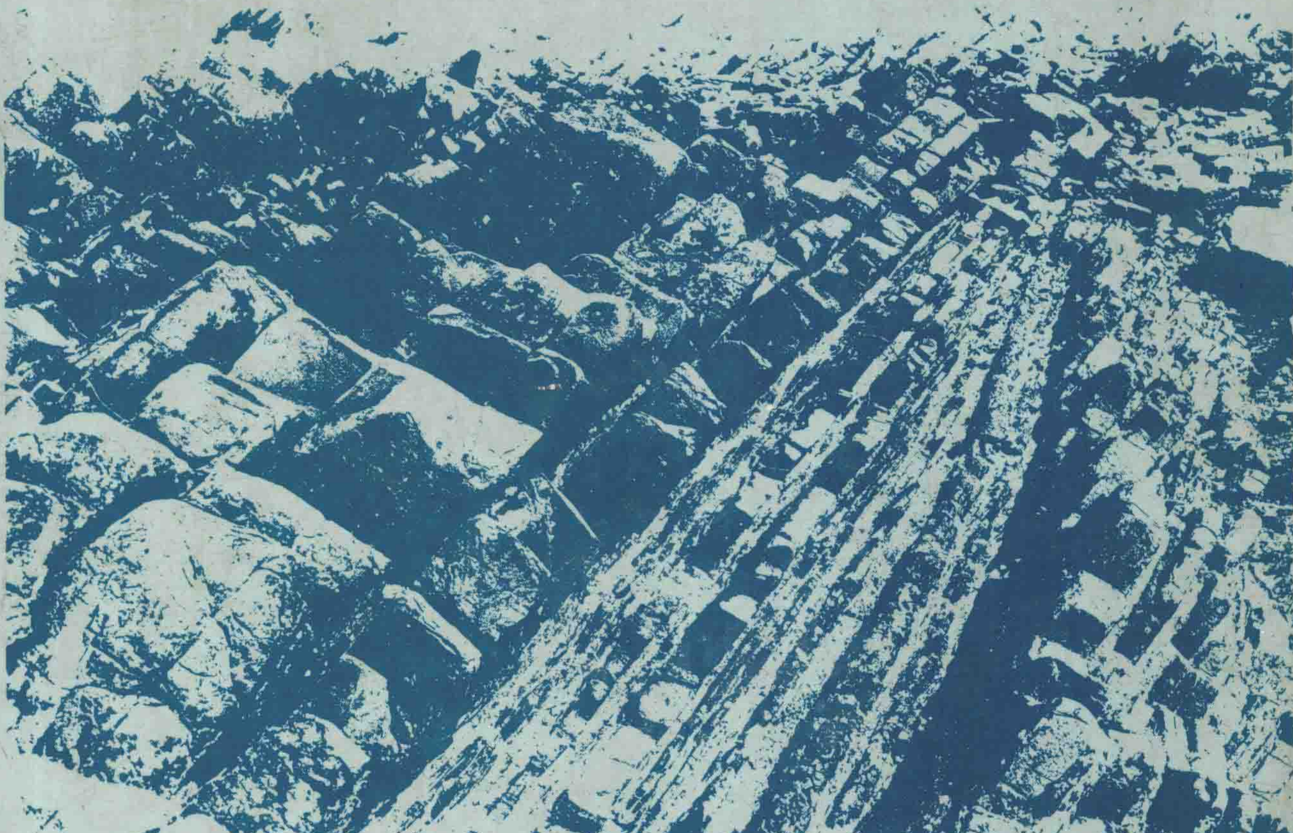
Marine Clastic Sedimentology

Concepts and Case Studies



edited by

J. K. Leggett and G. G. Zuffa

Graham & Trotman

Marine Clastic Sedimentology
Concepts and Case Studies

A volume in memory of C. Tarquin Teale

edited by

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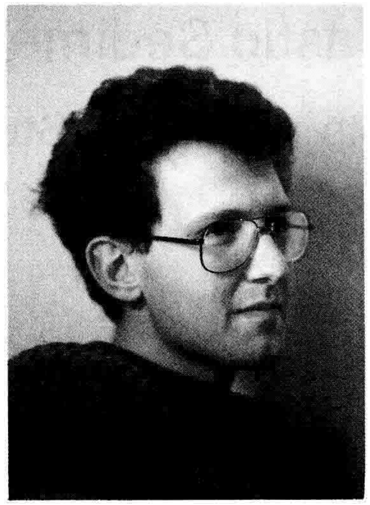

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Preface

Tarquin Teale, a sedimentology/stratigraphy postgraduate student at the Royal School of Mines, was killed in a road accident south of Rome on 17 October 1985. Premature death is a form of tragedy which can make havoc of the ordered progress which we try to impose on our lives. As parents, relatives and friends, we all know this, and yet somehow when it touches our own world there is no consolation to be found anywhere. In Tarquin's case the enormity of the loss felt by those of us who knew him can barely be expressed in words.

Tarquin had everything which we aspire to. His fellow graduate students envied his dramatic progress in research. We his advisors, in appreciating this progress, marvelled at how refreshingly rare it was to see such precocious talent combined with such a caring, modest and well-balanced personality. He was destined for the highest honours in geoscience and there is no doubt that he would have lived a life, had he been granted the chance, which would have spread colour, intellectual insight and goodness.

