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

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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.

Keywords
turbidite, deep water, hierarchy, hierarchical scheme, channel, lobe

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 & Normark, 1987; Ghosh & Lowe, 1993; Pickering et al., 1995; Beaubouef et al., 1999; Gardner & 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 & 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 & Van Wagoner, 1991; Neal & 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., 2016). These largely descriptive hierarchical schemes have also been used to inform models of deep-marine processes (e.g., Gardner et al., 2003; McHargue et al., 2011; Macauley & 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 & Normark, 1987; Shanmugam & Moiola, 1988; Weimer & 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. 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 & Normark, 1987; Ghosh & Lowe, 1991; Pickering et al., 1995). Secondly, we review subsequent schemes that contributed significant concepts to hierarchical classifications, based on insights derived from outcrops (Gardner & Borer, 2000; Pickering & Cantalejo, 2015; Terlaky et al., 2016) and reflection-seismic data (Prather et al., 2000; Navarre et al., 2002; Sprague et al., 2005). 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., 2006a; 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. Table 1 lists all the considered hierarchical schemes and highlights their key attributes.

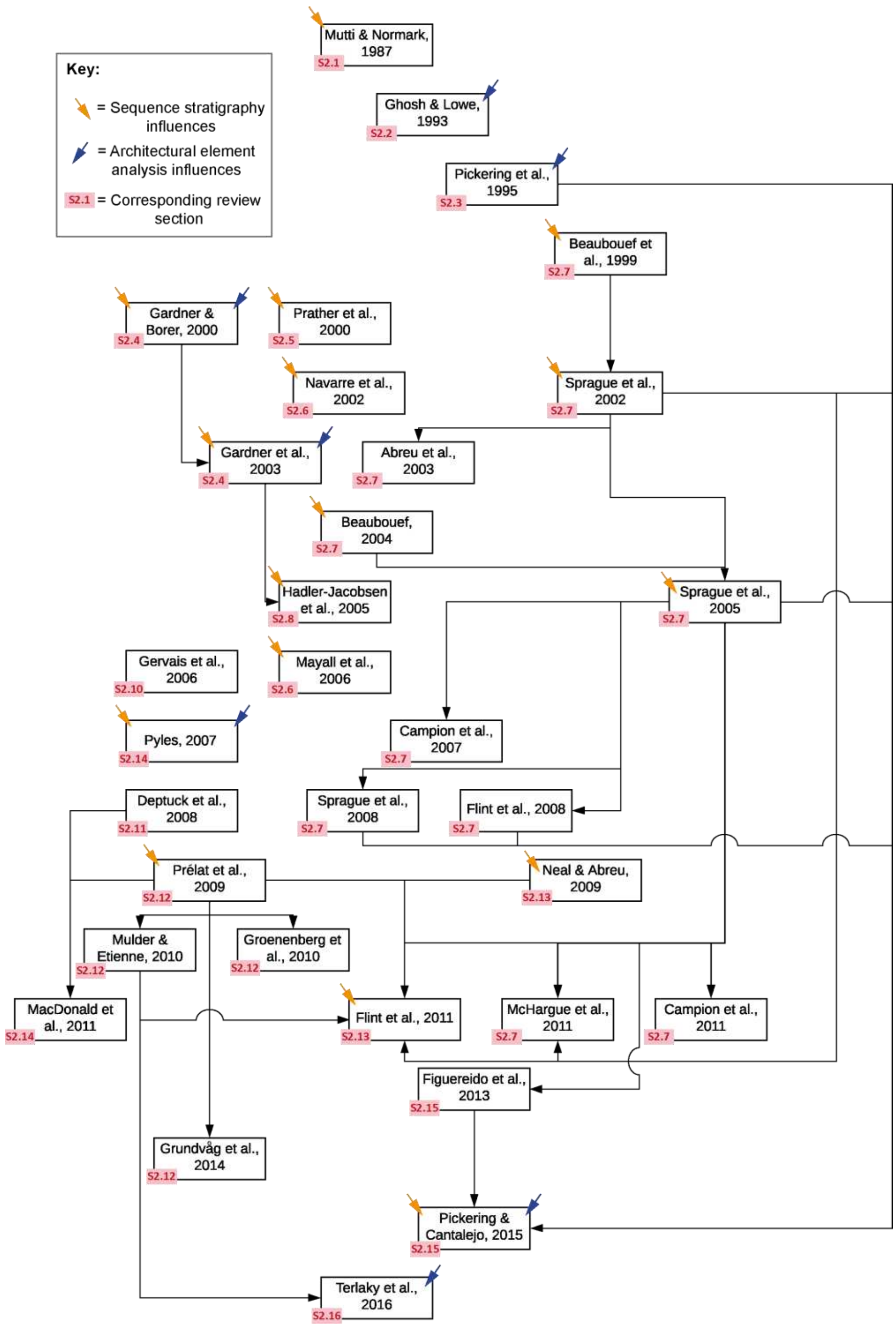

Fig. 1. Citations flowchart documenting the influences of earlier hierarchical schemes over later schemes. Each box represents a paper detailing a certain hierarchical scheme; the publications are arranged chronologically from top to bottom. Lines represent citations between the various schemes (arrow pointing to younger paper). Orange arrows represent citations to key sequence stratigraphy works or direct reference to sequence stratigraphic units (e.g., systems tracts or depositional sequences) or to timescales derived from either Vail et al. (1977), Mitchum (1977), Van Wagoner et al. (1988), Mitchum & Van Wagoner (1991) or Van der Merwe (2010). Blue arrows represent citations to key publications on architectural element analysis or reference to a given hierarchy of bounding surfaces, e.g., by McKee & Weir (1953), Brookfield (1977), Allen (1983) or Miall (1985, 1987, 1989).

Study	Hierarchy objective	Number of hierarchical orders	Data type, domain of application	Physiographic setting	Architectural element focus	Case study(ies)	Age of deposits	Additional boundary conditions	Influences	Hydrocarbon industry affiliations	Google scholar citations
Mutti & Normark, 1987	Designed to reconcile studies of modern and ancient turbidite systems, and associated data types	5	Seismic and outcrop datasets	Slope to basin floor	-	-	Applicable to ancient and modern systems	-	Devised as relatable to the sequence stratigraphy framework	-	680
Ghosh & Lowe, 1993	Channel hierarchy by using detailed facies analysis and lateral and vertical facies correlations	5	Outcrop	'mid-fan' (after Normark, 1970; Walker, 1978; Mutti & Ricci Lucchi, 1972) (CLTZ)	Channels	Venado Sandstone Member, California	Applied to Cretaceous	Coarse sand to conglomeratic system	Bounding-surface hierarchy of Allen (1983); architectural-element analysis of Miall (1987, 1989)	-	39
Pickering et al., 1995	Founded on architectural element analysis; hierarchy is emplaced using bounding surfaces	7	Seismic and outcrop datasets	Slope to basin floor	-	-	Applicable to ancient and modern systems	Sand-rich system	Bounding-surface hierarchy of Allen (1983); architectural-element analysis of Miall (1985)	Sponsored by Shell Exploration	84
Beaubouef et al., 1999	Based upon sequence stratigraphy; divisions reflect sequence boundaries	5	Outcrop and well data	Slope to basin floor	Channels	Brushy Canyon Formation, West Texas	Applied to Permian	Tectonically stable shelf with gradually decreasing subsidence rates	Sequence stratigraphy concepts	Workers from Exxon Production Research Company	100
Prather et al., 2000	Largely concerned with seismic scales	7	Seismic and well-log and core data	Slope to basin floor	-	General reference to Central Gulf of Mexico intraslope basins	Applicable to ancient and modern systems	Sand-rich system	-	Workers from Shell International E&P	33
Gardner & Borer, 2000	Specific to channel-lobe transition zone (CLTZ)	4	Outcrop	Slope to basin transition zone (CLTZ)	-	Brushy Canyon Formation, West Texas	Applied to Permian	Sand-rich system	Architectural-element analysis	Sponsored by 13 different research and exploration petroleum companies	130
Navarre et al., 2002	Produced to aid reservoir characterisation through recognition of turbidite stratigraphic architecture	6	Seismic and core and well-log data	Slope to basin floor	-	Gulf of Guinea, West Africa	Applied to Tertiary	-	-	Workers from TotalFinaElf	55
Gardner et al., 2003	Modification of scheme by Gardner and Borer's (2000): formative processes now considered	4	Outcrop	Slope to basin transition zone (CLTZ)	-	Brushy Canyon Formation, West Texas	Applied to Permian	Sand-rich system	Architectural-element analysis	Sponsored by 23 research and exploration petroleum companies	129
Abreu et al., 2003	Modification to hierarchy of Sprague et al. (2002); includes LAPs in channel systems	4	Seismic, well data, and outcrop datasets	Slope	Channel lateral accretion packages (LAPs)	Dalia and Grissol fields, offshore Angola	Applied to Miocene	-	Sprague et al. (2002)	Workers from ExxonMobil Upstream Research Company. Seismic data was supplied by 5 petroleum companies	294
Sprague et al., 2005	Physical stratigraphic framework developed for hydrocarbon reservoir prediction in slope and basin settings	8	3D seismic and well-log and core data	Slope to basin floor	-	Off-shore west Africa	Applied to Miocene and Pliocene	-	Beaubouef (1999); Campion et al. (2000); sequence stratigraphy concepts	Workers from ExxonMobil & Shell Deep Water Services Company	41

Hadler-Jacobsen et al., 2005	Chronostratigraphic orders assigned based on sequence stratigraphic principles, at seismic scale	5	Seismic and outcrop datasets	Shelf to basin floor	-	Finnmark Platform; Porcupine Basin; Viking Graben; Central Basin in Spitsbergen; Tanqua Karoo Basin; Brushy Canyon Formation	Applicable to ancient systems	Sand-rich system	Sequence stratigraphy concepts	Sponsored by Statoil	51
Gervais et al., 2006	Based upon internal geometry of lobes, observed and interpreted via seismic facies	3	High-resolution seismic	Basin floor	Lobes	Golo basin, East Corsica	Applied to Pleistocene to Holocene	Sand-rich system, ponded basin	-	-	93
Mayall et al., 2006	Based upon recognition of likely stratigraphic setting, and channel element characteristics (sinuosity, facies, cutting and filling, stacking patterns) at each level	3	High-resolution seismic and outcrop datasets	Slope	Erosionally confined channels	Seismic data from a range of studies; outcrop examples from the Brushy Canyon Formation	Applied to Pleistocene and modern systems	-	Sequence stratigraphy concepts	Sponsored by BP, Sonangol, Total, ExxonMobil, Statoil, Norsk Hydro, ENI	243
Deptuck et al., 2008	Applicable to lobes; influenced by recognition of scales of compensational stacking	4	High-resolution seismic, cores	Basin floor	Lobes	Golo basin, East Corsica	Applied to Pleistocene to Holocene	Sand-rich system, ponded basin	-	-	115
Prélat et al., 2009	Based upon characteristics and geometry of fine-grained units between sand-prone lobes	4	Outcrop	Basin floor	Lobes	Tanqua depocentre, Karoo basin, South Africa	Applied to Permian	-	-	Sponsored by Chevron, Maersk, Petrobas, PetroSA, StatoilHydro, Total	138
MacDonald et al., 2011	Based on hierarchy of Deptuck et al. (2008), with modifications in light of process sedimentology	3	Outcrop	Basin floor	Lobes	Ross Formation, Ireland	Applied to Carboniferous	Sand-rich system	Deptuck et al. (2008)	-	33
Flint et al., 2011	Based on regionally mappable hemipelagic claystones; utilises sequence stratigraphy concepts; lobe hierarchy related to sea-level fluctuations	3	Outcrop	Slope to basin floor	Lobes	Lainsburg depocentre, Karoo Basin, South Africa	Applied to Permian		Sprague et al. (2002); Neal & Abreu (2009); sequence stratigraphy concepts	Sponsored by ExxonMobil	93
Pickering & Cantalejo, 2015	Used to characterise and correlate stratigraphic surfaces at many scales, allowing identification of bounding surfaces of architectural elements	10	Outcrop, cores	Slope (or basin floor, origin of deposits is debated)	Channels (and MTD/MTC components)	Upper Hecho Group, Ainsa Basin, Spain	Applied to Eocene	Coarse clastic sediment entering from a point source	Flint et al. (2008); Sprague et al. (2008); facies terminology of Pickering et al. (1986; 1989)	Sponsored by CNOOC-Nexen Petroleum UK Ltd	2
Terlaky et al., 2016	Derived from existing schemes; focuses upon recognition of scale and context of channel avulsion	7	Outcrop	Basin floor	-	Windermere Supergroup, British Columbia, Canada	Applied to Neoproterozoic	Mixed-sediment system	Architectural-element analysis; Mulder & Etienne's (2010) review, itself influenced by Prélat et al. (2009)	Sponsored by 7 research and exploration petroleum companies	8

Table 1 – Summary table for all works evaluated within this review. The table notes the objectives and deep-marine setting for each study. The case-study examples used within the original studies are also recorded, along with any peer-reviewed literature or sedimentological concepts the study states to have greatly influenced the development of the resultant hierarchy. Citation statistics as of January 2018.

2.1 Mutti & Normark, 1987

The hierarchical scheme developed by Mutti & 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 & Lowe, 1993; Clark & Pickering, 1996; Shanmugam, 2000; Weimer & 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 & Normak's (1987) scheme and their own orders (e.g., Ghosh & 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 & 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 & 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 & 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**' (1-10 metres thick), which equate to individual periods of deposition, bypass or erosion within a specific stage of growth. Mutti & 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 & Normark (1987; 1991) as 5th order units, and 'sub-stages' (4th order) are stated to be typically only visible below conventional seismic resolution; thus, the applicability of these elements of Mutti & Normark's (1987) hierarchy to conventional seismic datasets is limited. A '**turbidite stage**' (3rd 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 3rd 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 & Normark (1987) accredit the formation of recognisable 'elements' in the deep-marine environment. Mutti & 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;
- overbank deposits, i.e., laterally extensive fine-grained deposits adjacent to major channels;
- channel-lobe transitions, i.e., a mix of depositional and erosional elements reflecting a transformation of flow, where turbidity currents commonly experience hydraulic jumps.

These elements are described as basic 'mappable' units which can have either erosional or depositional characteristics.

'Turbidite stages' stack to form a '**turbidite system**' (0.1-1 Myr); these deposits are said to be characterised by short-term sea-level change or tectonic activity, whereby no major breaks in sedimentation are seen. Similar sequences in 'turbidite stage' stacking are observed and interpreted to be the product of an overall reduction in flow volume, as relative sea level gradually rises. A 'turbidite system' (2^{nd} order) may contain only a single 'turbidite stage', or it may be a composite unit made of multiple stages of growth. A 'system' is seen by Mutti & Normark (1987) to always terminate with a mudstone interval, interpreted to be the product of a highstand systems tract (HST) in response to short-term sea-level change. A 'turbidite system' is defined by the authors as being a 'part' of a depositional sequence *sensu* Vail et al. (1977) which is defined as a relatively conformable succession of genetically related strata, typically bounded at its top and bottom by unconformities, representing a cycle of sea-level change. The identification of higher orders in the hierarchy (2^{nd} and 1^{st} orders) relies strongly upon the recognition of erosional surfaces that envelope lower-order genetically related units. The largest hierarchical order recognised by Mutti & Normark (1987) is termed a '**turbidite complex**' (1^{st} order). A unit of this order reflects a complete basin-fill succession built through stacking of 'turbidite systems' in the same long-lived depocentre (1 to 10 Myr duration). These sedimentary units are bounded by long-term unconformities, and may be seen to contain multiple 'depositional sequences'. 'Turbidite complex' depositional bodies may reach volumes over 100 km^3 and thus far outreach the scales of investigation of almost all outcrop studies.

Although the scheme aims at being broad, the assignment of hierarchical orders is stated by Mutti & Normark (1987; 1991) to only be effective after an initial categorisation process, whereby studies are categorised into their 'basin types'. Basin types are identified by a number of criteria (e.g., basin size, rate of sediment supply, crustal mobility, syndepositional tectonics), to ensure that potential comparisons are made between relatable basin environments, with the aim of producing more reliable and meaningful comparative analyses.

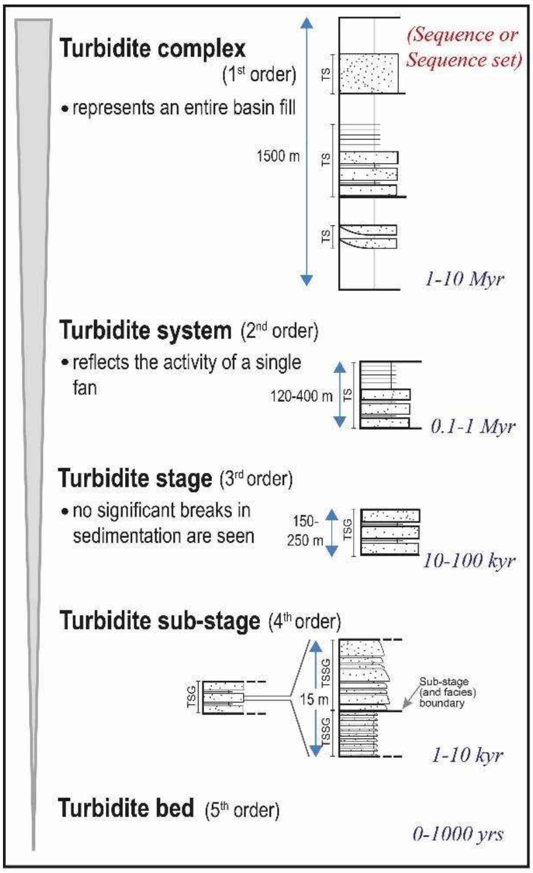

Figure 2:- Hierarchical classification of Mutti & Normark (1987), showing the five hierarchical orders, as well as the associated typical thicknesses and durations (blue italic text) proposed for each order. Correspondence with sequence stratigraphic units is also noted (red italic text). Modified after Mutti & Normark (1987).

2.2 Ghosh & Lowe, 1993

The hierarchy of Ghosh & Lowe (1993) deals with the nested architecture of channel deposits in the geological record. Until the early '90s, the internal sedimentary architecture of channel units was relatively poorly characterised, due to the limited resolution of seismic datasets and dominantly one-dimensional facies descriptions, as well as the limited lateral extent of most studied outcrops. Ghosh & Lowe (1993) carried out detailed lateral correlations of closely spaced vertical sections in the Venado Sandstone Member (Great Valley Group, Sacramento Basin, California) and developed a hierarchy focussing upon the internal architecture of channel deposits. Through facies analyses, the study established links between processes of turbidity current erosion and sedimentation, and the resultant channel-deposit architecture.

Ghosh & Lowe (1993) were influenced by Brookfield (1977), Allen (1983) and Miall's (1987; 1989) clastic hierarchical classifications, based upon the recognition of bounding surfaces of different types to distinguish hierarchical orders. Similarly to the approaches taken by these authors, Ghosh & Lowe's (1993) order numbering is from smallest to largest, as opposed to the scheme of Mutti & Normark (1987), which followed sequence stratigraphic convention. Six orders are proposed, although only five were identified in the Venado Sandstone, based upon correlations made between three measured sections over a distance of 475 m, see Fig. 3.

Sedimentary gravity flow deposits are typically heterogeneous with regards to sediment texture and structure. Internal variations in grain-size or sedimentary structures define divisions at the smallest and finest scale of this scheme, i.e., '**first-order**' elements. These elements correspond to Bouma divisions (e.g., T_a, T_b or T_c, Bouma 1962) or high-density turbidity current divisions (e.g., S_1, S_2 or R_1 of Lowe, 1982) and represent deposition over minute to hour timescales, by reference to the work of Sadler (1981). These elements are bounded by first-order bounding surfaces, which according to Ghosh & Lowe (1993) record processes of transport and deposition during flow evolution. It is also understood that the arrangement of these first-order divisions within their 'second-order' elements are controlled by the evolution of the flow and its effect upon grain-size distribution. The recognition of these 'first-order' elements is difficult in some cases, especially in massive units such as conglomerates and debris flows, like those found in the basal section of the Venado Sandstone, where the identification of surfaces can be highly uncertain.

The '**second-order**' element is described as a single sedimentation unit based on the terminology of Allen (1983). In the case of heterogeneous deposits, these units comprise a number of 'first-order' elements. Massive deposits, where internal divisions are not easily recognised, will have equivalent 'first-order' and 'second-order' bounding surfaces. These 'second-order' surfaces are recognised as 'inter-flow' surfaces (deposited over day, 10^{-3} yr, timescales) between depositing currents, and are thus stated to be useful indicators of the currents character, e.g., whether flows are depositional, erosional or mixed. Sedimentation units can usually be divided into textural zones representing surges within a single turbidity current. Twelve 'second-order' units were identified by Ghosh & Lowe (1993) in the Venado Sandstone, with thicknesses in the range of 0.05-8 m and with some inter-channel units extending laterally over the entire 475-m-wide outcrop. The lateral correlation of 'second-order' units can be affected by erosion and scouring of subsequent flows and internal lateral variability can be seen due to the arrangement of internal 'first-order' elements. Grain-size contrasts, internal grading and scoured bases are all facies characters used to determine individual sedimentation units; it can therefore be hard to decipher 'second-order' units within conglomerates, as well as in amalgamated deposits.

'**Third-order**' elements bound groups of 'second-order' sedimentation units. These units are compared to the '5th order' (the 'turbidite-bed') of Mutti & Normark (1987) which Ghosh & Lowe (1993) additionally term a 'macroform'. At least 8 'third-order' elements, between 5-30 m thick, are identified in the Venado Sandstone as 'channel infilling' units, encapsulating deposits of similar flow units. These units are correlated more readily over greater distances than 'second-order' units, as little lateral change can be seen with regards to their internal character. 'Third-order' units are bound by third-order bounding surfaces and are recognised based upon similar internal lithologies and depositional styles. In particular, three types of 'third-order' units are described in this outcrop, respectively made of 1) conglomeratic thick-bedded sandstone, 2) thick-bedded sandstone and 3) thin-bedded mudstone and sandstone interpreted as inter-channel units.

'**Fourth-order**' elements represent individual channel systems and are also termed channel complexes. These units are deposited over 1-10 kyr timescales. Five 'fourth-order' units (50-75 m thick) were recognised in the Venado Sandstone, each showing fining-upwards trends in bed thickness and grain size. These units are made comparable to Mutti & Normark's (1987) '4th order' and '3rd order' ('turbidite sub-stage' and 'stage') elements. Ghosh & Lowe (1993) stated that the genetic significance of 'fourth-order' units still needed to be elucidated. These 'fourth-order' elements separate individual channel units in a multi-channel complex, the '**fifth-order**' hierarchical element. The entire Venado Sandstone Member at Monticello Dam (400-1000 m thick) is recognised as a single 'fifth-order' element. The boundary between the Venado Sandstone and its overlying unit (Yolo shale) can be traced throughout the basin, reflecting the regional scale of this unit. Durations between 0.1-1 Myr are assigned to these 'multi-storey channel stack' units based upon the stratigraphic timescales proposed by Sadler (1981). This order is compared to the '2nd order, depositional system' of Mutti & Normark (1987). A '**sixth-order**' is also made comparable to Mutti & Normark's (1987) '1st order', termed by Ghosh & Lowe (1993) as a 'fan complex'. No such elements are identified in the Venado Sandstone. Ghosh & Lowe (1993) consider units at this order to develop over 1-10 Myr timescales, based on the work by Sadler (1981).

