Earth-Science Reviews 201 (2020) 103062

Contents lists available at ScienceDirect

Earth-Science Reviews

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

On the geological significance of clastic parasequences

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ARTICLE INFO

Keywords:
Sequence stratigraphy
Shallow marine
Shoreface
Delta lobe
Sea level
Autogenic

ABSTRACT

Parasequences recognized in clastic sedimentary successions of shallow-marine origin are considered by some geologists to be the fundamental building blocks of depositional sequences, even though problems in their definition and application have been identified by others, who instead advocate their abandonment as formal sequence stratigraphic units.

To elucidate the geological significance of clastic parasequences and inform the debate on their use in stratigraphy, a quantitative characterization of the geometry, facies characteristics and timescale of deposition of 1163 parasequences has been undertaken based on a synthesis of data from outcrop and subsurface studies that are available in the scientific literature. Through a database compilation, the attributes of the studied parasequences are analysed with respect to the interpreted geological origin of the units, and with consideration of sources of bias and uncertainty.

Particular emphasis is placed on assessing the following: (i) the importance of heuristics, and of data types and coverage in the recognition of parasequences; (ii) differences in parasequence characteristics observed across deltaic and shoreface depositional systems, and between the Quaternary and the ancient rock record; (iii) possible explanations for the range in timescales of deposition of parasequences; and (iv) the role of autogenic dynamics on the development of deltaic parasequences, partly based on a comparison with the recent evolution of modern deltas.

The results demonstrate that parasequence definition and physical correlation suffer from subjectivity, and that significant variability exists in the spatio-temporal and architectural attributes of clastic parasequences. This gives rise to uncertainty that affects the use of parasequences as a framework for comparison of the architecture of packages of strata originating via shoreline regression: this uncertainty must be considered when using analogue data for subsurface predictions or when attempting comparative studies of clastic successions.

1. Introduction

The term parasequence, introduced in the 1980s (Van Wagoner, 1985), refers to “a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces and their correlative surfaces”, where a flooding surface is a surface “across which there is evidence of an abrupt increase in water depth”, commonly marked by non-Waltherian facies shifts (Van Wagoner et al., 1988, 1990). This definition applies to marine and lacustrine strata alike (Kamola and Van Wagoner, 1995).

Together with flooding surfaces, internal facies characteristics that testify to a regressive trend are taken as defining attributes of parasequences, and these are used to subdivide clastic successions accordingly. The vertical lithofacies succession within a single parasequence records conditions of progressive upward shallowing (i.e., shoaling), whose expression varies depending on location (e.g., relatively more landward or offshore) and depositional context (e.g., shoreface, tidal flat, deltaic settings). Parasequences are most commonly recognized in successions of shallow-water and paralic strata, where they typically exhibit a generally coarsening-upward Waltherian (Walther, 1894) profile from offshore to littoral deposits, or a generally fining-upward profile from subtidal to supratidal deposits (Van Wagoner et al., 1988, 1990). Parasequences are also recognized in some mud-dominated shelf deposits, when these are carefully examined (cf. Bohacs et al., 2014; Li and Schieber, 2019). However, the definition of a parasequence renders these units virtually unrecognizable in continental fluvial and aeolian successions, except where deposits may be correlated to time-equivalent nearshore stratal packages (Shanley and McCabe, 1994; Posamentier and Allen, 1999). Where observable, internal architectural features that are indicative of shoreline progradation (e.g., stratal terminations, clinoforms; cf. Lobo et al., 2001; Hampson et al., 2008), or ichnological evidence of bathymetric change or rapid flooding events

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https://doi.org/10.1016/j.earscirev.2019.103062
Received 1 October 2019; Received in revised form 4 December 2019; Accepted 10 December 2019
Available online 14 December 2019

(e.g., MacEachern and Pemberton, 1997; Sadeque et al., 2009), are also considered for the segmentation of clastic successions in parasequences.

Parasequences are of prime importance for sequence-stratigraphic practice. Groups of parasequences are commonly arranged into 'parasequence sets'. These sets are classified according to stacking patterns that can be 'progradational', 'aggradational' or 'retrogradational', depending on the overall direction and degree of progressive seaward or landward dislocation of stratal packages of the same general origin across parasequences in each set. These stratal patterns develop in response to the interplay between the rates of creation of accommodation and sediment supply (Van Wagoner et al., 1988). In sequence stratigraphy, the stacking pattern of parasequences is a key diagnostic attribute for the classification of systems tracts (i.e., the preserved record of linked depositional systems associated with a given relative sea-level state; Posamentier et al., 1988; Catuneanu et al., 2009), and for the placement of boundaries between other types of sequence-stratigraphic units, such as 'genetic stratigraphic sequences' (Galloway, 1989; cf. Frazier, 1974) or 'accommodation successions' (Neal and Abreu, 2009; Neal et al., 2016).

As originally conceived, parasequences should represent the preserved expression of changes in the balance between sediment supply and relative sea-level change, occurring in a manner comparable to that experienced by depositional systems through a paracycle (*sensu* Vail et al., 1977): in accord with the nature of paracycles, parasequences should not bear evidence of relative sea-level fall (Kamola and Van Wagoner, 1995). Allogenic factors (eustasy, climate and tectonics) are commonly invoked as forcing mechanisms that cause successions to be organized into parasequences, through their controls on accommodation generation and sediment supply (Brenchley et al., 1993; Kamola and Van Wagoner, 1995; Storms and Swift, 2003; Catuneanu and Zecchin, 2013; Hampson, 2016). However, it is also argued that in some cases parasequences represent units whose development may result from, or be influenced by, autogenic mechanisms. In particular, it is thought that parasequence tops may record local autogenic flooding, associated with avulsion of coastal-plain distributaries and delta-lobe abandonment (e.g., Mitchum Jr and Van Wagoner, 1991; Kosters and Suter, 1993; Kamola and Van Wagoner, 1995; Emery and Myers, 1996; Posamentier and Allen, 1999). Moreover, parasequence development might also be influenced by intrinsic shoreline dynamics related to temporal variations in sediment-storage capacity across the dip profile of a delta (cf. Muto and Steel, 1997). Although it is clear that both autogenic and allogenic factors may play a role in governing the formation of parasequences, their relative dominance still needs to be elucidated.

Considering that parasequence generation can arise from different genetic processes, and acknowledging that their definition and diagnostic criteria are equivocal, are difficult to apply in practice, and have been used somewhat inconsistently (see discussions in: Posamentier and James, 1993; Arnott, 1995; Kamola and Van Wagoner, 1995; Embry, 2009; Zecchin, 2010; Catuneanu, 2019a, 2019b), it is likely that the term has been applied to units that are fundamentally different geologically, in terms of both sedimentological character and origin. This consideration, compounded with the dubious utility of parasequences for scopes of stratigraphic correlation, has led some authors to suggest discontinuing the usage of the parasequence concept and terminology (Embry et al., 2007; Zecchin, 2010; Miall, 2016; Catuneanu, 2019a, 2019b). However, the usefulness of parasequences as operative units in outcrop studies and as descriptors of heterogeneity in the characterization of the subsurface has been advocated by others (cf. Hampson et al., 2008; Vakarelov and Bhattacharya, 2009; Ainsworth et al., 2018, 2019).

To establish whether the parasequence has still some use as a paradigm for stratigraphic practice in research and industry, it is desirable to consider the degree to which units that are termed parasequences in different contexts are comparable and thereby serve as analogues to each other. A compound analysis of many instances of the application of parasequences can offer insight into their significance and usefulness.

This work aims to assess the geological significance and practical value of shallow-water parasequences in clastic successions, through a quantitative analysis of their characteristics in a wide range of studies. Specific objectives are as follows: (i) to determine the importance of biases and uncertainty in the definition of parasequences; (ii) to quantify differences in parasequence characteristics with respect to their origin and geological boundary conditions (e.g., deltaic *vs* shoreface systems, Mesozoic greenhouse *vs* Quaternary icehouse sea-level behaviours), including their temporal significance and the time-scale dependency of their properties; (iii) to assess the role of autogenic dynamics on deltaic-parasequence development; (iv) to consider scales at which stratigraphic compartmentalization is captured in subsurface studies of shallow-marine siliciclastic aquifers and hydrocarbon reservoirs.

We present results of quantitative analyses of parasequence characteristics with some interpretations, and then discuss the implication of these findings for their use in stratigraphic studies. What we do not treat in this paper is the role of accommodation and sediment supply in determining parasequence architectures. This is an important subject, because it relates to the use of parasequences for subsurface prediction and for interpretation of the rock record, but is beyond the scope of this paper and requires a comprehensive analysis that is best discussed separately. This is the subject of ongoing work.

2. Data and methods

This work is based on a synthesis of sedimentological and stratigraphic data from many published case studies. The data were collated from published sources and unpublished dissertations, and were stored following a defined standard in a SQL relational database, the Shallow-Marine Architecture Knowledge Store (SMAKS; Colombera et al., 2016). SMAKS stores data on sedimentary units of different types, for shallow-water and paralic depositional systems, and on the depositional context, geological boundary conditions, and metadata of each dataset and system.

64 case studies detailing 1163 parasequences were considered in total for the analyses presented in this work, as summarized in Table 1. A SMAKS case study is made of one or more datasets on a depositional system, as presented in a given published source or set of related publications. Different datasets are merged in the same case study if they were intended to be complementary by the original authors. The data were extracted from 132 literature sources (Table 1).

Units that are termed 'parasequences' by the original authors and that have been defined in a way that aligns with the definition of Van Wagoner et al. (1990) are coded in SMAKS following the interpretations provided in the original literature sources. No attempt has been made to define flooding surfaces, parasequences or other types of sequence stratigraphic units, based on reinterpretation of the original datasets; this means that only publications that postdate the coining of the term 'parasequence' have been considered. Whenever the attribution of parts of a succession to parasequences in a dataset released over multiple publications vary across the published sources, more recent interpretations are favoured over older ones (cf. Simpson and Eriksson, 1990 *vs* Eriksson et al., 2019; Holgate et al., 2013 *vs* Holgate et al., 2015). Although new interpretations are not imposed on a dataset, original interpretations are discarded if they contrast with definitions that form the database standard; so, for example, stratigraphic units originally termed 'parasequences' but recognized to record shallowing-deepening cycles (cf. Bowman, 2003) or displaying deepening-upward trends (cf. Blondel et al., 1993) are not considered in the subsequent analyses.

In SMAKS several attributes are used to describe clastic parasequences (Fig. 1), including alternative genetic classifications of their deposits.

The parasequences are classified on the interpreted type of

Table 1
Summary of the 64 SMAKS (Colombera et al., 2016) case studies of sequence stratigraphic interpretations considered in this work.

