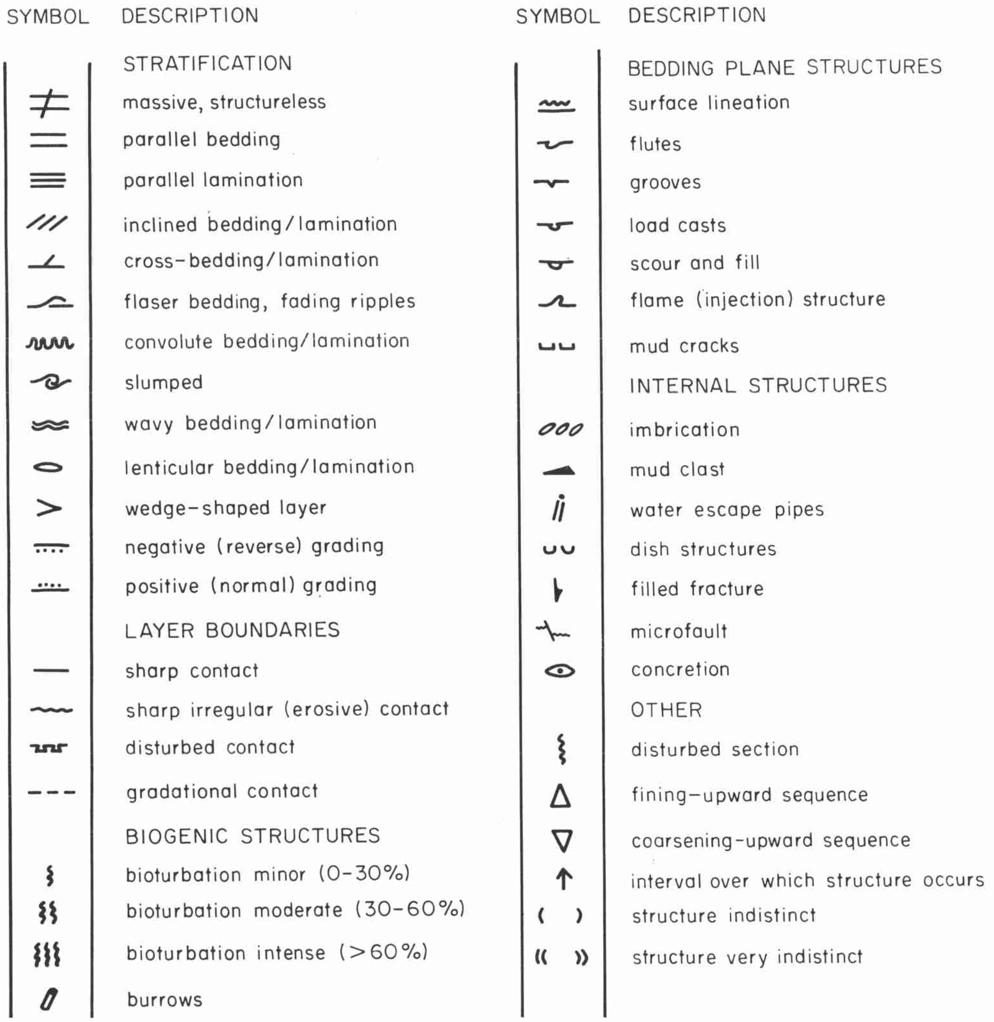
In Fig. 4 we list the common sedimentary structures encountered in fine-grained sediments and show the symbols most often to represent them graphically. Standardization in this aspect of description and terminology would be very helpful.

TABLE 5. *Stratification types and thicknesses (after Ingram 1954)*

Very thickly bedded	> 1 m
Thickly bedded	30–100 cm
Medium bedded	10–30 cm
Thinly bedded	3–10 cm
Very thinly bedded	1–3 cm
Thickly laminated	3–10 mm
Thinly laminated	1–3 mm
Very thinly laminated	< 1 mm

Interpretative terminology

The first phase of a study is, clearly, to describe the sediments and their characteristics, as far as possible objectively and using a standard format. The second phase involves interpretation of these primary data in terms of depositional processes, environmental setting, stratigraphic position and so on. International stratigraphic terminology is



SYMBOL	DESCRIPTION
	STRATIFICATION
	massive, structureless
=	parallel bedding
≡	parallel lamination
///	inclined bedding/lamination
	cross-bedding/lamination
	flaser bedding, fading ripples
	convolute bedding/lamination
	slumped
≈	wavy bedding/lamination
	lenticular bedding/lamination
>	wedge-shaped layer
	negative (reverse) grading
	positive (normal) grading
	LAYER BOUNDARIES
—	sharp contact
~	sharp irregular (erosive) contact
	disturbed contact
---	gradational contact
	BIOGENIC STRUCTURES
	bioturbation minor (0–30%)
	bioturbation moderate (30–60%)
	bioturbation intense (>60%)
	burrows