The strong reliance on the identification of small-scale facies characters, along with the importance of lateral correlations in defining lithological variations, prevents this hierarchy from being easily applied to seismic datasets. However, this scheme has been used in several studies, and featured in the popular textbook by Reading (1996). The scheme has been used to classify hierarchy in a variety of conglomeratic channel environments, such as the Juniper Ridge Conglomerate (Great Valley Group, California, USA; Hickson & Lowe, 2002), the Cerro Torro Formation (Magallanes Basin, Chile; Hubbard et al., 2008) and the Peri-Adriatic basin (Central Italy; Di Celma et al., 2010; Di Celma 2011), as well as both channel and lobe deposits of the fine-grained Lower Mount Messenger Formation (Taranaki Basin, New Zealand; Masalimova et al., 2016). The study by Hickson & Lowe (2002), which is also focussed on the Great Valley Group, expands upon the original hierarchy of Ghosh & Lowe (1993). For example, Hickson & Lowe (2002) specify that this scheme is open-ended and thus a variable number of hierarchical orders may be recognised for different case-studies, although only 'third-' and 'fourth-' orders are confidently identified in their study. Hickson & Lowe (2002) also state that each hierarchical order should be assigned based on descriptive features only, and that genetic interpretations of element orders should only be attempted after descriptions have been made.

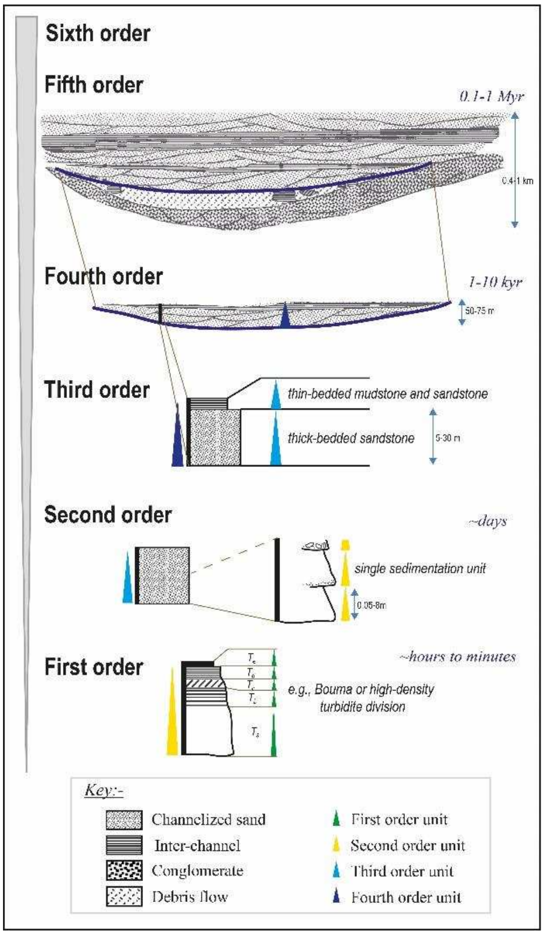

Fig. 3. Hierarchical classification developed by Ghosh & Lowe (1993) based upon the coarse channel-fills of the Venado Sandstone. Values of thickness based on field measurements and durations based upon the sedimentation rates of Sadler (1981) are included. Figure modified after Ghosh & Lowe (1993).

2.3 Pickering et al., 1995

Similarly to Ghosh & Lowe (1993), Pickering et al. (1995) were inspired by the works of Allen (1983) and Miall (1985), and their development of a hierarchy of bounding surfaces. Pickering et al.’s (1995) hierarchy is stated to be directly influenced by the methods of architectural-element analysis, expressed through the diagnosis of characteristic ‘building blocks’ of sedimentary architecture based on the recognition of facies associations, sedimentary-body geometries and a bounding-surface hierarchy. However, like the scheme of Mutti & Normark (1987), the hierarchy of Pickering et al. (1995) targeted the characterisation of both ancient and modern systems. Thus, a particular focus was placed upon the recognition of surfaces and their 2D and 3D expressions in deep-marine architecture, as opposed to Ghosh & Lowe’s (1993) mainly facies-based approach.

Pickering et al. (1995) utilise the three-tiered bounding-surface hierarchy originally employed by Allen (1983). Allen’s (1983) hierarchy for fluvial deposits envisaged depositional bodies as being divisible into ‘packets’ of genetically related strata through the observation of bounding surfaces. This approach was deemed by Pickering et al. (1995) to be transferable to deep-marine systems, as bounding surfaces can be recognised and classified in a similar manner based upon their nature and cross-cut relationships. Four types of bounding surfaces were identified by Allen (1983): ‘concordant non-erosional/normal', 'concordant erosional', 'discordant non-erosional' and 'discordant erosional' contacts. This bounding-surface set was applied to deep-marine deposits by Pickering et al. (1995), and the hierarchy was extended through the addition of higher spatial and temporal orders (fourth, fifth, and sixth hierarchical orders), to allow basin-scale deep-marine architectures to also be classified, similarly to Miall's (1985) extension of Allen's (1983) orders for fluvial deposits. The identification of bounding surfaces, their corresponding architectural geometry and internal facies characters are used to generate a sedimentological hierarchical framework, which Pickering et al. (1995) claim ensures a defendable methodical approach to architectural classification in the deep-marine realm (see Fig. 4).

In this seven-tiered classification established upon the hierarchy of bounding surfaces, each hierarchical order is associated with both a descriptive name as well as a numerical order referring to a bounding-surface level. '**Bedding contacts**' describe the smallest (zeroth) order (Fig. 4); they are described by Pickering et al. (1995) as normal, concordant bedding contacts found between strata and laminae. These 'bedding contacts' are bound by first-order bounding surfaces, to separate deposits known as '**bedding packages**', i.e., packages of cross-bedding or "concordant beds" (Pickering et al., 1995). Both these zeroth and first order sedimentary packages are comparable to Campbell's (1967) definitions of lamina and beds. Second-order '**sedimentary complexes**' form distinct sedimentary bodies of genetically related facies with a "similar" palaeocurrent direction, though similarity is not defined by Pickering et al. (1995). This hierarchical order was considered comparable to the fluvial 'storey' definition of Friend et al. (1979). Orders zeroth to third are strongly based upon facies descriptors and the associated bounding surfaces are all of limited extent. However, at the third order of the hierarchy, major erosional surfaces are seen to encapsulate multiple 'sedimentary complexes' to form a '**depositional body**'. At this order, distinct architectural-element styles are observed, which reflect different architectural geometries (e.g., channelized, sheet-like, etc.). The fourth order refers to erosional contacts that can be basin-wide, defining groups of third order channels and palaeovalleys, observable at what is described as "mappable stratigraphic scales". Units at this fourth order were termed '**members/sub-members**' by Pickering et al. (1995) and were described as being a hierarchical order that would further subdivide the 'turbidite stage (3rd order)' of Mutti & Normark (1987, 1991). A 'turbidite stage' *sensu* Mutti & Normark (1987) is described as being either a single stage of deposition (hence comparable to the third-order single-channel architectural element of Pickering et al., 1995), or as containing multiple stages of growth, reflecting a composite depositional feature, hence represented by the fourth-order of Pickering et al. (1995). Fifth-order surfaces bound '**individual fan systems**'; these are simply stated by Pickering et al. (1995) to be equivalent to Mutti & Normark's (1987) 'turbidite systems' with no further reasoning. The sixth-order bounding surfaces of Pickering et al., 1995, delineate a whole '**basin-fill sequence**', which is made comparable to Mutti & Normark's 'turbidite complex'.

Pickering et al. (1995) also classify sedimentary units on their cross-sectional and planform geometries (Fig. 4b & c). Such geometrical notation is not limited to any particular hierarchical order, however Pickering et al. (1995) note that such classification is limited by the capabilities of the method of data acquisition. The sedimentary units are also characterised by their internal facies associations based on the facies classification scheme of Pickering et al. (1986). 'Bounding surfaces' are noted as being either erosional or conformable. However, with the exception of facies changes, no criteria are provided by Pickering et al. (1995) as to how significant conformable bounding surfaces would be confidently identified, for example, in lobe settings.

Pickering et al. (1995) also stress that not all hierarchical levels may be present in all deep-marine turbiditic systems, as some systems may be more ‘punctuated’ than others, meaning that hierarchical orders may be missing in some deep-marine systems. The hierarchical divisions are therefore seen to only act as a guide. No dimensional attributes are provided as criteria for the recognition of these hierarchical orders, as bounding-surface levels are seen by Pickering et al. (1995) to be independent of such spatial classifications. Scale is simply implied through the observation of the bounding-surface hierarchy. The concept of scale is therefore expressed in this hierarchy through bounding surfaces being linked on a one-to-one basis to an architectural element; clearly this linkage will fail where an element is bound by a higher-order surface, for example due to punctuation (*sensu* Pickering et al., 1995).

It should be noted that more recent work undertaken by the same group employs a modified hierarchical classification, which includes mass-transport deposit classes and dimensional characteristics for each order; this classification is outlined in detail by Pickering & Cantalejo (2015); see section 2.15.

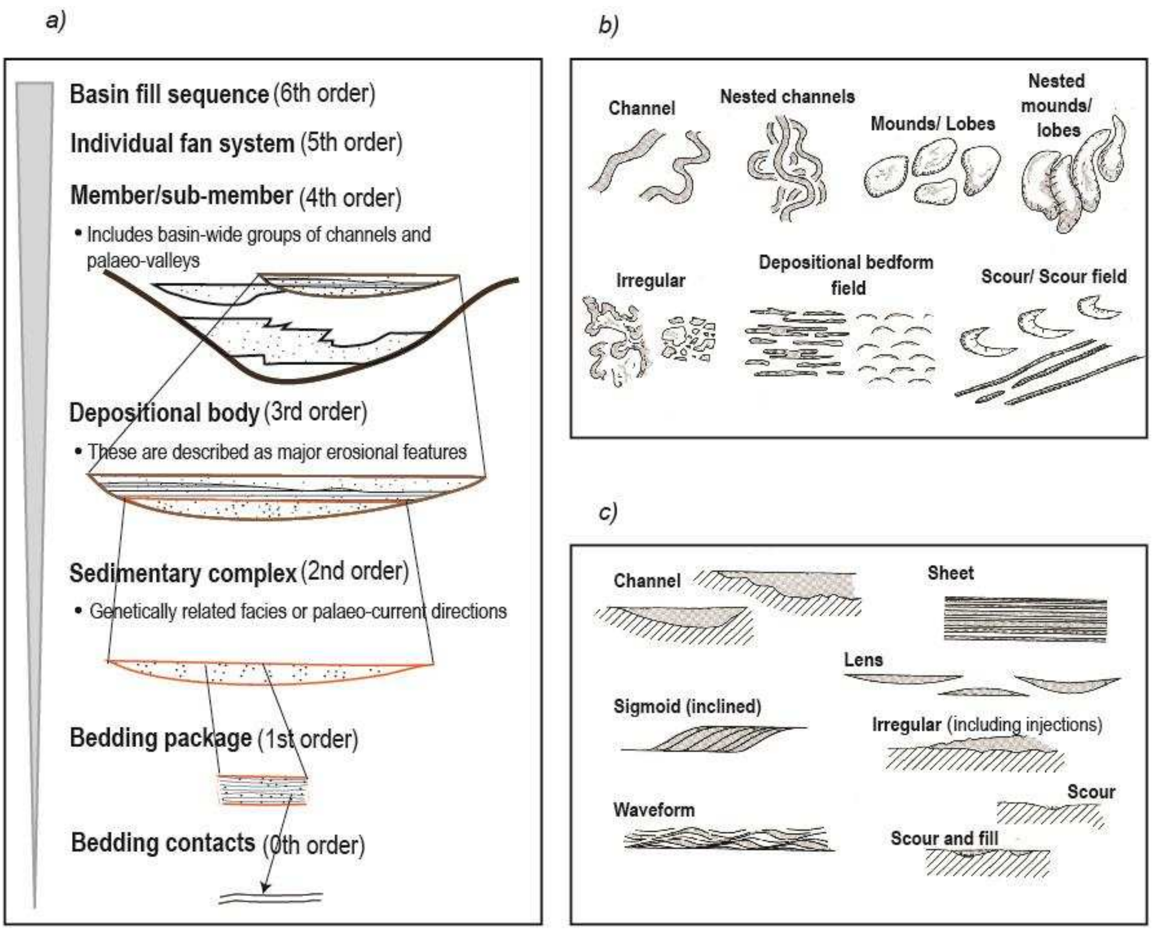

Fig. 4. *a)* Hierarchical classification of Pickering et al. (1995), showing the nomenclature and numbering associated to bounding-surface orders. The *b*) planform classification of deep-water architectural geometries, and *c*) cross-sectional classification of deep-water architectural geometries by Pickering et al. (1995) are also shown. These geometrical classifications are applicable over a wide range of scales. Figures modified after Pickering et al. (1995).

2.4 Gardner & Borer, 2000, and later studies by these authors

A four-fold hierarchy was developed by Gardner & Borer (2000), specifically to characterise the 'channel-lobe transition zone' (CLTZ hereafter) in deep-marine deposits, and solely based upon outcrop data. As well as developing a hierarchy specific to a single method of data acquisition, this hierarchy was amongst the first to be focused on a specific depositional environment. This hierarchy is stated to be based upon sedimentary, palaeogeographic, stratigraphic and architectural-element analysis concepts, and thus considers bounding surfaces and their cross-cutting relationships. This scheme is based upon four extensive outcrop studies from the Permian Brushy Canyon Formation (Texas, USA) and is largely concerned with the spatial and temporal changes of channel forms in the CLTZ. Significantly, Gardner & Borer (2000) note that in the changing flow regime of the CLTZ, the spatial dimensions of architectural products of corresponding duration will differ as deposition moves downstream; this point establishes the concept that depositional units of similar spatial scales at different positions along-dip may not reflect similar time intervals and thus hierarchical levels. The hierarchical divisions are recognised mainly through the cyclical increases in architectural-element geometry and size, denoted by their bounding surfaces (Fig. 5a). Gardner & Borer (2000) refer to the resultant four-tiered hierarchy as a stratigraphic framework of architectural elements.

At the lowest order, a '**single story channel**' (up to 7 m thick and 200 m wide, based upon field measurements) represents a discrete channel fill which may contain multiple sediment bodies with erosional bases termed as 'geobodies'. A geobody is not further defined. The 'single story channel' hierarchical order, through the use of Gardner & Borers' (2000) 'scalar' terminology, is also defined as an 'architectural element'. The next discrete order, the '**channel complex**' (or architectural element set; on average 25 m thick, 800 m wide) is interpreted as reflecting a 5th-order cycle in accordance with the sequence stratigraphic framework (Vail et al., 1977). These units represent "sand bodies with serrated margins" that shingle to form clinoform packages known as '**submarine fan conduits**'. This hierarchical order is said to reflect a 4th-order sequence stratigraphic cycle, forming 1-2 km wide sand fairways. In turn, units at this level stack to form the largest hierarchical order, a '**submarine fan conduit complex**' (or depositional sequence), reflecting the cumulative sediment pathway that remained active during the depositional lifetime of a fan. This unit was considered comparable to a 3rd-order sequence stratigraphic cycle.

'Single story channels' and 'channel complexes' are noted by Gardner & Borer (2000) to record recognisable cycles of sediment deposition and bypass, termed 'build-cut-fill-spill' sequences. These build-cut-fill-spill phases record different facies patterns, each of them being a consequence of differing sedimentological processes and energy trends, related to the position of a phase along the slope-to-basin profile. These phases can occur at multiple temporal and spatial scales. The 'build' component records the depositional phase that precedes channelization, and so it is shown by an erosional surface marking sediment bypass within upper-slope regions.

2.4.1 *Gardner & Borer's CLTZ hierarchy amendments*

The original Gardner & Borer (2000) CLTZ hierarchy was updated by Gardner et al. (2003) to include sedimentary processes and allow each hierarchical division to also be associated with (and thus identified by) the processes controlling the emplacement and geomorphic character of deposits at each level. This update modified the terminology of the scheme (e.g., the definition of a channel complex), its 'scalar' divisions (e.g., the largest order is no longer affiliated with a 'depositional sequence' but only with a lowstand systems tract), and the correspondence with sequence stratigraphic cycles (e.g., the highest hierarchical order is given a 4^{th}-order cycle status, instead of a 3^{rd}-order as in the original hierarchy). This revised scheme was still based upon studies of the Brushy Canyon Formation, but no explicit justification for these alterations was made. The differences between the two versions of the scheme are reported in Figure 4 and Table 1.

The revised hierarchy remains four-tiered. The lowest hierarchical order defined as an '**elementary channel fill and lobe (single story)**' is still referred to by Gardner et al. (2003) as an 'architectural element' in light of their 'scalar' terminology. An 'elementary channel fill and lobe (single story)' is composed of both unconfined sandbodies (lobes) and erosionally confined channel fills, built up from multiple lower-level cut-and-fill units, or 'geobodies'. Like Gardner & Borer (2000), a 'geobody' is recognised as the smallest sedimentary building block, however yet again it is not defined clearly. The 'elementary channel fills and lobes (single story)' stack to form compound sandstone bodies termed '**composite channels**'. A 'composite channel', also termed an 'architectural complex', records genetically related sandbodies that show a common migration pathway. On average they are 10 m thick and 350 m wide, based upon the examples measured in the study. Multiple genetically related 'composite channels' (including both their lobe and channel-fill architectures) and their associated overbank wedges form a 6^{th}-order-cycle '**channel complex**', otherwise known as a 'channel belt'. This sedimentary unit can be described as showing either a 'migrated' or 'confined' stacking pattern, according to whether the formative channel was laterally mobile or entrenched within an erosional depression, respectively. The build-cut-fill-spill cycles of Gardner & Borer (2000) are still recognised by Gardner et al. (2003), observed at the scales of a 'single story' to 6^{th} order 'channel belts' (see facies patterns in Fig. 5b). The largest hierarchical order, the '**submarine channel fairway**' is similar in its definition to Gardner & Borer's (2000) 'submarine fan conduit complex', as it represents a long-lived sediment fairway, encompassing the area where channels reoccupy the same position through repeated cycles of fan growth. Similarity in the scale of submarine channel fairways and conduit complexes is also seen in the overlap of their dimensions (Fig. 5). However, Gardner et al. (2003) reinterpret units of this level as the preserved expression of a 4^{th}-order sequence stratigraphic cycle, as opposed to Gardner & Borer's (2000) previous 3^{rd}-order interpretation. In the 2003 scheme, units at this order are suggested to only reflect the lowstand systems tract (LST) of a 3^{rd}-order depositional sequence, as opposed to an entire 'depositional sequence' as previously proposed by Gardner & Borer (2000).

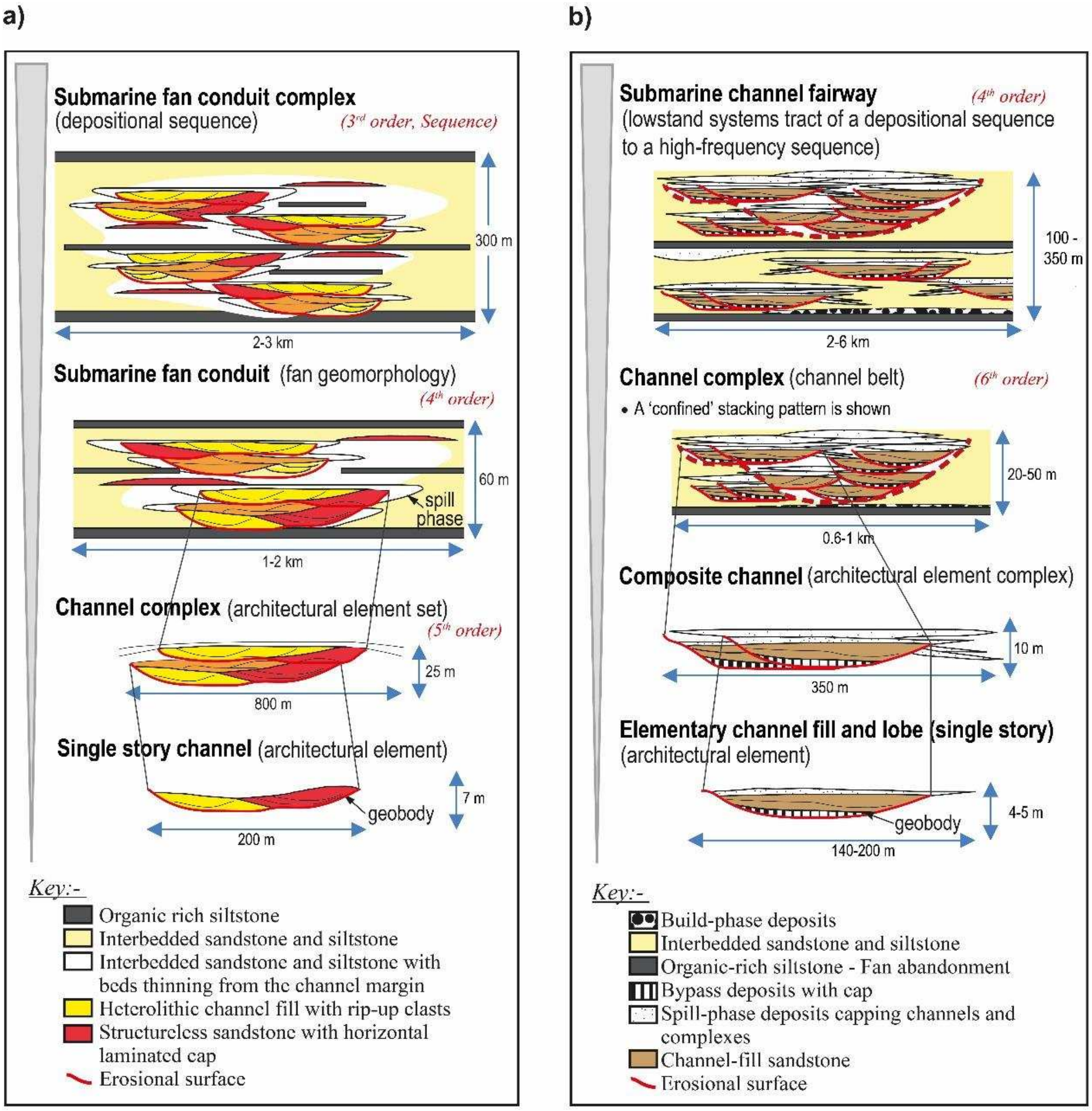

Fig. 5. Comparison of the CLTZ hierarchical classifications of *a*) Gardner & Borer (2000) and *b*) Gardner et al. (2003). The dimensions proposed for each hierarchical order are maximum measurements in part *a*) and average ranges in part *b*) calculated based on the studies outcrop investigation of the Brushy Canyon Formation (Texas, USA). Each hierarchical order corresponds to a specific 'scalar term', provided in brackets. The suggested equivalence to sequence stratigraphic orders is also stated (red italics); each key presents classes of deposits provided by each study. Figures modified after Gardner & Borer (2000) and Gardner et al. (2003), for parts *a*) and *b*), respectively.