Succession	Location	Age	Data types	N	Sources
Battfjellet Formation	Spitsbergen, Norway	Eocene	Outcrop	15	Gjelberg (2010), Helland-Hansen (2010)
Bell Island Group	Newfoundland, Canada	Lower Ordovician	Outcrop	8	Brenchley et al. (1993)
Blackhawk Formation	Utah, USA	Upper Cretaceous	Outcrop	38	Reynolds (1999), data from: Balsley (1983), Taylor and Lovell (1992), Van Wagoner (1992), O'Byrne and Flint (1993)
Bouzergoun Formation	Morocco	Lower Cretaceous	Outcrop	3	Nouidar and Chellaï (2002)
Cliff House Sandstone	New Mexico, USA	Upper Cretaceous	Outcrop	12	Jordan et al. (2016)
Ferron Sandstone 'Last Chance Delta'	Utah, USA	Upper Cretaceous	Outcrop	44	Garrison Jr. and van den Bergh (2004), van den Bergh and Garrison Jr. (2004)
Ferron Sandstone 'Notom Delta'	Utah, USA	Upper Cretaceous	Outcrop	43	Li et al. (2010, 2011a, 2011b, 2012), Zhu et al. (2012)
Foreknobs Formation	Virginia/West Virginia, USA	Upper Devonian	Outcrop	51	McClung et al. (2013, 2016), Eriksson et al. (2019)
Frontier Formation	Wyoming, USA	Upper Cretaceous	Outcrop	11	Feldman et al. (2014)
Gallup Formation	New Mexico, USA	Upper Cretaceous	Outcrop	61	Lin et al. (2019)
Gelincik Formation	Turkey	Miocene	Outcrop	34	Ilgar (2015)
Gros Morne Formation	Trinidad	Pliocene	Outcrop	13	Bowman (2003)
Hosta Tongue	New Mexico, USA	Upper Cretaceous	Outcrop	1	Sixsmith et al. (2008)
Jurassic of East Greenland	Greenland	Lower to Upper Jurassic	Outcrop	27	Surlyk (1991), Dam and Surlyk (1995), Larsen and Surlyk (2003), Engkilde and Surlyk (2003), Vosgerau et al. (2004)
Lajas Formation	Argentina	Middle Jurassic	Outcrop	26	McIlroy et al. (2005)
Valimi Formation*	Greece	Pleistocene	Outcrop	37	Ambrosetti et al. (2017)
Mayaro Formation	Trinidad	Pliocene	Outcrop	18	Bowman (2003, 2016), Bowman and Johnson (2014)
Mesaverde Group	Wyoming, USA	Upper Cretaceous	Outcrop	13	Fitzsimmons and Johnson (2000)
Mulichinco Formation	Argentina	Lower Cretaceous	Outcrop	19	Wesolowski et al. (2018)
Neill Klinter Group	Greenland	Lower Jurassic	Outcrop	16	Eide et al. (2016)
Oligocene-Early Miocene of northern Taiwan	Taiwan	Oligocene to Miocene	Outcrop	55	Teng and Tai (1996)
Pilmatué Member, Agrio Formation	Argentina	Lower Cretaceous	Outcrop	17	Isla et al. (2018), Schwarz et al. (2018)
Pliocene of Dacian Basin	Romania	Pliocene	Outcrop	15	Jorissen et al. (2018)
Pliocene of Val d'Orcia Basin	Italy	Pliocene	Outcrop	4	Ghinassi (2007)
Point Lookout Sandstone	Colorado, USA	Upper Cretaceous	Outcrop	16	Crandall (1992), Katzman and Wright-Dunbar (1992), Wright-Dunbar et al. (1992)
Potrerillos Formation of Mexico	Mexico	Paleocene	Outcrop	29	Shelley and Lawton (2005)
Star Point Sandstone	Utah, USA	Upper Cretaceous	Outcrop	5	Hampson et al. (2011)
Straight Cliffs Formation	Utah, USA	Upper Cretaceous	Outcrop	11	McCabe and Shanley (1992)
Uppermost Kubang Pasu Formation	Malaysia	Cisuralian	Outcrop	8	Hassan et al. (2013, 2017)
Yenimahalle Formation*	Turkey	Miocene	Outcrop	18	Ilgar and Nemec (2005)
Battfjellet Formation	Spitsbergen, Norway	Eocene	Outcrop and subsurface	19	Grundvåg et al. (2014)
Blackhawk Formation and Castlegate Sandstone	Utah, USA	Upper Cretaceous	Outcrop and subsurface	29	Hampson and Storms (2003), Hampson and Howell (2005), Hampson et al. (2008), Charvin et al. (2010), Hampson (2010)
Blackhawk Formation and Castlegate Sandstone	Utah/Colorado, USA	Upper Cretaceous	Outcrop and subsurface	29	Pattison (2010, 2018, 2019a, 2019b)
Brejning Formation and Ribe Group	Denmark	Miocene	Outcrop and subsurface	6	Rasmussen et al. (2004), Rasmussen and Dybkjær (2005), Hansen and Rasmussen (2008), Rasmussen (2009)
Cozzette Sandstone	Utah/Colorado, USA	Upper Cretaceous	Outcrop and subsurface	6	Madof et al. (2015, 2016)
Emery Sandstone	Utah, USA	Upper Cretaceous	Outcrop and subsurface	17	Edwards et al. (2005)
Fox Hills Formation	Wyoming, USA	Upper Cretaceous	Outcrop and subsurface	16	Carvajal and Steel (2009), Olariu et al. (2012)
Frontier Formation	Utah/Colorado/Wyoming, USA	Upper Cretaceous	Outcrop and subsurface	9	Hutsky et al. (2016), Hutsky and Fielding (2016, 2017)
Mesaverde Group	Wyoming, USA	Upper Cretaceous	Outcrop and subsurface	23	Klug (1993)
Muskiki and Marshybank formations	Alberta, Canada	Upper Cretaceous	Outcrop and subsurface	15	Plint (1990, 1991), Plint and Norris (1991)
Point Lookout Sandstone	New Mexico, USA	Upper Cretaceous	Outcrop and subsurface	11	Devine (1991)
Quaternary of Paraná coastal plain	Brazil	Pleistocene to Holocene	Outcrop and subsurface	2	Angulo et al. (2009), Souza et al. (2012), Berton et al. (2019)
Rio Bonito and Palermo formations	Brazil	Cisuralian	Outcrop and subsurface	9	Holz (2003), Ketzer et al. (2003), Holz and Kalkreuth (2004), Holz et al. (2006)
Second Frontier sandstone, Frontier Formation	Wyoming, USA	Upper Cretaceous	Outcrop and subsurface	7	Vakarelov and Bhattacharya (2009)
Upper Almond Formation	Wyoming, USA	Upper Cretaceous	Outcrop and subsurface	21	Merletti et al. (2018)
Upper Sego Sandstone and Iles Formation	Colorado, USA	Upper Cretaceous	Outcrop and subsurface	24	Kirschbaum and Hettinger (2004), Kirschbaum and Cumella (2015)
Wall Creek Member, Frontier Formation	Wyoming, USA	Upper Cretaceous	Outcrop and subsurface	9	Lee et al. (2005, 2007a, 2007b), Gani and Bhattacharya (2007), Sadeque et al. (2009)
22 Sand of Columbus Basin	Trinidad	Pliocene	Subsurface	18	Bowman (2003)
Arida and Diba formations	Libya	Oligocene	Subsurface	7	Gruenwald (2001)

(*continued on next page*)

Table 1 (*continued*)

Succession	Location	Age	Data types	N	Sources
Barrow Group	Northwest Shelf, Australia	Lower Cretaceous	Subsurface	40	Ainsworth et al. (2018)
Brigadier Formation	Northwest Shelf, Australia	Upper Triassic	Subsurface	16	Ainsworth et al. (2016, 2018)
Calcasieu incised valley	Louisiana, USA	Pleistocene to Holocene	Subsurface	3	Nichol et al. (1996)
Dunvegan Formation	Alberta, Canada	Upper Cretaceous	Subsurface	19	Bhattacharya (1989, 1992), Bhattacharya and Walker (1991a, 1991b), Bhattacharya and MacEachern (2009)
Gulf of Cádiz shelf	Spain	Pleistocene to Holocene	Subsurface	4	Lobo et al. (2001), Gonzalez et al. (2004)
Gulf of Lion, inner shelf and Rhone Delta	France	Pleistocene to Holocene	Subsurface	10	Boyer et al. (2005), Labaune et al. (2005, 2008), Berné et al. (2007), Jouët (2007)
Gulf of Lion, outer shelf	France	Pleistocene	Subsurface	7	Berné et al. (1998), Rabineau et al. (2005), Jouet et al. (2006), Bassetti et al. (2006, 2008)
Hazad Member, Ankleshwar Formation	India	Eocene	Subsurface	21	Jaiswal et al. (2018)
Holocene of the Po Plain	Italy	Holocene	Subsurface	8	Amorosi et al. (2005, 2017), Campo et al. (2017)
Krossfjord and Fensfjord formations	Norway	Middle Jurassic	Subsurface	9	Holgate et al. (2013, 2015), Holgate (2014)
Late Quaternary of Tuscany	Italy	Pleistocene	Subsurface	3	Amorosi et al. (2008, 2013), Rossi et al. (2017)
Lower Parkwood tongue	Mississippi/Alabama, USA	Upper Mississippian	Subsurface	33	Mars and Thomas (1999)
Palaeo-Changjiang delta	China	Pleistocene to Holocene	Subsurface	3	Zhang et al. (2017)
Plover and Laminaria formations	Timor Sea	Middle Jurassic	Subsurface	23	Ainsworth (2005), Ainsworth et al. (2008)
Viking Formation	Alberta, Canada	Lower Cretaceous	Subsurface	19	Boreen and Walker (1991), Pattison (1991, 1992)

A case study is a dataset on a particular succession, by some author(s) or research group, as presented in a published source or Thesis (or in a set of related publications). This table only includes references to literature sources that contain the sequence-stratigraphic interpretations and/or data relating to units reported as parasequences. Asterisks (*) denote lacustrine successions; all other successions are paralic to shallow marine in origin. 'N' indicates the number of parasequences considered in each case study.

formative shoreline, according to two separate schemes, and relying on corresponding original interpretations when made in the same terms. A classification is made of the interpreted depositional environment of parasequences and of their associated shallow-water sandstones. According to this classification, the units are classified as (i) 'deltaic', (ii) 'shoreface' – a term that is here applied *sensu lato* to describe the preserved expression of non-deltaic linear coasts, such as those associated with strandplains or barrier systems – or (iii) as 'deltaic-shoreface' – a term used where both previous types of shoreline-shelf systems are interpreted to have formed the units. These terms are not applied to deposits of uncertain attribution, which are instead left unclassified.

The parasequences are also classified on the interpreted dominant process regime under which they accumulated. This categorization is made on classes that define the interpreted relative importance played by wave, tidal and fluvial processes in shaping parasequences and their shallow-water sands or sandstones. The domain of this attribute includes the 15 discrete categories defined in Ainsworth et al. (2011). For example, 'F' = fluvial dominated; 'Wf' = wave dominated, fluvial influenced; 'Twf' = tide dominated, wave influenced, fluvial affected. Moreover, three more generic categories are used when only the main dominant process is inferred: 'W-' = wave dominated, 'T-' = tide dominated, 'F-' = fluvial dominated, each possibly recording the influence of other processes that themselves remain unspecified.

Qualitative attributes are also used to record the range of subenvironments covered by the observation window over which the parasequence is described, along its dip profile, and the type of vertical facies succession observed at the location where the parasequence thickness is measured. The interpreted subenvironments used to record the down-dip and vertical coverage of a parasequence are classified as 'onshore', 'nearshore', or 'offshore'; the term 'nearshore' refers to subaqueous nearshore environments (e.g., delta front, foreshore/shoreface, barrier-lagoon systems); the term 'offshore' refers to mud-dominated environments that occur offshore of sand-prone shoreface or delta-front environments, and as such does not have a specific bathymetric connotation; the term 'onshore' refers to environments that occur landward of the shoreline and which are mostly subaerial.

Quantitative parameters are used to characterize the spatial and temporal characteristics of each parasequence. These are assigned based on data extracted from the published sources, as derived from text and tables or as measured from figures. These attributes include the thickness of a parasequence, the thickness and downdip length of its shallow-water sand belt, and quantities that track the regressive evolution of the parasequence, consisting of its progradation distance (i.e., the amount of shoreline progradation recorded in the parasequence), its stratigraphic rise (i.e., the amount of aggradation at the shoreline) and the resulting progradation angle (defined as the angle of the direction of progradation of the parasequence relative to a datum that approximates the palaeo-horizontal; i.e., a solely regressive shoreline trajectory; Helland-Hansen and Martinsen, 1996). The temporal significance of the parasequences is recorded in terms of estimated length of time during which they were accumulated (duration) and/or corresponding timescale expressed as order of magnitude; both attributes are assigned based on inferences reported in the original sources. For attributes that specifically relate to the parasequence sand belts, i.e., to facies belts corresponding to littoral or delta-front sands or sandstones, the sand-mud boundaries placed in the original works were considered, even though it is recognized that this transition is typically not sharp. Geometric parameters are classified by observation type, as 'real', 'apparent', 'partial' (when the location of termination of a unit at one end is unknown), or 'unlimited' (when the location of termination of a unit at both ends is unknown; Geehan and Underwood, 1993). No correction has been applied to the thickness of sedimentary units to account for sediment compaction, which can vary significantly across Quaternary and ancient successions.

The total data pool is based on studies that have global distribution, and that are based on outcrop and/or subsurface analyses, and different

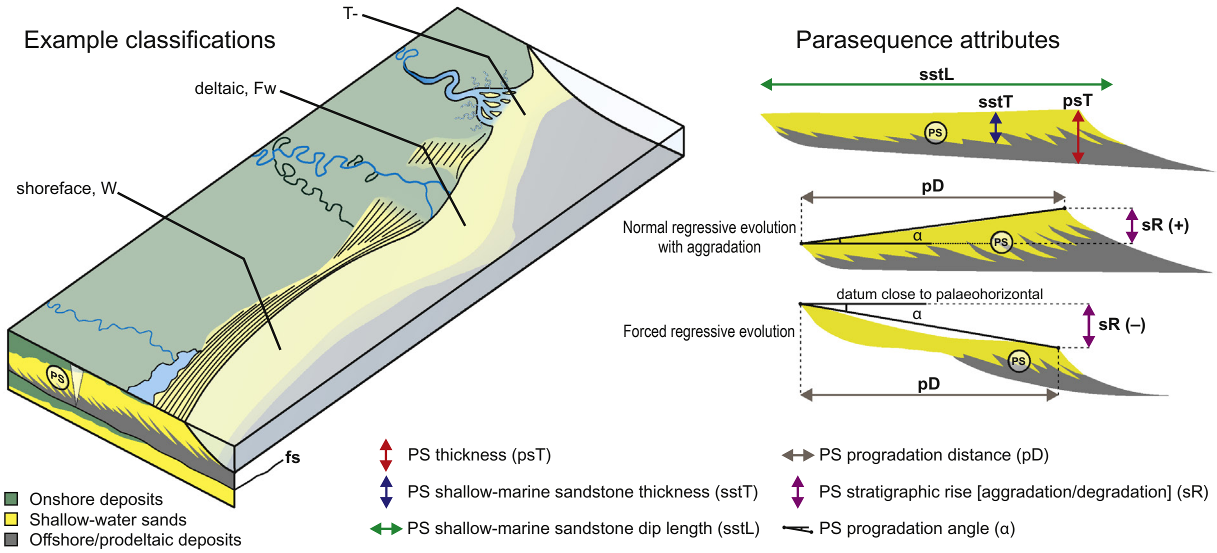

Fig. 1. Definition diagram of parasequence attributes. The diagram illustrates (i) the attributes employed in SMAKS (Colombera et al., 2016) to categorize parasequences, presented in the form of example classifications of the interpreted origin and recorded process dominance of shallow-water parasequence deposits, and (ii) the parameters used to describe the anatomy of parasequences and associated shallow-water sand belts.

combinations of data types (Table 1, Fig. 2). The case studies cover Phanerozoic successions of different ages, but with an evident bias for Upper Cretaceous successions of the Western Interior Seaway of North America, and with limited representation of Paleozoic examples (Table 1, Fig. 2). It must be noted that other datasets on the sedimentology and architecture of clastic parasequences exist in the published literature, and that in this study the coverage of the geological record is not as comprehensive as it would have been had all available data been included: the selection of datasets for inclusion in this study has been made based on their suitability to the problems treated in this article.

In a limited number of cases, the studied parasequences might be composed of mixed siliciclastic–carbonate deposits with a subordinate calcareous component (e.g., Gruenwald, 2001). In two cases, the studied successions were accumulated in lacustrine basins (see Tab. 1).

Statistical analyses of the data were conducted in R 3.5.1 (R Core Team, 2018).

