The shape of deep-water siliciclastic systems: A discussion

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ABSTRACT

Deep-water siliciclastic systems are classified primarily on their shape as: submarine fans with well developed or poorly developed morphology, slope drapes, for example, over relatively stable basin margins, fault-scarp aprons, canyons and large channels, under-supplied sheet systems such as abyssal plains, non-fan ponded systems such as over-supplied perched basins, and fan deltas. Collectively, or separately, these systems may form sedimentary basin fills that can be over or under-supplied with respect to the sediment input although most systems will tend toward over-supply/overflow with time. Finally, the sum total of the siliciclastic systems and basins can be used to define the tectonic milieux such as passive, strike-slip and convergent margins.

INTRODUCTION

The depositional setting of most deep-water siliciclastic systems, formed below wave-base, is defined by many researchers on the basis of the overall tectonic milieu *vis a vis* passive, convergent and strike-slip basins. While this classification is easily applied to modern deep oceanic settings, it is more difficult with ancient successions through lack of exposure and the absence of a stratigraphic framework into which an isolated formation can be placed.

Often, the only reliable statements about an ancient succession relation to the possible morphology of the siliciclastic body, i.e., the shape, while the interpreted plate tectonic milieu is even less certain. Therefore, it is proposed that ancient deep-water sedimentary bodies (on a scale of formations and groups) be defined on the intrinsic properties of the succession rather than primarily by analogy with modern plate tectonic settings. Naturally, the latter stage in interpretation is worthwhile, but it should not take on undue significance in terms of reconstructing the paleogeography.

The advent of the submarine fan model has led to the almost wholesale reinterpretation of flysch successions as fans, and, undoubtedly, this was justified in many cases on the basis of identifying many of the features occurring in modern submarine fans [1]. However, in other cases, either clear differences exist between the facies and facies-associations of the submarine fan model [2-6] and the supposedly analogous model for which little or no explanation is given [compare 6 and 7], or the submarine fan model has been extrapolated to successions where no indication of fan sedimentation is discernible. Also, the fan model is inadequate or inappropriate for many ancient deep-water systems [8].

The purpose of this contribution is to highlight some of the alternative, and infrequently used, models for deep-water sedimentation. An appropriate way of outlining the various models is via the following classification:

1. submarine fans with well developed or poorly developed morphology;
2. slope drapes;
3. fault scarp aprons;
4. canyons and large channels;
5. under-supplied sheet systems;
6. non-fan ponded systems, and
7. fan deltas.

SUBMARINE FANS

Morphologically Well Developed Fans. Submarine fans are well documented from modern and ancient deep-water environments [4,5]. The facies, facies-associations [5,6,9] and sequences [10] that characterize such deposits were applied widely to various ancient successions [1,11].

The submarine fan model represents an idealized spatial and temporal distribution of deposits with easily recognizable inner,

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middle and outer fan deposits. Clearly defined proximal to distal and axial to lateral changes in the type and distribution of facies, facies-associations and sequences occur [4-6]. However, the recognition of an ancient submarine fan should be based on the following criteria: 1. inner, middle and outer fan physiography as expressed in the deposits; 2. a radial spread of paleocurrents about a point source or several closely spaced point sources, and 3. a downslope transition from inner through middle to outer fan deposits. Naturally, the last criterion often relies upon vertical sequence analysis. If these criteria are not met, then alternative models should be considered rather than trying to force analogies between the idealized (morphologically well developed) fan model and the succession in question.

The lithofacies patterns of submarine fans will depend on the structural/tectonic setting and the associated physiography of the basin, the type and rate of sediment input, the physical oceanographic parameters and the climatic/eustatic oscillations [modified after 12]. However, unless the fan is demonstrably cone-shaped with relatively free bounding margins with other parts of the basin, in both the proximal-distal and axial-lateral directions, then it should be assigned to the category of fans that are morphologically poorly developed.