2.5 Prather et al., 2000

By the turn of the millennium, Prather et al. (2000) noted that the subdivision of deep-water successions into hierarchical units had become well-established practice. The adoption of different approaches was seen by Prather et al. (2000) to result from the variations in spatial and temporal scales between differing datasets, as well as in relation to the environmental variability of deep-marine systems. Writing from a hydrocarbon-industry perspective, Prather et al. (2000) present a scheme that tries to more readily accommodate the scales of seismically resolvable units in sand-prone deep-water hydrocarbon reservoirs. The hierarchy is produced with consideration of the limits of seismic-data interpretation, and is based upon examples from intraslope basins in the Gulf of Mexico. The hierarchy is structured into four seismic orders and three sub-seismic orders (i.e., orders below conventional seismic resolution), which are applicable to architectural units associated with both channel and lobe environments (see Fig. 6). Prather et al. (2000) are able to directly compare their classification against the outcrop and seismic-based hierarchies of Mutti & Normark (1987) and Pickering et al. (1995), as well as Miall's (1985) hierarchy for fluvial deposits, due common diagnostic characters for the attribution to hierarchical levels, i.e., based on the recognition of external and internal facies geometries, stacking patterns and bounding-surface orders. Prather et al. (2000) concede that significant uncertainty is inherent in the assignment of the sub-seismic orders, because of the inability to easily identify these units using conventional seismic techniques. No reference is made to the role that higher-resolution seismic techniques might play in resolving such uncertainties.

The smallest hierarchical order ('**third order, sub-seismic**') is compared by Prather et al. (2000) to both the 'turbidite bed' and 'bedding package' hierarchical orders of Mutti & Normark (1987) and Pickering et al. (1995), respectively. The largest sub-seismic order, the '**first order, sub-seismic**' level, describes the 'loop morphology' of a sedimentary unit via the identification of erosional surfaces that bound the products of compensational cycles, classified as either 'channel sands' or 'sheet sands' based upon their sub-environment of deposition. Prather et al. (2000) recognises that modelling channel reservoirs may lead to oversimplification due to their variable sand distributions over shorter bed lengths, as opposed to the sheet sands. Due to this increased challenge, Prather et al. (2000) propose the introduction of a distinctive "building block" order, known as a '**second order, sub-seismic**', whereby the 'first-order' sub-seismic channel-fill sequences can be divided into margin and core blocks, characterised by consistent reservoir properties (e.g., sand fraction) useful for hydrocarbon reservoir modelling. The core and margin block stratal divisions typically cross-cut the 'first order, sub-seismic' stratigraphic boundaries, creating artificial separations within a discrete unit; this in turn allows determination of the connectivity potential of the reservoir under investigation. This style of subdivision of sedimentary architecture, through the segmentation of parent-element packages discordantly to any internal bounding surfaces, is unique to this hierarchical classification.

Units at the smallest seismic-scale order classified by Prather et al. (2000) are termed 'loops'. These '**fourth order, seismic**' loops determine the scale of individual reservoirs and are imaged well through conventional seismic techniques. These loops have characteristic planform shapes (e.g., shoestring, ribbon, sheet, pod-like) and cross-sectional geometries; they can also show locally shingled seismic geometries. This 'loop' hierarchical level is thus the focus of most efforts on the collation of information concerning the geometry of reservoir units, with the scope to constrain reservoir simulations. The '**third order, seismic**' hierarchical level is described as a 'facies unit' or 'loopset', which can be characterised by seismic reflectivity, geometry, lateral continuity and bounding-surface type. However, how these characters help to define this level is not stated by Prather et al. (2000). At this hierarchical scale, geometric characteristics have been used to categorise three primary seismic facies, namely 'draping', 'convergent' and 'chaotic', as previously established by Prather et al. (1998). Prather et al. (2000) state that the consideration of well-log data is useful to reduce some of the uncertainty associated with predictions of lithofacies and sand content in hydrocarbon-reservoir intervals. The degree of wavelet amalgamation has also been used to define the style of stacking in units of this scale, via the non-amalgamated, loosely amalgamated, or highly amalgamated shingling of 'fourth-order, seismic loops'.

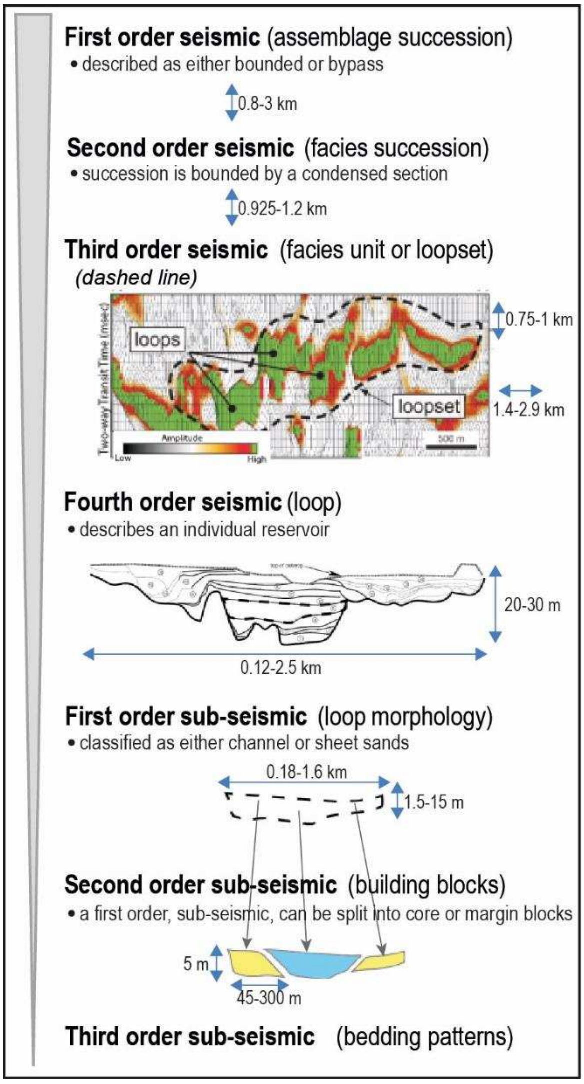

Fig. 6. Hierarchical classification of Prather et al. (2000), including thickness and width dimensions taken from summary diagrams and seismic lines from the Central Gulf of Mexico intraslope basins and the Permian Brushy Canyon Formation, USA. Figure modified after Prather et al. (2000).

Repetitive successions of seismic facies define the '**second order, seismic**' level, also described as a 'facies succession'. 'Second order, seismic' units consist of stacked packages of 'third order, seismic' units and are typically bounded by a condensed zone, formed via waning deposition (Prather et al., 1998). They are interpreted to reflect the filling patterns of different types of accommodation space and are therefore seen to reflect the external controls upon reservoir architecture, which Prather et al. (2000) state help produce "depositional sequence scale" (or basin scale) stratigraphic models. 'Second order, seismic' facies successions that stack into common packages of seismic facies delineate '**first order, seismic**' bodies or an 'assemblage succession'. The 'first order seismic' level is the largest hierarchical order identified. In the case study from the Gulf of Mexico, these 'assemblage successions' are classified as either ponded or bypass assemblages, and recognising such units enabled Prather et al. (2000) to characterise reservoir-seal architectures. The largest stratigraphic scale is described to record a common assemblage of seismic facies; however, no defining criteria were provided by Prather et al. (2000) to explain what constitutes these 'common assemblages'. Hierarchical-order dimensions based upon the measurements documented within Prather et al. (2000) are shown in Fig. 6.

The seven hierarchical classes (Fig. 6) map onto the variable scales of interest at the different stages of reservoir exploration, appraisal, development and production. Prather et al. (2000) state that characterisation at the 'first order' and 'second order' seismic scales is desirable to help determine reservoir potential during the explorative phase; for instance, the initial seismic facies analysis undertaken in the Gulf of Mexico study helped identify sand-prone intervals (Prather et al., 2000). 'Third order' and 'fourth order' seismic scales are useful in the assessment of stacking patterns and architectural classes (e.g., channel or sheet depositional environments), which can facilitate the evaluation of the extent of a reservoir. Sub-seismic levels help to assess heterogeneities at the 'intra-reservoir' scales; they are thus regarded as important scales of analysis for reservoir development, as information relating to units at these orders can be used to make inferences with respect to reservoir connectivity.

2.6 Navarre et al., 2002

The hierarchical classification of Navarre et al. (2002) was produced with the aim of aiding the characterisation of hydrocarbon reservoirs through the use of 3D seismic and well-log datasets. The approach aims to honour the stratigraphic architecture of turbidite deposits through the 3D observation of sedimentary units at different spatial and temporal scales, including their lateral continuity. Shaly deposits and erosional bases are recorded as important characteristics, marking the subdivision of units within each hierarchical level. These characteristics are noted as significant because they act as possible barriers to flow in corresponding reservoirs, affecting reservoir connectivity. The hierarchy was tested upon the Gulf of Guinea Tertiary turbidite system, offshore West Africa, and is largely based on 3D seismic data but well-log and core data have also been used to help characterise the smaller hierarchical orders.

The six-tiered hierarchy Navarre et al. (2002) propose is stated to be applicable to both lobate and channelized architectural units and this physiographic distinction is denoted within the hierarchical classification by the use of 'lobe' or 'channel' prefixes in the naming of some of the orders (see Fig. 7). However, in practice the hierarchical arrangement described by Navarre et al. (2002) is predominantly focused upon channel architectures.

The smallest recognised hierarchical order corresponds to units termed '**facies associations**'. However, specific criteria for the attribution of sedimentary bodies to this order are not given; these units are solely noted to have limited widths, thicknesses and lateral continuities in comparison to the '**channel or lobe phases**' they stack into. 'Phases' are sub-seismic-scale units, which are composed of genetically related facies linked to a common depositional environment. These units typically display an overall vertical facies succession observed through porosity, permeability and grain size calibrated from well-log data. Both the 'facies association' and 'phase' hierarchical orders are associated with the level of resolution desired for reservoir models; these orders are therefore comparable in scope to Prather et al.'s (2000) sub-seismic orders.

Five distinct phases, reflecting different evolutionary steps within a depositional environment, are typically seen in a predictable succession within the case-study examples investigated by Navarre et al. (2002) – these consist of ‘erosive’, ‘fill’, ‘plugging’, ‘spill’ and ‘constructive’ phases. However, other possible phases are acknowledged to exist within the synthetic channel phase succession model, namely ‘abandonment’ and ‘starvation’ phases (see Fig. 7). These phases stack progressively, starting with an ‘erosive’ phase marked by cutting and infill of deposits; typically this basal infill will be related to deposition by a debris flow or slump. A ‘fill’ phase typically follows, composed of homogenous sandy deposits, indicative of a sandy bar deposition, followed by shaly facies of the ‘plugging’ phase, which marks the abandonment of a channel form. ‘Spill’ phases result in sandy channel overspill deposits that indicate unconfined turbidity flows, which later progress to form ‘constructive’ levee deposits, which are deposited parallel to the channel axis. The possible ‘abandonment’ and ‘starvation’ phases are composed predominately of mud-prone internal-levee facies, which in the case of the ‘starvation’ phase can represent a baffle between ‘channel stories’. ‘Lobe phases’ are also recognised to exist within the hierarchy, but no explicit link is made to the channel-related evolutionary phases, nor is the genetic significance of lobe phases in distributary environments discussed.

Channel phases stack to form a ‘**channel story**’, ranging from around 30 to 40 m thick and 250 to 800 m wide (based on data from the 3 ‘channel stories’ identified in the study; Fig. 7). The ‘channel story’ is analogous in some regards to the build-cut-fill-spill depositional cycle of Gardner & Borer (2000). A ‘channel story’ may display all types of ‘channel phases’, but local preservation may be affected by backstepping or progradation; regardless, an erosional base and shaly top are stated to always be observed. Each ‘story’ fines-upwards. Multiple genetically related ‘channel stories’ (again, lobe equivalents are not characterised) are seen to vertically stack to form a ‘**channel complex**’ (110 m thick and 1-2 km wide, based on the two examples identified in the study); each component ‘channel story’ is separated by background muds and limited by stratigraphic surfaces, which in the studied examples are inferred to have developed over a timescale of ~0.1 Myr, based on biostratigraphy.

Hierarchical levels above the ‘channel complex’ reflect more regional, basin-wide controls. Multiple ‘channel complexes’ may be bounded by an erosional base and capped by an extensive mud: this composite unit is named a ‘**depositional system**’, for which a duration of 1-2 Myr, corresponding in magnitude to a 3^{rd}-order sequence stratigraphic cycle, is inferred based on biostratigraphy. However, even at this scale, only one dominant architectural element style is envisaged, as sediments are described in this scheme as showing either channelized or lobate forms. The largest order recognised in this hierarchy is the ‘**megasequence**’ (~200 m thick, 3-4 km wide), which represents the complete product of genetically related turbidity flows, and thus is seen to include both lobe and channel architectural units. This hierarchical order is defined by surfaces that embody two major events, interpreted as either maximum flooding surfaces or unconformities of 2^{nd} order (associated with sequence stratigraphic sequence boundaries). Breaks in sedimentation that bound this ‘megasequence’ are interpreted to be, for example, the product of long-term relative sea-level change or tectonic salt activity.

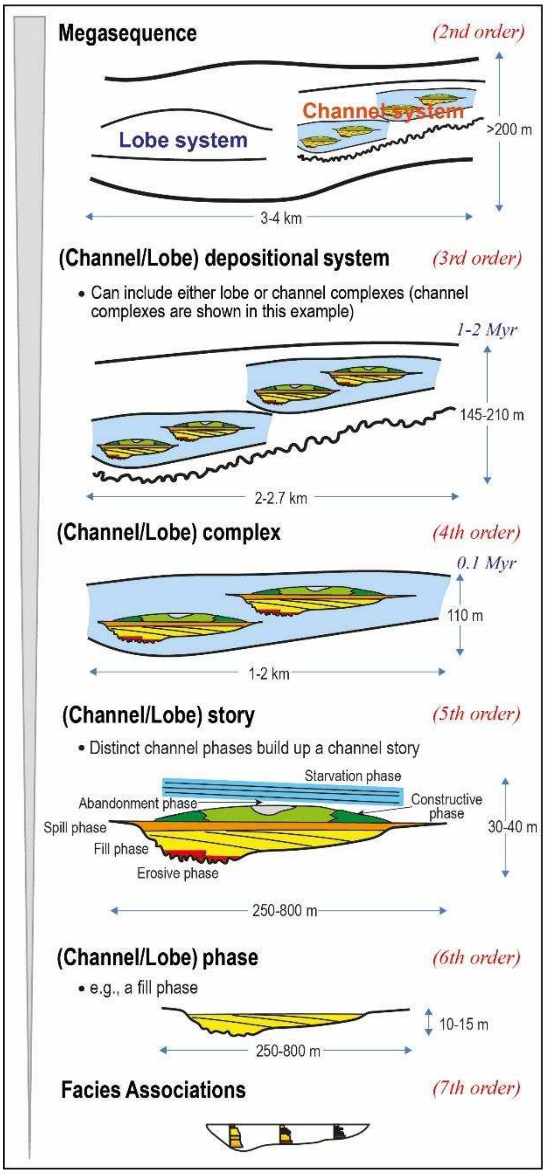

Fig. 7. Hierarchical classification developed by Navarre et al. (2002). Dimensions are taken from the seismic dataset analysed in the original paper; durations (blue italic) are provided for those orders that have been temporally defined; numbering related to sequence stratigraphic orders are shown in red italics. The distinct channel phases building a 'channel story' are also shown (modified after Navarre et al., 2002).

2.7 Sprague et al., 2005

In the pursuit to better understand and predict hydrocarbon-reservoir properties (reservoir geometries, continuity, net-to-gross, porosity, permeability, etc.) Sprague et al. (2002; 2005) developed a 'deep-water hierarchy' inspired by some of the principles of sequence stratigraphy. This hierarchy was designed to acknowledge spatial and temporal controls on reservoir architecture at multiple scales, for subsurface predictions. The framework was proposed to act as a 'standard' hierarchy, applicable to genetically related deep-marine stratal elements from turbidite settings that include confined and unconfined basin plains and slopes (albeit without mention of channel-lobe transition zones), and has since been applied to a number of case studies (see below). The scheme is based primarily upon interpretations of 3D seismic datasets, but is also supported by well and core analysis. The applied value of this integrated approach was realised through its widespread application within ExxonMobil and Shell, resulting in a reported doubling in accuracy of net-to-gross predictions when well-log data was used along-side seismic to analyse potential reservoirs in West Africa (Sprague et al., 2005). This framework acknowledges earlier works by Beaubouef et al. (1999; 2000), which used sequence stratigraphic terminology and concepts to help define the outcrop-based hierarchical arrangement of channel deposits of the Brushy Canyon Formation (Fig. 8). Sprague and co-workers originally articulated this 'deep-water hierarchy' through an oral presentation given at the AAPG Annual Conference and Exhibition (ACE) in 2002 (Sprague et al., 2002), whose abstract remains highly cited (although a specific citation statistic cannot be attained). They successively expanded the scheme by widening the temporal framework through the addition of higher orders in a later conference paper (Sprague et al., 2005).

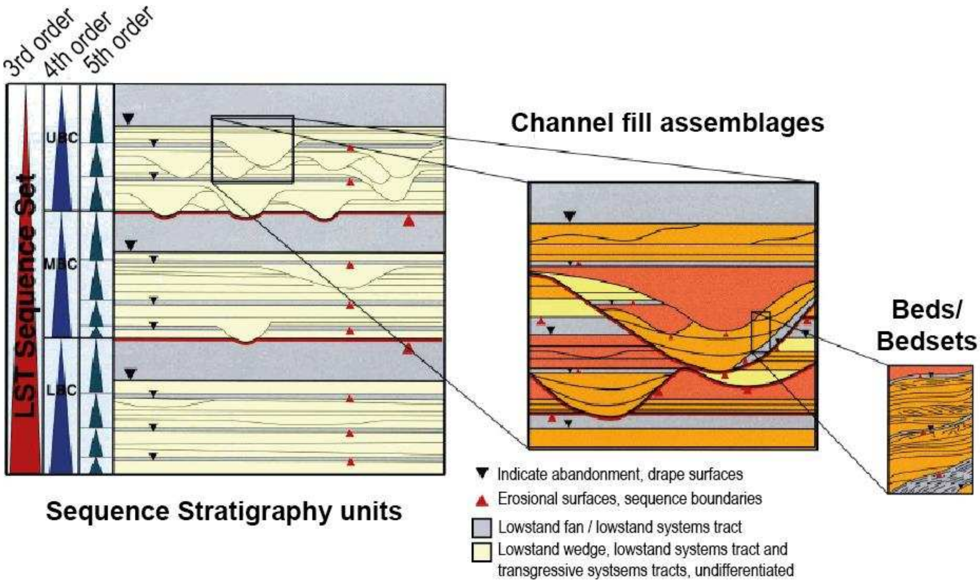

Fig. 8. The stratigraphic hierarchy erected by Beaubouef et al., (1999) for their study on the channelized architecture of the Brushy Canyon Formation. The hierarchy recognises sedimentary units through their higher surface orders (e.g., channel fill assemblages and bedsets). It is based on sequence stratigraphic concepts but also incorporates small-scale divisions that are not easily identified at seismic scale. The '4^{th}-order' units are split into 3 units, which correspond to the Lower, Middle and Upper members of the Brushy Canyon Formation. Figure after Beaubouef et al. (1999).

The framework attempts to allow systematic description of, and comparison between, deep-marine systems, and it is founded upon the sequence stratigraphic framework (Vail et al., 1977) in a manner similar to Beaubeouf's (1999) original effort. Hence, strong alignments are evident between the 'deep-water hierarchy' of Sprague et al. (2005) and the sequence stratigraphic framework, in relation to the choice of similar criteria to recognise each hierarchical order, i.e., the physical and genetic relationships of strata, their resultant geometry defined by correlatable major surfaces (unconformities), as well as the vertical and lateral stacking patterns of these resultant architectures. The hierarchy is stated to be applicable to both channelized and distributary environments (Fig. 9). Sprague et al. (2005) therefore state the importance of using a 'prefix modifier', similar to Navarre et al. (2002) to record the level of confinement for an environment (as confined, weakly confined, or lobe/unconfined); these in turn provide a relative physiographic position of the studied section relative to the depositional dip profile. These prefixes are the only variable identifiers used in the scheme to differentiate between the different positions of units in a basin. Differing ranges of dimensions are also recognised for hierarchical orders across these environments (Fig. 9). Although sequence stratigraphic terminological equivalents are provided (Fig. 9), the resultant hierarchy of nested stratal elements does not utilise sequence stratigraphic terminology directly. Instead, it uses a collection of terms that prevail in the scientific literature.

The lowest orders in the scheme by Sprague et al. (2005) are represented by '**beds**', i.e., layers of sedimentary rock bounded above and below by bedding surfaces or unconformities, and '**bedsets**', i.e., the repetition of two or more beds characterised by the same composition, texture and sedimentary structures, based upon definitions of Campbell (1967). The next hierarchical order is a '**storey**', which is based upon the descriptive terminology for fluvial deposits of Friend et al. (1979). A 'storey' is recognised as a scour-based, sub-channel stratal element that shows strong lateral changes in facies organization (i.e., from its 'axis' to its 'margin'). However, this facies-based description is not entirely unique to this architectural order, as 'channel fills' are also described as expressing lateral facies changes and erosive bases. Sprague et al. (2005) do not provide clear criteria on how to identify 'lobe storeys', although these subcomponents of a lobe have been illustrated within the distributary hierarchy as a volume of genetically related facies (Fig. 9b). The hierarchical order to which '**channel fills**' and '**lobes**' belong is described as the fundamental building block of deep-water depositional systems. At both this hierarchical level and at the higher-scale '**channel/lobe complex**' order, the sedimentary units are characterised by only one style of architecture. A 'channel fill' is interpreted to be the deposit of a single cycle of channel-filling and abandonment, and is described as being generally the smallest seismically resolvable order in the hierarchy. The 'channel-fill' units and their sub-component 'storey' hierarchical orders are also interpreted by Sprague et al. (2005) as a way of dividing Mutti & Normark's (1987) 'turbidite sub-stage' order into the separate components of deposition, bypass and erosion (components that Mutti & Normark, 1987 did acknowledge to exist), as well as the total product of this evolutionary cycle of deposition. A channel 'complex' reflects a group of seismically resolvable, genetically related channel fills (i.e., with similar architectural styles), which show lateral facies changes along strike (orthogonal to flow direction: channel-complex axis to channel-complex margin). Lobe unit equivalents to the 'fill' or 'complex' hierarchy orders are not specifically defined by Sprague et al. (2005); however, radial planform patterns are noted for these distributary architectures. For the subsequent larger-scale orders, only architectures of confined channelized setting are considered in detail. The '**channel complex set**' order is seen to be directly comparable to a lowstand systems tract (LST) of a depositional sequence. In contrast to the 'fill' and 'complex' orders, at this level multiple architectural styles (*sensu* Sprague et al., 2005) or element types (*sensu* Mutti & Normark, 1987) might form a unit (e.g., a unit may contain extensive background deposits surrounding channel elements; Fig. 9a). The 'channel complex set' is a channelized unit composed of two or more genetically related 'channel complexes', typically showing a vertical stacking pattern, which is notably capped by a hemipelagic drape, marking a temporary cessation of active channel deposition. A 'complex set' is also typically bounded at its base by an unconformity, supporting the comparison made by Sprague et al. (2005) between this hierarchical order and the depositional sequence (i.e., a relatively conformable succession of genetically related strata with chronostratigraphic significance, typically showing no apparent internal unconformities, bounded by unconformable surfaces and their correlative conformities; Vail et al., 1977; Mitchum et al., 1977; Van Wagoner et al., 1988; Mitchum & Van Wagoner, 1991).