3. Variability and uncertainty in parasequence identification

First, we present a quantitative assessment of factors that affect the recognition of parasequences in stratigraphic successions, and of associated measures that describe the context within which they were recognized. The purpose of this is twofold: to offer a dataset that can inform any discussion of the significance of the parasequence term, and to provide a measure of the biases and uncertainty that are inherent in any tentative comparison of these units across studies and in their application (e.g., to the subsurface).

3.1. Facies successions and observation window

The types of subenvironments recorded in the facies belts of a parasequence (Fig. 3A), both vertically where its maximum observed thickness was recorded and along its depositional dip profile (dip coverage), are expected to reflect different factors, including: (i) the breadth of data coverage, (ii) the ability to correlate across facies belts, (iii) the possible lack of facies belts because of non-preservation (e.g., due to ravinement), (iv) the possible lack of a facies belt because it did not develop as part of the sedimentary unit. An example of this last situation is given by deposits that do not represent full shoaling to subaerial conditions, but rather progradation of facies belts under fully subaqueous conditions and that are physically decoupled from correlative subaerial deposits (e.g., so-called subaqueous deltas; cf. Holgate et al., 2015; Patruno et al., 2015).

Out of the studied 1163 parasequences, the range of subenvironments recorded across the full mapped extent of the units could not be determined in 19% of the cases, the majority of which are from subsurface studies. Most commonly, for 36% of all studied parasequences, offshore to nearshore facies belts are recognized along their dip profile, with no record of onshore deposits (Fig. 3B). The full spectrum of offshore to onshore facies belts was only identified in 20% of all parasequences, and in 25% of those for which subenvironments could be interpreted (Fig. 3B). For parasequences within which subenvironments could be interpreted, the location of maximum observed parasequence thickness occurs most commonly (50% of the cases) where the vertical facies succession is represented by offshore to nearshore deposits and does not include onshore deposits. The same offshore-nearshore vertical facies succession is also the most common for the subset of parasequences with a dip coverage that encompasses onshore to offshore facies belts (43% of these; Fig. 3B), followed by a full offshore-to-onshore shallowing-upward succession (25%; Fig. 3B).

Parasequences that only display onshore deposits where they are thickest, are thicker on average than others with the same facies-belt dip coverage (Fig. 3C). Implicit in this is the recognition that parasequences that show the full offshore-to-onshore coverage are thicker on average in their onshore part, and not where they display sand-prone nearshore deposits. This suggests that the role played by accommodation in controlling preserved parasequence thickness may overwhelm that of sediment compaction. This might in part reflect the nature of accommodation generation in commonly backtilting foreland basins, where the majority (59%) of the studied parasequences have been recognized.

Parasequences that display only nearshore deposits where they are thickest are on average thinner than others with the same dip coverage (Fig. 3C). Implicitly, in cases where the dip coverage is limited to the nearshore facies belt, parasequences are on average thinner than others (mean values: 9.6 m *vs* 15.4 m). This might relate to limited preservation of parasequence deposits associated with transgressive conditions, since 43% of parasequences with dip coverage on nearshore deposits only are contained in retrogradational parasequence sets, against 25% of other parasequences (N = 414). Correspondingly, 36% of parasequences that display a vertical facies succession that

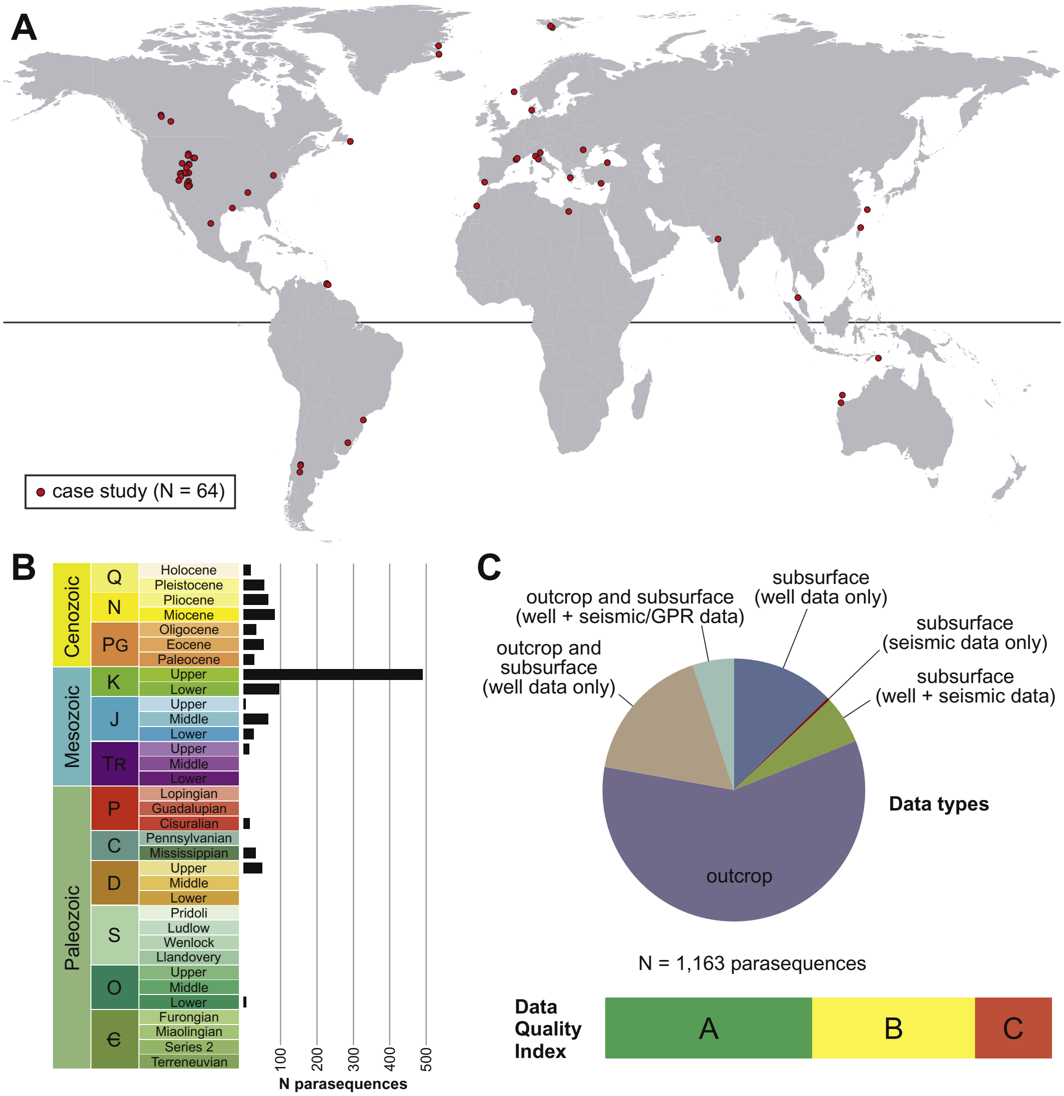

Fig. 2. Summary of case studies on clastic parasequences. A) Geographic distribution of the 64 SMAKS (Colombera et al., 2016) case studies considered in this work (see Table 1). B) Bar chart presenting the distribution of the studied parasequences through geological time, by epoch. C) Summary of data types and quality for the considered case studies. The pie chart reports the relative proportion of parasequences according to the types of observations (or combinations thereof) based on which they have been interpreted. The stacked bar chart at the bottom reports the relative proportion of parasequences according to a 'data quality index', which is a measure of the perceived quality of a dataset and its interpretations, assigned on the basis of dataset type, extent and resolution, and on expert judgement; classes 'C' to 'A' denote datasets of increasing quality (Colombera et al., 2016).

exclusively includes nearshore deposits at their thickest section are contained in transgressive systems tracts, compared to 10% of parasequences with a vertical profile of any other type (N = 288).

Differences in thickness statistics as a function of parasequence dip coverage will in part reflect differences in the extent of the observation windows. Differences in thickness statistics seen in relation to the type of vertical facies succession will also reflect the variable amount of aggradation along depositional dip. Any evaluation and comparison of the geometry of parasequences, including this and previous studies (e.g., Ainsworth et al., 2018, 2019), is affected by this variability, i.e., by uncertainty regarding the representativeness of local observations.

3.2. Parasequence recognition in different data types

In subsurface datasets, the physical correlation of sub-seismic parasequences and bounding surfaces is necessarily uncertain, and can therefore result in a number of equally acceptable reconstructions that vary with respect to parasequence numbers and geometries (Burton and Walker, 1999; Bhattacharya, 2011). We can assess the impact of this uncertainty on resulting parasequence interpretations by comparison with data from outcropping successions. The studied parasequences were originally recognized in outcrop and/or subsurface datasets, the latter including different combinations of data from wells (cores, cuttings, wireline logs – including image logs), reflection-seismic surveys (of different vintages, and including high-resolution shallow acquisitions) and ground-penetrating radar (Fig. 2C). For purposes of analysis, the datasets were grouped into three classes, based on whether the underlying data are from outcrop only, from the subsurface only, or from a combination of outcrop and subsurface observations (Table 1).

Across these three groups, we analysed variations in the distributions of the thickness of parasequences and of the thickness and dip length of the associated shallow-water sands or sandstones (Fig. 4). Parasequences recognized in subsurface studies are, on average, thicker than those recognized in outcrop (mean values: 19.0 m *vs* 13.6 m, N = 1064; Fig. 4A), to a degree that is statically significant (two-sample t-test: T = −5.32, d.f. = 367, p-value < 0.001). When interpreted in subsurface studies, parasequence components composed of sand belts of shallow-water origin are, on average, thinner than those identified in

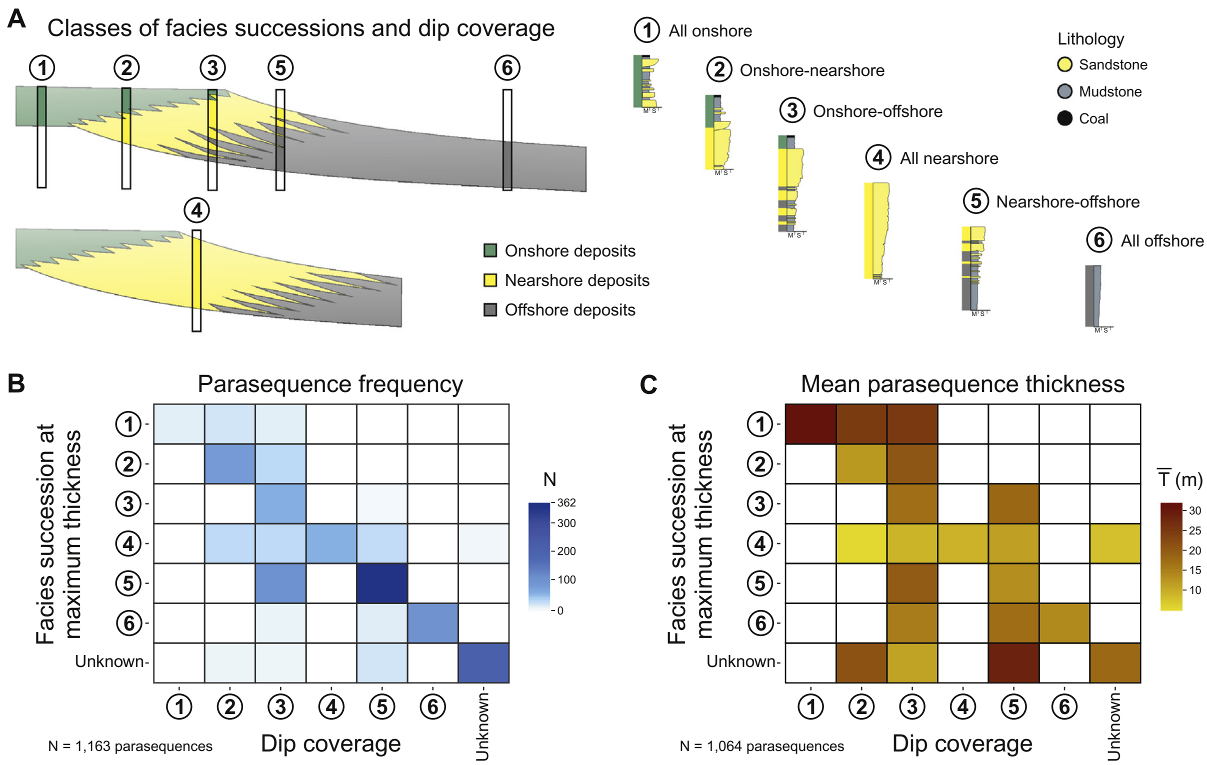

Fig. 3. Characteristics of parasequences by vertical facies successions and down-dip coverage of depositional environments. A) Diagram that illustrates the facies-tract categories used to classify (i) one-dimensional facies successions at the location where the largest value of parasequence thickness is observed, with idealized vertical sections represented for each, and (ii) the range of depositional environments that are covered by the parasequence along its dip-oriented observation window. B) Heat map that shows proportions of parasequences as a function of the type of vertical facies successions seen where the parasequence appears thickest and the range of depositional environments recorded along the dip profile of the parasequence (dip coverage). C) Heat map that shows the average thickness of parasequences as a function of the type of vertical facies successions seen where the parasequence appears thickest and the range of depositional environments recorded along the dip profile of the parasequence (dip coverage). These data are based on 1064 parasequences whose full thickness is recorded. Thickness values on which the means are computed include apparent values (e.g., from well data).

outcrop (mean values: 7.8 m *vs* 10.0 m, N = 647; Fig. 4B; two-sample t-test: T = 2.99, d.f. = 254, p-value = 0.003), presumably because of the number of apparent observations from well data, but also significantly longer on average along their dip extent (mean values: 39.7 km *vs* 11.2 km, N = 488; Fig. 4C; two-sample t-test: T = −5.46, d.f. = 56, p-value < 0.001). The dip length of parasequence sand belts seen in subsurface studies is larger, on average, than that of outcropping parasequences even in cases where the full dip extent of the units can be mapped (Fig. 4D), suggesting that this difference is likely to reflect the effect of over-correlation, rather than that of a larger observation window, in subsurface datasets.