Recently, Mutti [13] identified high and low efficiency submarine fans based mainly on the overall amount of sand or sandstone within the system and other features such as whether or not lobes are connected to middle fan channels. Should this classification become widely accepted, then such fans would represent a more detailed fan subdivision for both the morphologically well and poorly developed types.

Morphologically Poorly Developed Fans. The constraints on fan growth mentioned above, may militate against the growth of cone-shaped fans. Maldonado and Stanley [12] have shown that while the Menorca Fan, formed on the Balearic Rise, exhibits well developed fan channels and lobes, the Rosetta Fan on the Nile Cone has a poorly developed channel network and lobes are absent. Thus, the Rosetta Fan does not display the features ostensibly typifying the submarine fan model [4-6] and it emphasizes the ambiguities that are inherent in using the term 'submarine fan' as a bucket descriptor for any sediment wedge formed from a point source.

I would suggest that depositional systems showing features in common with fans such as the Rosetta Fan, or indeed any clastic wedge fed from a point source, or several closely spaced sources, in which well defined inner, middle and outer fan environments are absent should be referred to as morphologically poorly developed. The usefulness of this classification is that it highlights the specific constraints that operated to inhibit the more idealized fan growth.

Into this category, the precursors of many submarine fans could be fitted, that is, a submarine fan, whether morphologically well or poorly developed, does not instantly exist—it must have been formed on a favorable template: deposition and erosion must have preceded any clearly defined fan sedimentation. Such pre-fan deposits have not been recognized in ancient deposits, and obviously in modern basins it would be difficult to predict fan development on what is presently a non-fan succession. The recognition of ancient inchoate fan systems must be hypothetical because there is no data to draw upon. Erosion may have eliminated some pre-fan deposits, but this argument cannot be invoked as a major cause against hitherto unrecognized fan precursors.

Perhaps, pre-fan deposits might be recognized using the following criteria: 1. occurrence toward the base of flysch successions interpreted as submarine fans; 2. poor to absent packeting of deposits on the basis of grain size, bed thickness and other sedimentary attributes; 3. sheet, channel and scour deposits vertically and laterally mixed over short distances (possibly tens of meters laterally and only meters vertically), and 4. great variability in paleocurrent directions due to the absence of well-developed canyons or other point sources. The disorganization of flyschoid deposits should not be used in isolation to infer pre-fan sedimentation. It should be demonstrated that there is an upward transition to more organized deposits in order to compare sections. This is clearly an area of study requiring further research.

Finally, it should be noted that morphologically well-developed fans may be superceded by poorly developed fans and vice versa. Such changes may result from the filling up of a basin, tectonism destroying earlier sedimentation patterns and sea-level changes causing different volumes and/or types of sediments to be supplied. Although it will undoubtedly prove difficult to recognize such deposits, research must move in this direction if we are to increase our understanding of fan sedimentation.

SLOPE DRAPES

Large tracts of continental slopes and rises are covered by *relatively* monotonous deposits that are fine-grained, thin-bedded and petrographically similar; the main sediment transport processes being turbidity currents, contour currents, other sediment-reworking currents and hemipelagic sedimentation. Examples of such sedimentation systems occur along the eastern U.S. continental slope [14]: convergent margins will have slope regions that are similar in appearance although they may be distinguished on the basis of petrography, syn-sedimentary tectonic effects and regional geological considerations. The rationale behind grouping slope drapes from active and passive margins is that the shape of the systems may be similar, especially in terms of recognition in ancient rocks, i.e. essentially sheet-like deposits of relatively thin-bedded, fine-grained sediments.

Basin slopes with finer grained and thinner bedded sedimentation as the main form of accretion tend to occur above relatively stable basin margins where tectonic factors are not predominant, and such slope areas tend to occur on passive continental margins. The eastern U.S. continental slope presently overlies a fault-controlled margin, though the faults are believed to be at depths of 6 to 12 km below the surface [15]. The tectonic quiescence of the margin, combined with the wide shelf and the paucity of large sediment input points (rivers and deltas), favors the accumulation of large thicknesses of finer grained lithologies. Sea-level changes have led to the slope alternating between erosion and deposition-dominant regimes [14].