At Sheffield University he gained the reputation of being one of the finest undergraduates to ever pass through that Department. Yet he also managed to be active in a number of extra-curricular fields, was Secretary of the student Geology Society, and ran regularly for the university in cross-country, track, and orienteering events. One of his tutors, Jack Soper, commented in a written reference that Tarquin combined "... high intelligence with a degree of dedication unusual in a young person with such a wide range of other interests. His work capacity far exceeds that of the average student. He has flair and originality and has great research potential ..." Tarquin left Sheffield in the summer of 1983 with a First Class Honours Degree, the Fearnsides Prize for fieldwork, and the Laverick-Webster Prize for the best undergraduate performance of the year.

And so he joined Imperial College. His task was to investigate the sedimentary-tectonic history of the Longobucco sequence, a Jurassic rift-basin succession in NE Calabria. Exposed in mountainous and remote country, the rocks in question had been little-studied. They were believed to record rifting on the "African" margin of Tethys during the particularly interesting, but little-understood, Mesozoic history of the Calabrian arc. The project grew from a special relationship which exists between Imperial College and the Dipartimento di Scienze della Terra of the University of Calabria, where one of us (GZ) was then head of department. We both knew the difficulties awaiting the student who, under our joint supervision, was to undertake the project, but neither of us came near to predicting the scientific rewards.

The fact that Gianni Zuffa was ill when Tarquin started his research meant that he commenced his first long field season in a very foreign environment and culture almost alone, no easy task for such a sociable person. However, by the end of the season he had managed to do much basic groundwork, and started on his long trail of geological discoveries and reinterpretations. Moreover, Tarquin managed not just to live in Longobucco but to become an accepted member of the village community. Those of us who were lucky enough to visit him in his field area will never forget walking with him down the crowded *piazza* during *passagiata* hour. Scores of people would greet him with enthusiasm and animation. Their regard and affection for him was obvious, as was his for them. He was truly at home with his friends there in the *cantine* of Longobucco.

He made friends wherever he went, but in Italy this called for more than just his personality. He acquired a thorough knowledge of not only standard Italian, but also the *dialletto* spoken in rural Calabria. I once went to visit Tarquin in Longobucco with an educated North Italian geologist. He had difficulty understanding the locals' dialect, and it was soon evident that, apart from being compatriots, he and they had little in common. Later he said to me while Tarquin was in full flight, "Tarquinio speaks Italian like a peasant". It was a great compliment.

In his subsequent field seasons Tarquin completed the mapping of the entire Longobucco Basin, some 330 square kilometres, at a scale of 1:10,000. This he complemented with some 2 km of sedimentary logs. In addition, his collaboration with Italian palaeontologist Massimo Santantonio led to extension of his research into previously unstudied Jurassic pelagic sequences outside the Longobucco basin.

Tarquin was a first class field geologist, with a knack for finding key outcrops. His abilities and dedication produced rapid results. He was already publishing on three major aspects of his research. With

Massimo and two London-based nannofossil workers—Jeremy Young and Paul Bown—he had produced a complete revision of the stratigraphy and biostratigraphy of the Longobucco Group. They proved that the sequence was entirely Liassic in age rather than ranging up to Cretaceous. This effectively stood previous reconstructions of the Calabrian arc on their heads.

His identification, with Emiliano Mutti, of house-sized olistoliths of shelf sediments enclosed within turbidites of the Longobucco Group led inevitably to a reassessment of the basin configuration and the role of syn-sedimentary extensional tectonics. He went beyond this, however, producing an elegant model for the mode of emplacement of these olistoliths, with the aid of modern analogs and field evidence. This work, published in this volume, we believe will stand as a valuable contribution to sedimentary geology.

Tarquin had also nearly completed a major paper, with Massimo, on the Caloveto Group pelagic sediments. From these isolated patches of condensed sequences they were able to reconstruct a fascinating sequence of Jurassic environments. This again had considerable implications for the tectonic evolution of the region, and this volume contains a paper summarizing that work.

Tarquin had mastered not just the basics but the details of several sub-disciplines of our science, and so his talents did not end with sedimentology. He had become increasingly involved in structural interpretation. For the Longobucco basin he had assembled evidence for syn-sedimentary rifting, subsequent compressional telescoping of the unit and associated, previously unidentified, strike-slip deformation. His final field project, with Steve Knott from Oxford, had been on the structural evolution of the Calabrian arc.

In addition, the journal *Sedimentology* had also just accepted a long article on bentonites in the Welsh Borderland. These he had discovered during his undergraduate mapping, and characteristically he pursued the topic vigorously, with Alan Spiers of Sheffield.

With his wide-ranging and deep knowledge of geology Tarquin was much in demand at Imperial College as a demonstrator, on field trips and in practicals. Through these, his active involvement in the De La Bêche club, and his never-failing charm and consideration for others, he became unquestionably one of the best known, and well-loved, members of the Geology Department at Imperial. He was equally popular at Calabria University, where he had worked with several members of the staff, and seemed to know virtually every student. From here he had led a party of fifty of the most eminent geoscientists in sedimentary geology to Longobucco, after a major international conference in 1984.