These results suggest that, as might be expected, the amalgamation of regressive units is under-recognized in subsurface studies. More specifically, data on parasequence sand belts suggest that parasequence identification might be rendered particularly difficult by amalgamation through dominantly lateral stacking, with limited vertical offset, rather than by vertical stacking of units displaying sand-on-sand contacts and significant vertical offset. The higher resolution and continuity of outcrop observations from areas with uninterrupted rock exposure and limited tectonic disturbance makes it possible to discern internal architectures and lithological contrasts and to trace surfaces across such outcrops. This enables distinction of laterally equivalent units. In contrast, over-correlation of parasequences across well arrays is likely to be common in subsurface studies of shallow-marine successions, because of undersampling of the complexity of their parasequence organization. Even where a parasequence-bounding surface can be readily recognized in 1D well data, multiple parasequences can peel off from this capping surface due to offlap and lateral overlap, and these units can be missed or miss-correlated (Bhattacharya, 2011).

3.3. Subjectivity in parasequence interpretations

The subdivision of strata into parasequences and the recognition of flooding surfaces are subjective and heuristic processes. In particular, the identification of flooding surfaces on the basis of facies dislocations and/or other proxies for bathymetric change is fundamentally uncertain (Klug, 1993; Hampson, 2000; Zecchin and Catuneanu, 2013), especially in borehole data and where sand-rich portions of separate parasequences are amalgamated (e.g., Fitzsimmons and Johnson, 2000). The uncertainty in parasequence definition is highlighted by the fact that attributions change through time, because of reinterpretation or as new data become available (cf. Simpson and Eriksson, 1990*vs*Eriksson et al., 2019; Schattner et al., 2010*vs*Schattner and Lazar, 2016; Holgate et al., 2013*vs*Holgate et al., 2015; Pattison, 1995*vs*Pattison, 2019a). Additionally, stratal patterns that can be formalized in parasequences are sometimes recognized to develop at different scales, as reflected in parasequences of different hierarchies that occur nested within each other, despite their supposed scale-dependent nature (e.g., Devine, 1991; Ilgar, 2015; Lin et al., 2019).

The subjectivity and resulting uncertainty in parasequence attribution are particularly evident in well-studied successions where multiple interpretations by different groups, underpinned by intensive research efforts, are available. One such example is offered by the Campanian Blackhawk Formation, which crops out exquisitely for tens of kilometres along a depositional-dip profile in the Book Cliffs of Utah (USA). This succession lends itself to this type of comparison (cf. Hampson, 2000) thanks to the number of sedimentological studies that have been undertaken to investigate its parasequence organization. Here we compare three alternative sets of interpretations, respectively from (i)

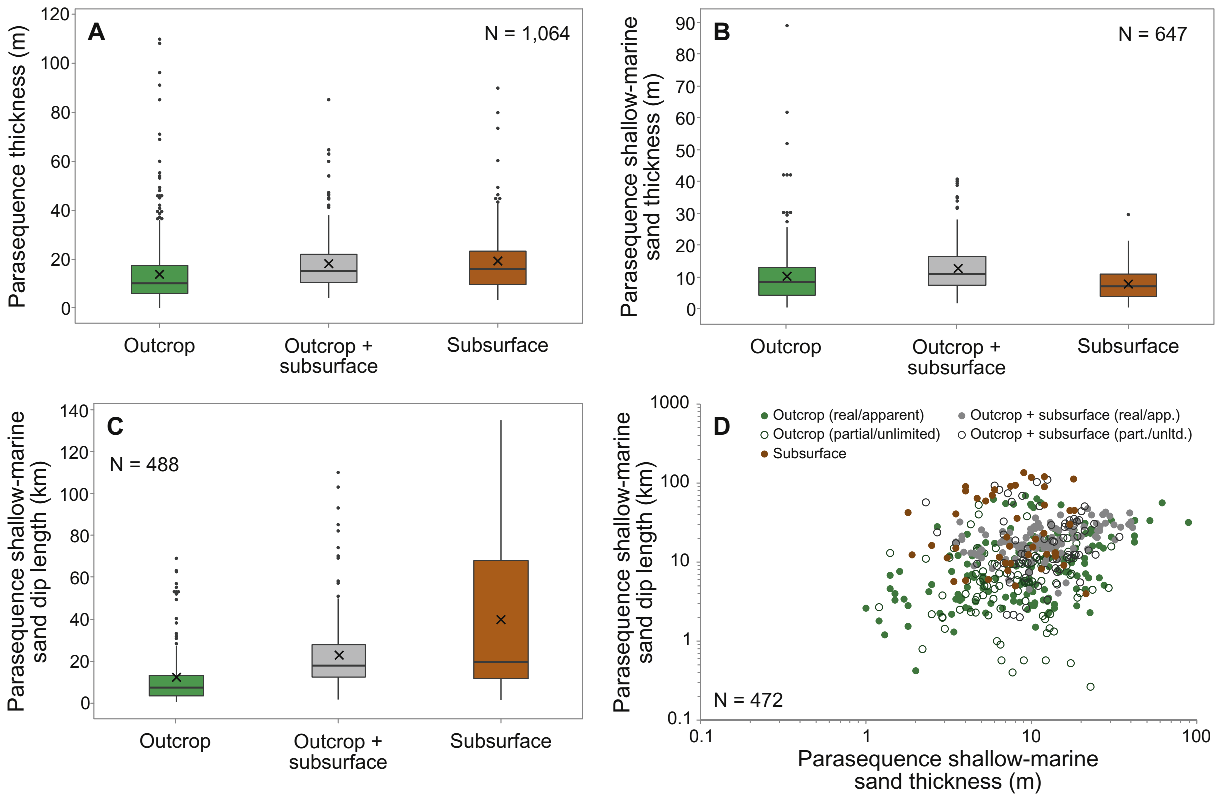

Fig. 4. Parasequence geometries by type of observation. A) Boxplots of the distribution of the maximum observed thickness of parasequences, grouped by dataset types. B) Boxplots of the distribution of the maximum observed thickness of parasequence-scale sands or sandstones of shallow-marine origin, grouped by dataset types. C) Boxplots of the distribution of the observed down-dip length of parasequence-scale sands or sandstones of shallow-marine origin, grouped by dataset types. In all boxplots, boxes represent interquartile ranges, horizontal bars in boxes represent medians, crosses (x) represent means, and spots represent outliers. D) Scatterplot of parasequence-scale shallow-marine sand/sandstone dip length versus thickness, grouped by dataset types and type of dip-length observation (as real or apparent versus partial or unlimited, see text). 'N' indicates the number of parasequences.

Reynolds (1999), itself a compilation of primary data from work by Balsley (1983), Taylor and Lovell (1992), Van Wagoner (1992), and O'Byrne and Flint (1993); (ii) Hampson and co-workers (as presented in: Hampson and Storms, 2003; Hampson and Howell, 2005; Hampson et al., 2008; Charvin et al., 2010; Hampson, 2010); (iii) and Pattison (as presented in: Pattison, 2010, 2018, 2019a, 2019b).

For these studies, the number of recognized parasequences and the geometry of their associated shallow-marine sandstones are separately compared for the Aberdeen, Kenilworth, Sunnyside, and Grassy members of the Blackhawk Formation (Fig. 5). This comparison demonstrates differences across the datasets that reflect variability in the stratigraphic frameworks and in the way lithological boundaries are characterized and placed. It is significant that the datasets that are being compared do not even represent the full range of available interpretations (cf. Taylor and Lovell, 1992, 1995; O'Byrne and Flint, 1995; Pattison, 1995; Van Wagoner, 1995), some of which vary considerably from the ones reported here; for instance, a total of 22 parasequences were identified in the Grassy Member by Van Wagoner (1995), instead of two to four (Fig. 5). It appears that these sequence stratigraphic interpretations vary because of discrepancies between the authors' views on parasequence definition and because of differences in the inferred significance of certain surfaces and in stratal correlations, themselves likely affected by the lack of a reliable datum (Pattison, 2019a) and by density and location of observations (i.e., vertical measured sections) as causes for parasequence aliasing (Lin et al., 2019).

Expectedly, differences in the preferred stratigraphic framework translate to differences in parasequence sand-body characteristics. Interpretations envisaging a larger number of parasequences in the Sunnyside Member (Reynolds, 1999; Fig. 5) result in the recognition of parasequence sandstones of shallow-marine origin that are on average less extensive along their depositional dip (Fig. 5). This observation highlights that the uncertainty in attempting to resolve laterally stacked units is not limited to the subsurface, as it also affects studies of well-exposed outcrop successions. Even where there are convergent views on parasequence attribution (e.g., Hampson, 2010 *vs* Pattison, 2019a; cf. O'Byrne and Flint, 1995), differences are seen with regards to how sandstone bodies are mapped.

The uncertainty associated with variability in parasequence interpretations and lithological attributions will affect any tentative comparisons between successions, including those made in this article, and the application of outcrop-analogue studies for reservoir characterization.

4. Parasequences and timescales

Parasequences are commonly assumed to reflect sediment accumulation at 10^3 to 10^5 yr timescales (Van Wagoner et al., 1990; Mitchum Jr and Van Wagoner, 1991; Swift et al., 1991), but it is recognized that units classified as parasequences in Quaternary successions have developed over shorter timescales, as low as 10^2 yr (Catuneanu, 2019b, and references therein). This notion is supported by the data on parasequence duration that are available for successions in which temporal constraints exist (Fig. 6), which cover five orders of magnitude in timescale (10^2 to 10^6 yr). It is likely that the wide range of timescales of parasequence development reflects both an inability to effectively resolve durations in deep time, because of age extrapolation being attempted without accounting for hiatuses (cf. Sadler, 1981), and some degree of scale independence in sedimentary architecture (cf. Schlager, 2004, 2010; Catuneanu, 2019b), whereby different formative

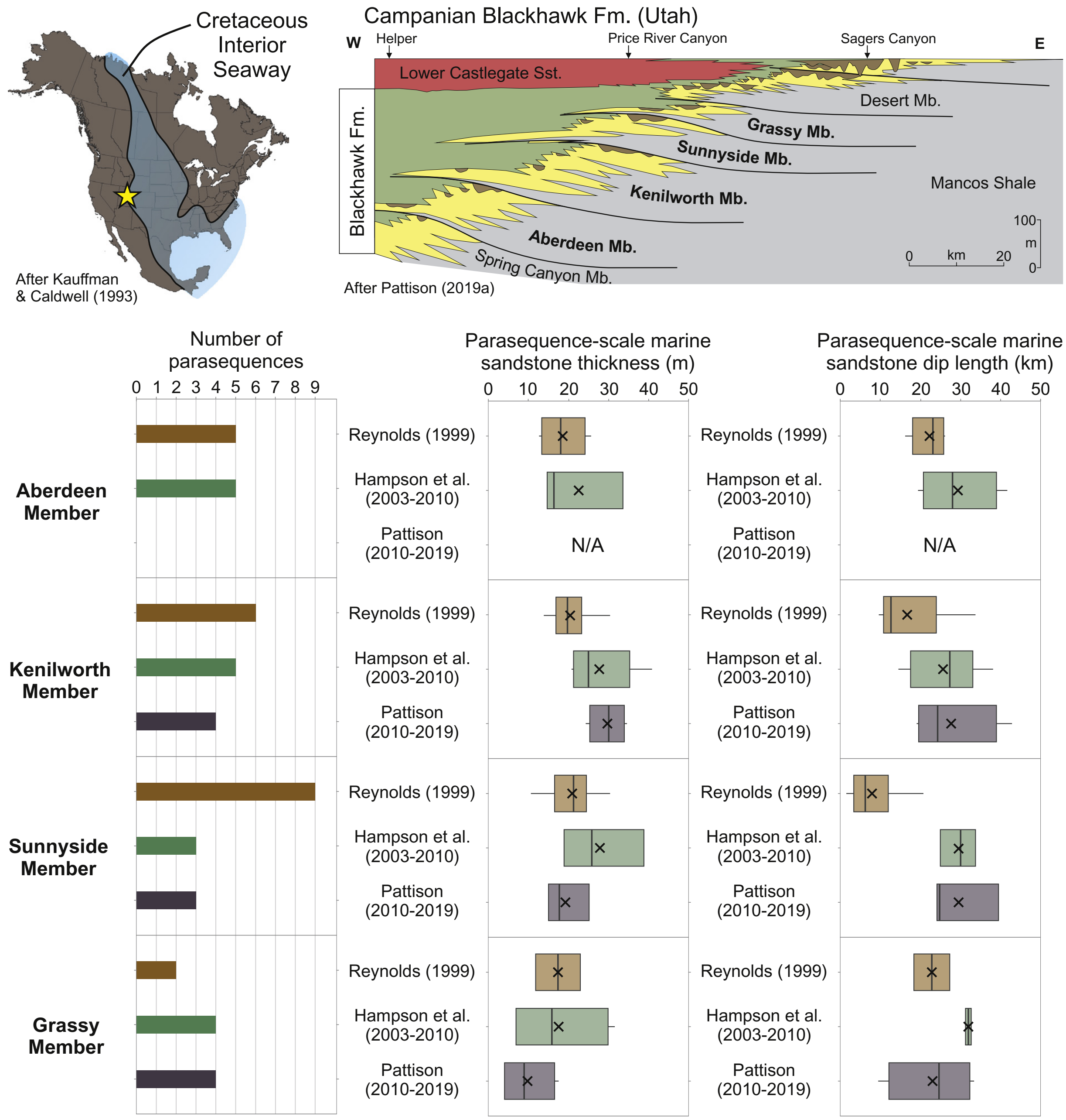

Fig. 5. Quantitative comparison of three interpretations of the parasequence organization in the Aberdeen, Kenilworth, Sunnyside, and Grassy members of the Campanian Blackhawk Formation of the Western Interior Basin in Utah (USA). A comparisons is presented of datasets by Reynolds (1999; based on a compilation of primary data from works by: Balsley, 1983; Taylor and Lovell, 1992; Van Wagoner, 1992; O'Byrne and Flint, 1993), by Hampson and co-authors (Hampson and Storms, 2003; Hampson and Howell, 2005; Hampson et al., 2008; Charvin et al., 2010; Hampson, 2010), and by Pattison (2010, 2018, 2019a, 2019b); see Table 1. For each of the four members, a comparison is made of the number of parasequences recognized by the different authors (bar charts on the left-hand side), and of the distributions in thickness (boxplots in the centre) and down-dip length (right-hand side) of parasequence-scale sandstones of shallow-marine origin. In the boxplots, boxes represent interquartile ranges, horizontal bars in boxes represent medians, crosses (x) represent means, and spots represent outliers (Kauffman and Caldwell, 1993).

processes and controls operating over markedly different durations give rise to similar patterns, including shallowing-upward regressive units.