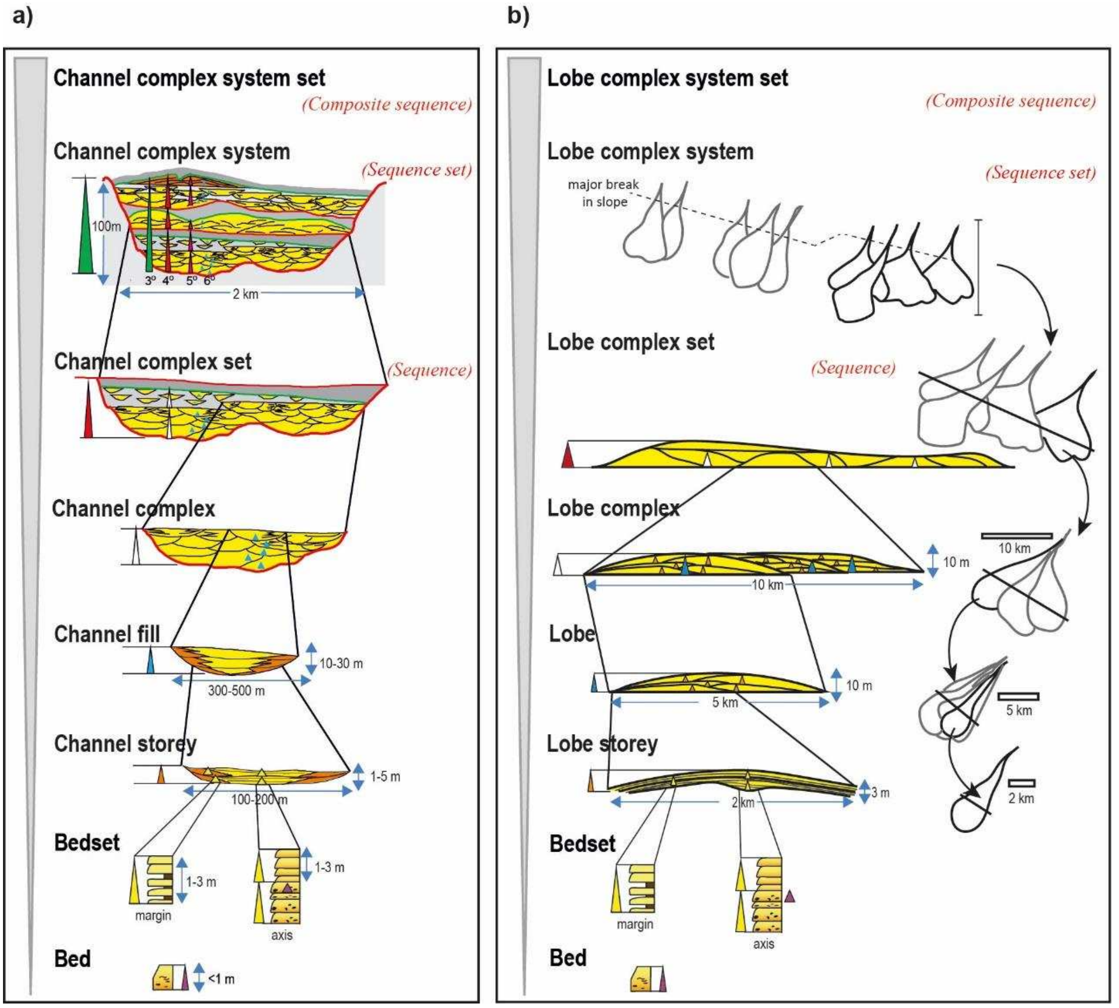

Fig. 9. The 'deep-water hierarchy' classification of Sprague et al. (2005) of *a*) channelized units in confined settings and *b*) distributary environments. The proposed dimensions for elements of each hierarchical order are also included and equivalent sequence stratigraphic terminology is shown in red italics, when present in the original work. Modified after Sprague et al. (2005).

'Channel complex sets' stack into '**channel complex systems**', which Sprague et al. (2005) state as being capped by a regional abandonment surface and bounded by a composite sequence boundary below. Sprague et al. (2005) compare these units to a 'stratigraphic sequence set', reflecting long-term effects of relative sea-level change. Multiple cycles of 'channel complex systems' stack to form '**channel complex system sets**' within the basin which Sprague et al. (2005) compare to a 'composite sequence' based upon sequence stratigraphic terminology. This hierarchical order is also stated to directly compare to the 'turbidite system' level of Mutti & Normark (1987). Interestingly, the largest hierarchical order of Mutti & Normark (1987), the 'turbidite complex', originally considered equivalent to a 'composite sequence set' of sequence stratigraphic terminology, is not defined or recognised as significant in the hierarchy of Sprague et al. (2005).

2.7.1 Application and amendments to the hierarchy by Sprague et al. (2005)

The deep-water hierarchy of Sprague et al. (2002; 2005) was formulated and originally applied to seismic data from Tertiary deep-marine deposits off-shore West Africa (Sprague et al., 2005). Beaubouef (2004) instead applies this classification and its terminology to an outcrop-based study of the Cerro Toro Formation. Sprague et al. (2005) also cites Beaubouef as employing this hierarchical classification in his studies on outcrops of the Brushy Canyon Formation undertaken in 1999 and 2000, though no clear link to this hierarchy is acknowledged in either of these works.

Campion et al. (2007; 2011) also adopt some hierarchical orders from this scheme ('bedset' to 'channel complex set') to categorise an outcrop of the channelized Capistrano Formation. In this context, Campion et al. (2011) also further defines a 'storey' as being a fundamental building block of a channel. 'Storeys' are observed to be confined within the channel-fill elements, as storey bases onlap or coalesce to form the base of channels (lobe storeys are not considered). Each storey contains stacked 'bedsets' that not only show distinct and predictable facies associations that vary laterally (e.g., distinct thickening- and coarsening-upwards packages at the channel axis, as opposed to fining-upwards packages at the channel margins), but also distinct vertical facies changes, whereby the stacked 'bedsets' of a single story reflect a depositional evolution from erosion to bypass and ultimately channel plugging (Campion et al., 2011).

The hierarchy of Sprague et al. (2002; 2005) has also provided a strong foundation for a number of other hierarchical concepts. For example, Abreu et al. (2003) modify the hierarchical structure and terminology of Sprague et al. (2002) to accommodate lateral accretionary packages (LAPs), which embody the preserved product of lateral migration of a channel (Fig. 10). This is done through the revision of the definition of a 'channel complex', to allow differing architectural styles, including LAPs, to be included as complex-forming units, as well as units below this hierarchical order. However, despite the initial outward commitment to utilising the deep-water hierarchy of Sprague et al. (2002) differences can be seen in the way a 'channel complex' has been graphically illustrated. Abreu et al.'s (2003) representation of Sprague et al. (2002) hierarchy shows two 'channel complexes' (*sensu* Sprague et al. 2002) to represent a single complex, differing from the original design of Sprague et al. (2002; compare Fig. 9a with Fig. 10a). This may suggest that a different interpretation of the Sprague et al. (2002) stacking patterns has been made to be able to incorporate LAPs into the hierarchy; however, no discussion is provided by Abreu et al. (2003) as to why such discrepancies arose.

McHargue et al. (2011) used the hierarchical concepts of Sprague et al. (2002; 2005) to build subsurface models of continental slope channels. McHargue et al. (2011) identified the importance of recognising hierarchical orders in event-based forward modelling in order to produce more realistic model outputs, suitable for quantitative reservoir simulation. Their work focuses on three key scales from the hierarchy of Sprague et al. (2005): the 'channel fill' (denoted as a 'channel element' within McHargue et al., 2011, and also stated to be comprised of vertically stacked 'stories'), 'channel complex' and 'channel complex set'. McHargue et al. (2011) state that some terminological modifications have been made, including the separation of temporal and physical scales in the definitions of these elements. McHargue et al. (2011) also state that all three hierarchical scales considered in their model display cycles of waxing and waning flow energy. This cyclicity at the channel complex set scale is highlighted by different stacking patterns as flow behaviour changes from erosional to depositional. Overall a transition is observed from a less to a more 'organised' stacking pattern; the latter being linked to higher rates of aggradation resulting in the younger channel element pathway more closely matching the one of the older channel element.

The original hierarchical concepts of Sprague et al. (2002; 2005) have since been updated and modified by Sprague and other co-workers (Sprague et al., 2008; Flint et al., 2008). In these revised schemes, the definitions of orders have been strengthened to incorporate the scale of well-log and core data and to extend the applicability of the scheme to lobe and overbank/levee element types. This has been achieved via an extensive outcrop study on the seismic to sub-seismic scale deposits of the Karoo Basin. This has helped to more closely align the original hierarchical orders to sequence stratigraphic concepts, due to an improved focus upon recognising the regional connectivity of sequence boundaries through the assessment of allogenic versus autogenic controls (Flint et al., 2008). 'Channel-fills' are here referred to as 'storey sets' by Sprague et al. (2008) and Flint et al. (2008). This terminology and expanded applicability of Sprague's deep-water hierarchy was subsequently used as the basis for Pickering & Cantalejo's (2015) most recent hierarchical classification approach (see section 2.15). Recent work by Sprague et al. (2014) has concentrated on the characterisation of the main lithofacies forming the 'sequence' (*sensu* Vail et al., 1977) or 'complex set' (*sensu* Sprague et al., 2005) hierarchical orders, in an attempt to improve characterisation of reservoir properties and assess stratigraphic-trap characteristics in basin-floor settings of the Karoo Basin. This work thus expands the applicability of this hierarchy to outcrop-based distributary environments. The influential relationships shared between these derivative hierarchical schemes and the 'deep-water hierarchy' of Sprague et al. (2002; 2005) are illustrated in Fig. 1.

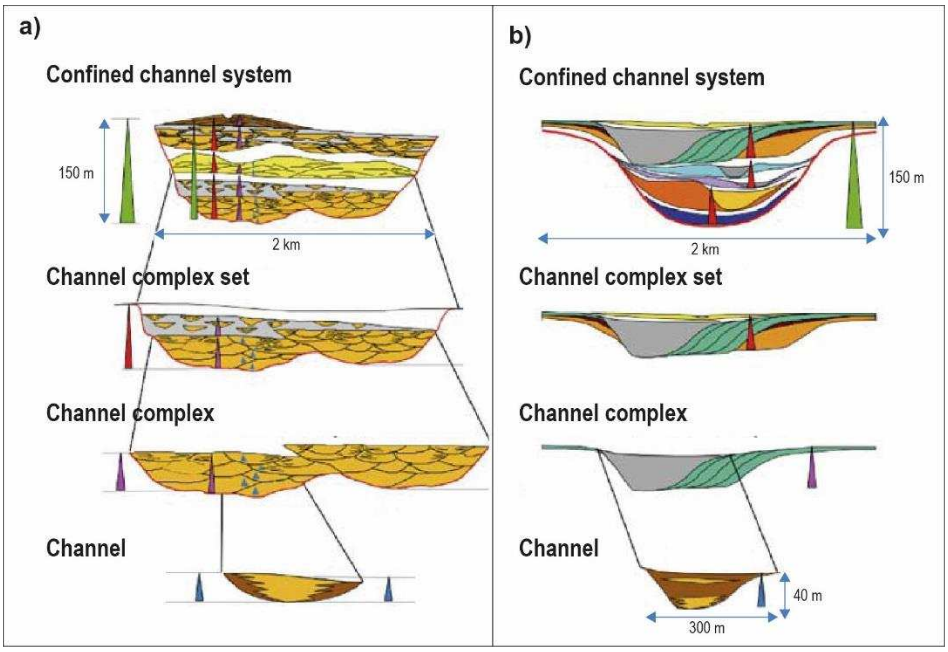

Fig. 10. Comparison between *a*) the hierarchical scheme of Sprague et al. (2002; 2005) and *b*) the stratigraphic hierarchy used by Abreu et al. (2003) to classify the channel and LAP architecture in a study based on a seismic dataset of the Dalia M9 Upper Channel System, offshore Angola. Figure taken from Abreu et al. (2003).

2.8 Hadler-Jacobsen et al., 2005

With the purpose of providing a more accurate and predictive conceptual model for lithology distribution in submarine fans, Hadler-Jacobsen et al. (2005), of Statoil, conducted an investigation to identify and characterise submarine fans at seismically resolvable scales. The recognition of seismic patterns in sandy distributary deposits was tested upon a number of both seismic datasets (the Triassic Finnmark Platform, the Eocene Porcupine Basin, and the Paleocene/Eocene Viking Graben) and 'analogue' outcrops (the Eocene Central Basin in Spitsbergen, the Permian Karoo Basin and the Permian Brushy Canyon Formation). These datasets were hierarchically classified in terms of the sequence stratigraphic framework (Vail et al., 1977; Mitchum & Van Wagoner, 1991). This link to sequence stratigraphic hierarchies was seen as natural by Hadler-Jacobsen et al. (2005) due to the intimate relationship between subsurface lithological investigations and sequence stratigraphy. However, due to new insights in deep-marine sedimentology resulting from improved seismic acquisition, some of the original concepts of sequence stratigraphy, such as systems-tract nomenclature and depositional-sequence boundaries, were amended by Hadler-Jacobsen et al. (2005). A stratigraphic framework for shelf-slope-basin settings was thus established based upon the identification of shelf maximum flooding surfaces and their coeval slope and basin condensed sections, a genetic stratigraphic marker previously utilised by Galloway (1989).

The hierarchical orders are called 'cycles', as in sequence stratigraphic parlance, and are associated with durations comparable to those of sequence stratigraphic units proposed by Mitchum & Van Wagoner (1991; Fig. 11). Second, third, fourth, fifth and sixth orders are noted by Hadler-Jacobsen et al. (2005); however, they do not recognise all these five orders in all the datasets incorporated in their review, and they never identify a 'first order' stratigraphic division. The recognition of fourth, fifth and sixth orders is also stated by Hadler-Jacobsen et al. (2005) to be more difficult to achieve due to limited data resolution, and therefore confidence in the assignment of units to these hierarchical orders is low.

Tentative '**fifth order**' cycles are typically observed in seismic datasets as individual seismic reflectors, displayed as a single clinoform geometry, typically capped by a condensed section. These 'fifth order' units have been identified by Hadler-Jacobsen et al. (2005) on outcrops of the Brushy Canyon Formation (Gardner et al., 2003); they reach thicknesses of up to 100 m, and have formed over 0.01-0.5 Myr (based upon proposed durations taken from the original case-studies). These 'fifth order' fan cycles can be internally divided via facies assemblages into 'initiation', 'growth' and 'retreat' phases, *sensu* Gardner et al. (2003), which represent '**sixth order**' cycles. Hadler-Jacobsen et al. (2005) recognise these 'sixth order' cycles in the Delaware Basin and tentatively in the Tanqua Basin and in the Finnmark Platform. These 'sixth order' units are typically only identifiable below conventional seismic resolution, and are only generically defined by Hadler-Jacobsen et al. (2005). These 'sixth order' cycles, along with 'fourth order', 'third order' and 'second order' cycles can all be divided into initiation, growth and retreat phases of a fan, following the evolutionary sequence of Gardner et al. (2003). A seismically resolvable '**fourth order**' cycle (0.1-1 Myr) is composed of stacked 'fifth order' units. They are identified by their bright amplitude in seismic imaging and by a well-defined shelf-break, which may include condensed section intervals and were observed between 30-200 m thick. The 'fourth' and 'fifth' orders are also interpreted by Hadler-Jacobsen et al. (2005) to represent the main building blocks of a submarine fan. The shelf-to-basin clinoform geometries of the 'fourth order' units typically stack into prograding '**third order**' units (e.g., as identified in the study of the Porcupine Basin; Fig. 11a). Again, the three distinct phases of initiation, growth, and retreat are recognised. However, according to Hadler-Jacobsen et al. (2005) each phase (1-3 Myr) at this scale can be recognised through seismic-facies assemblages, which can show channel and incised-valley features on the shelf, as well as the presence of onlapping surface geometries at the shelf-edge to slope-break , or distinct downlap across the basin. Examples of 'third order' thicknesses range from 155-400 m. The largest order recognised, a '**second order**' cycle (5-13 Myr, 600 m in thickness, based upon the measured Tanqua Karoo example), represents a progradational basin-ward stacked clinoform package, which can record a number of shifts in the shelf-edge position throughout the evolution of the fan.

Hadler-Jacobsen et al. (2005) recognise two end-member basin styles: (i) high shelf-to-basin relief, sediment underfilled basins (high SBR/SUB) and (ii) low shelf-to-basin relief, sediment overfilled basins (low SBR/SOB). These two basin styles are observed over 'third' and 'second order' scales and are largely inferred from the stacking patterns detected within the 'fourth' and 'fifth order' building blocks.

Regarding the applicability of their scheme, Hadler-Jacobsen et al. (2005) state that extensive, ideally basin-wide, observations are desirable to apply this hierarchy to outcrop studies in a confident manner. In particular, chronostratigraphic constraints, through biostratigraphical attributions, are seen as crucial in its application to outcrop studies (see example from the Tanqua depocentre of the Karoo Basin, South Africa in Fig. 11b).

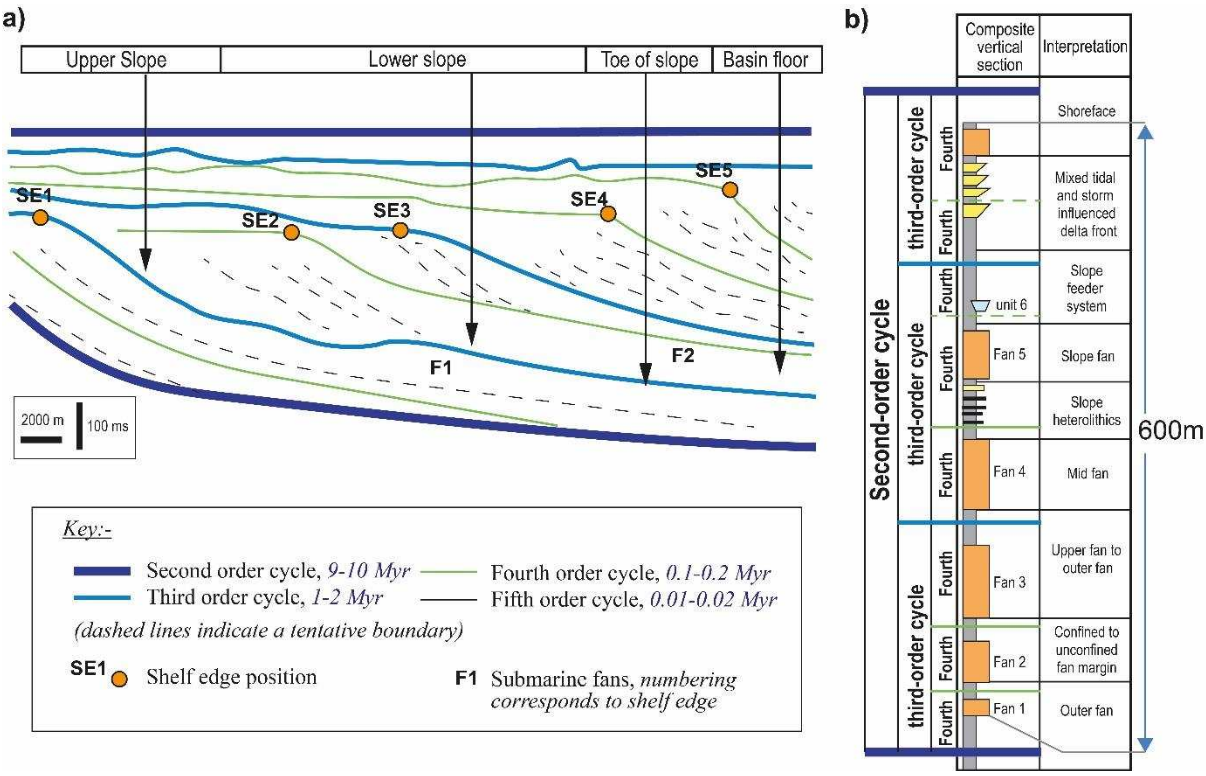

Fig. 11. Applications of Hadler-Jacobsen et al.'s (2005) deep-marine hierarchical classification. *a*) Seismic dip section of the Porcupine Basin (Ireland) divided into clinoform packages, termed 'cycles'. SE1-5 notation shows shelf-edge progradation between the fourth-order cycles; F1 and F2 are interpreted by Hadler-Jacobsen et al. (2005) as the fan components of the corresponding SE1 and SE2 shelf-edges. *b*) Shallowing-up vertical succession from the Tanqua Karoo outcrop dataset. Each sandy fan cycle has been interpreted as a fourth-order cycle. Order durations are inferred based upon relationships with sequence boundaries. Modified after Hadler-Jacobsen et al. (2005).

2.9 Mayall et al., 2006

Mayall et al. (2006) reviewed a number of published studies based on high-resolution seismic and outcrop datasets of turbidite channel architectures (such as Navarre et al., 2002; Campion et al., 2000; Gardner et al., 2003; Abreu et al., 2003; Beaubouef, 2004), in order to establish an effective method of 'sequence stratigraphic' channel reservoir evaluation and classification. In contrast to previous studies, Mayall et al. (2006) highlight the unique nature of every channel and its infill, and acknowledge the difficulty of developing or applying a single, or even multiple, depositional models. Therefore an alternative approach to hierarchical channel classification is proposed, associated with the identification of four recurring characteristics of channel forms (sinuosity, facies, cutting and filling, and stacking patterns), applicable to the characterisation of reservoir facies distribution. However, to be able to compare and classify the channel architectures drawn from multiple literature studies, Mayall et al. (2006) recognise the need to employ a standard set of terminology to describe the variability in channel-form size (Fig. 12). The authors avoid using any existing terminologies for hierarchical classification, even those from the hierarchy studies considered in their review (e.g., Gardner & Borer, 2000; Navarre et al., 2002), due to the desire to use "simple terminology" based upon sequence stratigraphic principles (i.e., in relation to sequence stratigraphic boundaries and temporal orders) to describe the channel bodies and their internal architecture in a scalar manner.

