Earth-Science Reviews 179 (2018) 38–71

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Hierarchical classifications of the sedimentary architecture of deep-marine depositional systems

Sophie Cullis*, Luca Colombera, Marco Patacci, William D. McCaffrey

Turbidites Research Group, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

ARTICLE INFO

Keywords:
Turbidite
Deep water
Hierarchy
Hierarchical scheme
Channel
Lobe

ABSTRACT

Hierarchical classifications are used in the field of clastic deep-marine sedimentary geology to assign spatial and temporal order to the sedimentary architecture of preserved deep-marine deposits and to genetically related modern landforms. Although such classifications aim to simplify the description of complex systems, the wide range of developed approaches limits the ease with which deep-marine architectural data derived from different sources can be reconciled and compared. This work systematically reviews and compares a selection of the most significant published hierarchical schemes for the description of deep-marine sedimentary architecture. A detailed account of each scheme is provided, outlining its aims, environmental contexts and methods of data collection, together with the diagnostic criteria used to discern each hierarchical order from observational standpoints (e.g., via facies associations, geometry, scale and bounding-surface relationships) and also on interpretational grounds (e.g., processes and sub-environments of deposition). The inconsistencies and pitfalls in the application of each scheme are also considered.

The immediate goal of this review is to assist sedimentologists in their attempts to apply hierarchical classifications, both in the contexts in which the classifications were originally developed and in alternative settings. An additional goal is to assess the causes of similarities and differences between schemes, which may arise, for example, in relation to their different aims, scales of interest or environmental focus (e.g., channelized or lobate units, or both). Similarities are found between the approaches that commonly underlie the hierarchical classifications. Hierarchies are largely erected on the basis of common types of observations, in particular relating to the lithology and geometries of deposits, in association with analysis of bounding-surface characteristics and relationships. These factors are commonly considered in parallel with their associated genetic interpretations in terms of processes or (sub-) environments of deposition. A final goal of the review is to assess whether a universal standard for the description of deep-marine sedimentary architecture can be devised. Despite the commonalities that exist between classification approaches, a confident reconciliation of the different hierarchical classification schemes does not appear to be achievable in the current state of knowledge.

1. Introduction

In the field of deep-marine clastic sedimentology, a wide variety of hierarchical schemes has been proposed to categorise sedimentary deposits, particularly those associated with sediment gravity flows (e.g., Mutti and Normark, 1987; Ghosh and Lowe, 1993; Pickering et al., 1995; Beaubouef et al., 1999; Gardner and Borer, 2000; Prather et al., 2000; Navarre et al., 2002; Gardner et al., 2003; Sprague et al., 2005; Hadler-Jacobsen et al., 2005; Mayall et al., 2006; Gervais et al., 2006a; Deptuck et al., 2008; Prélat et al., 2009; Campion et al., 2011; Flint et al., 2011; MacDonald et al., 2011; Pickering and Cantalejo, 2015; Terlaky et al., 2016). These hierarchies all attempt to classify deep-marine sedimentary architecture by assigning spatial and temporal order or genetic significance to sedimentary packages. Similar hierarchical approaches have also been applied to aeolian (e.g., Brookfield, 1977), fluvial (e.g., Allen, 1983; Miall, 1985), and sequence stratigraphic classifications (e.g., Mitchum and Van Wagoner, 1991; Neal and Abreu, 2009; Catuneanu et al., 2011).

The identification of deep-marine hierarchy has enabled stratigraphic heterogeneities to be better characterised and communicated – an approach which has benefitted hydrocarbon reservoir modelling, resulting for example in more accurate history matching of fluid flow in channel deposits (Stewart et al., 2008) and in improved connectivity models in lobe deposits (Zhang et al., 2009; Hofstra et al., 2017). These largely descriptive hierarchical schemes have also been used to inform models of deep-marine processes (e.g., Gardner et al., 2003; McHargue

* Corresponding author.
E-mail address: eesle@leeds.ac.uk (S. Cullis).

https://doi.org/10.1016/j.earscirev.2018.01.016
Received 18 March 2017; Received in revised form 19 January 2018; Accepted 22 January 2018

et al., 2011; Macauley and Hubbard, 2013; Terlaky et al., 2016; Hamilton et al., 2017).

However, it can be argued that the wide variety of hierarchical schemes of deep-marine sedimentary architecture no longer simplifies the analysis of deep-marine deposits. Schemes may vary in the number of significant orders, terminology and observational or interpretative criteria used to define significant hierarchical orders. This lack of standardisation significantly hampers comparative studies between different depositional systems and datasets, in turn limiting the effectiveness of predictions or insight derived from the comparison. Terminological variability - a long-standing problem in deep-marine studies (cf. Mutti and Normark, 1987; Shanmugam and Moiola, 1988; Weimer and Slatt, 2007; Terlaky et al., 2016) - also calls into question the consistency with which primary sedimentological studies are undertaken.

The aims of this paper are as follows:

- To review the variety seen within and between hierarchical classifications of clastic deep-marine deposits. To this end, the most widely adopted and distinctive deep-marine hierarchy schemes are described in detail. The motivation behind each of these schemes and the scope of each study is assessed. The diagnostic tools used within each hierarchy to identify discrete architectural levels are also evaluated.
- To evaluate the possible causes of variety observed in hierarchical approaches, considering whether the range of observed approaches is a consequence of excessive categorisation or whether it reflects a genuine variability in the organisational styles of deep-marine clastic depositional systems.
- To establish the degree to which hierarchical classifications can be reconciled. Is a 'Rosetta stone' approach, whereby all classifications can be reassigned to a common standard, feasible?