With regards to the last point, the observed separation in the distribution of durations for parasequences of Quaternary and pre-Quaternary (almost exclusively Upper Cretaceous) age is compatible with the view that Quaternary parasequences largely record minor relative fluctuations or stillstands in sea level (e.g., stadials) and possibly pulses of sediment supply or autogenic dynamics (particularly avulsion periods; see below), whereas ancient parasequences are more likely to represent units that develop in response to orbitally driven eustatic cycles. For the distribution in durations of parasequences from the rock record, a mode centred on 17 kyr (and therefore relatively close to the periods of climate precession for the Upper Cretaceous; Waltham, 2015) and secondary modes close to 40 kyr and 100 kyr are identified (Fig. 6B). These modes could be loosely tied to the periodicity of Milankovitch cycles and interpreted as forcing by precession cycles being possibly dominant in determining parasequence generation. This is an interpretation that necessitates the assumption that discrepancies are due to geochronometric error and/or to approximations introduced by the extrapolation of durations based on limited temporal constraints (cf.

Garrison Jr. and van den Bergh, 2004; Runkel et al., 2007; Zhu et al., 2012). Although any inference of orbital forcing would need substantially more data to be corroborated, it can generally be argued that the timescales associated with ancient parasequences are compatible with lengths of time at which external controls operate to determine relative sea-level change, but the relative importance of the ultimate allogenic driver – be it eustatic, tectonic, or climatic – remains uncertain. Almost all (N = 89) examples of pre-Quaternary parasequences considered here are from the Late Cretaceous (Plint, 1991; Garrison Jr. and van den Bergh, 2004; Zhu et al., 2012). Because of the magnitude and periodicity of eustatic changes for the greenhouse climate of the Late Cretaceous (cf. Miller et al., 2005, 2011; Kominz et al., 2008; Haq, 2014; Hay, 2017), it is difficult to demonstrate whether these units are more likely to represent true paracycles or rather high-frequency sequences. Yet, given the postulated presence of ephemeral continental ice sheets (cf. Miller et al., 2011) and the possible role of aquifer eustasy in controlling global sea level (Wendler et al., 2016) at the time, it is plausible that formative shorelines and shelves experienced eustatic sea-level falls over 10^4 to 10^5 yr timescales. Eustatic sea-level changes might have been of modest magnitude, but possibly rapid enough to outpace tectonic subsidence and thereby result in overall relative sea-level falls. It is also conceivable, though perhaps not likely, that parasequences were generated in response to cyclical variations in rates of sediment supply, which could have been determined by the effect of orbital climate oscillations on precipitation and sediment yield experienced at the latitudes of the Western Interior Basin of North America in the Late Cretaceous (Swift et al., 1991).

Parasequences contained in transgressive systems tracts and expressed as retrogradational parasequence sets might be expected to embody a shorter length of time, typically, than others, since parasequences of this type should represent episodic regressions punctuating conditions of overall transgression (e.g., because of stasis in relative sea-level rise, or increases in sediment-supply rate). However, parasequences associated with transgressive systems tracts or those arranged in retrogradational stacking patterns return estimated durations that are larger on average than the ones associated with progradational or aggradational stacking patterns or contained in other types of systems tracts (mean values: 31.1 kyr *vs* 25.0 kyr; standard deviations: 36.5 kyr *vs* 42.4 kyr; N = 19 *vs* N = 67). Differences in mean duration cannot be discriminated statistically (two-sample t-test: T = 0.40, d.f. = 33, p-value = 0.691), suggesting the possible dominance of a common control, irrespective of the longer-term sea-level behaviour. It is also hypothesized that parasequences associated with falling-stage or lowstand systems tracts may record typically longer lengths of time than those associated with transgressive or highstand systems tract, because the entrenchment of the fluvial systems feeding the shorelines, driven by forced regression, would hinder river diversion (Bhattacharya et al., 2019; Wang et al., 2019, 2020). Yet, the idea that in a context of forced regression and lowstand the limited effectiveness of river avulsion may result in longer-lived shoreline regressions capable of generating parasequences is not supported by data on parasequence duration, which tends to be shorter on average for parasequences contained in falling-stage or lowstand systems tracts (mean value of 26.6 kyr *vs* 35.1 kyr for highstand and transgressive parasequences; standard deviations: 50.2 kyr *vs* 42.9 kyr; N = 29 *vs* N = 80; two-sample t-test: T = 0.81, d.f. = 43, p-value = 0.425).

Distributions in parameters that describe the anatomy of clastic parasequences can be compared by the timescale over which they have developed (Fig. 7). When distributions in parasequence thickness are compared, a difference in average thickness is seen across the 10^2–10^3 *vs* 10^4–10^6 yr timescales (10.8 m *vs* 14.0 m), which is statistically significant (two-sample t-test: T = −2.72, d.f. = 117, p-value = 0.008). This difference is seen despite the likely counteracting effect of sediment compaction, given that units developed over temporal scales of 10^2–10^3 yr are in large part Quaternary (51% *vs* <1% at 10^4–10^5 yr). These results suggest that the different timescales attributed to the units

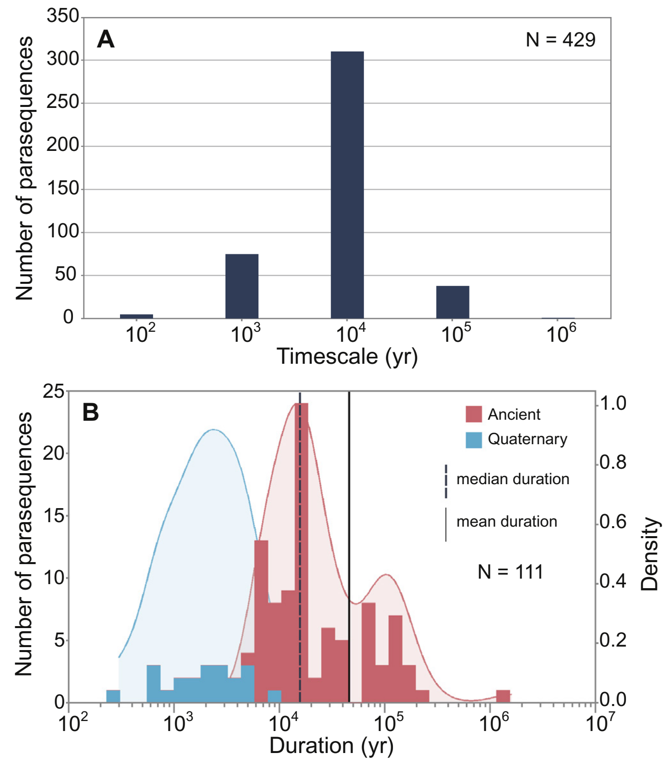

Fig. 6. Temporal significance of studied clastic parasequences. (A) Bar chart of the frequency of timescales of parasequence development. (B) Stacked histogram and kernel density plots of the distributions of the estimated length of time recorded in ancient (i.e., pre-Quaternary, N = 90) and Quaternary (N = 21) shallow-marine parasequences. Note that durations are shown on a logarithmic scale. Mean (45.8 kyr) and median (15.6 kyr) duration values are reported for all 111 parasequences. Quaternary parasequences return mean and median durations of 2.6 kyr and 2.0 kyr respectively; the mean and median values for the duration of ancient parasequences are 55.9 kyr and 17.0 kyr.

do not merely relate apparent durations arising from the so-called Sadler effect (Sadler, 1981; see below), and that units classified as parasequences in Quaternary successions are more likely to be unresolved in the rock record. A comparison of the down-dip lengths of shallow-marine parasequence sand belts indicates that the average sand/sandstone dip length differs markedly across the 10^2–10^3 *vs* 10^4–10^6 yr timescales (7.1 km *vs* 24.8 km; N = 232) to a statistically significant level (two-sample t-test: T = −8.48, d.f. = 228, p-value < 0.001). This difference is paralleled by an increase in the average parasequence progradation distance with timescale (2.9 km, 8.4 km and 11.8 km, from 10^3 to 10^5 yr; N = 82; Fig. 7). These differences in sandstone dip extent and progradation distance reflect the variable length of time over which shoreline progradation took place, and possibly the variable degree to which lateral amalgamation of shallow-marine sands is resolved and associated parasequence flooding surfaces are recognized.

Because of the range of timescales covered by the parasequences analysed here, it is reasonable to assume that estimations of durations of parasequence development and associated rates of accretion are affected by the Sadler effect (cf. Paola et al., 2018; Bhattacharya et al., 2019). The average length of breaks in sedimentation contained within the parasequences – or, equivalently, the likelihood for parasequences of recording a ‘significant’ hiatus – is expected to increase with timescale (Sadler, 1981). This will affect estimated rates of aggradation and progradation. Additionally, for parasequences whose duration is extrapolated by averaging lengths of time for groups of units between dated horizons, gaps in sedimentation at parasequence boundaries can cause overestimation of the duration of the parasequences themselves, in turn leading to underestimation of aggradation and progradation

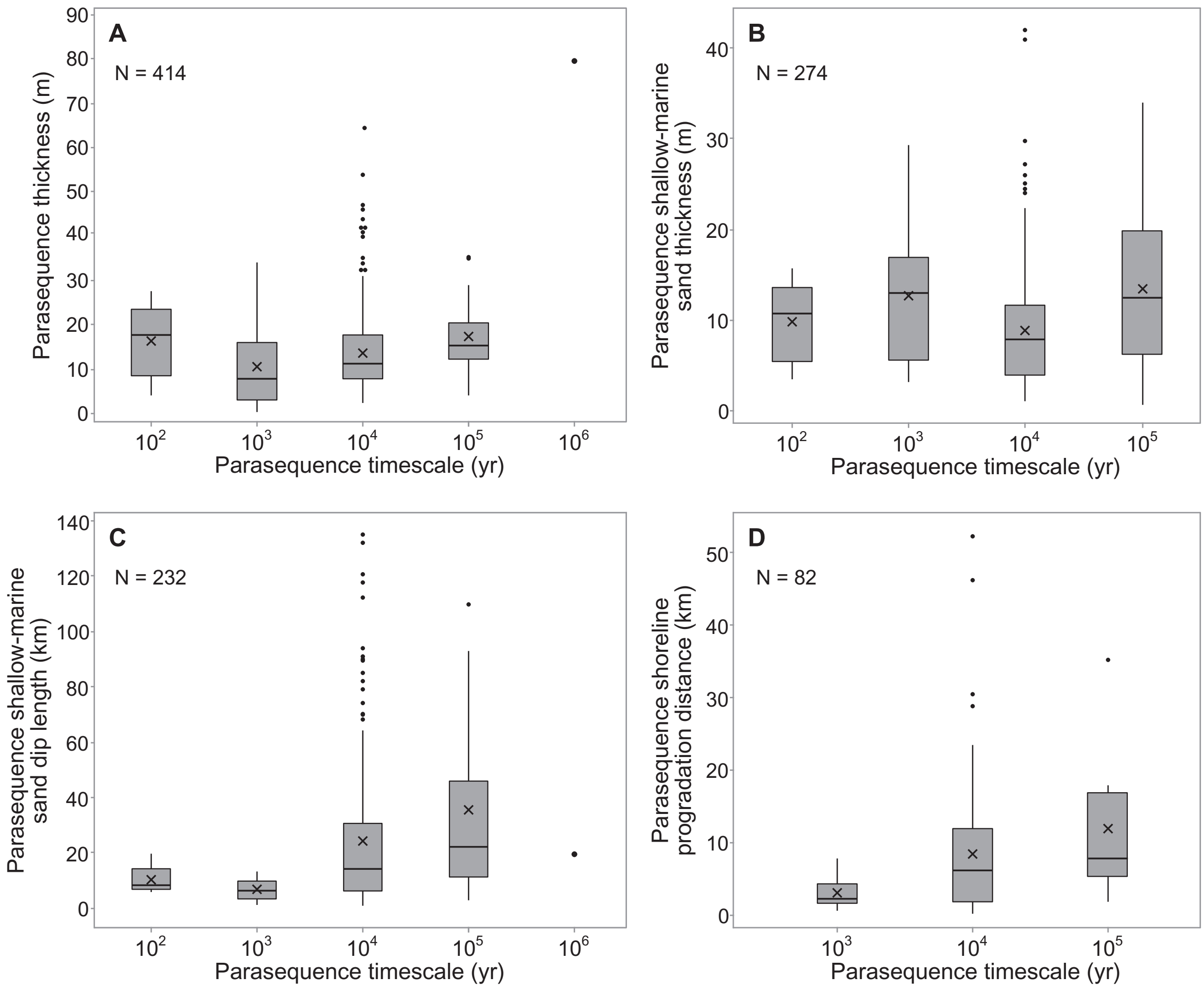

Fig. 7. Parasequence geometries by timescale of deposition. A) Boxplots of the distribution of the maximum observed thickness of parasequences, grouped by the timescale at which they are known or inferred to have developed. B) Boxplots of the distribution of the maximum observed thickness of parasequence-scale sands or sandstones of shallow-marine origin, grouped by timescale. C) Boxplots of the distribution of the observed down-dip length of parasequence-scale sands or sandstones of shallow-marine origin, grouped by timescale. D) Boxplots of the distribution of the shoreline progradation distance recorded in the parasequences, grouped by timescale. Boxes represent interquartile ranges, horizontal bars in boxes represent medians, crosses (x) represent means, and spots represent outliers. 'N' indicates the number of parasequences.

rates. As a result, both aggradation and progradation rates are expected to vary as a function of the time over which they are estimated (cf. Sadler and Jerolmack, 2015). For parasequences for which estimations of durations exist, based on available geochronometric constraints, an assessment of Sadler effects on parasequence-scale aggradation and shoreline progradation can be made (Fig. 8). Negative relationships are indeed seen between the length of time over which parasequences developed and both their aggradation rate in nearshore areas (Pearson correlation coefficient of log-transformed values: $R = -0.562$, p-value < 0.001; Fig. 8A) and their shoreline progradation rate (Pearson correlation coefficient of log-transformed values: $R = -0.736$, p-value $<$ 0.001; Fig. 8B). No significant correlation is seen between parasequence duration and positive progradation angles (Fig. 1), i.e., normal regressive parasequence shoreline trajectories recording the relative rates of shoreline progradation and aggradation ($R = -0.122$, p-value $= 0.410$, $N = 48$). The time dependency of parasequence progradation rates reflect different mechanisms that govern the punctuation of shoreline progradation, through episodic deposition, stasis, erosion and reactivation, at different timescales. Shoreline progradation rates are time-dependent even on human timescales (Dolan et al., 1991), and this relates intuitively to the unsteadiness in local shore progradation seen for modern strandplains, barriers and deltas (cf. Coleman, 1988; Stapor Jr et al., 1991; Taylor and Stone, 1996; Brooke et al., 2008; Muñoz-Salinas et al., 2018). On geological timescales, it is likely that both autogenic (e.g., avulsion-driven relocation of distributary mouths) and allogenic (e.g., wind-direction change) factors play a role in developing gaps in time of variable magnitude within parasequence shoreline-shelf deposits.