The study is focussed on erosionally confined channels, hierarchically bounded by a '3rd-order' sequence boundary. These '**3rd order**' channel bodies are bound at the base by a large erosional surface and they are stated by Mayall et al. (2006) as typically 1-3 km wide and 50-200 m thick. The '3rd-order' sequence boundaries are also identified by their stratigraphic position between '3rd-order' (1-2 Myr) maximum flooding surfaces. These maximum flooding surfaces are often associated with diagnostic biostratigraphic controls, aiding the identification of chronostratigraphic timescales in the basin. According to Mayall et al. (2006), most infill within these channel bodies is associated with periods of 3rd-order eustatic lowstand (and thus embodies lowstand systems tracts; LST), while a thinner overlying mud-prone section is determined to be the product of transgressive and highstand systems tracts (TST/HST). The internal fill of the '3rd-order' channels is complex and smaller erosional cuts within these units reflect '**4th order**' (otherwise termed 'channel systems') and '**5th order**' surfaces. According to Mayall et al. (2006), discrimination between '4th order' and '5th orders' is hard to achieve with confidence, as periods of abandonment within the '3rd-order' channel may be associated with autogenic channel switching, as opposed to higher-order eustatic controls. Mayall et al. (2006) also state that in the down-dip reaches of a channel element, at the more distal positions, a '3rd order' fill may split into separate '4th order' channels as a result of channel bifurcation; thus, channel bifurcations translate into a downdip reduction of the hierarchical order of the channel forms. The smallest channel elements (10-30 m thick), recognised within a '3rd order' unit are interpreted to represent 'individual channels'. However, these units are not specified by Mayall et al. (2006) to correspond with either a '4th order' or '5th order' and thus their position in the hierarchy is unknown. The stacking patterns of '4th order' and '5th order' channels are recognised by Mayall et al. (2006) to have a critical impact upon facies distribution in turbidite reservoirs.

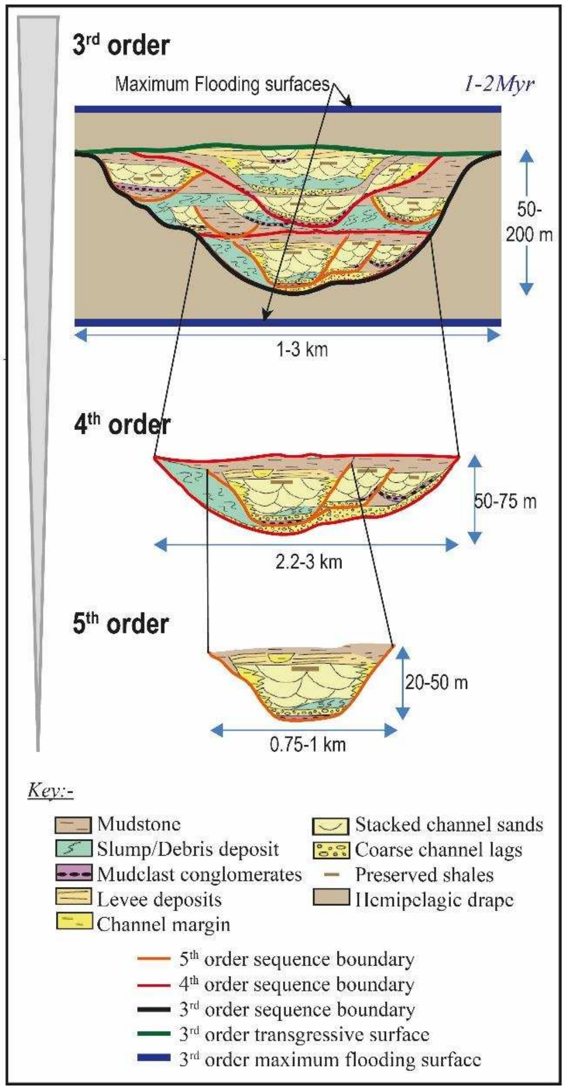

Fig. 12. Hierarchical classification for channel deposits by Mayall et al. (2006). Orders are determined by sequence boundaries and order durations are shown in blue italics. Widths and thicknesses ranges for the 4th and 5th order are calculated from the summary diagram presented by the study, while the '3rd order' values are based upon averages explicitly stated by Mayall et al. (2006). Modified after Mayall et al. (2006).

2.10 Gervais et al., 2006

The hierarchical scheme of Gervais et al. (2006a) was inspired by the improved quality of seismic surveys of submarine fans, revealing details of the geometry and stacking of distal lobe architectures. For example, the sonar-imaging and seismic profiling of Twichell et al. (1992) and Gervais et al. (2004) helped to reveal that lobes in sandy systems were not entirely sheet-like deposits but characterised by channelized geometries, and were equally not the product of a single 'bed'. Building upon these insights Gervais et al. (2006a) used high-resolution seismic data to generate a pseudo-3D model of the lobes of the Golo fan (East Corsican margin). This was one of the first models to help illustrate the lithological heterogeneity of sandy lobe deposits and associated hemipelagic drapes, which resulted in a three-fold hierarchy (Fig. 13).

Depositional elements at the smallest hierarchical scale, termed '**elementary bodies**', are composed of bedded facies which stack in such a way to produce local gradient changes, which in turn alter the flow dynamics in the system. These 'elementary bodies' are characterised by two principal geometries: 'sheet' and 'channel'; channels can be associated with levees. Continuous stacking of these 'elementary body' geometries produce higher-scale '**units**'. 'Units' are preferentially deposited with compensational stacking patterns. These depositional bodies are separated by surfaces that may alternate between erosive or concordant character, and breaks in sedimentation can be seen to separate these lobate 'unit' geometries from other 'units'. Numerous successive events, expressed as genetically related 'units', stack to form '**lobe**' deposits' (also known as 'lobe complexes') which are fed by a major channel or channel-levee complex in the turbidite system. A complete 'lobe' deposit is separated from others via a regionally extensive hemipelagic drape, which covers the whole lobe surface. This is recognised by Gervais et al. (2006a) by its lateral continuity and bedded, non-chaotic, seismic facies. The degree of lateral and longitudinal confinement is also stated by Gervais et al. (2006a) to be an important control on the geometry of a lobe. This, in turn, is believed to greatly influence the stacking patterns of its hierarchical components.

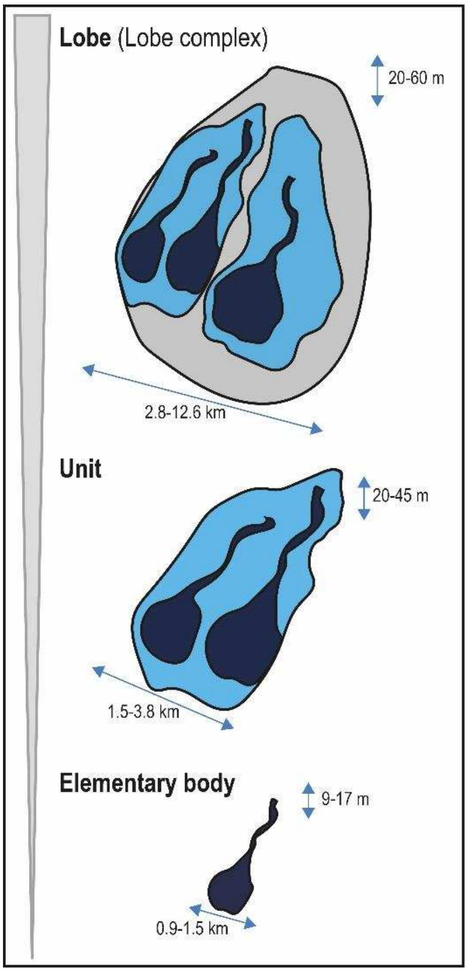

Fig. 13. The three-tiered hierarchical scheme used to classify lobe deposits of the Golo fan developed by Gervais et al. (2006a). Reported values of thickness and width are measured from the elements identified by Gervais et al. (2006a) in the original seismic dataset. Figure modified after Gervais et al. (2006a).

2.11 Deptuck et al., 2008

The scheme proposed by Deptuck et al. (2008) is based on the same high-resolution shallow subsurface seismic dataset of the Golo Basin studied by Gervais et al. (2006a; 2006b), and was co-authored by many of the same workers, including B. Gervais and A. Savoye. Similarities between the schemes in the two studies are therefore expected. However, there are notable differences in the interpreted hierarchical organisation of lobe architecture (compare Fig. 13 and Fig. 14). The study undertaken by Deptuck et al. (2008) focussed upon the investigation of both the cause of geometrical variability and the internally heterogeneous nature of sandy lobes identified by Gervais et al. (2004; 2006a and 2006b). The observed systematic variability associated with compensational stacking of lobe deposits is seen to highly influence the resultant hierarchy; a four-fold hierarchy is recognised, within which compensational stacking is seen to occur at three different levels (i.e., for the 'lobe element', 'composite lobe' and 'lobe complex' components).

'**Beds or bed-sets**' represent the smallest hierarchical scale and are stated to reflect deposits from a single flow. However, how beds and bed-sets differ to one another is not stated. These 'beds and bed-sets' typically stack in such a way that their respective thickest parts show a systematic lateral offset of up to 500 m; this is referred to by Deptuck et al. (2008) as 'bed compensation'. This level of offset does not result in any lobe-wide discontinuities. The continuous stacking of 'beds and bed-sets' forms a unit termed a '**lobe element**'. 'Lobe elements' are separated by erosive surfaces and represent deposition from a number of similar flows. Deptuck et al. (2008) also note that the 'lobe element' hierarchical order may itself contain two hierarchical levels of stacking, based upon the element's bounding surface. Two or more 'lobe elements' may show compensational stacking (500-2000 m lateral offset) as a result of local channel avulsions, to form a deposit known as a '**composite lobe**'. These units can be separated by disconformable surfaces, abrupt vertical shifts in acoustic facies, or by the presence of thin drapes (the lithological nature of which is not specified). A '**lobe complex**' consists of stacked 'composite lobes' that were fed by the same primary conduit. The lateral shift between the thickest parts of 'composite lobes' (3-5 km) within a 'complex' is interpreted as the result of large-scale channel-mouth avulsions. Abandoned 'composite lobes' can be blanketed by several metres of hemipelagic drape, however this may be eroded by subsequent events. Temporal scales are provided for this hierarchy based upon previously calculated carbon (^{14}C) dating results for key seismic reflectors (Gervais, 2002), see Fig. 14.

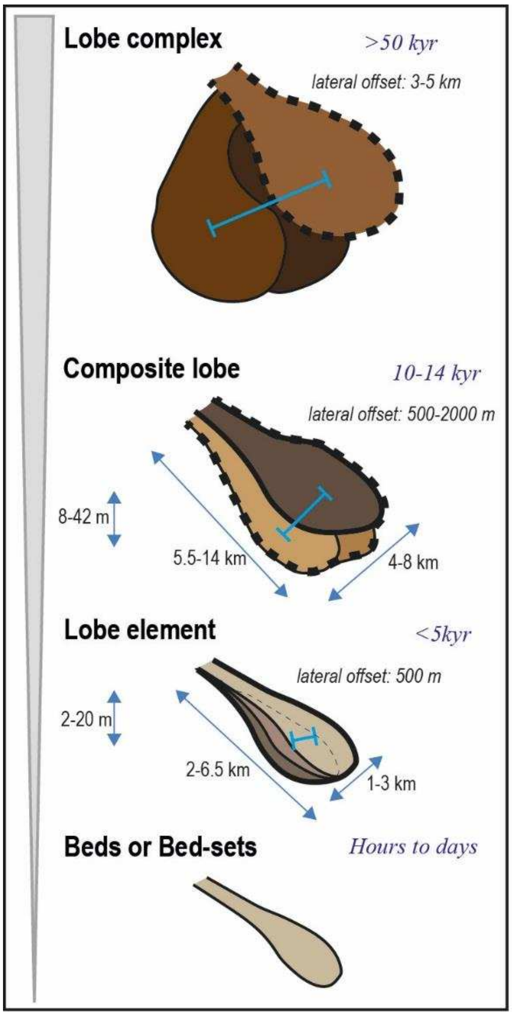

Fig. 14. Hierarchical classification employed by Deptuck et al. (2008). Inferred duration for each hierarchical order is shown in blue italics and the magnitude of lateral offset between the thickest parts of each lobate component at a given order is also reported. These lateral offsets also highlight the stacking patterns observed. Modified after Deptuck et al. (2008).

2.12 Prélat et al., 2009

Prélat et al. (2009) proposed an outcrop-based hierarchy for lobe architectures, which is distinguished from other distributary hierarchical schemes by its critical recognition of fine-grained deposits between sand-rich bodies, otherwise known as 'interlobe' architectural units (Fig. 15). A four-fold hierarchy was developed associated with these depositional 'interlobe' elements thanks to good lateral exposure along outcrops of Permian deposits of the Tanqua depocentre of the Karoo Basin, South Africa. This allowed detailed lithological studies that provided the foundation for this hierarchical classification which has since been applied to several other examples (see below).

A unit at the smallest hierarchical order, i.e., a '**bed**', can be 100s of metres wide and up to 0.5 m thick and is interpreted to represent a single depositional event. 'Beds' stack to form a '**lobe element**' that can be up to 2 m thick (Fig. 15). The 'lobe element' scale is the lowest order at which inter-sandbody fine-grained units are identified (typically <2 cm thick). Although they may be locally eroded or amalgamated at this scale, '*interlobe elements*' are observed to separate vertically stacked, genetically related 'lobe elements'. 'Lobe elements' stack compensationally in topographic lows between previously accumulated depositional forms to form '**lobe**' bodies, which can be up to

5 m thick and over 20 km wide and also show thicker '*interlobe*' caps, which are up to 2 m thick. 'Lobe' bodies are fed by a single channel upstream and these in turn stack to form '**lobe complexes**' which can be up to 40 km wide and 50 m thick. The '*interlobe complex*' depositional elements are not only thicker than corresponding units at lower scales (they can be in excess of 50 cm), but they are also finer (clay grainsize) than the silty deposits of corresponding units at lower orders. The thick hemipelagic claystones, which mark 'interlobe complexes', are interpreted to be deposited as a result of widespread basin starvation, driven by sea-level change. This allogenically controlled event has also been given a sequence stratigraphic significance by Prélat et al. (2009), who compare the 'interlobe complex' to the transgressive and highstand systems tracts (TST/HST) of a depositional sequence; this is in-line with the interpretation of the Tanqua fan system made by Johnson et al. (2001).

Prélat et al. (2009), also recognise that the 'lobe' hierarchical level is indicative of a transition from autogenic-dominant controls to allogenic-dominant controls. However, Prélat et al. (2009) state that it is difficult to infer the relative importance that autogenic and allogenic controls play at particular hierarchical levels in outcrop studies, due to the way autogenic and allogenic controls can mutually interact.

2.12.1 Use and application of the facies-based lobe hierarchy by Prélat et al. (2009)

This distributary-lobe hierarchical classification developed by Prélat et al. (2009) has been highly regarded by other authors (e.g., Mulder & Etienne, 2010; MacDonald et al., 2011), and has been modified to suit a variety of other studies concerning the architecture of deep-marine lobes (e.g., Macdonald et al. 2011, see section 2.14; Grundvåg et al., 2014; Terlaky et al., 2016; see section 2.16). This hierarchy has also been evaluated against a numerical model by Groenenberg et al. (2010). Outputs of the process-based model employed by Groenenberg et al. (2010) supported the hierarchical framework devised by Prélat et al. (2009), with respect to stacking patterns and the digitate geometries of the lobe architectural units. More recent hierarchical schemes that have links to the scheme and concepts of Prélat et al. (2009) are shown in Fig. 1.

Prélat et al. (2010) also applied this hierarchical scheme to a number of other systems, whereby the nomenclature and classifications of previous deep-marine lobe deposits (e.g., the Zaire, Amazon, and Golo systems) from a number of different workers (e.g., Golo data from: Gervais et al., 2006a; 2006b; see section 2.10; Deptuck et al., 2008; see section 2.11) were all standardised to the hierarchy of Prélat et al. (2009). Such a process entails uncertainties in the resultant comparison, given the contrast between the nature of the criteria adopted for the facies-based hierarchy devised for the Karoo Basin and the datasets of the other systems, which consist predominantly of seismic data (see also the Discussion).

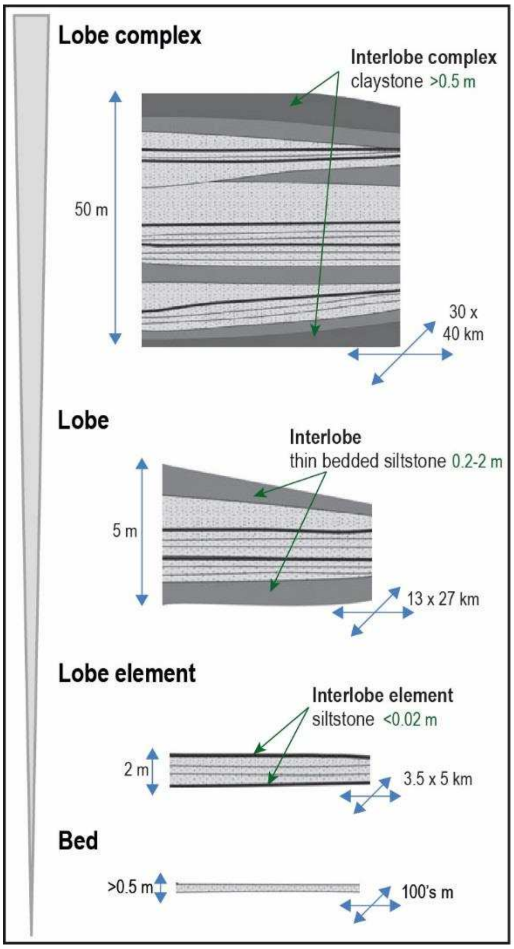

Fig. 15. Hierarchical classification of Prélat et al. (2009), showing the four hierarchical orders and their 'interlobe' sedimentary components. Values of sedimentary-body dimensions that are indicated by Prélat et al. (2009) as typical for each order are reported. Modified after Prélat et al. (2009).

2.13 Flint et al., 2011

The authors of this outcrop study on the lobe architecture of the Laingsburg depocentre of the Karoo Basin (South Africa) have not devised their own hierarchical classification but have utilised multiple concepts on hierarchical organisation, in order to establish a classification for slope to basin-floor deep-water architecture that aims to aid sequence stratigraphic interpretations. It therefore focuses upon the recognition of basin-wide sea-level changes through the preservation of predictable stacking patterns (Fig. 16).

Flint et al. (2011) state that the terminology used in this three-tiered hierarchical arrangement is based upon: (i) the sequence stratigraphy hierarchical review of Neal & Abreu (2009), whereby each sequence stratigraphic order *sensu* Mitchum et al. (1977) is noted by its varying magnitude and duration of accommodation space creation, as well as (ii) the 'sequence stratigraphic framework' definitions of Sprague et al. (2002). The hierarchy is significantly based upon the recognition of regional hemipelagic claystone units, which Flint et al. (2011) describe as the "most readily identifiable and correlatable 'surfaces' at outcrop". These units are interpreted to be the product of low sediment supply during increased shelf accommodation. They are seen to be contemporaneous to shelfal highstand and transgressive systems tracts (HST and TST), and are thus regarded as ‘sequence boundaries’ *sensu* Van der Merwe et al. (2010). They can also be paralleled to the maximum flooding surfaces and associated condensed sections of Galloway (1989) and Hadler-Jacobsen et al. (2005). Identifiable increases in the thickness of these hemipelagic claystone boundary units are notably used by these authors to mark the succession of hierarchical orders and are also used, in the absence of age controls, as indicators of relative depositional timescales in a laterally extensive outcrop case study.

A ‘**sequence**’ is the smallest hierarchical order defined by Flint et al. (2011). These depositional bodies exhibit predictable stacking patterns, as sand-prone units (0-150 m thick) overlain by claystone units (1-5 m) are interpreted to reflect LST and TST/HST deposition, respectively. A ‘sequence’ in the hierarchy of Flint et al. (2011) is therefore comparable to the 3rd-order depositional sequence of the sequence stratigraphic framework (Mitchum & Van Wagoner, 1991). However, Flint et al. (2011) also draw attention to the fact that seismically resolved ‘sequences’ may have been misinterpreted, in that they may actually reflect larger-scale units at the scale of the ‘composite sequence’. ‘Sequences’ are seen to stack into ‘**composite sequences**’, which are overlain by a thicker hemipelagic claystone unit (10-20 m). These units can exhibit either progradational, aggradational or retrogradational stacking patterns. ‘Composite sequences’ are capped by an even thicker hemipelagic claystone unit (20-50 m) to form a ‘**composite sequence set**’. Total thickness estimates for each hierarchical order based on their outcrop data are reported in Fig. 16.

The ability to assign sequence stratigraphic classes (sequence boundaries, systems tracts, and systems tract sets, etc.) was achieved by Flint et al. (2011) thanks to the extensive lateral and vertical exposures of outcrops in the Karoo Basin outcrops and to the large body of knowledge on this basin. This allowed units to be mapped and correlated from the basin plain to shelf-edge deltas, in a manner similar to the work of Hadler-Jacobsen et al. (2005).

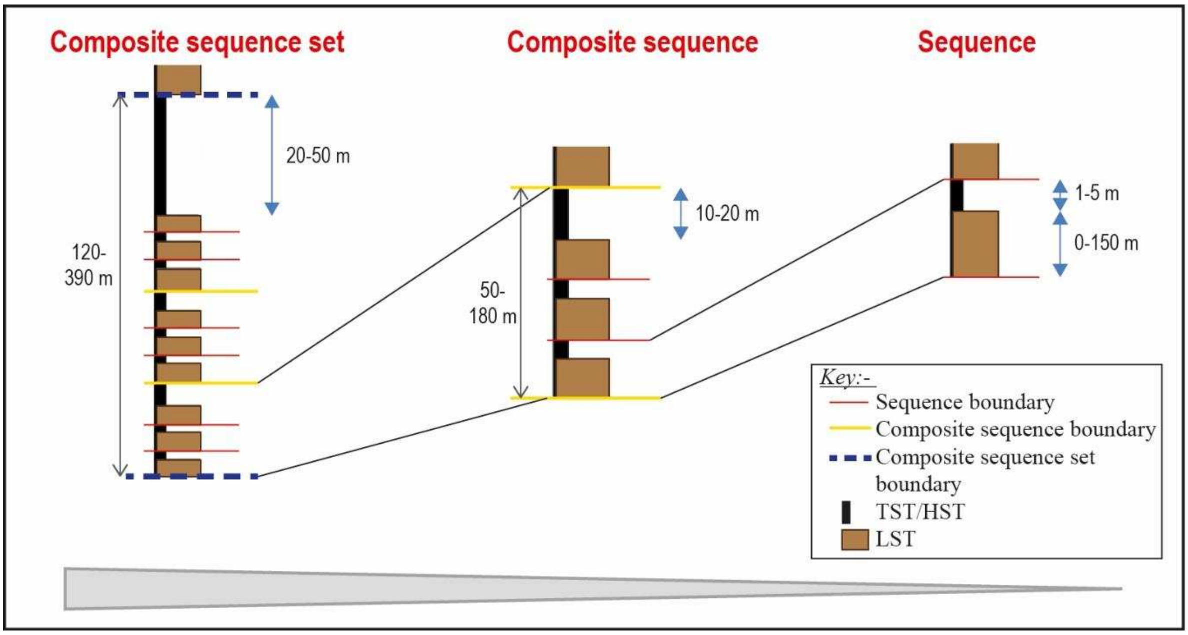

Fig. 16. Hierarchical classification developed by Flint et al. (2011) to study lobe architecture from the outcrops of the Karoo Basin. The terminology is related to sequence stratigraphic concepts and thus shown in red. The model is based upon the thicknesses of the hemipelagic transgressive and highstand systems tract; average thicknesses of hemipelagic mudstones, as well as the sand thickness in a ‘sequence’ as stated by the study are provided. Complete thicknesses for the

composite sequence and composite sequence set are also included (calculated from the studies outcrop data). Figure modified from Flint et al. (2011).