The finer grained and thinner bedded nature of these slope drapes, compared to other clastic wedges, in many cases does not imply slow rates of sedimentation, for example fast sedimentation is recorded from the upper continental slope of the northern Gulf of Mexico which, in turn, has caused sediment instability and sliding [16]. Ancient slope deposits that could be classified as slope drapes include the late Cambro-Ordovician of central Nevada, U.S. [17]; the Eocene Elkton Siltstone Member of the Tyee Formation, Oregon, U.S. [18], and the lower parts of the Båsnaering Formation, Finnmark, N. Norway [19].

Slope drapes of this type may be recognized by their relative homogeneity compared to other deep-water clastic wedges over large vertical and lateral distances, paleocurrents suggesting downslope or slope-parallel (contour) currents, and possible abundant soft-sediment deformation features such as large-scale slides. Important unconformities may exist due to periods of nondeposition or active erosion, possibly caused by sea-level changes. Typically, the overall shape of slope drapes may resemble the 'prograding clinoforms' recorded from off the east coast of the U.S. [20].

FAULT-SCARP APRONS

Submarine faults that intersect or come close to the surface of basins, especially basin margins, appear to favor sedimentation that is distinct from other deep-water siliciclastic wedges. Perhaps, the best documented examples occur in the California basins [21]. Many of the basins are fault-controlled and, in some cases, studies have shown that sediment mass flows other than turbidity currents account for much of the resedimented material [22].

Strike-slip basins, in the regions adjacent to the faults, often are typified by conglomeratic and coarse-grained detritus [23, 24]. Clastic wedges appear to be relatively small in aerial extent but with a marked linearity parallel, or subparallel, with the faults influencing sedimentation.

Ancient examples of fault scarp aprons include the Middle Cambrian outer-shelf margin in eastern California and western Nevada [25], and the Middle Jurassic under the Blake Plateau [26]: the latter example now being fault-controlled at depth and, therefore, a slope drape. Another ancient fault-scarp apron occurs in the Upper Jurassic Kimmeridgian 'Boulder Beds' and related deposits in northeast Scotland [27–29]. In this example, the Helmsdale Fault is thought to have been only tens to hundreds of meters away from the present day outcrop during deposition of these beds. The 'Boulder Beds' are characterized by a variety of deep-water deposits with abundant debris flow deposits. Bedding is generally irregular with abrupt lateral thickness changes.

Faulting in the Karoo Troughs in the early Jurassic (southern Tanzania) appears to have generated boulder beds and coarse-grained pebbly sandstones along the basin margins [30], and this example, along with others such as parts of the northern Spanish continental margin [31], may be classified as fault-scarp aprons.

Recognition of this type of slope apron relies upon locating the fault(s) controlling sedimentation, and the deposits may be typified by: 1. a variety of sediment mass flow processes, possible with turbidity current deposits as subordinate components; 2. common slide and slump deposits; 3. very irregular bedding and lensing of beds over meters and tens of meters; 4. paleocurrents typically perpendicular with the fault traces, and 5. abrupt lateral facies changes. Periodic fault movements may generate slides, slumps and debris flows, and the resulting deposits may be the most significant sedimentation as the fault-scarp talus.

CANYONS AND LARGE CHANNELS

This category of sedimentary systems is reserved for linear features such as submarine canyons and other large channels (excluding those channels that form part of submarine fans) in which terrigenous supply is almost exclusively axis-parallel *vis a vis* sediment movement through the system. However, sediment failure along the margins may contribute substantial volumes of sediment to the canyon or channel infill.

Modern examples of submarine canyons and channels are well documented, for example east of the Baltimore Canyon Trough [32–34], and the Labrador Channel [35]. One of the interesting features of the Labrador Trough is the development of a large channel containing a meandering thalweg channel parallel with the basin margins. In many respects, a number of recently described submarine canyons appear to show features that are analogous to fluvial systems [32,33].