5. Parasequences and depositional environment

The origin of clastic sedimentary units interpretable as parasequences in littoral and shelf environments can be varied (Van Wagoner, 1985), but archetypal parasequences are portrayed as coarsening-upward successions resulting from basinward progradation of beach-to-shelf profiles and deltas (Van Wagoner et al., 1990). Looking at parasequences that are classified according to the interpreted depositional context and dominant process regime under which they were deposited can shed light on the relative dominance of types of formative environments, and can help determine whether there exists a preferential setting that generates stratal patterns interpretable as parasequences.

The interpreted depositional environment of parasequences is classified as representing 'deltaic', 'shoreface' *sensu lato*, or mixed 'deltaic-

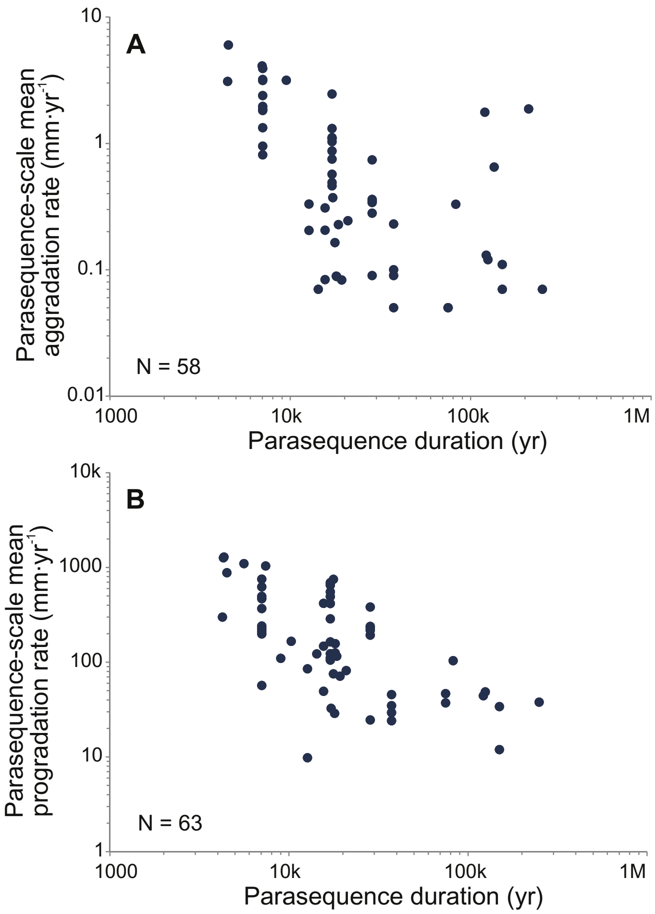

Fig. 8. Timescale-dependency of aggradation and progradation rates. A) Scatterplot of the aggradation rate of parasequences versus the length of time under which they are inferred to have developed (Pearson correlation coefficient of log-transformed values: $R = -0.562$, p-value < 0.001). Aggradation rates are evaluated for the sedimentary record of nearshore environments. B) Scatterplot of the shoreline-progradation rate of parasequences versus the length of time under which they are inferred to have developed (Pearson correlation coefficient of log-transformed values: $R = -0.736$, p-value < 0.001). 'N' indicates the number of parasequences.

shoreface' systems, the latter term being used when both types of shoreline-shelf systems are interpreted from the parasequence deposits (e.g., Forzoni et al., 2015). Only a small part (14%; Fig. 9A) of the studied parasequences were not classified according to the type of shoreline depositional environment. Parasequences are left unclassified either when an interpretation is not given, and this might be because distinguishing between a shoreface and a delta-front environment is not straightforward (e.g., Bassetti et al., 2008), or when a parasequence is thought to have formed in a different environmental setting (e.g., as the product of progradational facies belts in an estuary-mouth setting; cf. Dam and Surlyk, 1995). Assuming that our sample is representative and that interpretations given in the primary data sources are sound, shoreface environments are preserved in parasequence deposits slightly more frequently than deltaic environments (42% *vs* 34%; Fig. 9A).

The majority of parasequences that are classified according to the inferred dominant process regime (67%) are interpreted to have accumulated in wave-dominated environments (Fig. 9B, C), and these include wave-dominated deltas (6% of all parasequences). River-dominated and tide-dominated parasequences represent 24% and 9% of all the studied examples, respectively (Fig. 9B), and are both considerably more frequent in association with deltaic systems.

Any comparisons between deltaic and shoreface parasequences is biased by the fact that 44% of studied shoreface parasequences are from the Cretaceous Western Interior Seaway (compared to only 18% of deltaic parasequences), where they developed on the ramp of a shallow epeiric sea in a backtilted foreland basin under greenhouse climate. Distributions of true and apparent thicknesses of deltaic and shoreface parasequences are similar (Fig. 9D), with mean thicknesses of 16.7 m and 15.3 m respectively ($N = 796$), which do not differ statistically (two-sample t-test: $T = 1.51$, d.f. $= 793$, p-value $= 0.132$). Distributions of true and apparent thicknesses of river- and wave-dominated parasequences are also similar (Fig. 9E), with mean values of 15.0 m and 15.8 m respectively. In the limited number of cases where thickness values are thought to represent true maximum thicknesses, deltaic parasequences appear thicker on average (27.1 m *vs* 21.1 m, $N = 99$), but this difference is not significant at $\alpha = 0.05$ (two-sample t-test: $T = 1.88$, d.f. $= 83$, p-value $= 0.063$). The thickness of shoreline-shelf parasequences will largely reflect any pre-existing accommodation on the area of shelf in which they build out and the amount of accommodation generated through the parasequence history (Posamentier and Allen, 1999; Ainsworth et al., 2018). The fact that deltaic parasequences tend to be thicker could be explained by the higher sediment supply rates that might be expected for river-fed coastlines, which would favour faster progradation into deeper shelf areas and more rapid sediment compaction due to loading, or by the possible role of growth faulting. The assumption that parasequence thickness might reflect furthest shore progradation is at odds with the observed differences in recorded shoreline progradation distance, which is larger on average for shoreface parasequences (mean values: 12.7 km *vs* 4.7 km, $N = 91$).

The geometry of shallow-marine sand belts can also be characterized for parasequences classified on depositional environment and dominant process regime (Fig. 9F, G). The thickness – true or apparent – of parasequence sands or sandstones or shallow-marine origin is larger, on average, for shoreface parasequences compared to deltaic ones (mean values: 11.6 m *vs* 8.9 m, $N = 502$), to a level that is statistically significant (two-sample t-test: $T = -3.98$, d.f. $= 495$, p-value $<$ 0.001), and for wave-dominated compared to river-dominated ones (mean values: 12.2 m *vs* 11.2 m, $N = 434$), but not to a statistically significant level in this case (two-sample t-test: $T = -1.06$, d.f. $= 200$, p-value $= 0.289$). These observations could be interpreted as a signature of the relationship between wave climate and the depth of sand-mud transition on inner continental shelves (cf. Dunbar and Barrett, 2005; George and Hill, 2008), but could also merely reflect an increased difficulty in resolving amalgamated units in wave-dominated shoreline-shelf successions compared to deltaic ones. This would be in agreement with the observed – albeit weak – positive relationship between sand-belt thickness and length seen in shoreface parasequences (Pearson's $R = 0.300$, $p < 0.001$, Fig. 9F), and with the fact that shoreline progradation distances tend to be longer for these compared to their deltaic counterparts.

The possible unrecognized amalgamation of shoreface parasequences might also be indicated by observations on estimated parasequence durations, which are on average longer for shoreface parasequences (mean $= 120.0$ kyr, standard deviation $= 285.4$ kyr, $N = 26$), compared to deltaic ones (mean $= 9.2$ kyr; standard deviation $= 7.0$ kyr; $N = 38$). This difference in timescales between shoreface and deltaic parasequences is also seen in the subset of ancient (pre-Quaternary) examples, for which it is statistically significant (mean shoreface parasequence duration $= 124.6$ kyr, $N = 25$; mean deltaic parasequence duration $= 14.5$ kyr, $N = 22$; two-sample t-test of log-transformed values: $T = -5.08$, d.f. $= 27$, p-value < 0.001). Correspondingly parasequences classified as wave dominated tend to embody on average longer temporal durations (mean $= 101.1$ kyr, standard deviation $= 228.5$ kyr, $N = 42$) than river-dominated ones (mean $= 14.7$ kyr, standard deviation $= 8.0$ kyr, $N = 34$).

Observations on deltaic parasequences – which record shorter lengths of time, contain less extensive sand belts, and display smaller progradation distances than shoreface ones – raise the question as to

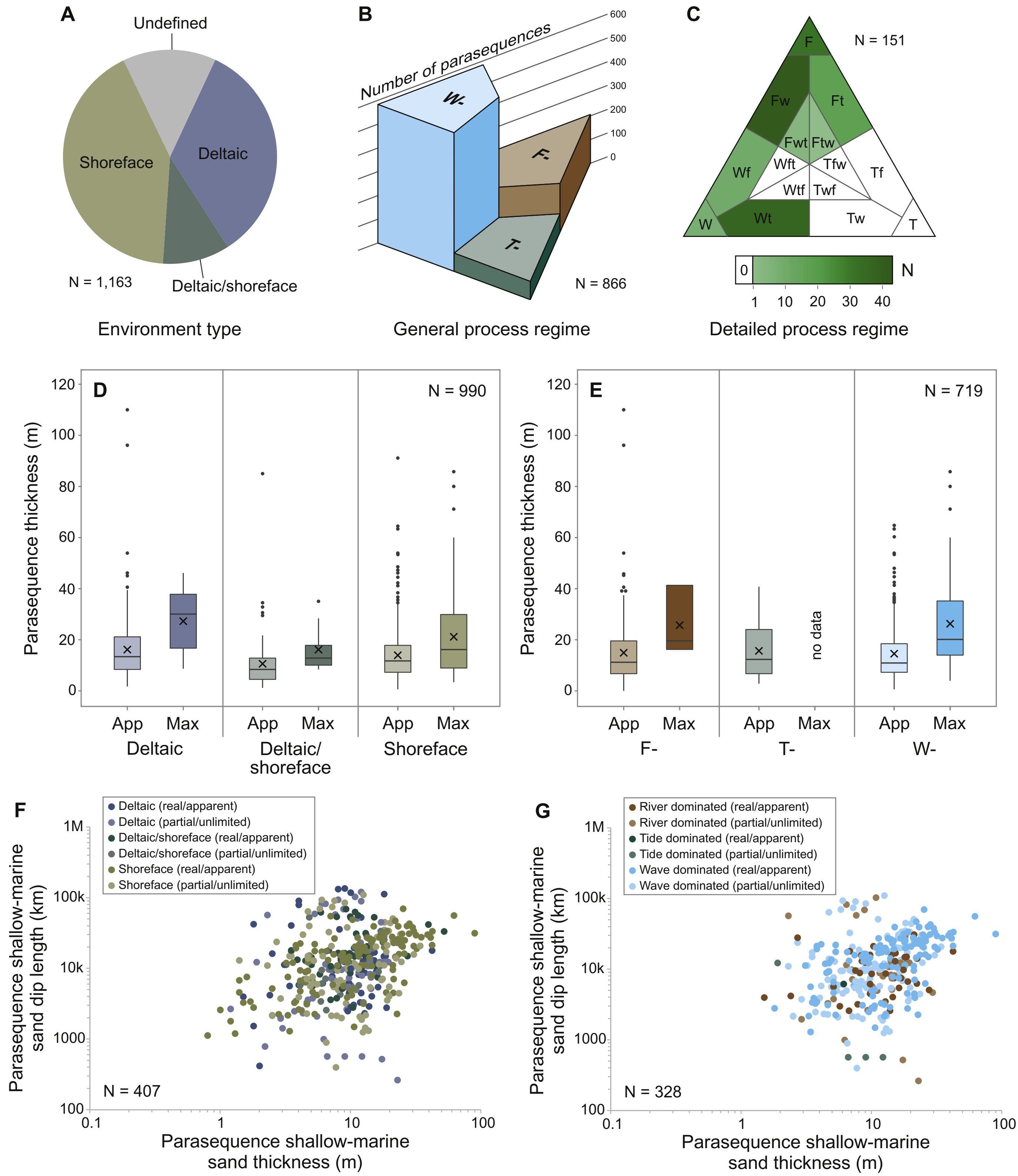

Fig. 9. Frequency and attributes of parasequences of different origin. A) Relative proportion of parasequence types, classified according to their interpreted formative littoral depositional environment. B) Relative proportion of parasequence types, classified according to the general process regime they are interpreted to record (see text for codes). C) Heat map of the frequency of parasequences for detailed classes of process regime (see text for codes; cf. Ainsworth et al., 2011). D) Boxplots of the distribution of the observed thickness of parasequences, grouped by littoral depositional environment. True maximum ('Max') and apparent ('App') thickness values are differentiated for each group. E) Boxplots of the distribution of the observed thickness of parasequences, grouped by general process regime. True maximum ('Max') and apparent ('App') thickness values are differentiated for each group. Boxes represent interquartile ranges, horizontal bars in boxes represent medians, crosses (x) represent means, and spots represent outliers. F) Scatterplot of parasequence-scale shallow-marine sand/sandstone dip length versus thickness, grouped by littoral depositional environment and type of dip-length observation (as real or apparent versus partial or unlimited, see text). G) Scatterplot of parasequence-scale shallow-marine sand/sandstone dip length versus thickness, grouped by general process regime and type of dip-length observation (as real or apparent versus partial or unlimited, see text). 'N' indicates the number of parasequences.