2.14 MacDonald et al., 2011

MacDonald et al. (2011) conducted their outcrop study of the Carboniferous Ross Sandstone Formation (Ireland) with the hope of elucidating the process sedimentology of lobe deposits. MacDonald et al. (2011) state that previous lobe architecture studies have resulted in the production of two similar hierarchical schemes (Deptuck et al., 2008; Prélat et al., 2009), which primarily focused upon the internal architecture of lobe deposits. However, key differences are observed between these two schemes – see Sections 2.11 and 2.12 – for instance with respect to the terminology they employ, as well as their differing 'lobe-element' definitions, particularly in regard to their consideration of bounding surfaces. MacDonald et al. (2011) derive a hierarchy that is focused on process sedimentology, incorporating process understanding into the hierarchy of Deptuck et al. (2008), based on results from high-resolution facies analysis. Interestingly, MacDonald et al. (2011) discard the possibility of adopting the outcrop-based hierarchy of Prélat et al. (2009; section 2.11), which is also based upon detailed facies analysis; no reason is given as to why this hierarchy is disregarded.

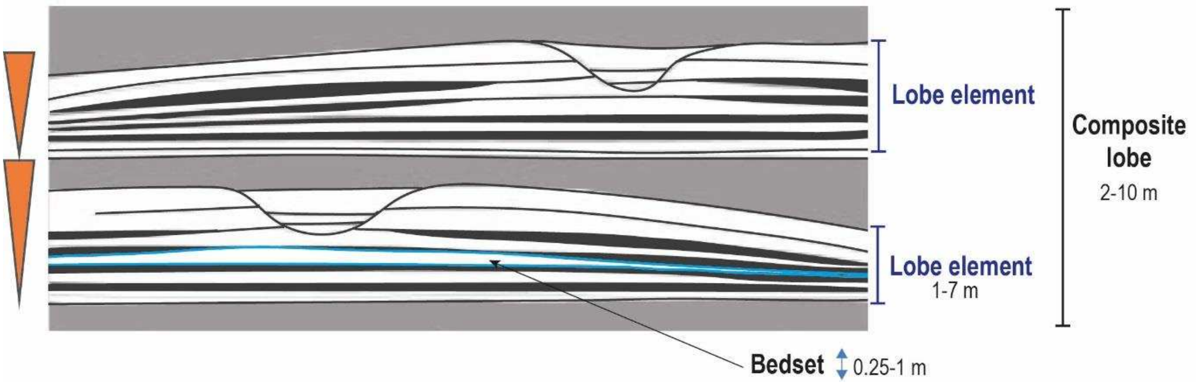

Fig. 17. Hierarchical classification used by MacDonald et al. (2011) based upon vertical facies changes. Thickening-upwards trends are seen within the prograding lobe elements. Average unit dimensions are also provided. Modified after MacDonald et al. (2011).

The hierarchy used to classify the architecture of the Ross Formation adopts the same nomenclature of the scheme by Deptuck et al. (2008); however, only three orders are recognised in this study ('bed-set', 'lobe-elements', and 'composite lobes', Fig. 17). The smallest hierarchical order, '**Bed-sets**', are stated to include stacked beds and bed-sets, but no information is provided to distinguish between beds and bed-sets. This order is stated to reflect the depositional product of a single flow, and stack into thickening-upwards packages to form '**lobe-elements**'. MacDonald et al. (2011) state that their use of this term aligns with usage by both Deptuck et al. (2008) and Prélat et al. (2009). 'Lobe-elements' typically contain a mudstone part at the base of each package formed during a depositional 'shutdown' period. The thickness and presence of these basal mudstones is interpreted by MacDonald et al. (2011) to be determined by the lateral distance and duration of avulsion experienced by the subsequent 'lobe-elements'. MacDonald et al. (2011) also propose that a six-stage evolutionary sequence can be observed in the formation of a 'lobe-element'. This sequence includes phases of deposition, amalgamation, bypass and multiple transition events (see MacDonald et al., 2011). This evolutionary model is used to explain why resultant thickening-upwards packages are observed in 'lobe-elements': each depositional body is interpreted as a progradational cycle of distal to proximal deposits, identified through facies changes and an increase in the amount of megaflutes. 'Lobe-elements' are subsequently seen to stack compensationally, forming '**composite lobes**'.

Pyles (2007) also studied these deep-marine architectures of the Ross Sandstone. He, in turn, implemented a hierarchical scheme which involved the recognition of 'architectural elements', based on the method of architectural-element analysis of Miall (1985). However, the lobe architecture is identified to be simple, showing no internal hierarchical organisation.

2.15 Pickering & Cantalejo, 2015

Pickering & Cantalejo (2015) have recently proposed a deep-marine hierarchical classification based on outcrop studies of the Eocene Ainsa Basin (Spanish Pyrenees). This hierarchy has since been applied by the same research group to additional datasets from the same basin (Bayliss & Pickering, 2015a; 2015b; Pickering et al., 2015). The devised hierarchy relies on correlation of key stratigraphic surfaces at a variety of scales, allowing bounding surfaces for architectural elements to be defined. The hierarchy is therefore based upon similar criteria to the ones adopted in the original scheme by Pickering et al. (1995): (i) internal facies associations (based upon the facies classification of Pickering et al., 1986), (ii) architectural geometry, and (iii) associated bounding surfaces. However, the way this information is organised and described (Fig. 18) differs from the original hierarchy of Pickering et al. (1995; Fig. 4a).

The nomenclature used within the hierarchy of Pickering & Cantalejo (2015) is based upon terminology proposed by Flint et al. (2008), Sprague et al. (2002; 2005; 2008; section 2.7), and Figuereido et al.'s (2013) work on the Karoo Basin. This terminology covers a wide range of scales, from seismic to core or outcrop studies. Compared to Pickering et al., 1995, this nomenclature more closely aligns with current sequence stratigraphic concepts, which in turn helps to support the aims of Pickering & Cantalejo's (2015) study, i.e., to improve stratigraphic surface correlation through the recognition of sequence boundaries across the basin. However, this focus limits the applicability of this scheme where the scale of observation is limited.

'**Lamina**' and '**laminaset**' define the 1st hierarchical order of the classification, representing the smallest identifiable package of sediments that tend to lack internal layering, having a uniform lithology. One or more 'laminasets' compose a '**bed**', which represents the 2nd-order division and is described as the fundamental building block of stratigraphy. Based on the definition of Campbell (1967), a 'bed', is interpreted as a deposit formed by a single depositional event; it is also considered to be a time stratigraphic unit, a property which Pickering & Cantalejo (2015) state can allow for inter-basinal correlations, *sensu* Van Wagoner (1990). A 3rd-order '**bedset**' is constrained when a bed immediately above or below differs in composition, texture or sedimentary structures. Pickering & Cantalejo (2015) explain that the definition of their 4th-order unit, the '**storey**', was originally used to characterise fluvial deposits (Friend et al., 1979), and has thus been modified to accommodate deep-marine deposits; uniquely, Pickering & Cantalejo (2015) also apply the term to classify mass-transport deposits (MTDs) *sensu stricto* Pickering & Corregidor (2005). Two types of 'storey' are identified, and categorised based upon distinct facies associations: 'sandy storeys' (on average 300 m wide and 3 m thick, based upon 66 examples) and ‘mass-transport storeys’ (on average 700 m wide and 6 m thick, based upon 32 examples). 5th-order units consisting of multiple ‘storeys’, are termed ‘**elements**’, and are classified either as channel fill or mass-transport elements. These units typically have an erosional base and commonly show fining-upward trends in their axial domain. ‘Channel-fill elements’, on average 1000 m wide, 14 m thick (based upon 64 examples) can be divided into distinct regions, i.e., as axis, off-axis, margin and levee regions, but no guidelines on how such regions are recognised are provided. A 6th-order ‘**complex**’, classified as a ‘mass-transport complex’ (MTC) or ‘channel complex’ (on average 1400 m wide and 37 m thick, based upon 38 examples) is commonly erosional at the base, and can show either fining- or coarsening-upwards cycles depending on the stacking of its internal elements. A unit composed of multiple ‘complexes’ is termed a 7th-order ‘**sandbody**’ (on average 2200 m wide and 90 m thick, based upon 19 examples). Pickering & Cantalejo (2015) state that these 7th-order units can also be referred to as ‘sequences’; however this term is not favoured by Pickering & Cantalejo (2015) themselves due to the common association of this term with depositional units that are typically larger. In the Ainsa Basin ‘sandbodies’ are marked by an MTD/MTC at their base and capped by a basin-wide drape, otherwise known as abandonment facies. This order signifies a major basin-wide re-organisation, as each ‘sandbody’ is interpreted to reflect a shift in the depocentre position. Two or more ‘sandbodies’, typically separated by fine-grained marly sediments in this depositional system, are recognised as 8th-order ‘**systems**’. Multiple sandy ‘systems’ are briefly noted by Pickering & Cantalejo (2015) to stack into either fining or coarsening upward packages known as ‘**system sets**’. In turn these ‘system sets' can stack into a 'group', which is the largest hierarchical order of sedimentary unit identified in the Ainsa Basin.

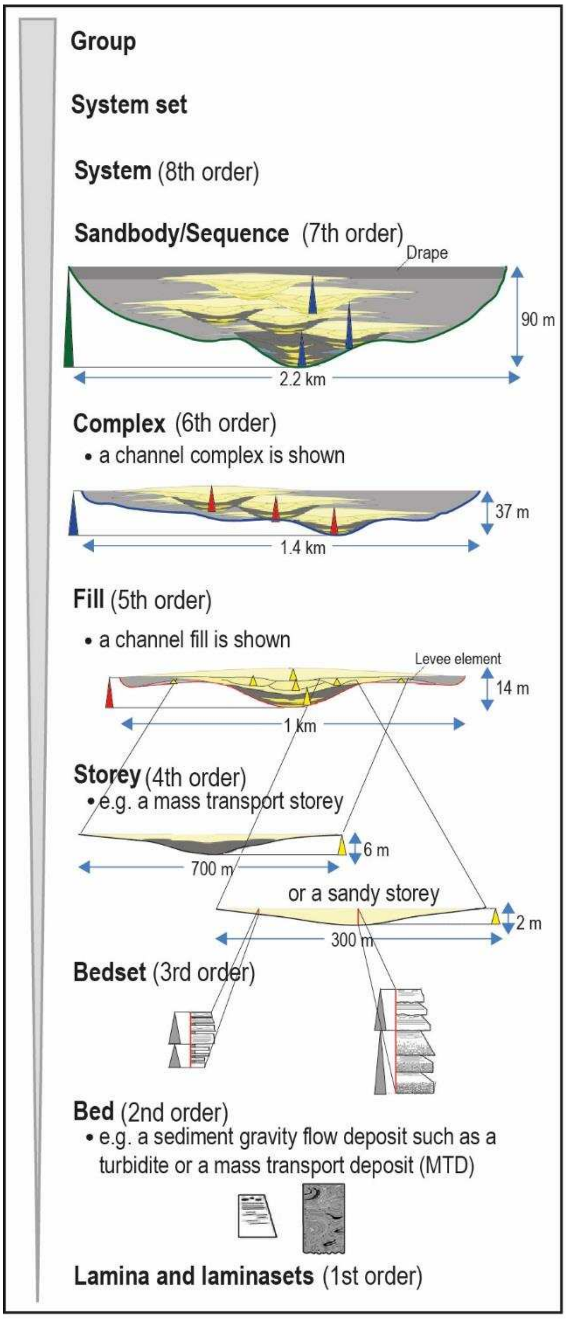

Fig. 18. Hierarchical classification developed by Pickering & Cantalejo (2015) and employed in the Ainsa Basin, for channelized environments. Numerical orders and average dimensions of corresponding units are shown, numbering indicates the bounding surface order of the depositional body. Figure modified after Pickering & Cantalejo (2015).

2.16 Terlaky et al., 2016

Terlaky et al. (2016) establish their 'avulsion-based' hierarchy building upon existing hierarchical classifications found in the literature. The hierarchy makes reference to architectural-element analysis principles and is based upon the work by Mulder & Etienne (2010), which in turn adopts the hierarchical classification of Prélat et al. (2009). Terlaky et al. (2016) state that differences between their hierarchy and those it is based upon arise in relation to differing types of observations: whereas other hierarchies focus upon the nature of fine-grained inter-sandbody deposits (for instance Gardner & Borer, 2000; Prélat et al., 2009; Grundvåg et al., 2014), Terlaky et al. (2016) develop their hierarchy around the identification of surfaces and the location of avulsion nodes.

Each hierarchical division within the seven-tiered hierarchy is therefore defined by the increasing order of the drainage-pattern hierarchy at which avulsion occurred (Fig. 19). This idea is also seen by Terlaky et al. (2016) as a methodology to help bridge the gap between outcrop and modern seismic studies, although the framework is developed from outcrop data (Neoproterozoic Windermere Supergroup, British Columbia, Canada).

The smallest hierarchical division recognised by the framework is the '**lamina**'; laminae stack to form '**beds**', which themselves are interpreted to be the deposit of a single flow. 'Beds' stack to form what is known as an '**architectural element**' when a 3D view of the depositional body is known, or a 'stratal element' if the element is expressed only in 2D. Terlaky et al. (2016) define this 'architectural element' hierarchical order making reference to key characteristics used as criteria for the attribution of corresponding orders in other schemes. For example, Terlaky et al. (2016) describe this order as a mesoscale lithosome (a defining character of Miall's, 1985, fluvial architectural elements) of 'mappable' scale (*sensu* Mutti & Normark, 1987). Terlaky et al. (2016) define architectural elements as the preserved products of deposition taking place between two successive distributary-channel avulsion events. Depositional bodies of this type are characterised by distinctive external shape, bounding surfaces and internal arrangement of sedimentary facies, in agreement with the characteristic properties used by Pickering et al. (1995), Gardner & Borer (2000), Pyles (2007), Prélat et al. (2009), and Grundvåg et al. (2014), in their schemes. Terlaky et al. (2016) use these criteria to define 'architectural elements' as the fundamental building blocks of larger stratigraphic units. This 'stratal/architectural element' order includes units interpreted to have formed under a distinctive set of depositional conditions. Six typical stratal elements recognised in the basin-floor environment of the Kaza Formation are identified by Terlaky et al. (2016) as:

- isolated scours,
- feeder channels,
- distributary channels,
- terminal splays,
- avulsion splays
- (sheet-like) distal and off-axis fine-grained turbidites.

The nomenclature used to describe these geometries is said to be taken from several studies of submarine fans. These 'architectural elements' are also compared by Terlaky et al. (2016) with the 'lobe element' units of Prélat et al. (2009).

Genetically related 'architectural elements', which Terlaky et al. (2016) state can also include debrite, slump and slide bodies, stack to form a '**lobe**'. A lobe is seen to embody the overall active depositional area at any one time on the basin floor, and to form the units deposited between two events of feeder-channel avulsion. 'Lobes' are identified by Terlaky et al. (2016) as the point of transition within the hierarchy, as it is at this level that more basin-wide allogenic controls begin to dominate sedimentary processes (similarly to the 'lobe' order of Prélat et al., 2009). A '**lobe complex**' is produced by the stacking of multiple 'lobes' and may also include genetic debrites, slumps and slide bodies – however, these bodies are not genetically defined by Terlaky et al. (2016).

A ‘lobe complex’ is seen to be the consequence of an episode of channel-levee-system avulsion, which makes this order comparable to the ‘lobe complex’ of Prélat et al. (2009). A ‘**fan**’ is formed by avulsion of a feeder canyon, an event that Terlaky et al. (2016) state will be reflected in the stacking pattern of the ‘lobe complexes’. In turn, multiple ‘fans’ stack to form ‘**fan complexes**’, the largest recognised hierarchical order. Terlaky et al. (2016) do however state that it will be difficult, especially in outcrop studies, to discern the higher orders of this hierarchical framework.

Other hierarchies based upon distributary ‘interlobe’ stratigraphic markers (e.g., the hierarchy of Prélat et al., 2009) are not readily applicable to the outcrop studied by Terlaky et al. (2016), due to the limited preservation of fine-grained deposits in the Kaza Formation. Additionally, the scheme by Terlaky et al. (2016) could be applied to datasets with limited facies data, as local evidence of avulsion (marked by lithological boundaries and/or stratal trends) can be combined with basin-wide observations of element position and stacking. However, this scheme can only be applied if extensive, basin-wide correlations can be established, and traced to areas updip of the channel-lobe transition zone.

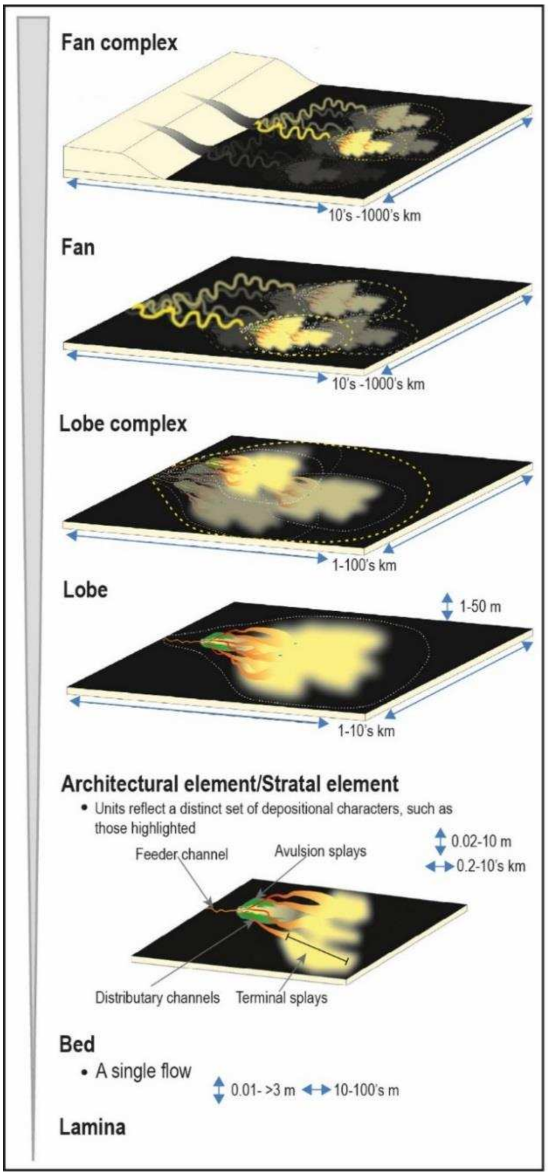

Fig. 19. Hierarchical classification for an idealised submarine-fan complex by Terlaky et al. (2016). Dimensions are estimates taken from the study. Figure modified after Terlaky et al. (2016).

3 Discussion

Hierarchical classifications attempt to assign order to otherwise complex systems, allowing the spatial and relative temporal evolution of deep-marine systems to be studied. As demonstrated by the schemes reviewed in this paper, hierarchical classifications provide a method to better understand this complexity, as they help geologists, both in academia and industry, to:

i) better constrain reservoir models, e.g., by improving the characterisation of hydrocarbon-reservoir properties (such as geometry, facies distribution and connectivity) – objectives intended by the hierarchical schemes of Prather et al. (2000), Sprague et al. (2005) and Gervais et al. (2006a);

ii) Establish analogy between outcrop and subsurface data, and enable comparative analyses between both modern and ancient systems – drivers that motivated Mutti & Normark (1987), Hadler-Jacobsen et al. (2005), Mayall et al. (2006) and Prélat et al. (2010) to develop their hierarchical schemes. The hierarchical schemes reviewed in Section 2 are summarised in Table 1.

However, significant differences exist between hierarchical schemes, casting doubt over their wider utility. The possible causes of these differences, such as differing data-types and environmental controls are evaluated below; in parallel inter-scheme similarities, with respect to both sedimentological observations and common genetic interpretations are reviewed. These analyses can be used to assess whether a common standard for deep-marine architectural hierarchy is possible.

3.1 The influence of research aims on the structure of hierarchical schemes

Hierarchical schemes and the number of significant orders they recognise differ in relation to the particular architectural elements, sub-environments or physiographic settings they focus on (see Table 1). Because of differences in the aims of the research and types of data underlying each scheme, some hierarchies may be applicable to entire systems, whereas others can be restricted in scope, for example to just 'channelized' or 'lobate' environments, or to the CLTZ setting (Fig. 20). Hierarchies that are solely restricted in their application to distributary lobe environments (i.e., Gervais et al., 2006a; Deptuck et al., 2008; Prélat et al., 2009; MacDonald et al., 2011; Flint et al., 2011) commonly recognise only three or four significant orders, starting from a bed or bed-set scale, regardless of whether the underlying dataset is based on seismic or outcrop. Hierarchies developed specifically for channel environments can contain anywhere from three (e.g., Mayall et al., 2006) to ten (e.g., Pickering and Cantalejo, 2015) significant orders, with more complex hierarchies being typical for schemes founded on outcrop datasets due to their higher resolution. Hierarchies that are not restricted in application to a specific sub-environment typically contain five to eight orders; schemes of this type include those of: Mutti & Normark (1987), Pickering et al. (1995), Beaubouef et al. (1999), Prather et al. (2000), Navarre et al. (2002), Hadler-Jacobsen et al. (2005), Sprague et al. (2005) and Terlaky et al. (2016). These schemes display less variability in the number of hierarchical orders than those focussing on channel environments, notwithstanding the wider environmental domain they are applied to. Most of the publications detailing system-wide hierarchies do not address possible differences in hierarchy between channelized and lobate (or distributary) environments. Only Sprague et al. (2005; Fig. 9) and Navarre et al. (2002; Fig. 7) distinguish between these settings through the use of environmental prefixes associated with the different architectural geometries. Sprague et al. (2005) also provide distinct ranges of dimensions for the different units associated with these two environments.

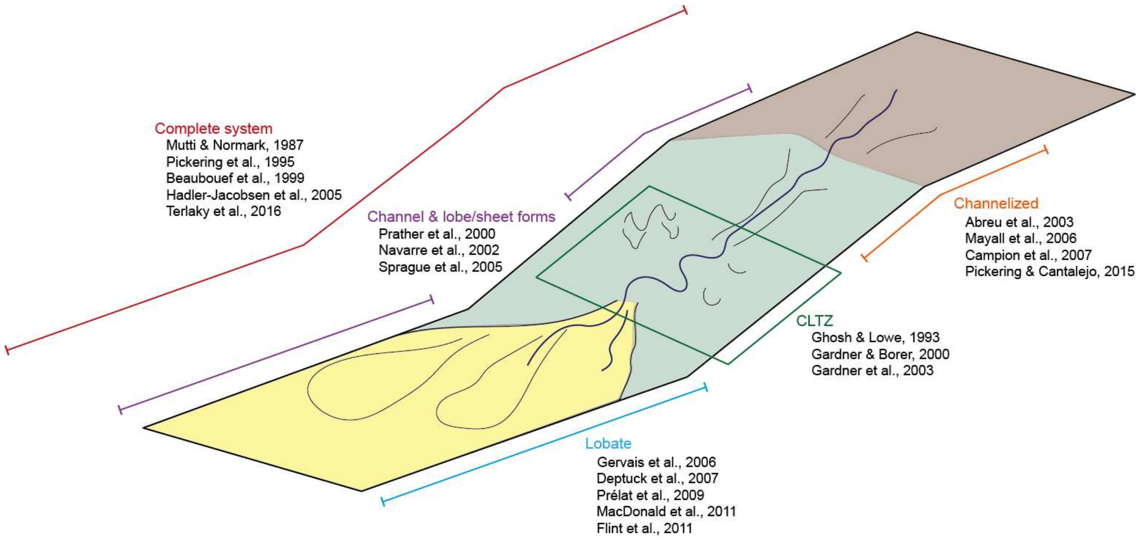

Fig. 20 – The range of deep-marine sub-environments considered by each hierarchical scheme reviewed in this paper.