Tarquin seemed destined to shoot to the top of whichever branch of geology he chose to invest his talents. In addition to his published work, he had assembled an encyclopaedic knowledge of the sedimentology, stratigraphy, ichnology and palaeogeography of the Longobucco basin. He had unravelled its structural history and greatly contributed to knowledge of the structural development of the Calabrian Arc. This research, which was intended to be his Ph.D thesis, seemed certain to be an outstanding piece of work. Following this Tarquin had hoped to return to Italy to do full-time post-doctoral research with Emiliano Mutti.

Those of us who worked with or knew him were devastated by his loss and we resolved to provide a deeply symbolic memorial to him: one which would be lasting and useful, so that we may gather some small solace every time we think, over the years, of his tragically early departure. This book is part of that memorial. The other part is the Tarquin Teale Memorial Fund, which each year will pay for an outstanding British graduate student to do sedimentological fieldwork in Italy, or for an outstanding Italian graduate student to do fieldwork in Britain. All the royalties from this book will go towards that fund.

Tarquin, this is your book.

Jeremy Leggett
Gian Gaspare Zuffa

Introduction

The geologist, perhaps more than any other breed of natural scientist, loves to try and impose order on the many natural processes which arouse his/her interest. Models and classification schemes abound in all the many sub-disciplines of geoscience. Who of suitable vintage can forget, for example, the many types of "geosyncline" which in the mid-1960s purported to classify the multifarious sedimentary basins of the planet, and their ancient equivalents in the mountain belts?

Plate tectonics has been a fertile breeding ground for models. Many models which have sprung from the "mobilist" philosophies behind plate tectonics have splendidly stood the tests of an ever-expanding data-base. Recently, however, it has become clear that one of the most important models in sedimentary geology has not.

Submarine fans, large cones of clastic detritus which accumulate in great thicknesses on the floors of sedimentary basins of all scales, are particularly important because of their petroleum potential. Once buried, and slightly deformed, their muddier portions often provide a source for hydrocarbons, and their sandier portions often provide reservoirs. In consequence, commercial interest in submarine fans, modern and ancient, has been intense over the years.

One of the most sought-after consultants on this topic has been Emiliano Mutti of the University of Parma. This is because in 1972, together with his colleague Franco Ricci Lucchi, he published a predictive model for sand-body geometry in submarine fans. It was based on a marriage of knowledge from ancient submarine-fan strata superbly exposed in the Italian Apennines with what little was then known of the physiography of modern fans. Since then the Mutti/Ricci Lucchi model has been applied enthusiastically all over the world. Its success was guaranteed in that it predicted successfully "ahead-of-the-drill" enough times to keep oil company sedimentologists happy.

But as his work continued, Mutti grew progressively less happy. In particular, he was uneasy with the increasing complexity being revealed in modern fans by the research of oceanographer-geologists such as William Normark of the USGS. In addition, his commercial work began to reveal increasingly sophisticated seismic reflection profiles which showed unexpected patterns. Finally last year, he decided to team up with Normark to refute his own, by most yardsticks hugely successful, early work. The philosophy he now advances is that there are too many complex interacting factors which control submarine fan sedimentation (sea-level, tectonics, sediment supply, etc.) to enable us to arrive at predictive models until we know much more about both modern and ancient examples.

In February 1986, nearly four hundred geologists were privileged to see Normark and Mutti in London, presenting their arguments for a more anarchistic approach to submarine fan sedimentation. The occasion was a symposium organized by the De La Bêche Club, the student geologists' society of Imperial College. The symposium was organized by the students to provide a memorial to a graduate member of their community who had been killed in a road accident in Italy, Tarquin Teale.

Tarquin had worked in the field with both Mutti and Normark prior to his tragically premature death. His research, complete and all but written-up when he was killed driving to the airport returning home from his field area, concerned both submarine fans and the evolution of mountain belts—those of Calabria in southern Italy. He was respected by all geologists who knew him, both as a precociously talented sedimentologist, and as a warm and genuine person with time for all, irrespective of status, race or sex. Most particularly he was admired for his capacity for painstaking work in the field. At the Imperial College meeting Mutti referred to this quality of Tarquin's. Given a natural span of time and experience, his work would no doubt have added significantly to our progress in developing reliable predictive modelling in submarine fan environments. The same, of course, applies to unravelling the mountain belts.

The ten papers in Tarquin's Memorial Volume fall into four groups. The first two concern models of deep-water clastic sedimentation. We believe that the long paper by Mutti and Normark, based on their presentation at the DLB symposium, will become a landmark in the history of sedimentary geology. Gianni Zuffa's paper builds on the theme of how to read geological history from deep-water clastics by interpreting their petrography.

The next five papers provide case histories: from the Tethyan rocks of Calabria, and the Lower Palaeozoic Appalachian-Caledonian belt. The two Tethyan papers summarize the main discoveries which Tarquin Teale made in the Longobucco Basin. We believe they will be of interest to all those concerned with sedimentary basins and their tectonic settings. The first, jointly researched with Massimo Santantonio, describes how detailed biostratigraphic and facies work can be utilized to work out the relationship between sedimentation and tectonics in a rift basin. The second describes huge allochtonous blocks which fell from the edge of the basin as it evolved. This case study, we believe, will be of great interest to those involved in sediment dynamics and the processes involved in the emplacement of olistoliths.