SYMBOL	DESCRIPTION
	BEDDING PLANE STRUCTURES
	surface lineation
	flutes
	grooves
	load casts
	scour and fill
	flame (injection) structure
	mud cracks
	INTERNAL STRUCTURES
	imbrication
	mud clast
	water escape pipes
	dish structures
	filled fracture
	microfault
	concretion
	OTHER
	disturbed section
Δ	fining-upward sequence
∇	coarsening-upward sequence
↑	interval over which structure occurs
( )	structure indistinct
(( ))	structure very indistinct

FIG. 4. Typical sedimentary structures and recommended graphic symbols (modified from Bouma 1962, and DSDP schemes).

well established (Hedberg 1976; Holland *et al.* 1978).

Environmental terms present more of a problem, particularly with regard to interpretation of palaeoenvironments. Deep-water morphological environments in which fine-grained sediments accumulate have been initially defined in large oceans (Heezen *et al.* 1959) as continental *shelf* (especially outer shelf), *slope, rise* and *abyssal plain*. The terms *basin slope*, *basin rise* and *basin plain* are more applicable to smaller basins (such as in the Mediterranean sea or California Borderland). *Deep-sea fans* are large morphogenetic environments that include both rise and plain settings.

Many terms have been applied to particular subenvironments or morphological elements within these larger-scale settings (e.g. Stow, in press). The most common include canyons, channels, gullies, levees, interchannel areas, lobes, slump masses, debris-flow masses, slump scars, sediment drifts, upper, middle and lower fans, and so on. Such present day morphological features are easily recognized by acoustic profiling in the oceans, but their recognition in ancient rock sequences requires a detailed knowledge of stratigraphic relationships and large-scale facies associations and sequences. This is particularly difficult in fine-grained rocks because of their paucity of diagnostic facies indicators and their common high degree of tectonic deformation. Extreme caution should therefore be used in

TABLE 6. *Deep-water fine-grained sediment facies (from Stow & Piper, this volume)*

Facies	*Characteristics*		*Depositional process*
Silt turbidite	> 50% silt	standard structural sequence	turbidity current
Mud turbidite	> 50% mud		
Biogenic turbidite	> 50% biogenics		
Disorganized turbidite	mud or biogenics or mixture	no sequence	
Silty (sandy) contourite	> 50% silt or fine sand size	commonly mixed biogenic-terrigenous, irregular 'sequence', bioturbated.	bottom (contour) current
Muddy contourite	> 50% mud size		
Pelagic ooze	> 2/3 biogenic (planktonics)	no structural sequence, rhythmic inter-bedding common, bioturbated	pelagic settling
Hemipelagite	biogenic-terrigenous mix		
Pelagic clay	> 2/3 terrigenous clay (mud).		

making palaeoenvironmental interpretations for ancient fine-grained rock successions.

There are three main groups of processes by which fine-grained sediments are deposited in the deep-sea (Gorsline, this volume; McCave, this volume). (a) *Resedimentation* processes (synonymous with mass gravity transport) are all those processes that move sediment downslope over the sea floor from shallower to deeper water and that are driven by gravitational forces. For fine-grained sediments the most important of these are slides and slumps, sediment creep, debris-flows and turbidity currents. (b) *Normal bottom currents* are all those deep currents that erode, transport and deposit sediment on the sea floor and that are driven by normal thermohaline or wind-driven circulation within the oceans. They include, internal tides and waves, canyon currents, bottom (contour) currents and deep surface currents. (c) *Pelagic settling* through the water column is an ubiquitous, slow and predominantly vertical process under the influence of gravity. Much of the sediment settles as flocs and faecal pellets rather than individual particles.

Fine-grained sediment facies in deep water can mostly be interpreted in terms of these depositional processes, although it must be recognized that the processes are in fact part of a continuum, and that a similar continuum of facies therefore exists. Stow & Piper (this volume) have identified nine separate facies models (Table 6), each related to a specific depositional process and each characterized by a standard sequence of structures or a standard suite of sedimentary features.

We suggest that these facies models, although not exhaustive of the possible processes and facies in the deep sea, are all relatively well documented and understood. Until similar evidence exists for other facies (e.g. the 'nepheloidites' or 'suspension cascadites' invoked by some authors), it seems better not to use the terms. Similarly, purely descriptive facies terms such as 'laminites' and 'unifites' would be better replaced by the standard descriptive terminology outlined previously.

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Processes