The difference in the number of significant orders established for channel and lobe environments suggests that it might not be possible to capture the internal organization of these two environments by using a single hierarchy. It also suggests that the number of hierarchical orders might vary as the system and its architecture evolve downstream. This concept is something Mayall et al. (2006) alluded to in their study, as they proposed that a channel body could display a downstream decrease in hierarchical organization of its deposits, as energy drops and the channel bifurcates becoming simpler in form.

In addition to hierarchical schemes being developed for a specific depositional domain (sub-environment), others have been proposed by studies which focus on partiular architectural elements (e.g., lateral-accretion packages; Abreu et al., 2003), tectonic settings (e.g., confined basins; Mayall et al., 2006), or specific basins (e.g., the Ainsa Basin; Pickering & Cantalejo, 2015). It is therefore reasonable that the variety observed in the way hierarchical approaches are structured reflects different research focuses. Some hierarchical approaches are accompanied by explicit caveats regarding the particular environment each scheme is supposed to be applicable to (e.g., schemes for sand-rich systems by Pickering et al., 1995, Prather et al., 2000 and Gardner et al., 2003). A question arises as to whether the development of new hierarchical approaches is undertaken without consideration of the available existing schemes, and thus whether enough testing has been done to reject the use of existing ones. On some occasions, new hierarchical schemes are seen to modify existing models based upon new insights or needs. For example, the modification of Gardner & Borer's (2000) CLTZ hierarchy by Gardner et al. (2003) was based upon a process-driven model which was thought to better inform the interpretation of the architecture. Similarly, Abreu et al.'s (2003) adaption of the scheme by Sprague et al. (2002) was designed to accommodate lateral-accretion packages. Typically, the majority of hierarchies presented in this review have only been applied to, or demonstrated through, single case studies (see Table 1), raising the question as to whether their broader applicability has been robustly established.

3.2 Data types: biases and pitfalls

The method of investigation and the available data can also influence the resultant structure of the hierarchical schemes. For example, outcrop studies are often limited in their scales of observation, because of partial preservation and the quality of exposure. This has brought about the notion that only seismic investigations can capture basin-scale architectures (Prather et al., 2000; Gardner et al., 2003; Posamentier & Kolla, 2003; Prélat et al., 2010; Flint et al., 2011; Terlaky et al., 2016). Most often hierarchical approaches based on seismic datasets include orders that are applicable basin-wide or to the scale of the entire system (e.g., the 'megasequence' of Navarre et al., 2002; the 'turbidite-complex' of Mutti & Normark, 1987). However, the dimensional scales of the largest outcrop-derived architectural orders are comparable to those of the seismic 'basin-wide' architectures; this is evident in the values of lobe thickness reported by Flint et al. (2011), and in the thickness and width measures for the interpreted LST 'submarine channel fairway' depositional body of Gardner et al. (2003), which encompass the scalar ranges of the 'megasequence' basin-fill order of Navarre et al. (2002, see Figs. 21 and 22, below).

The resolution of the data provided by different methods of acquisition can also affect the resultant hierarchical classification. The poorer resolution of seismic datasets, as opposed to outcrops, results in a diminished ability to recognise lower-order units; thus, 'bed' or individual 'facies' orders are usually not considered in seismic datasets. The resolution of seismic data is known to vary depending on the method (Posamentier et al., 2000; Weimer & Slatt, 2007); however, even on high-resolution seismic profiles, the smallest order described often correspond to bed packages; these include, for example the 'elementary body' of Gervais et al. (2006a) and the 'beds and bed-sets' of Deptuck et al. (2008). Navarre et al. (2002) state that only their 'channel complex' and 'storey' hierarchical levels were confidently recognised in their study, whereas Mayall et al. (2006) point out that discerning between their '4th order' and '5th order' units might be difficult. The uncertainties caused by poor data resolution in identifying architectures at particular scales hinders the quality and integrity of the hierarchical approaches underpinned by such datasets. This affects the confidence with which hierarchical classifications based on outcrop and seismic datasets can be reconciled, and any subsequent attempt to develop a common hierarchical standard. However, research on large outcrop exposures, at 'seismic' scales, is being undertaken that can help reconcile hierarchies developed using different data types; works of this type include, for example, those on the Karoo Basin (South Africa; Prélat et al., 2009; Flint et al., 2011), the Magallanes Basin (Chile; Romans et al., 2011; Pemberton et al., 2016) and the Brushy Canyon Formation (USA; Gardner & Borer, 2000; Gardner et al., 2003, Pyles et al., 2010).

In an attempt to overcome scale limitations in seismic datasets, some studies supplement seismic data with 'sub-seismic' facies-scale observations (e.g., Prather et al., 2000; Navarre et al., 2002; Sprague et al., 2005) or integrate both data types to inform their hierarchical approaches (e.g., Mutti & Normark, 1987; Pickering et al., 1995; Hadler-Jacobsen et al., 2005; Mayall et al., 2006). The integration of core and well-log data with seismic data helps overcome limitations in vertical resolution. Such integration however has not resulted in consistency across the different hierarchical schemes: variation is still seen in the number of significant orders that are recognised (ranging from three to eight orders, see Table 1), as well as in the terminology used (see Figs. 4, 6 and 11). However, all the schemes, bar the hierarchy of Mayall et al. (2006), are seen to incorporate 'basin-wide' hierarchical orders as they capture both channel and lobe environments. Hierarchical schemes developed in the hydrocarbon industry have tended to integrate data of different types (e.g., outcrop, core, well logs, seismic, bathymetry, biostratigraphy) to develop more geologically sound schemes; however, the manner and degree of integration cannot be directly assessed due to the proprietary nature of the data (e.g., Navarre et al., 2002; Abreu et al., 2003 and Sprague et al., 2005).

3.3 Hierarchical-order nomenclature

Comparison between hierarchical schemes is hindered by variability in hierarchical nomenclature, arising from:

i) redundancy in terminology; for example, the terms 'channel-fill' (Sprague et al., 2005), 'channel story' (Navarre et al., 2002), and 'elementary channel fill' (Gardner et al., 2003) are all terms used to identify the interpreted products of a single cycle of fill and abandonment of a discrete channel form;
ii) variations in the meaning of like terms; an example of this is the usage of the term 'storey' (or 'story' in US English), cf. the definition of a 'channel story' in the hierarchy of Navarre et al. (2002) as opposed to the scour based, sub-channel 'storey' of Sprague et al. (2005).

Terminological discrepancies have arisen because some hierarchical approaches have been influenced by, or have used, components of previous hierarchical classifications. Sharing terminology and definitions can be problematic, as often concepts undergo some re-interpretation when applied in a new scheme. For example, MacDonald et al. (2011) state that they use the 'lobe-element' definition of Deptuck et al. (2008) and Prélat et al. (2009) but do not reconcile the differences between these definitions. Thus, the lobe-element definition of Deptuck et al. (2008) is recognised to potentially display relationships with more than one order of bounding surfaces, i.e., this order does not share a one-to-one bounding-surface to element-order relationship; on the contrary, Prélat et al. (2009) recognise a lobe element as being encapsulated by bounding surfaces that belong to the same order as the element. Such differences contribute to the potential for misinterpretation when trying to compare approaches.

Nomenclature is also often amended through time to keep terminology up-to-date, as scientific understanding improves. For example, the definition of a 'storey' has been amended multiple times. The original meaning, coined by Friend et al. (1979) was used as a basic descriptive term for fluvial deposits. However, Sprague et al. (2005) redefined the term to describe deep-marine channel bodies showing predictable lateral and vertical bedset facies changes. This definition has since been adopted and expanded by Sprague et al. (2008) to include lobe and levee/overbank deposits and further amended by Pickering & Cantalejo (2016) to incorporate mass-transport deposits. As terminology evolves the risk of inconsistent application may arise.

3.4 Common criteria used to diagnose hierarchy in architecture

While a wide range of terminology is used in hierarchical schemes, similarities between order definitions can be found, based largely upon the common descriptive characteristics used to diagnose hierarchy. For example, when discernible, internal facies characteristics, the nature of the bounding surfaces, their scale and observable geometries are all used to distinguish similar hierarchical orders in all schemes reviewed in this paper. Additional criteria that are sometime used to establish hierarchy include sedimentary-unit stacking patterns, dimensions, and absolute or relative durations or timescales.

These diagnostic characteristics – facies associations, geometry, scale and bounding surface relationships – are also the common criteria used in the 'architectural-element analysis' approach applied to categorise both fluvial and aeolian sedimentary successions (e.g., Brookfield, 1977; Allen, 1983; Miall, 1985). Although only some authors of deep-marine hierarchical schemes might have directly acknowledged these influences (e.g., Ghosh & Lowe, 1993, Pickering et al., 1995, Gardner & Borer, 2000, Gardner et al., 2003, Terlaky et al., 2016 and Pickering & Cantalejo, 2015; see Table 1 and Fig. 1), all the reviewed schemes implicitly recognise architectural hierarchy using the principles of architectural-element analysis to some degree. Such commonalities suggest that reconciliation between hierarchies should be possible (see also Section 3.5, below). Nevertheless, difficulties remain in trying to make definitive links between the hierarchical orders of different schemes. This is due in part to the differing significance given to particular types of diagnostic characteristic. For example, the hierarchy of Prélat et al. (2009) specifically focuses upon facies characteristics, while that of Deptuck et al. (2008) largely relies on stacking patterns of 3D architectural geometries. In addition, difficulties in observing key characters, as a result of the intrinsic complexity of sedimentary successions or because of limitations related to available data types (as discussed in Section 3.2), limit the confidence with which hierarchical units can be compared. For instance, Ghosh & Lowe (1993) note the difficulty in recognising bounding surfaces in conglomerates and debris-flow deposits, and in recognising architectural geometries within highly scoured, and subsequently amalgamated, 'first order' and 'second order' units.

Miall's (1985) explanation of the 'architectural-element analysis' was also accompanied by a number of cautions for its application to fluvial deposits, which are also applicable to deep-marine systems. Miall (1985) identified potential issues in identifying architecture in relation to differences in scale, interbedding (the interdigitation of background sedimentation being particularly relevant for deep-marine deposits) and intergradation between sub-environments. These problems make it difficult to establish correlations and delineate deep-marine architectures, particularly at the basin scale, directly impeding the development of a common hierarchy for deep-marine deposits.

3.5 Common stratigraphic architectures and their inferred formative processes

Sedimentological and stratigraphic observations of deep-marine deposits can be used to develop our understanding of formative depositional and erosional processes, in combination with numerical and physical experiments (e.g., Gardner et al., 2003; Talling et al., 2012). This is due to limitations in observing such processes first-hand in deep-marine systems, although significant insight has been drawn more recently from direct turbidity-flow monitoring and observations of the geomorphic expression of processes acting on the seafloor (e.g., Paull et al., 2010; Maier et al. 2011; Symons et al., 2017). In several cases common interpretations of formative processes are used in association with the recognition of diagnostic sedimentological features, facies associations, geometry, scale and bounding surface relationships to establish tentative links between hierarchical schemes. Such links are outlined below for the channel and lobe architectures reviewed in Section 2 in ascending scalar order, along with caveats in the use of the resulting genetic hierarchies.

Common channelized hierarchical architectures

A 'bed' is typically the most readily recognisable small-scale hierarchical unit included in schemes applicable to channelized deposits (Mutti & Normark, 1987, 1991; Ghosh & Lowe, 1993; Pickering et al., 1995; Beaubouef et al., 1999; Prather et al., 2000; Sprague et al., 2005; Campion et al., 2011; Pickering & Cantalejo, 2016; Terlaky et al., 2016). The description of a bed is widely influenced by the definition set by Campbell (1967), according to whom it is a layer of sedimentary rock bounded above and below by either accretionary or erosional bounding surfaces and that is not defined on its thickness. These units can be heterogeneous, and as such some schemes divide this unit further into facies divisions, recognised by changes in grain-size and sedimentary structures (e.g., the 'first order' and 'second order' of Ghosh & Lowe, 1993; the 'zeroth order' of Pickering et al., 1995; the 'lamina and laminasets' of Pickering & Cantalejo, 2015; Terlaky et al., 2016). In the reviewed schemes, a bed is consistently interpreted as representing a single depositional event, whereby any internal divisions relate to changes in sediment-gravity-flow conditions.

At a higher scale, units that are commonly described in channel environments are composed of vertically stacked, genetically related beds. These units are bound by erosive or accretionary bounding surfaces and are themselves contained within a larger channel form. Units of this type are typically noted as being unresolvable by conventional seismic methods due to their limited size (e.g., Mutti & Normark, 1987; Prather et al., 2000; Navarre et al., 2002; Sprague et al., 2005). These units show distinct lateral and vertical facies changes, categorised by some studies in terms of predictable organisation arising from variations in processes from channel axis to margin regions (e.g., Prather et al., 2000; Campion et al., 2007; Pickering & Cantalejo, 2015). A variety of terms have been coined to refer to deposits that display these characteristics: e.g., the 'turbidite sub-stage' of Mutti & Normark (1987; 1991), the 'sedimentary complex' of Pickering et al. (1995), the '1st order, sub-seismic' of Prather et al. (2000), the 'geobody' of Gardner & Borer (2000) and Gardner et al. (2003), the 'channel phase' of Navarre et al. (2002), and the 'storey' of Sprague et al. (2002; 2005), Campion et al. (2007; 2011), McHargue et al. (2011) and Pickering & Cantalejo (2015). This channel architecture is recurrently recognised in the deep-marine rock record, as noted by these hierarchical schemes, indicating its importance as a building block of channel deposits. These 'storey' deposits are commonly interpreted as the product of sequences of flows that progressively wax then wane in terms of their energy (McHargue et al., 2011). Periods of erosion, bypass and filling are commonly recorded in the facies patterns of these units (Mutti & Normark, 1987; 1991; Campion et al., 2011). These 'stories' are often termed 'sub-channel' elements due to their containment within larger confined channel forms (Sprague et al., 2005; Campion et al., 2007; 2011).

Multiple genetically related 'stories' stack with little lateral offset, to form a recognisable channel form bounded by a typically erosional basal surface. Units showing these characters have been termed as 'turbidite stages', (Mutti & Normark, 1987; 1991), 'fourth-order' units (Ghosh & Lowe, 1993; Prather et al., 2000), 'depositional bodies' (Pickering et al., 1995), 'channel fills' (Beaubouef et al., 1999; Sprague et al., 2002; 2005; Pickering & Cantalejo, 2015), 'channel stories' (Navarre et al., 2002), 'single-story channels' (Gardner & Borer, 2000), 'elementary channel fills' (Gardner et al., 2003), 'channels' (Abreu et al., 2003; Campion et al., 2007; 2011), 'sixth-order' units (deposits of the Delaware Basin; Hadler-Jacobsen et al., 2005;), 'channel elements' (McHargue et al., 2011) and 'architectural elements' (Terlaky et al., 2016). These 'channel' architectures show distinct cross-sectional and planform geometries (Pickering et al., 1995; Prather et al., 2000; Terlaky et al., 2016), discernible in both seismic and outcrop datasets. No significant unconformities are observed within these deposits, and their tops are typically marked by hemipelagic/pelagic background sedimentation (Mutti & Normark, 1987; Navarre et al., 2002). Mutti & Normark (1987) propose that such patterns in sedimentation are the result of short-term sea-level changes or tectonic activity, suggesting that units at this scale might record the effects of allogenic controls. The relative lack of significant background sedimentation internally suggests that these 'channel' units are interpretable as the product of a complete cycle of channel filling and abandonment (Sprague et al., 2002; 2005), itself recording multiple cycles of waxing and waning flow energy (McHargue et al., 2011). The stacked internal 'stories' are also seen by some to show a predictable evolutionary sequence, again relating to changes in environmental energy as flows vary through the stages of channel initiation (erosion), growth (filling) and retreat (abandonment or bypass), (Navarre et al., 2002; Gardner & Borer, 2000; Gardner et al., 2003; Sprague et al., 2005; Hadler-Jacobsen et al., 2005; McHargue et al., 2011). The recurrence of these facies successions has been used to produce models of flow evolution and energy trends in channels (Hubbard et al., 2014), as well as to map basin-ward changes (Gardner et al., 2003).

Based upon common sedimentological and stratigraphic observations, a larger-scale, 'regional' hierarchical order can be recognised (Ghosh & Lowe, 1993; Pickering et al., 1995). Erosional surfaces are seen to envelope deposits that contain multiple lower-order genetically related 'channel' architectures, as well as other associated element types (e.g., lateral-accretion packages; Abreu et al., 2003) (Mutti & Normark, 1987; Navarre et al., 2002; Sprague et al., 2005; McHargue et al., 2011). Vertical stacking trends no longer dominate this architecture. Packages of hemipelagic sediments, relatively thicker than those recognised in lower-scale units, are seen to delineate bodies that stack in highly- or non- amalgamated fashions (cf. 'fifth-order' of Ghosh & Lowe, 1993; 'members/sub-members' of Pickering et al., 1995; 'channel complex' of Gardner & Borer, 2000; Navarre et al., 2002; Sprague et al., 2005; Campion et al., 2011; Pickering & Cantalejo, 2015; 'composite channel' of Gardner et al., 2003; 'complex set' of McHargue et al., 2011). These units are interpreted as showing common migration pathways, as the successive internal units exhibit similar lateral and/or vertical patterns within the larger confining channel (Gardner et al., 2003; Campion et al., 2011). Again, such architecture is seen to be the product of a cycle of channel initiation, growth and retreat (Gardner et al., 2003; Hadler-Jacobsen et al., 2005; McHargue et al., 2011). With consideration of observations on hierarchy, McHargue et al. (2011) describe the internal stacking of channel 'complex' architectures, through forward modelling, as sequential – moving from amalgamated, low aggradational stacking to highly aggrading, vertically-stacked deposits. This model has since been supported and developed by Macauley & Hubbard (2013) and Jobe et al., (2016).

Broad correspondence is seen between higher scale units linked by their common generic 'basin-fill' interpretation, for example, the 'turbidite complex' of Mutti & Normark (1987; 1991), the 'sixth-order' of Ghosh & Lowe (1993), the basin-fill sequence' of Pickering et al. (1995), the 'megasequence' of Navarre et al. (2002). These units are inferred to encapsulate architecture spanning the lifetime of multiple submarine fans and their deposits, bound by long-term unconformities influenced by regional tectonics (Mutti & Normark, 1987; 1991; Navarre et al., 2002). The internal character of these deposits is not well-documented, but Mutti & Normark (1987) still infer cycles of initiation, growth and retreat at this scale.

Common hierarchical orders for 'lobe' or 'sheet' architectures

In 'depositional-lobe' deposits (*sensu* Mutti & Normark 1987; 1991), a 'bed' is often the smallest hierarchical division observed, although not always seen as a discrete class (Deptuck et al., 2008; MacDonald et al., 2011). A 'bed' is again interpreted as the product of a single depositional event. Genetically related 'bed' units are commonly observed to stack, separated by non-erosional surfaces, into distinctive lobate geometries, identifying a common hierarchical division often termed a 'lobe element' (Deptuck et al., 2008; Prélat et al., 2009; MacDonald et al., 2011), comparable to the 'elementary body' of Gervais et al. (2006a) and the 'architectural element' of Terlaky et al. (2016). In outcrop, units of this type predominantly show vertical internal stacking (Prélat et al., 2009; MacDonald et al., 2011), whereas in high-resolution seismic datasets the thickest part of internal bed deposits are seen to show some lateral offset (Gervais et al., 2006a; Deptuck et al., 2008), this discrepancy may be associated with data type limitations. This lateral offset, or 'bed compensation' (~500m, Deptuck et al., 2008), is seen to reflect local changes in gradient, not associated with basin-wide discontinuities. In deposits of the Karoo basin, Prélat et al. (2009) recognised that 'lobe element' units are bounded by thin (<2 cm thick) siltstone intervals, interpreted as a temporary depositional 'shutdown'. MacDonald et al. (2011) further recognise these 'lobe-elements' as the product of a predictable evolutionary cycle, as phases of deposition, amalgamation, bypass and abandonment are interpreted from the facies trends; such cycles mirror the initiation-growth-retreat cycles observed in channel deposits.

At a larger-scale, compensational stacking of depositional units is recognised as a key diagnostic character in the attribution of units termed 'lobe' by Sprague et al. (2005), Prélat et al. (2009), and Terlaky et al. (2016), 'lobe story' by Navarre et al. (2002), 'unit' by Gervais et al. (2006a), and 'composite lobe' by Deptuck et al. (2008) and MacDonald et al. (2011). Genetically related, lower-order architecture (typically the 'lobe elements' as previously described) stack within topographic lows to generate lobate or lenticular geometries. In deposits of the Karoo basin, Prélat et al. (2009) recognised that 'lobe' units are bounded by muddy intervals 0.2-2 m thick. The internal compensational stacking is seen to be a product of local feeder channel avulsion, associated with the upstream single channel that feeds this 'lobe' (Deptuck et al., 2008; Prélat et al., 2009; MacDonald et al., 2011; Terlaky et al., 2016). The understanding of drainage patterns and its avulsion-based hierarchy can thus be used to better inform lobe hierarchy, a property employed by Terlaky et al. (2016). These deposits are also interpreted by Prélat et al. (2009) and Terlaky et al. (2016) to mark the transition from autogenic- to allogenic-dominant depositional controls – although the precise effects of such controls are not specified.

Typically, the largest hierarchical orders identified in distributary environments are characterised by the occurrence of compensational stacking of genetically related 'lobes'. Units of this type are consistently termed as 'lobe complexes' (Gervais et al., 2006a, Deptuck et al., 2008, Prélat et al., 2009; Terlaky et al., 2016). In deposits of the Karoo basin, Prélat et al. (2009) recognised that these units are separated by basin-wide claystone intervals that are >50 cm thick (Prélat et al., 2009). The 'lobe complex' deposits of these authors are interpreted as being deposited from a single major channel system, whereby internal breaks in sedimentation and compensational stacking styles result from large-scale channel avulsions (Gervais et al., 2006a; Deptuck et al., 2008; Terlaky et al., 2016). These avulsions are more significant and occur further upstream in channel-levee systems than those experienced at lower hierarchical orders (Terlaky et al., 2016). The more significant clayey intervals or top bounding surfaces that mantle architectures of this scale are seen to be driven by widespread basin starvation, controlled by allogenic forcing, e.g., relative sea-level change (Prélat et al., 2009). As a consequence of the stacking and position of the internal 'lobe' units, Prélat et al. (2009) recognise phases of growth to be expressed in units of this type (lobe complex 'initiation', 'growth', 'building' and 'retreat'; cf. Hodgson et al., 2006).