The Appalachian-Caledonian case-histories are fine examples of what can be done with techniques for facies modelling (such as those articulated by Mutti and Normark) when diligent sedimentary geologists are faced with complex ancient terranes. The Welsh Basin was situated on the south side of the Iapetus Ocean during Early Palaeozoic times. Ru Smith describes aspects of its Silurian fill. The Southern Uplands, most geologists seem to believe, was a trench on the northern side of the Iapetus.

Next we move on to the mudrocks, the unromantic component of basin-fill and Charles Curtis gives us a masterly review of the geochemical processes which govern the diagenesis of these economically-important rocks. Alan Kemp describes how detailed facies analysis, coupled once again with diligent biostratigraphy, can be used to unravel the changing geometry of its fill during Silurian times. Andrew Thickpenny describes a Lower Palaeozoic case-history: the Scandinavian Alum Shales. Keith Myers describes his important new technique for relating gamma-ray logs of mudrock successions to original sedimentary processes.

The palaeogeographic position of basins in an orogenic belt such as that built during, and after, Iapetus closed is not always clear. Kevin Pickering reconstructs the history of a foreland basin from the Quebec Appalachians, and compares the history of that basin with a more-complicated Appalachian basin in Newfoundland.

All the contributors to this volume knew Tarquin Teale well; the editors were his supervisors. Emiliano Mutti and Bill Normark went into the field with Tarquin at various times for guided tours in the Longobucco Basin. That they chose to contribute their important new paper here, and not to a journal such as the *American Association Of Petroleum Geologists' Bulletin*, demonstrates their regard for Tarquin.

Massimo Santantonio and Jeremy Young were collaborators of Tarquin's. Andy Thickpenny and Keith Myers were fellow graduate students at Imperial. Ru Smith, Alan Kemp and Kevin Pickering knew Tarquin from his presentations, and conviviality, at the annual British Sedimentological Research Group meetings. Charles Curtis taught him as an undergraduate. We all miss him.

There is an old maxim that the more you research something the more complicated it becomes. In the mountain belts and on the basin floors it is certainly true: we have moved on from the days of the simple cartoon models of the early- and mid-1970s. Tarquin Teale would have been closely involved at the cutting edge in helping modern sedimentology move on still further.

Jeremy Leggett
Gian Gaspare Zuffa

Contents

Chapter 1

Comparing Examples of Modern and Ancient Turbidite Systems: Problems and Concepts

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ABSTRACT

A useful comparison of modern and ancient submarine fans can be based only on well-understood and thoroughly mapped systems. In addition, the examples selected for comparison must represent depositional systems similar in such characteristics as type of basin, size of sediment source, physical and temporal scales, and stage of development. Many fan sedimentation models presently in use do not meet these criteria.

A conceptual framework for comparing modern with ancient, ancient with ancient, and modern with modern turbidite systems defines our approach to the problems involved. To attempt to select similar depositional systems, we define four basic types of turbidite basins based on size, mobility of the crust, effects of syndepositional tectonic activity, and volume of sediment available in the source areas. The difference in physical scale and the great dissimilarities in types of data available are particularly important in the comparison of modern and ancient deposits. Comparisons can be done for basin-fill sequences or complexes (1st order), for individual fan systems (2nd order), for stages of growth within an individual system (3rd order), or for the scale of specific elements (facies associations and component substages) within a system, e.g. lobes, channel deposits, overbank deposits (4th order). Valid comparison requires that the field mapping is sufficient to recognize the stage of development of the system.

To facilitate application of this conceptual framework, working definitions of individual fan elements attempt to provide criteria applicable to both modern and ancient settings. These elements are channels, overbank deposits, lobes, channel/lobe transition features, and scours (major erosional nonchannel features). *Derived* characteristics, such as fan divisions and sedimentation models, are considered as secondary points only used as necessary for discussion. The use of morphologic terms to describe ancient deposits is also qualified. The primary emphasis remains on detailed, complete field work, both on land and at sea, to provide factual characterizations of the sediment and rock assemblages to ensure that similar features are being compared in terms of both temporal and physical scales.

INTRODUCTION

The recent review of 28 separate modern and ancient submarine fans provided by the international COMFAN (COMmittee on FANs) meeting in 1982 (Bouma *et al.*, 1985a; Normark *et al.*, 1985) has helped identify major problems in developing generalized fan models. Developing generalizations (models) for understanding the growth of submarine turbidite systems, however, is as complicated as attempting to judge the wide variety of wines in the world by a single set of criteria. What is required is a clear definition of the common characteristics of the

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objects being compared as well as an appreciation of the wide range of variables that influence their development. (This applies to wines as well as to submarine fans.) Many of the existing fan models have not adequately dealt with the following limitations:

1. Not all turbidite systems have formed submarine fan sequences. The characteristic turbidite facies can be developed in a variety of restricted basins and in tectonically active regions that do not permit the development of complete fan systems.
2. It is necessary to recognize the major factors that control the growth of submarine fan complexes. As a minimum, these factors include (a) the type of crust on which the turbidite system is formed, (b) the longevity of the sediment source(s) and the rate of sediment supply, and (c) the local tectonic and global sea-level controls on sediment supply.
3. Comparison of modern and ancient fans, or modern with modern and ancient with ancient, cannot provide valid results unless the scale of observations is similar. These scale problems include both time—the length of time over which the turbidite system develops—and spatial dimensions.
4. Studies of modern and ancient turbidite systems are based on different types of data that provide different degrees of resolution and reflect differing physical attributes of the deposits.
5. There are complications caused by the terminology used to describe turbidite systems. These complications result from (a) the lack of accepted definitions of features in the mapping of either modern or ancient systems and (b) the use of morphologic terms to describe ancient turbidite sequences where, except for local channels, little original morphologic relief is preserved.