2. Approaches to hierarchical classification

A selection of key hierarchical schemes available in the literature will be reviewed in this section, demonstrating the breadth of hierarchical concepts that exist and are used in deep-marine sedimentary geology. Table 1 lists all the considered hierarchical schemes and highlights their key attributes. These schemes have been chosen due to their importance in the way hierarchical organisation is formalised and/or because of their broad acceptance and usage. The degree and manner in which each scheme has been taken up by fellow scientists are either considered in each summary section or presented in separate extended subsections. 'Cited by' scores (as of January 2018) are also recorded in Table 1; however, caution should be exercised in interpreting these metrics: the citations of an article do not necessarily relate to the popularity of the hierarchical scheme proposed therein, as the same article might be cited for other reasons.

Firstly, a review is undertaken of early studies that popularised the use of hierarchical schemes in deep-marine clastic depositional systems (Mutti and Normark, 1987; Ghosh and Lowe, 1993; Pickering et al., 1995). Secondly, we review subsequent schemes that contributed significant concepts to hierarchical classifications, based on insights derived from outcrops (Gardner and Borer, 2000; Pickering and Cantalejo, 2015; Terlaky et al., 2016) and reflection-seismic data (Prather et al., 2000; Navarre et al., 2002). Thirdly, a series of schemes is reviewed that attempted to assign sequence stratigraphic significance to hierarchical orders (e.g., Sprague et al., 2005; Hadler-Jacobsen et al., 2005; Mayall et al., 2006). Finally, schemes that were specifically developed for depositional lobes, based on both outcrop and seismic data, are reviewed (Gervais et al., 2006aa; Deptuck et al., 2008; Prélat et al., 2009; Flint et al., 2011; MacDonald et al., 2011).

The focus of these hierarchical summaries will be upon understanding the basis on which each hierarchical classification has been formulated, and on explaining how to recognise the discrete hierarchical levels identified in each scheme. This section will therefore examine the key principles and criteria used by each particular scheme, and describe how these principles for hierarchical division have developed over time. The hierarchies will be reviewed in order of publication; follow-on alterations of the schemes will be considered in sequence with the original study. A summary flowchart (Fig. 1) illustrates the influences of earlier hierarchical schemes on subsequent schemes.

2.1. *Mutti and Normark, 1987*

The hierarchical scheme developed by Mutti and Normark (1987, 1991) is recognised by many as the first attempt to adopt a hierarchical classification that spanned both ancient and modern deep-marine environments (Pickering et al., 1995; Ghosh and Lowe, 1993; Clark and Pickering, 1996; Shanmugam, 2000; Weimer and Slatt, 2007). While the application of this particular scheme in following studies has been somewhat limited, many authors have drawn comparisons between hierarchical orders in Mutti and Normark's (1987) scheme and their own orders (e.g., Ghosh and Lowe, 1993; Pickering et al., 1995; Prather et al., 2000; Sprague et al., 2005).

This hierarchy was designed to reconcile the differences between datasets of modern marine environments, acquired by seismic techniques and ancient outcrops of turbidite deposits. Mutti and Normark (1987) recognised that the key difficulty in classifying and thus comparing systems lies in recognising sedimentary bodies that were deposited over similar timescales within the deep-marine realm. Therefore, they aimed to develop a hierarchy that would enable recognisable turbidite bodies ("elements") to be compared over similar temporal as well as spatial scales.

Mutti and Normark (1987) identify five main orders of scale (see Fig. 2), which link to the sequence stratigraphic framework of Vail et al. (1977) on the basis of the proposed timescales reflected by each order. Mutti & Normark's estimated timescale ranges are based upon interpretations of the likely cause and extent of the breaks in sedimentation associated with a particular hierarchical order. The smallest recognised hierarchical order is a '**turbidite bed**', which is interpreted by Mutti and Normark (1987, 1991) as being a "normal" small-scale erosional and depositional feature, deposited over "virtually instantaneous", or 1–1000 years, timespans. Genetically related 'turbidite beds' stack laterally and vertically to form facies associations known as '**turbidite sub-stages**' (5–10 m thick), which equate to individual periods of deposition, bypass or erosion within a specific stage of growth. Mutti and Normark (1987) note that some depositional systems may consist of only one such 'sub-stage' facies character. These 'sub-stage' units are described to be high-frequency deposits, deposited over 1 to 10 kyr timescales. 'Turbidite beds', also described by Mutti and Normark (1987, 1991) as 5^{th}-order units, and 'sub-stages' (4^{th}-order) are stated to be typically only visible below conventional seismic resolution; thus, the applicability of these elements of Mutti and Normark's (1987) hierarchy to conventional seismic datasets is limited. A '**turbidite stage**' (3^{rd}-order) is formed by the stacking of 'turbidite sub-stages' and records what is termed as a specific growth period, consisting of associated facies associations with no significant breaks in sedimentation (unconformities) within the unit. This 3^{rd}-order hierarchical level is stated to be seismically resolvable if the thickness of the unit exceeds several tens of metres.

It is at the 'turbidite stage' or 'turbidite sub-stage' that Mutti and Normark (1987) accredit the formation of recognisable 'elements' in the deep-marine environment. Mutti and Normark (1987, 1991) document five element types that are common to both modern and ancient systems, and that can be differentiated in terms of geometries, resulting from different sets of depositional processes:

- channels, i.e., negative relief pathways for sediment transport;
- major erosional non-channel features, i.e., scours and slope failures;
- depositional lobes, i.e., typically sandy distributary deposits;