Notes on the application of an observation-based genetic hierarchy

While commonalities can be found between hierarchical schemes based upon sedimentological descriptions and their interpreted genetic processes, caution in exercising such comparison is necessary. As a general rule, architectural complexity is seen to increase as the scale of deposition increases, with associated difficulties in capturing the architecture of larger bodies. In part these difficulties arises because of the increasingly compound and diachronous nature of deposits at larger scales and in part due to the fact that key observations on which hierarchical orders are defined change with scale. For example, at lower scales, facies characteristics, which are more easily described in outcrop, are heavily relied upon to classify the hierarchy of sedimentary bodies (such as for channelized 'beds' and 'storeys'). At larger scales, the recognition of hierarchy becomes more reliant upon the geometry of deposits ('channels' or 'lobe elements'), and their stacking patterns ('channel complexes', 'lobes' and 'lobe complexes'). Such differences explain the difficulties in reconciling hierarchical schemes for seismic and outcrop datasets, compounded by the fact that the recognition of larger hierarchical orders often depends on recognising the nature of lower-scale internal bodies. Where lower orders cannot readily be identified (e.g., in seismic datasets or in coarse amalgamated deposits; cf. Ghosh & Lowe, 1993) uncertainty may cascade upward through the hierarchical classification, affecting the confidence with which larger orders can be recognised and interpreted.

A genetic hierarchy would ideally relate deposits to processes that are exclusive to specific scales. In practice, however, it is not possible to confidently relate observations in the rock record to specific suites of genetic mechanisms, i.e., the possible four-dimensional expressions of all plausible combinations of depositional and erosional mechanisms cannot be reconciled. Application of a genetic hierarchy is also impeded by uncertainty in process interpretations deriving from difficulties in discriminating the effects of autogenic dynamics and allogenic controls. While allogenic controls (e.g., regional basin tectonics, eustatic sea-level changes, rate and calibre of sediment supply) are widely recognised to affect sedimentary architectures (Stow et al., 1996), their expression and degree of interaction cannot be confidently recognised in a way that enables ties to scales of depositional architecture (McHargue et al., 2011). Hence, links between hierarchical orders and allogenic or autogenic controls are often speculative (e.g., short-term and long-term relative sea-level changes; Mutti & Normark, 1987; 1991) or based on considerations on the physical scale at which processes are excepted to occur (e.g., the 'bed-compensation' order of Deptuck et al., 2008, which is interpreted as the product of an autogenic mechanism due to the local extent of discontinuities).

Cycles of 'initiation, growth and retreat' are commonly identified in all channelized hierarchical orders (excluding 'beds'). Similar cyclical evolutionary patterns of deposition have also been identified for depositional-lobe deposits (*sensu* Mutti & Normark, 1987; 1991), (e.g., Hodgson et al., 2006; Prélat et al., 2009; MacDonald et al., 2011), as well as for complete depositional systems (cf. 'fan cycles' of Hadler-Jacobsen et al., 2005). Such commonalities suggest that some degree of common hierarchical organisation can be recognised within deep-marine systems. However, the fact that these depositional processes occur over a range of scales limits their value as a criterion for proposing a 'genetic' hierarchy, or as the basis for confident translations between hierarchical orders in different schemes.

3.6 Spatial and temporal scales of hierarchical orders

The temporal and spatial expression of hierarchical scales is often described, at least tentatively, by the authors of the schemes.

Relationships between hierarchical orders and physical scale are proposed for the majority of hierarchical schemes in the form of dimensional parameters that describe the size of the deposits (see Figs. 21 and 22), for sedimentary bodies at all or some of the hierarchical orders in the schemes. Ranges in width and thickness are presented in Figs. 21 and 22 respectively. The data have been derived from the publications where the schemes were presented, and represent: (i) values that were stated as representative of the particular hierarchical order, (ii) scales depicted graphically in synthetic summary models, (iii) values relating to case-study examples referred in the original paper. As far as it can be ascertained, width values reflect 'true' measurements (*sensu* Geehan & Underwood, 1993), whereby a width measurement is taken perpendicular to the modal palaeoflow direction of the deposit. Discrepancies exist between some studies regarding the importance of deposit dimensions as a criterion in hierarchical classifications. For instance, Pickering et al. (1995) state that the characterisation of an architectural geometry does not need to be dependent upon scale; rather, in their view, scale is implicit in the ordering of bounding surfaces, which denote 'relative' scalar relationships.

System controls (e.g., tectonic setting, dominant grain size) affect the magnitude of deep-marine depositional processes and thus their architectural expressions (Richards et al., 1998; Weimer & Slatt, 2007). This phenomenon hinders the use of absolute scale as a universal criterion to determine hierarchy in deep-marine systems; indeed, overlaps between hierarchical order dimensions can be found within single system datasets, e.g., most notable in Gardner & Borer (2000); Prather et al. (2000); Gardner et al. (2003) and Gervais et al. (2006a). Nonetheless, some general associations between hierarchical orders and dimensions of sedimentary units can be found for selected environmental settings or types of deposits (e.g., channels vs. lobes). For example, in channel environments, sub-channel 'storeys' *sensu* Sprague et al. (2002; 2005) and broadly equivalent deposits (see Section 3.5) usually range in thickness from 1 to 15 m fairly consistently across the different schemes. However, further research is warranted to assess the extent to which geological controls influence the geometrical expression of any recognised hierarchy. For example, Prélat et al. (2010; cf. Zhang et al., 2017) test the effects of topographic confinement on the size of lobe deposits across six depositional systems, identifying areally smaller but thicker deposits within topographically confined systems.

Temporal scale can also be used to define hierarchy. Some studies provide timescales for some or all of their hierarchical orders (Fig. 23), usually to allow comparison to sequence stratigraphic orders (Mutti & Normark, 1987; Navarre et al., 2002; Hadler-Jacobsen et al., 2005; Mayall et al., 2006). The temporal expression of hierarchical orders in selected schemes is shown in Fig. 23. The data have been derived from the publications where the schemes were presented, and represent: i) data ranges based on chronostratigraphic constraints (e.g., Navarre et al., 2002) or radiometric dating (e.g., Deptuck et al., 2008), ii) inferred temporal magnitude, estimated either on the basis of known relationships between sedimentation rates and timescales (Sadler, 1981; cf. Ghosh & Lowe, 1993) or by reference to the presumed temporal significance of sequence-stratigraphic orders (Vail et al., 1977; Mitchum & Van Wagoner, 1991).

Correspondences between hierarchical orders can be seen across the schemes on the basis of their timescales, largely through interpretations of their equivalence to sequence stratigraphic scales. For example, Mitchum & Van Wagoner (1991) suggest that 3rd-order depositional sequences should be recognisable in deep-marine successions through the recognition of bounding surfaces and condensed sections. Units of this type, interpreted to embody a time span of 1-2 Myr, can be compared to the '3rd order' units of Hadler-Jacobsen et al. (2005) and Mayall et al. (2006), and to the 'depositional sequence' of Navarre et al. (2002) (Fig. 23). The 'turbidite complex' of Mutti & Normark (1987), and the comparable 'sixth order' unit of Ghosh & Lowe (1993), are interpreted as containing multiple depositional sequences. The ability to link hierarchy in stratigraphic architecture to traditional sequence stratigraphic timescales is, however, a questionable approach for assigning temporal significance to deep-marine deposits. Identification of sequence stratigraphic units in deep-marine successions is challenging (Catuneanu et al., 2011), largely due to difficulties in correlating time-equivalent packages across linked depositional systems and recognising the expression of surfaces with sequence stratigraphic significance. It is notable that significant discrepancies can be found in the study of Hadler-Jacobsen et al. (2005) between the inferred duration of the deposits and the timescale that is expected for the same orders in the scheme based on how units map onto the sequence stratigraphic framework.

The relative scarcity of radiometric ages for deep-marine deposits makes inferences of timescale challenging, particularly since extrapolation of durations to lower scales cannot be attempted based on limited constraints, since the average duration of hiatuses increases with the timescale (Sadler, 1981). Necessarily, the inherent incompleteness of the geological rock record must be taken into account in the classification of hierarchy. Findings in a range of marine and non-marine clastic environments highlight the fractal organisation in which time is recorded in their preserved stratigraphy, in relation to the dependency on timescale of sedimentation rates and durations of depositional gaps (Sadler, 1981, 1999; cf. Miall 2015, 2016). The identification of common cyclical processes in deep-marine environments, i.e., cycles of initiation, growth and retreat, could be used to suggest that a similar fractal organisation might exist in the stratigraphic architecture of deep-marine systems, at least over a certain range of scales. The idea that fractal modes of organisation might permeate aspects of sedimentary architectures has been probed by several authors (Thorne, 1995; Schlager, 2004; 2010; Catuneanu et al., 2011; Straub & Pyles, 2012; among others). Whether fractal patterns exist in the geometry of certain deep-marine deposits in relation to the scale-invariance of certain processes is a subject that deserves further investigation.

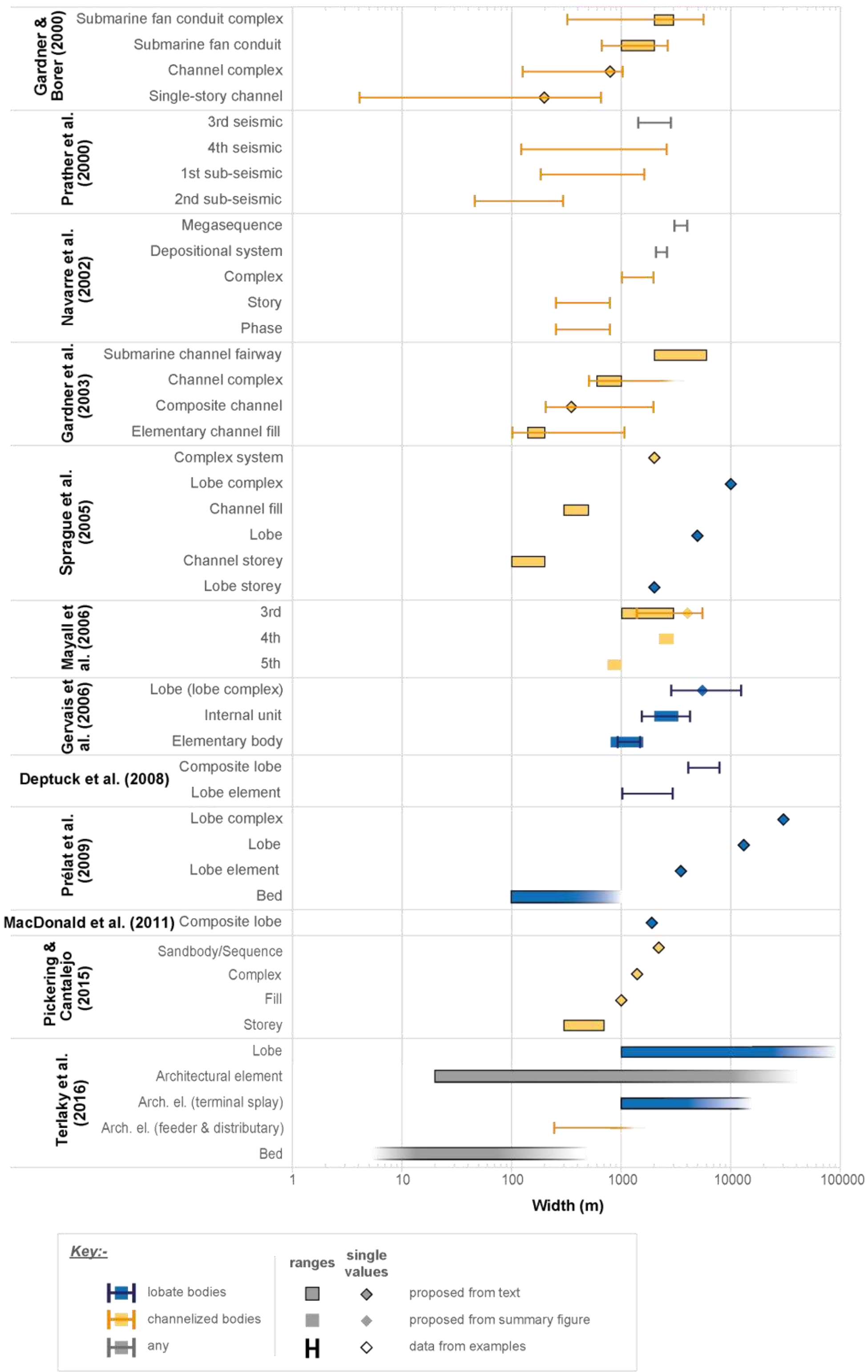

Fig. 21 - Element widths for specific hierarchical orders, taken from the original studies. Ranges (lines and bars) or single values (diamonds) have been sourced from the text (black outline), measured from summary figures (no outline) or represent data from examples shown in the paper (lines empty diamonds). Maximum widths, measured orthogonal to the dip or palaeoflow direction of the unit were recorded when possible. Colours denote the type of elements the ranges refer to (blue: lobe deposits; orange: channel deposits; grey: lobe and channel, other or unspecified deposits). Uncertainty on ranges is represented by faded lines and bars.

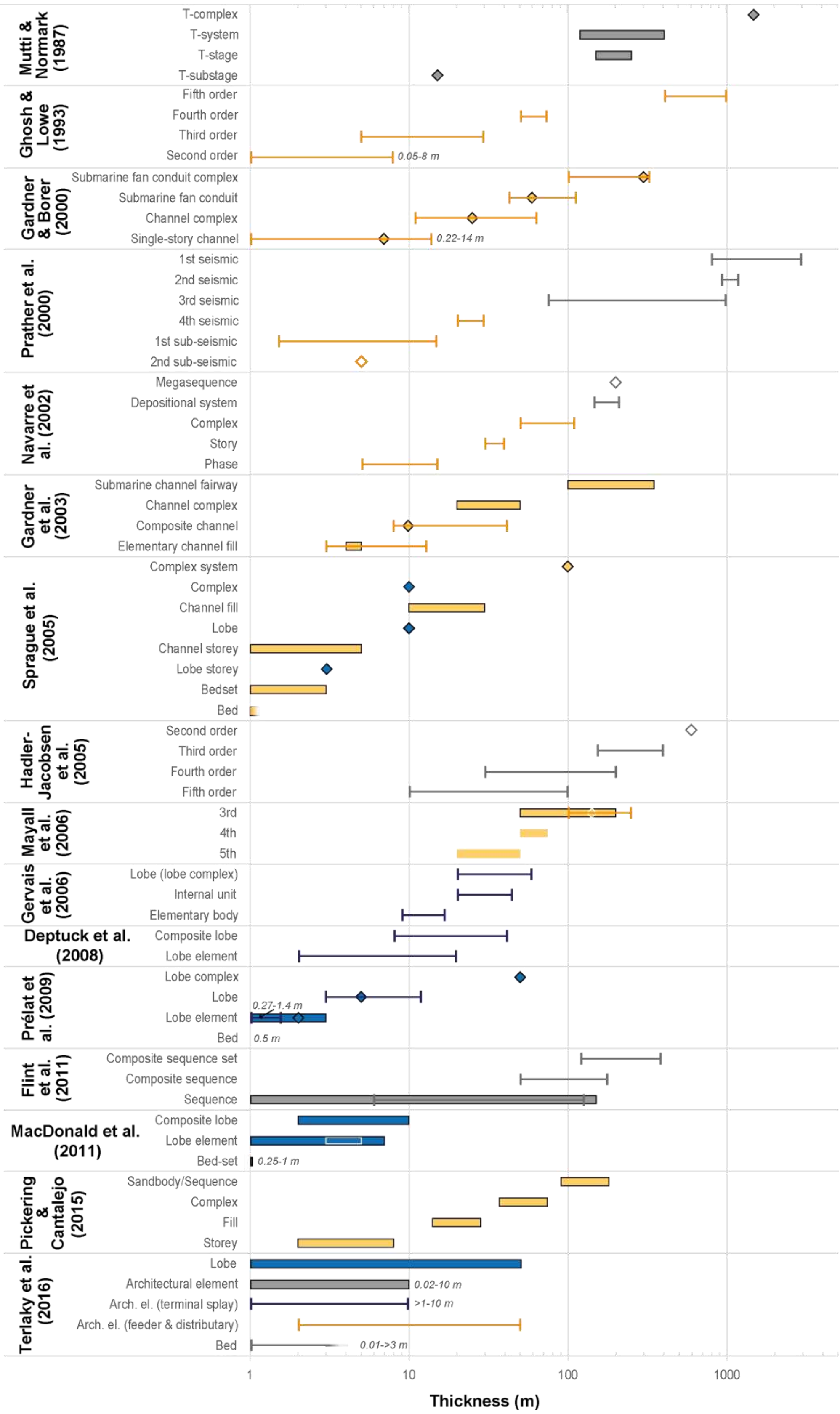

Fig. 22 - Element thicknesses for specific hierarchical orders, taken from the original studies. Ranges (lines and bars) or single values (diamonds) have been sourced from the text (black outline), measured from summary figures (no or white outline) or represent data from examples shown in the paper (lines or empty diamonds). Maximum thicknesses were recorded where possible. Colours

denote the type of elements the ranges refer to (blue: lobe deposits; orange: channel deposits; grey: lobe and channel, other or unspecified deposits). Uncertainty on ranges is represented by faded lines and bars. See key in Fig. 21.

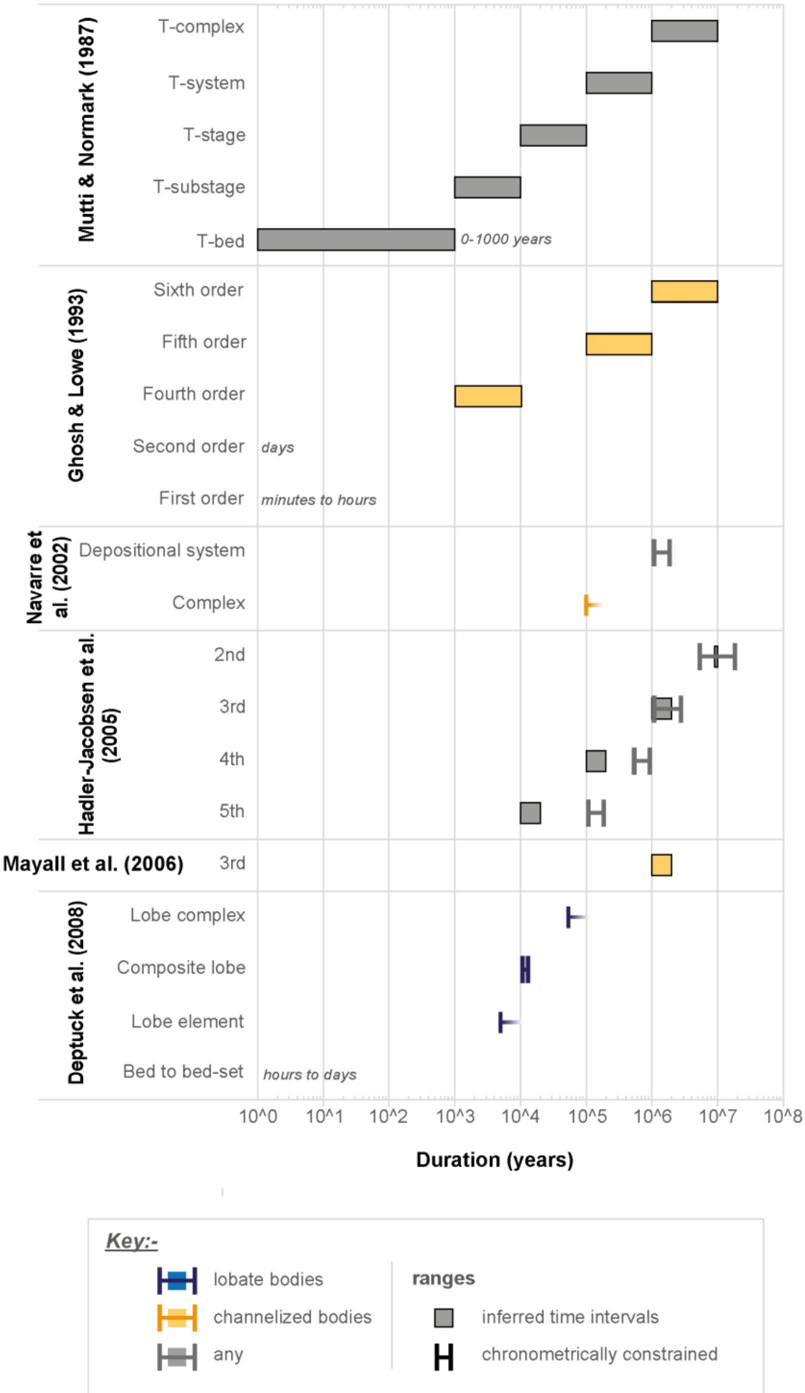

Fig. 23 - Compilation of documented durations for hierarchical orders, taken from those hierarchical schemes within the review that apply them. Ranges are based on each respective study, as either proposed ranges in inferred durations (bars) or as ranges in estimated durations based on available temporal constraints (lines), both as reported by the authors of the scheme. Uncertainties on minimum and maximum values are shown as fading bars and open-ended lines. Bar colour denotes the type of elements the ranges refer to (blue: lobe deposits; orange: channel deposits; grey: lobe and/or channel deposits, other deep-marine or unspecified deposits).

4 Conclusions

The widespread use of hierarchical classifications has helped make the complexity of deep-marine stratigraphy more tractable. However, many different hierarchical classification schemes have been devised to describe deep-marine sedimentary architecture, with new ones often being devised for new case studies, regardless of whether the aims of the study and the types of deposits being examined were comparable to those of previous investigations. This work, for the first time, has systematically reviewed and compared a representative selection of the most widely adopted deep-marine hierarchy schemes. By reviewing the principal characteristics of each hierarchical classification (i.e., the study aims, data types and scope) and the common diagnostic criteria used to attribute deposits to given hierarchical orders, the causes of similarity and variability between different schemes can be assessed. This review can therefore be used to aid sedimentologists who wish to classify a deep-marine system using an existing classification scheme, or who wish to compare their results, fully or partly, to those described using other classifications.

Notwithstanding the observed variety in hierarchical schemes, recurrent sets of observations are seen to underlie all the classification approaches detailed in this review. To define each hierarchical order these approaches commonly entail the recognition of lithological properties (notably facies associations) and architectural geometries, along with the recognition of bounding-surface characteristics and inter-surface relationships. Different classification approaches also apparently share similar genetic interpretations - derived from the sets of common sedimentological features - although this theme deserves further work. Such commonalities of approach may be used as a basis to justify a best-practice methodology for the description of the hierarchy of deep-marine clastic sedimentary architecture. Thus, it is recommended that hierarchical relationships be categorised on the basis of primary sedimentological observations (e.g., facies association, cross-cutting relationships, unconformities, and relative containment of sedimentary units within higher-scale bodies), rather than through predefined schemes developed for particular contexts and whose application entails interpretation.

The recognition of similar criteria for hierarchical classification supports the idea that at least some degree of hierarchical organisation in deep-marine depositional systems does occur. Nonetheless, it remains difficult to reconcile the different hierarchical schemes. Such difficulties arise in part from differences between the underlying studies (e.g., data types, scales of interest, specific environmental settings) and in the significance given to the diagnostic criteria, as well as from the adoption of non-standard terminology. Different numbers of hierarchical orders are commonly recognised for units in different sub-environments (such as channels *vs.* lobes), and furthermore, it remains unclear whether a particular hierarchal level in one sub-environment necessarily corresponds to the same level in another from a process standpoint. Such inconsistencies reflect an understudied problem in the erection of system-wide hierarchies. In the current state of knowledge, it is therefore concluded that a universal, process-based hierarchy, applicable to all data-types and across all deep-marine clastic systems cannot be established; the Rosetta stone remains elusive.

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