The problems of comparing turbidite systems are compounded by attempts to modify or develop depositional models based on poorly or incompletely mapped systems. For ancient fans, many of the difficulties in mapping stem from a lack of adequate exposure of the sedimentary sequences; for modern fans, the sheer size of the deposits and the lack of adequate sampling and imaging capabilities severely restrict our ability to map the systems. Therefore, we do not attempt to review all the various models or examples of turbidite systems to reconcile the present inherent discrepancies. Rather, we suggest a moratorium on model building until adequate field work has resolved many of the questions posed. Unfortunately, we shall need to use some model concepts to introduce and describe our stages. The purpose is not to promote or fully develop such models, however, as they are discussed elsewhere (Mutti, 1985). We also attempt to define the criteria to minimize the problems and to suggest some standardization of terms, wherever possible developing compatible definitions for modern and ancient turbidite systems.

Most of the work on both modern and ancient turbidite depositional systems over the past 15 years has been directed primarily to understand (1) facies and related depositional processes (see summaries in Carter, 1975; Lowe, 1972, 1979, 1982; Middleton and Hampton, 1973; Mutti and Ricci Lucchi, 1972, 1975; Nardin *et al.*, 1979, Walker, 1966, 1978; Walker and Mutti, 1973) and (2) the factors that control turbidite deposition and the growth of submarine turbidite systems (see, for example, summaries in Howell and Normark, 1982, Nelson and Nilsen, 1974; Normark, 1978; Pickering, 1982b; Stow *et al.*, 1985; Walker, 1978). In this paper, we emphasize the importance of framing turbidite deposits within accurate patterns of stratigraphic correlations established within the deposits. This stratigraphic framework, which is the prerequisite for comparison of turbidite depositional features, will be considered at different temporal and spatial scales, from that of seismic stratigraphy down to that of facies and facies association packages.

The examples of turbidite depositional systems that we will discuss in the following pages are, therefore, mainly selected from those with which we are most familiar, to ensure that these scale factors are correctly understood. In this way, we hope to show that valid comparisons of modern fans and ancient systems can provide very useful insights into the understanding of turbidite successions.

TYPES OF TURBIDITE BASINS

The morphology, internal structure, and facies associations of submarine fans are primarily controlled by the long-term stability of the basin and the volume of sediment supplied to the depositional area. The largest submarine fan complexes form over tens of millions of years and require not only a relatively stable basin but also a long-term supply of large volumes of sediment. It is probably within these long-lived systems that the effects of *global* sea-level changes (Vail *et al.*, 1977) are most pronounced. Turbidite basins formed in active tectonic settings tend to be short lived, especially in cases where both the source area and depositional basin are affected by crustal movements. In these short-lived systems, local tectonic control greatly influences the development of the turbidite deposit.

The major factor controlling the stability (or, conversely, the mobility) of the turbidite basin is the type of crust underlying the basin. Long-lived submarine fans are generally on oceanic crust, and the size of the fan reflects the amount of sediment supply and not the confines of the basin. Turbidite basins formed on continental crust, especially along active continental margins, tend to be short lived, even where sedimentation rates are relatively high.

The crustal setting of turbidite deposits must be considered for comparisons of modern and/or ancient examples as well as the effects of sediment supply. In reviewing the major turbidite deposits that have been described in the literature (see Barnes and Normark, 1985), we suggest that there are at least four main types of basin. For most turbidite systems mentioned in this section, the summary by Barnes and Normark (1985) provides references and tabulation of data.

Type A

Type A basins are those formed on oceanic crust with large, long-lived sediment source(s) and little or no tectonic activity. These conditions are generally found on mid-plate margins in the Atlantic and Indian Oceans. The largest fan complexes are all found offshore from major river systems and have been building for several million years to as much as 20 million years. Examples of this type include the Bengal, Indus, Amazon, Laurentian, and Mississippi Fans, which are all fed by large rivers (Bouma *et al.*, 1985b; Damuth and Flood, 1985; Emmel and Curray, 1985; Kolla and Coumes, 1985; Piper *et al.*, 1985). Small fans can also form within this type of basin wherever the source area is restricted, e.g. the four-million-year-old San Lucas Fan (off the Baja California peninsula; Normark, 1970a). Because large pieces of oceanic crust are not generally obducted or overthrust along continental margins, good ancient examples of these large deep-ocean fan complexes are rarely available.