Ancient submarine canyons have been recognized [36,37] along with possible linear troughs that may be more analogous to the Labrador Channel albeit on a smaller scale [38]. The type of sedimentary deposits infilling ancient canyons appears to be varied, some with a predominantly coarser grained infill and others with essentially finer grained deposits. Therefore, ancient successions that can be classified as canyons or large channels must be demonstrably linear with an axial derivation for the 'through-system' sediment flows. Ancient channel fills may display many of the features described by Hein and Walker [39]. While many ancient channel systems may be part of submarine fans, this will not always be the case, therefore, caution should be exercised in the interpretation of siliciclastic systems involving channel and related deposits.

UNDER-SUPPLIED SHEET SYSTEMS

Under-supplied systems include basins that are either starved of substantial terrigenous input or reveal slow rates of sedimentation. Naturally, such systems/basins may completely fill over very long time periods relative to the over-supplied basins (see below), but in general they may be thought of as basins and clastic bodies that were built up very slowly. With ancient successions, the rate of sedimentation may prove to be the main criterion on which this category of depositional system can be invoked.

Examples of under-supplied sheet systems range from the abyssal plains where red clays, siliceous oozes, calcareous oozes and terrigenous muds accumulate along with metalliferous sediments [40], to parts of trench floor successions. Most of the 30,000 km plus of trench floors fringing the Pacific are virtually devoid of a sedimentary fill, often containing between 100 to 200 m of pelagic and hemipelagic sediments [41]. Another example of an under-supplied clastic system occurs in the West Luzon Trough and the Manila Trough. These have been referred to as ponded, unfilled basins by Dickinson and Seely [42].

Under-supplied sheet systems are often sited in basins of prolonged sediment reworking and/or erosion by permanent and semi-permanent ocean currents. This reworking and erosion produces a variety of bedforms, for example, the 'abyssal furrows' reported from the Bahama Abyssal Plain [43].

NON-FAN PONDED SYSTEMS

Sedimentary bodies that cannot be classified as submarine fans and completely filled small-scale basins are placed into this category. Such basins are commonly referred to as comprising 'ponded sediments'.

One of the best documented examples of sedimentary bodies that have ponded a basin occurs in the deep sea 'terraces' of the northwest Pacific trench margins [44]. The terraces are basins from 20 to 50 km wide and up to 100 km long, dammed by terrigenous *not* pelagic sediments. Thus, the basins may be thought of as over-supplied or ponded by terrigenous clastics. Another example occurs on the lower slope between the trench and 'trench slope break' on the Sunda Arc in the Nias area, Central Sumatra Region [45]. In the Nias area, the ponded sediments occur in basins about 10 km wide and up to 3 to 4 km deep whereas toward the trench, away from the trench-slope break, the ponded sediments are in basins with smaller dimensions. In a further example from the Mexican ridges, southwestern Gulf of Mexico, the ponded sediments occur in basins of the order of 20 to 40 km wide and up to 3 km deep, decreasing to widths of about 10 km and shallower depths farther offshore [46]. In the latter case, slides and slumps are common within the successions.

The most favorable sites in which non-fan ponded systems develop appear to be active, convergent, margin settings especially in forearc basins as shown by Underwood and Bachman [47]. However, other possible non-fan ponded systems may be found in some of the fault-controlled Atlantic margin basins north of Cape Hatteras: the basins vary from 50 to 350 km wide [48].

It seems unlikely that non-fan ponded sedimentary systems can be defined on the basis of specific sedimentary attributes because the grain size, bed thickness, bed shape and the type of sediment gravity flow deposits will depend, to a large extent, on the source area, the way that sediments were fed to the basin and the physiography of the depositional basin. Recognition in ancient successions will rely upon demonstrating that the sediments occupied relatively small basins with sediment ponding of successive flows or, at least, many of the flows. In view of the formation and location of over-supplied or ponded systems, point sources for sediment supply over long periods may be poorly developed so that sheet-like deposits may be most common to the successions.