Table 2
Summary of the six SMAKS (Colombera et al., 2016) case studies of modern deltas considered in this work.

Delta	Location	Drainage area (km^2)	Delta-lobe width range	Sources
Burdekin	Queensland, Australia	130,000	8–38 km (N = 13)	Fielding et al. (2005a, 2005b, 2006)
Ebro	Spain	85,000	15–22 km (N = 4)	Somoza et al. (1998)
Mississippi	Louisiana, USA	3,345,000	23–115 km (N = 16)	Frazier (1967); Roberts (1997)
Po	Italy	74,000	19–48 km (N = 5)	Correggiari et al. (2005a, 2005b)
Rhône	France	98,000	4–30 km (N = 8)	Jouët (2007); Fanget et al. (2014)
Yellow River	China	752,000	27–66 km (N = 10)	Xue (1993); van Gelder et al. (1994); Wang et al. (2016)

A case study is a dataset on a particular succession, by some author(s) or research group, as presented in one or more related publications. The consulted literature sources that contain data on sedimentary bodies that represent deltaic constructional units (delta lobes and elements of higher hierarchy) are reported. Data on the range in longshore lateral extent of the units exclusively refer to sedimentary bodies that were originally termed 'delta lobes'.

whether mechanisms driving the emergence of stratal patterns interpretable as parasequences vary depending on the depositional context of origin. In deltaic settings – where sediment distribution at the shoreline is governed by drainage reorganization and delta-lobe abandonment, which can cause local marine flooding – the generation of parasequences may be more punctuated than it is for strandplains, for example, which might be expected to undergo relatively more steady progradation. In part, differences between river- and wave-dominated parasequences could be interpreted as a signature of the effectiveness of wave climate as a control on river-avulsion frequency: increased wave energy can suppress the avulsion of coastal distributaries through the effect of longshore transport as an inhibitor to stream lengthening and aggradation (Swenson, 2005; Bhattacharya et al., 2019) and through the construction of strandplains by accretion of sets of elevated beach ridges that may act to confine channels (Syvitski and Saito, 2007). With this in mind, it might seem reasonable to interpret our data in terms of differences that may exist in the relative likelihood of recording the effect of allogenic controls, across deltaic and shoreface systems. The view that more punctuated parasequence development might be associated with deltaic systems, possibly in relation to inherent coastal morphodynamics, is a view that can be substantiated with additional insight from preserved sedimentary architectures in the shallow subsurface of modern deltas, as considered next.

6. Deltaic constructional units and parasequences

The notion that delta-lobe switching acts as a parasequence-generating mechanism is reflected in interpretations of the rock record (cf. Bhattacharya and Walker, 1991a; Kosters and Suter, 1993; Bridge and Willis, 1994; Bohacs and Suter, 1997; Helland-Hansen, 2010; Chen et al., 2014; Grundvåg et al., 2014), and is fostered by results of numerical (e.g., Dalman et al., 2015) and physical (e.g., Straub et al., 2015) experiments. Accordingly, a deltaic parasequence would represent the preserved expression of a delta lobe. However, interpretations are also made of parasequences that may contain more than one delta lobe (cf. Bhattacharya and MacEachern, 2009; Amorosi et al., 2017; Ghinassi, 2007; Jouët, 2007; Ainsworth et al., 2018; Fanget et al., 2014; Hampson, 2016), in some cases associated with different feeder rivers (Olariu et al., 2012), or even of delta lobes that contain more than a single parasequence (Boyer et al., 2005). A comparison with Quaternary deltas can give some perspective on the possible origin of deltaic parasequences, and on the likelihood of interpretations of the stratigraphic record.

Before any comparison between parasequences and delta lobes can be made, however, it is necessary to consider how a delta lobe is defined. The term has been used for many decades in application to the recent and ancient stratigraphic record (e.g., Rusnak, 1960; Dondanville, 1963), and its usage has become entrenched in the discipline, yet a formal definition of 'delta lobe' does not seem to exist (Bhattacharya et al., 2019). The term has been applied to refer to geological entities that can be fundamentally very different, such as genetically related subaerial parts of a delta (Nijhuis et al., 2015) or delta-front sand-prone lobate units (Deveugle et al., 2011), for example. A commonly shared view is that a delta lobe is a sedimentary body that represents the product of progradation of a portion of a delta during a constructional phase, in relation to a certain state of river drainage, and that is typically made of cogenetic prodeltaic, delta-front and delta-top deposits (cf. Frazier, 1967; Coleman et al., 1998; Roberts et al., 2004; Wang et al., 2016; Fig. 11A). In this work we include data on units that are termed delta lobes and match with this definition. However, even when the term is used in this sense, specific recognition criteria can vary (e.g., facies trends, geometries, stacking pattern, internal architecture and stratal terminations), in part based on available data types. Also, deltaic units of this type can be variably related to the configuration of river drainage, to the point that the same 'lobe' definition could be applied to units at different scales, depending on the scale at which foci of sediment accumulation and changes in sediment dispersal are identified. This is reflected in attempts to erect a hierarchy of deltaic units (Frazier, 1967; Coleman, 1988; Xue, 1993; Roberts, 1997; Somoza et al., 1998; Vakarelov and Ainsworth, 2013), whereby multiple hierarchies are related to different scales at which drainage reorganization occurs, expressed for example in the drainage order or location at which stream avulsion or distributary activation takes place. A varied nomenclature is used for higher-order deltaic constructional units made of coalescing 'delta lobes', which includes terms like 'lobe complex', 'superlobe' or 'progradational unit' (Frazier, 1967; Xue, 1993; Somoza et al., 1998).

Here a comparison is made between deltaic parasequences and deltaic constructional units from published studies of the shallow subsurface of active deltas, based on a range of data types, including cores, well logs, shallow seismic surveys, geoelectrical surveys, and GPR surveys, integrated with observations on delta geomorphology. The data are from six deltas, linked to rivers of variable size and developed under different environmental conditions (Tab. 2, Fig. 10). Sedimentary bodies originally described as 'delta lobes' or representing higher-order units made of amalgamated delta lobes were coded in SMAKS (Colombera et al., 2016) as architectural elements (N = 84), which are characterized in terms of hierarchy and spatial and temporal scales. Bearing in mind the considerations made earlier, which highlight the uncertainty as to whether these units are even comparable between them, a comparison is attempted of the spatiotemporal scale of recent deltaic constructional units at different orders with that of deltaic parasequences (Fig. 11).

Necessarily, the timescale of development of delta lobes is shorter on average (mean value: 644 yr) than the duration of the higher-scale constructional units (e.g., channel complexes, superlobes) they form (mean value: 1488 yr). However, both types of units have a duration that is, on average, shorter than the duration of deltaic parasequences (mean value: 9211 yr). The difference in mean duration between parasequences and higher-scale deltaic units is statistically significant (two-sample t-test of log-transformed values: $T = 9.64$, d.f. $= 79$, p-value < 0.001), but the interquartile range of duration for deltaic units fall within the range of duration estimated for parasequences (Fig. 11B).

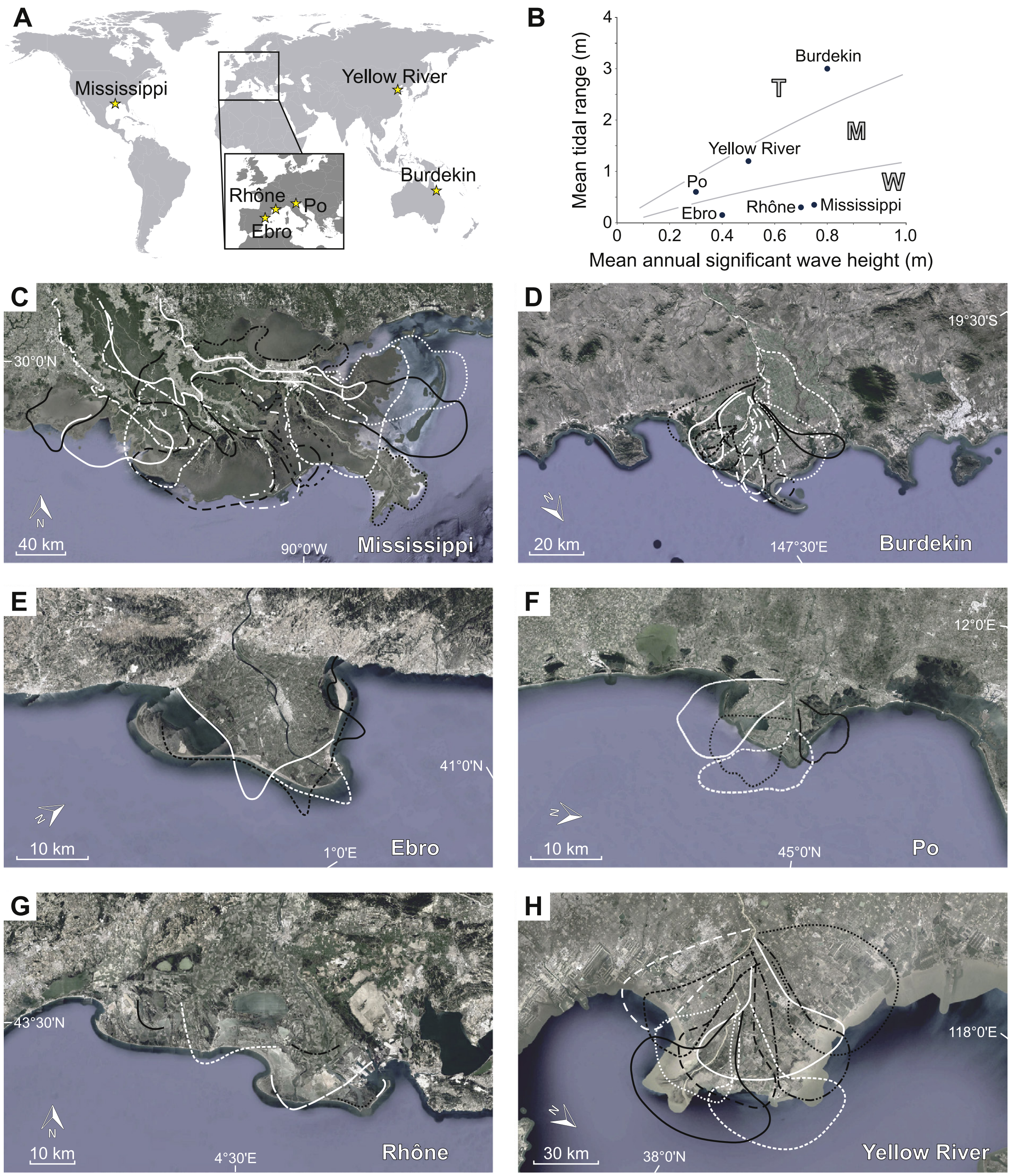

Fig. 10. Case studies of modern deltas and delta lobes. A) Geographic distribution of the six SMAKS (Colombera et al., 2016) case studies of the sedimentary architecture of modern deltas considered in this work (see Table 2). B) Scatterplot of mean tidal range versus mean annual significant wave height for the studied deltaic systems. The fields for wave- (W), mixed- (M), and tide-dominated (T) regimes (Hayes, 1979) are indicated. C-H) Planform shape of the recognized delta lobes, presented for each delta, based on their extent as mapped in the original source works (Table 2); variability in the mapped planforms might in part reflect differences with regards to the consideration of prodelta deposits and the ability to correlate delta lobes laterally. Full lobe planforms are mapped in C, D, F, and H, whereas shoreline extents only are mapped for delta lobes in E and G.

Deltaic parasequences (mean value: 16.7 m) are, on average, thicker than delta lobes (mean value: 10.7 m), to a statistically significant level (two-sample t-test: $T = 5.38$, d.f. $= 81$, p-value < 0.001), despite being subject to greater sediment compaction overall (Fig. 11C). Instead, the average thickness of larger-scale deltaic constructional units is the same as the mean thickness of parasequences (16.7 m), and larger than the mean thickness of parasequences developed at the 10^2–10^3 yr timescale (14.5 m).