Type B

Type B basins are formed on oceanic crust with relatively long-lived sediment source(s) but with tectonic activity in the source/basin transition area. These basins are also long lived, some exceeding 20 million years, but they generally have lower rates of sediment supply than do Type A basins, although the supply is sufficient to overcome the effects of tectonic activity. Two subtypes are common: (a) transform margins, where examples include the Monterey and Delgada fans on oceanic crust off central California (Normark, 1985; Normark and Gutmacher, 1985); and (b) subduction margins, in examples where the rate of sediment supply greatly exceeds the rate at which the fan is accreted to the margin. Examples of this type include the Astoria and Nitinat fans of the north-east Pacific (Nelson, 1985) and probably the Cretaceous fan of the Gottero Sandstone in north-western Italy (Nilsen and Abbate, 1985).

The mid-Tertiary-age Zodiac Fan in the Gulf of Alaska is a large, long-lived fan on the Pacific lithospheric plate; its supply of sediment has been cut off by the modern Aleutian trench (Stevenson *et al.*, 1983). Plate motion reconstructions show that when the fan was growing it was a Type B.

Some turbidite basins exhibit extensive zones of diapirism along the margin that can disrupt submarine fan development (e.g. Rhone Fan; Droz and Bellaiche, 1985); this disruption, however, generally does not prevent the development of long-lived systems so we do not include it as a separate subtype.

Type C

Type C basins are formed on continental crust with relatively large and long-lived sediment supply but with structural control of basin configuration and duration. Where continuing tectonic activity over several million years along the margin results in a migrating foreland basin, a succession of turbidite systems results. In the early stages of thrust propagation, relative and global sea-level variations are probably the main factor in controlling turbidite accumulation in basin development. Further orogenic shortening results in the narrowing and fragmentation of foreland basins; during this stage, uplift and emersion associated with frontal and lateral ramp areas of moving thrust sheets induce self-edge and/or intrabasinal instability processes that will lead to failures of unconsolidated or poorly consolidated sediment of shallow and/or deep-marine origin. Under these circumstances, tectonic control becomes of primary importance in turbidite deposition, regardless of global sea-level variations. The best-known examples of this type of basin are the Eocene Hecho Group turbidites of the south-central Pyrenees, Spain (Mutti, 1985; Mutti *et al.*, 1985), and the classic Oligocene to Pliocene foredeep sandy flysch of the northern Apennines of Italy (Ricci Lucchi and Ori, 1985). Few data are publically available from large modern examples of this type.

Type D

Type D basins are those formed on continental crust where continuing tectonic activity results in relatively rapid changes in basin shape and in short-lived sediment sources. The resulting turbidite deposits form in relatively short time-spans (10^4–10^5 years), are dominantly coarse-grained channel and lobe sequences, and are volumetrically much smaller than turbidite fill of the other three basin types. These small, actively deforming and short-lived basins form on all active margins: during early rifting phases of an opening ocean, along active transform margins, and during final stages of continental collision.

Modern examples include fans of the California Continental Borderland, e.g. Navy, La Jolla, and Redondo Fans in transform-controlled basins (Bachman and Graham, 1985; Haner, 1971; Normark *et al.*, 1979). Ancient examples are also common, and include the Tertiary Piedmont Basin of north-western Italy, an area of post-collision rifting (Cazzola *et al.*, 1985); the Upper Cretaceous Aren Sandstone of south-central Pyrenees in Spain that occurs within a foreland basin (Simó and Puigdefabregas, 1985), and the Jurassic deposits of Greenland (Surlyk, 1978) that formed during early stages of rifting.

In providing examples of modern and ancient submarine fans that fall into the four types of basins, we do *not* imply that these fans fit generalizations or 'models' for fan growth. In addition to the type of basin and degree of tectonism, it is necessary to consider the effects of scale differences and types of observations (data sets) used to map the fans before attempting comparisons.

SCALE FACTORS

A geologically significant comparison of modern and ancient turbidite deposits requires that the comparison be made at similar spatial and temporal scales. Figure 1 shows the spatial scale of features that comprise turbidite basin deposits and of the types of observations used to map the deposits. Figure 2 introduces the terminology we suggest for comparison of turbidite systems, and relates depositional events to both temporal and spatial scales.

Turbidite complexes ('suites' of Ricci Lucchi, 1975), systems, stages, and substages form the basis for the classification shown in Fig. 2. These units have been amply discussed in previous papers (Mutti, 1985; Mutti *et al.*, 1985), and will be briefly reviewed in a following section. Although these distinctions have been studied primarily in ancient sequences thus far, we think their recognition in modern fans would probably greatly improve the possibilities for significant comparative studies in the future.

A *turbidite complex* refers to a basin-fill succession and is composed of several turbidite systems that are stacked one upon the other.

A *turbidite system* is a body of genetically related mass-flow sediments deposited in stratigraphic continuity. Systems are commonly bounded, above and below, by mudstones (in many cases reflecting high stands of sea level) or by submarine erosional unconformities. As such, a turbidite system is part of a depositional sequence in the sense of Vail *et al.* (1977) and will commonly occur at the base of a sequence initiated during a relative low stand of sea level.

The definition of a turbidite system as given here is basically *sensu stricto*, and a later section will expand upon this usage. This *sensu stricto* usage should not be confused with that in the COMFAN discussions (Bouma *et al.*, 1985a) which is *sensu lato* in that 'related turbidite systems' are meant to include all turbidite deposits, many of which do not constitute recognizable submarine fans or represent short-lived episodes of deposition.