Unfortunatley, the submarine fan facies models and terminology are being over-emphasized in the active margin successions where fan morphology is generally unproven (though channels and sheet sandstones naturally occur together), as for example in the recent paper by Underwood and Bachman [47]. It may prove possible to define non-fan ponded systems on the basis of facies-associations, and this is clearly an area in which future research should develop because we are unable to do this at present.

FAN DELTAS

A category of deep-water siliciclastic systems displaying many of the features of submarine fans, but with relatively small dimensions although not necessarily sediment thicknesses, are fan deltas. The Yallahs Fan Delta is an example of the interaction of littoral processes and bathymetry [49], in which the submarine delta extends down to 1100 m below sea level over a horizontal distance of 4 km; it is over 500 m thick. The delta is believed to have formed in a fault-bounded basin, thus, it is a structurally formed and sedimentologically modified slope [49].

Fan deltas have not been studied sufficiently for a rigorous definition of the characteristic facies, facies-associations and sequences. However, research in this direction has been undertaken in the Pliocene fan deltas of the Intra-Apenninic Basin near Bologna, Italy, and the reader is referred to this work for a detailed description of a well documented fan delta system [50].

DISCUSSION

The purpose of the above classification is not simply an exercise in semantics, but a categorization of deep-water siliciclastic systems with an emphasis upon the shape and sedimentary nature of the system. Once the shape of a clastic body can be determined, then it is more likely that the factors governing sedimentation of that system can be ascertained. Also, this type of classification could provide a starting point from which to compare and contrast the sedimentation within clastic bodies with varying shapes, and to determine the importance of basin shape on the distribution of facies, facies-associations and sequences.

In studying ancient deep-water siliciclastic systems, I would suggest that the emphasis be shifted from interpreting their plate tectonic milieux to trying to determine the shape of the systems, with a view to comparative studies of varying basin settings in order to distinguish them on the basis of sedimentary attributes. Clearly, modern deep-water deposits are easily seen with respect to their plate tectonic and tectonic environments, whereas with ancient rocks such extrapolations often are based on poor evidence and tend to obfuscate one of the main considerations in any study, that is the shape of the system.

Exploration for hydrocarbons relies more heavily upon determining the shape of depositional systems, the continuity of potential traps, the dimensions of facies, facies-associations and sequences, than on defining the overall plate tectonic setting. Both are important, but for the sedimentologist and the exploration companies, the classification of deep-water clastics must be hierarchical, i.e., from facies, facies-associations and sequences, to the shape of the depositional system (and whether it represents an under- or over-supplied system), and only then, to the overall tectonic setting.

As with any classification, there are inherent ambiguities and problems in including all the examples within the scheme. Modern deep-water systems are extremely complex both spatially and temporally, and with ancient systems the paucity of data often makes over-simplified models seem very plausible. Carter and others [51] used the Conway Trough, a deep near-shore basin off New Zealand, to show the complexity of basin filling at the junction of the Alpine transform and the Hikurangi subduction plate. They define 'transform', 'transform-eustatic', and 'transduction' models with different stratigraphies, showing that the variability in facies-associations is a function of the tectonics. Another example of a complex basin fill occurs on the active transform margin off California in the Santa Monica Basin, described by Malouta and others [52]. The basin contains a submarine fan, slope drape and canyons around the margin. Thus, many basins may be defined in terms of the sedimentary components (Santa Monica Basin) although in many cases such compartmentalization of basins may prove difficult (Conway Trough)—in ancient rocks, the difficulties are magnified many times!

Despite the limitations of the classification of sedimentary systems by shape, such an approach, especially in ancient rocks, would serve to focus attention on the factors governing the development of specified sedimentary shapes. Although the geometry of ancient systems generally cannot be defined, often two-dimensional models can be erected to account for the distribution of facies, facies-associations and sequences. Therefore, the term 'shape' is preferred to the more specific, and obviously impracticable, classification of deep-water siliciclastic systems by geometry.

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