Differences in unit durations could be explained in part by the difficulty in constraining the duration of time gaps (e.g., associated with flooding surfaces) in the ancient rock record, which is consistent with observations of Sadler effect in parasequences (Fig. 8). Notwithstanding, combined data on the spatial and temporal significance of the units indicate that the majority of deltaic parasequences, at least when recognized in the rock record, are likely to contain multiple coalescent 'delta lobes', as commonly defined and recognized in modern deltas. On

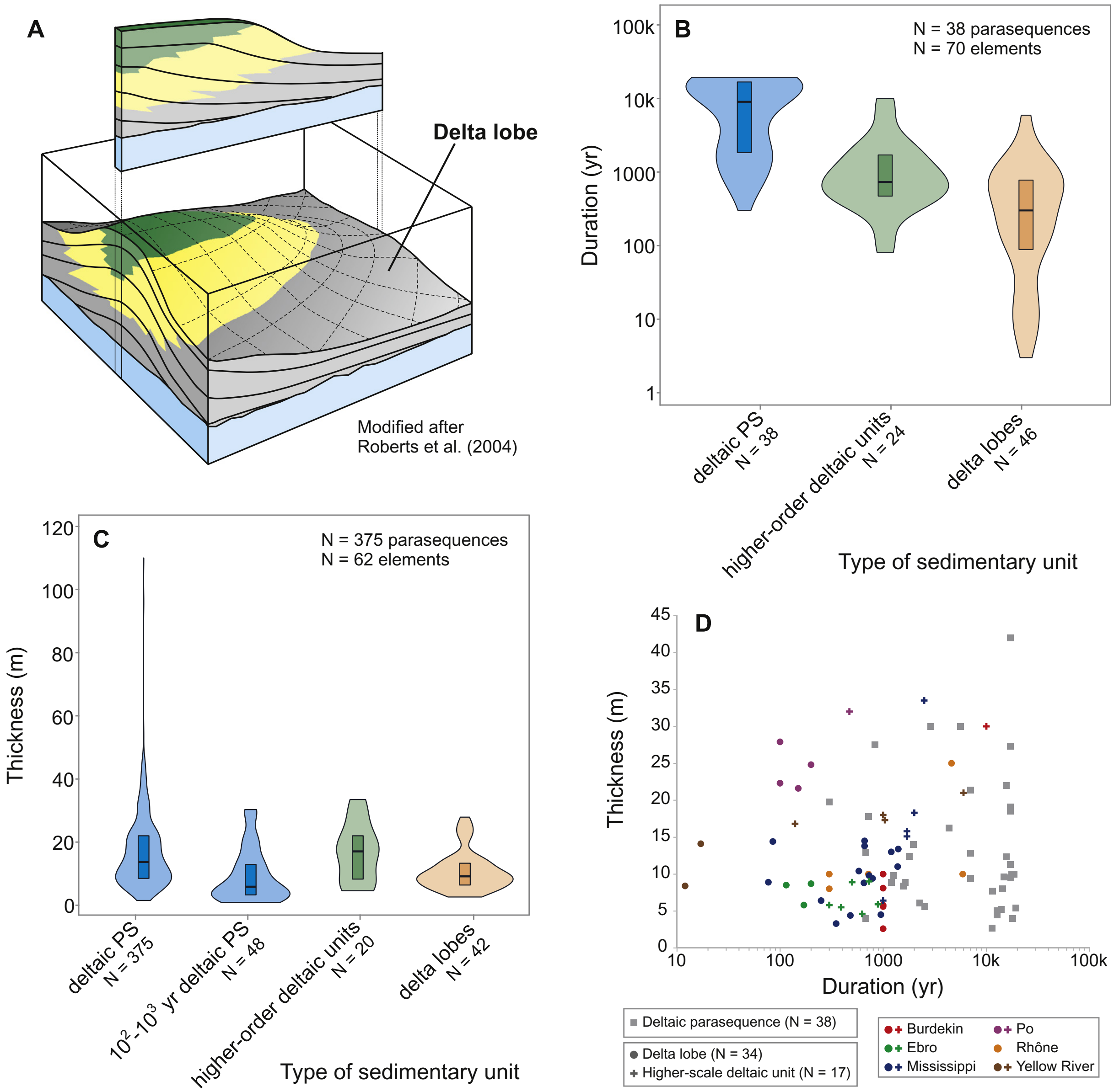

Fig. 11. Comparison of clastic parasequences with delta lobes and other higher-scale constructional units made of coalescing and genetically related lobes. (A) Idealized model of delta lobe as considered in this work (modified after Roberts et al., 2004). (B-C) Violin plots of distributions in the length of time over which these types of units have developed (B) and in their maximum observed thickness (C). Note that durations are shown on a logarithmic scale, and that kernel densities of durations were computed after log-scale transformation. Thickness distributions for parasequences developed at 10^2–10^3 yr timescales are also plotted separately. The boxes in the plots represent interquartile ranges and horizontal bars represent medians. The scatterplot (D) shows the maximum thickness of both parasequences and deltaic units versus the duration of time over which they have developed; deltaic units are grouped by deltaic system and hierarchy.

this basis, it seems more likely that delta-lobe switching might have a role in controlling the internal architecture of parasequences – in terms of compensational stacking of bedsets – rather than driving parasequence-scale flooding-surface formation. If the lithological and architectural motifs associated with deltaic parasequences are dominantly autogenic in origin, they appear more likely to reflect higher-scale deltaic constructional units, associated with major reconfigurations of fluvial drainage.

Data on deltaic units have implications for using observations from recent delta-lobe deposits to make inferences of scales of stratigraphic compartmentalization in deltaic successions: stratigraphic compartments of sand-prone deposits are likely to develop at a scale that is below the scale of the parasequences, as commonly recognized in the subsurface. The data also suggest that interpretations of the possible autogenic origin of deltaic parasequences (e.g., Emery and Myers, 1996) should be attempted with consideration of scale, especially given that drainage reorganization and the resulting abandonment of parts of a delta might be controlled by sea-level change (cf. Lowrie and Hamiter, 1995; Nijhuis et al., 2015), particularly at the temporal scale that might be relevant for the development of units that are recognized as parasequences.

7. Discussion

The results of this work can contribute to the current debate on the appropriateness and utility of parasequences for the practice of sequence stratigraphy. Parasequences would be most useful if their definition could be applied consistently and objectively, if they all had a similar geological origin, and if their characteristics rendered their physical correlation unambiguous.

However, inconsistency is seen in the application of the original definition and of associated diagnostic criteria, which has resulted in the use of the term parasequence to designate units that are not entirely comparable. It is notable that, in theory, parasequences should not contain lowstand deposits, as they were originally envisaged as the product of paracycles of relative sea-level rise followed by stillstands, with no relative sea-level fall, or of pulses of sediment supply (Kamola and Van Wagoner, 1995). In this respect, parasequences are different from high-resolution sequences. However, this is an element of the original view of a parasequence that has not always been adhered to in the application of the term, in part because the assumption of constantly positive accommodation may not be realistic in most geological contexts (Catuneanu, 2019b). There are cases in which sedimentary units that match with the definition of a parasequence by Van Wagoner et al. (1990), and that are classified accordingly, record a forced regressive evolution during relative sea-level fall (e.g., Plint, 1991; Pattison, 1995; Li et al., 2011a; El Euch-El Koundi et al., 2018; Berton et al., 2019), cases in which conventional parasequences are seen to transition laterally to successions that represent high-frequency sequences (Mitchum Jr and Van Wagoner, 1991; Ito et al., 1999), and even cases where the terms 'parasequence' and 'high-resolution sequence' are used interchangeably (cf. Swift et al., 1991; Schwarz et al., 2018; Pattison, 2019a). Given the timescales of deposition of the majority of parasequences with temporal control that have been considered in this study, which fall in the 10 kyr – 300 kyr range (Fig. 6), the assumption that the studied units only record normal regression may be unrealistic, even for the greenhouse climates of the Mesozoic (cf. Miller et al., 2011). Part of the deposits of these units might record intervals of forced regression – of some magnitude – whose stratal expression is subtle or not revealed within the observation window.

A consistent usage of parasequences is also rendered difficult by practical limitations in the primary data, which determine uncertainty in parasequence correlation between wells or outcrops. The identification of parasequences and the erection of resulting stratigraphic frameworks rely heavily on observations that are expected to vary in quality, coverage and resolution as a function of data types and dimensionality (Fig. 4), and are affected by subjectivity in establishing the significance of stratal trends and surfaces (Fig. 5). Parasequences commonly tend to be dominantly stacked laterally, along both depositional strike and dip (e.g., McIlroy et al., 2005; Vakarelov and Bhattacharya, 2009; Sadeque et al., 2009; Grundvåg et al., 2014): uncertainty as to how to resolve laterally amalgamated units affects both outcrop and subsurface studies, and should be considered when adopting parasequences for scopes of correlation and identification of reservoir units in the subsurface.

The compared units are linked to, and interpreted in terms of, processes operating over a wide range of timescales (Figs. 6 and 7), and are likely to be of different origin despite apparently conforming to the definition of parasequence (Fig. 9). In particular, differences in characteristic geometry and duration are seen between deltaic and shoreface parasequences, which could reflect differences in the dominant forcing mechanisms responsible for their generation. The timescales of ancient shoreface parasequences mostly fall in the range of the periodicities of orbital cycles. Autogenic dynamics might account for the shorter duration of the studied deltaic parasequences, even though a comparison with constructional units of modern deltas indicate that the timescale of accumulation of deltaic parasequences is generally longer than the typical period of lobe-switching events triggered by the inception of new distributaries on delta plains.

These considerations highlight the variability in the geological characteristics of parasequences, and could be held to support the view that the parasequence concept should be discontinued (Zecchin, 2010; Zecchin and Catuneanu, 2013; Miall, 2016; Catuneanu, 2019a, 2019b). Nevertheless, parasequences are widely employed as operative units for organizing sedimentological data relating to sandstone tongues, especially in normal-regressive successions, since, in practice, it is useful to define units that form compartments or reservoir units with local extent and that can be tentatively defined with a limited dataset (e.g., wireline logs only), regardless of whether these units are defined in a way that is coherent in sequence stratigraphic terms. The value of employing outcrop and Quaternary analogues for scopes of subsurface predictions is demonstrated by data on the lateral extent of parasequence sandstones, which reflect a tendency to underestimate the degree of stratigraphic compartmentalization in shallow-marine reservoirs (Fig. 4), and by data on delta-lobe architectures, which might represent a scale of compartmentalization, in the form of intra-parasequence bedsets, that can be expected in deltaic successions (Fig. 11). Concurrently, however, the results presented here provide a measure of the uncertainty that affects any attempt at comparing parasequence architectures of different successions and the application of analogue studies (e.g., Reynolds, 1999; Colombera et al., 2016; Ainsworth et al., 2018, 2019). This uncertainty derives in part from the misidentification of parasequences, for example because sandstone tongues that represent high-resolution sequences might have identical well-log expression (e.g., Plint, 1996), and is in part related to the fact that stratal architectures that match with parasequences develop over a range of spatiotemporal scales, presumably in response to very different controls.

8. Conclusions

A quantitative characterization of clastic parasequences has been undertaken with consideration of their geometry, internal facies characteristics, and temporal significance. These attributes are seen to vary significantly in relation to the interpreted geological origin of the parasequences, to the types of datasets in which they are observed, and to the subjective nature of their recognition.

Notwithstanding a proviso of uncertainty on whether a comparison of this type can even be attempted, the main findings of this work can be summarized as follows:

- The amalgamation of sandstones of shallow-water origin is likely under-recognized in subsurface studies in which the lateral correlation of parasequences is carried out, and may be dealt with in ways that differ considerably in outcrop studies undertaken by different geologists.
- The temporal scale over which parasequences are thought to accumulate apparently covers five orders of magnitude (10^2–10^6 yr), and Quaternary and ancient parasequences appear to map onto different timescales of development. Yet, estimations of parasequence duration are likely to suffer from the inability to constrain the duration of hiatuses, and so the actual variance in duration may be smaller.
- Significant differences in timescale of deposition are seen between shoreface *sensu lato* and deltaic parasequences, suggesting that corresponding stratal patterns that differ in terms of depositional context of origin may arise in response to fundamentally different controls.
- Data from parasequences in the stratigraphic record integrated with data on the architecture of the shallow subsurface of modern deltas indicate that the origin of deltaic parasequences is more likely to be controlled by changes in the state of drainage of coastal rivers, but over a temporal scale and at a level that are larger than those at which deltaic constructional units termed 'delta lobes' are commonly recognized.
- Shoreface parasequences largely develop at timescales that broadly align with those of Milankovitch cycles, i.e., over lengths of time for which the assumption of constantly positive accommodation may not be reasonable in most cases. Some of the studied units may even represent high-frequency sequences, rather than true parasequences *sensu* Van Wagoner (cf. Kamola and Van Wagoner, 1995), which may therefore have restricted applicability anyway.

The observed variability in origin, timescale and anatomy of clastic parasequences, along with inconsistencies in the application of the parasequence concept, have implications for the application of outcrop analogues to subsurface studies and for the feasibility of using parasequences for comparisons of the stratigraphic architecture of different clastic successions. Results of this work can be referred to for guiding the application of existing parasequence data in these contexts and for communicating the uncertainty associated with these data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The SMAKS database has been funded by the sponsors of the Shallow-Marine Research Group (De Beers and Engie [now Neptune]) and by NERC (Catalyst Fund award NE/M007324/1; Follow-on Fund NE/N017218/1). We also thank the sponsors of the Fluvial & Eolian Research Group (AkerBP, Areva [now Orano], BHPBilliton, Cairn India [Vedanta], ConocoPhillips, Chevron, Murphy Oil, Nexen-CNOOC, Occidental, Petrotechnical Data Systems [PDS], Saudi Aramco, Shell, Tullow Oil, Woodside and YPF) for financial support to our research. Ru Wang and Soma Budai are thanked for help with data collection. We thank Editor Chris Fielding and reviewers Janok Bhattacharya and Howard Feldman for their constructive comments, which helped improve the article significantly.

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