A *turbidite stage* consists of facies associations and erosional surfaces that formed during a specific period of growth within a system (*sensu stricto*). A *substage*, where more specific associations can be recognized, encompasses time-equivalent facies and erosional surfaces within a facies association.

The framework of Fig. 2 allows consideration of turbidite deposits within five main orders of scale that are discussed below in descending order of magnitude.

First order

First-order features are at the scale of entire basin-fills of successions of turbidites and thus encompass periods of time of several millions of years and longer. These features compare in significance to large fan complexes in that they are generally built up by the stacking of individual turbidite systems (*sensu stricto*) in the same long-lived depocenter. First-order complex successions, that may reach volumes up to several hundreds of thousands of km^3, can be split into major depositional sequences in the sense of Vail *et al.* (1977) through both seismic reflection techniques and through detailed stratigraphic mapping. These sequences allow the framing of turbidite sediments within relative variations of sea level (Mutti, 1985). Figure 3 shows an example of a first-order turbidite succession and its subdivision in

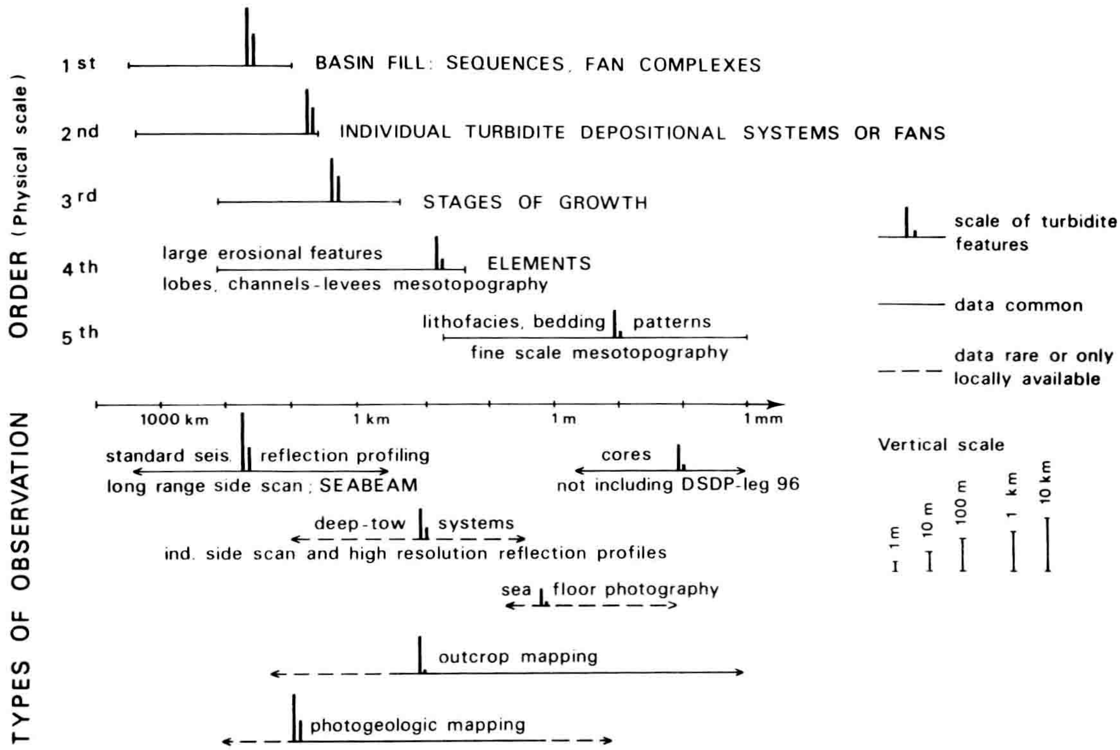

Fig. 1. Physical scale comparisons for vertical and horizontal dimensions of turbidite basin-fill and depositional features (upper), and of typical observations—outcrops, cores, geophysical records (lower). All multibeam echo-sounding systems are represented by the term SEABEAM in this diagram. The vertical scale for core samples does not include Deep Sea Drilling Program cores (Leg 96 is the Mississippi Fan sampling: Bouma *et al.* 1985c).

EVENTS	*TERMINOLOGY*	*HIERARCHY*	*DURATION (years)*
DEPOSITION AFFECTED BY MAJOR BREAKS IN SEDIMENTATION (UNCONFORMITIES) PRODUCED BY LONG-TERM SEA LEVEL VARIATIONS AND TECTONIC ACTIVITY	TURBIDITE COMPLEX	1st ORDER	x 10^6 to 10^7
SHORT-TERM SEA LEVEL VARIATIONS AND TECTONIC ACTIVITY PRODUCE CHANGES IN SEDIMENTATION BUT NO SIGNIFICANT BREAKS (UNCONFORMITIES)	TURBIDITE SYSTEM	2nd ORDER	x 10^5 – 10^6
	TURBIDITE STAGE	3rd ORDER	x 10^4 – 10^5
HIGH-FREQUENCY CHANGES IN DEPOSITIONAL AND EROSIONAL PROCESSES OF POORLY UNDERSTOOD ORIGIN	TURBIDITE FACIES ASSOCIATION AND COMPONENT SUB-STAGES	4th ORDER	x 10^3 – 10^4
"NORMAL" SMALL-SCALE EROSION AND DEPOSITION	BEDS AND THEIR FEATURES	5th ORDER	VIRTUALLY INSTANTANEOUS FEATURES

Fig. 2. Types of events characterizing turbidite systems and their physical scale subdivisions (re: Fig. 1) showing associated time scale for depositional units.

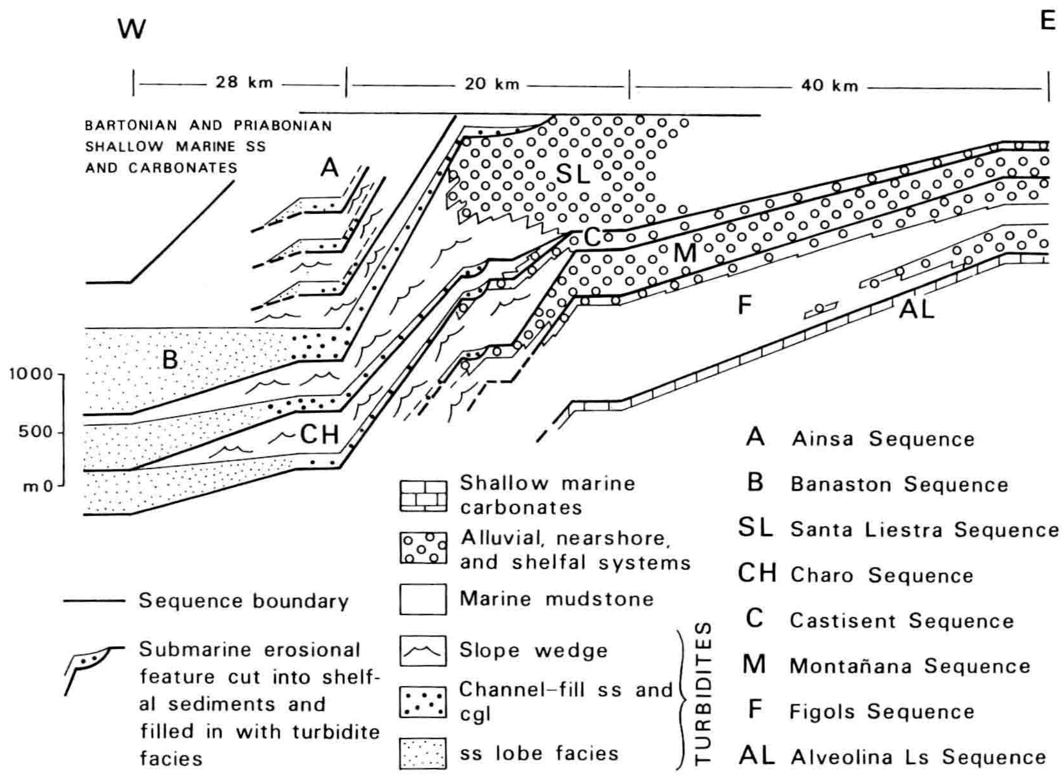

Fig. 3. Stratigraphic cross-section parallel to elongate axis of sedimentary fill in an Eocene foreland basin in the south-central Pyrenees, Spain. The turbidite complex fills the western, deeper sector of the basin and formed in about 10–12 million years between early and late middle Eocene. Six turbidite depositional systems are recognized. The three stratigraphically lower systems are examples of Type 1 deposits (Mutti, 1985) in which the bulk of the sand is deposited in the lobes. The three systems that are stratigraphically higher are smaller, and the sandstone facies are found predominantly as channel-fill and immediately adjacent lobe deposits (Mutti Type II, 1985). Thick overbank wedges form the upper part of each system along the eastern side of the basin. The basal boundary of most systems is correlative with a marked stratigraphic unconformity in the shelf-edge region. Modified from Mutti *et al.*, 1985.

depositional sequences from the Eocene Hecho Group basin, north-eastern Spain.

Second order

Second-order features, or turbidite depositional systems (*sensu stricto*), are bodies of turbidite sediments that occur within individual depositional sequences and are typically separated vertically by highstand mud facies. Most commonly, these systems encompass spans of geologic time measurable in the order of 10^5–10^6 years, and roughly match the physical scale of formations and/or members of conventional lithostratigraphic usage. Such units can therefore be mapped at appropriate scales in both surface and subsurface studies and in modern basins. Depending upon local conditions of sediment supply and basin size and configuration, such systems may reach thicknesses of several hundreds of meters, and lengths of as much as a thousand kilometers. Both thickness and length may be considerably affected by basin size.

Turbidite depositional systems (Mutti, 1985) have the same geologic significance as an individual fan-lobe deposit (Bouma *et al.*, 1985b), i.e. a package of turbidites that forms during a period of fan activity and is bounded above and below by fine-grained facies produced during phases of fan deactivation and/or by submarine unconformities (Feely *et al.*, 1985). Most commonly, each system develops through channel-fill deposits that are replaced in a down-current direction by non-channelized facies. Examples of ancient turbidite systems are those shown in Fig. 3; conceptually similar units are the