PSQuantitative Characterization of the Sedimentary Architecture of Shallow-Marine and Paralic Reservoir Analogs: A Database Approach*

Luca Colombera[1], Nigel P. Mountney[1], David Hodgson[1], and William D. McCaffrey[1]

Search and Discovery Article #41851 (2016)**
Posted August 15, 2016

*Adapted from poster presentation given at AAPG Annual Convention and Exhibition, Calgary, Alberta, Canada, June 19-22, 2016

[1]University of Leeds, Leeds, United Kingdom (l.colombera@leeds.ac.uk)

Abstract

Shallow-marine and paralic clastic depositional systems are described by a large volume of sedimentological, architectural and geomorphological data. A new method that enables the convergence of these datasets into a common descriptive scheme facilitates the identification and application of potential outcrop and modern hydrocarbon-reservoir analogs. To this end, a database has been developed for the collation of data in standardized format, in a way that allows significant comparisons between different depositional systems, and the derivation of consistently defined attributes that can be applied in subsurface studies. The Shallow Marine Architectural Knowledge Store is a relational database devised to include data on the sedimentary architecture of shallow marine and paralic ancient depositional systems, and on the geomorphic organization of corresponding modern environments. The database incorporates data on sedimentary bodies and surfaces and geomorphic units, which are classified on descriptive (e.g. grain size) and interpretive (e.g. sub-environment) categories, and characterized on a variety of attributes (e.g. geometries, spatial relationships, hierarchical relationships). Depositional systems, and stratigraphic intervals or planform segments thereof, are classified on descriptive parameters (e.g. shelf gradient) and controlling factors (e.g. tidal regime) to allow the selection of relevant outcrop or modern analogs. The database can be queried to return a quantified characterization of multiple analogs, and data can be synthesized in models that incorporate uncertainty related to variability in sedimentary heterogeneity. To illustrate the range of genetic units types, depositional systems, associated data and potential applications, example database output is showcased relating to: - the hierarchical arrangement and scaling relationships of architectural elements that form constructional units in Quaternary deltas of different types; - the facies organization of nearshore sandstone belts and the geometry of associated parasequences, from the Upper Cretaceous of the Western Interior Seaway in Utah (USA); - the geometry of modern geomorphic features, and their relations with the geometry of architectural elements interpreted as the preserved product of the morphodynamic evolution of corresponding landforms. Particular attention is paid to how the database output can be applied to the construction of accurate, quantitative 3D geological models.

SMRG

UNIVERSITY OF LEEDS

Quantitative characterization of the sedimentary architecture of shallow-marine and paralic reservoir analogs: a database approach

Luca Colombera, Nigel P. Mountney, David M. Hodgson, William D. McCaffrey

Shallow-Marine Research Group, University of Leeds, UK

Abstract

Shallow-marine and paralic clastic depositional systems are described by a large volume of sedimentological, architectural and geomorphological data. A new method that enables the convergence of these datasets into a common descriptive scheme facilitates the identification and application of potential outcrop and modern hydrocarbon-reservoir analogs. To this end, a database has been developed for the collation of data in standardized format, in a way that allows significant comparisons between different depositional systems, and the derivation of consistently defined attributes that can be applied in subsurface studies.

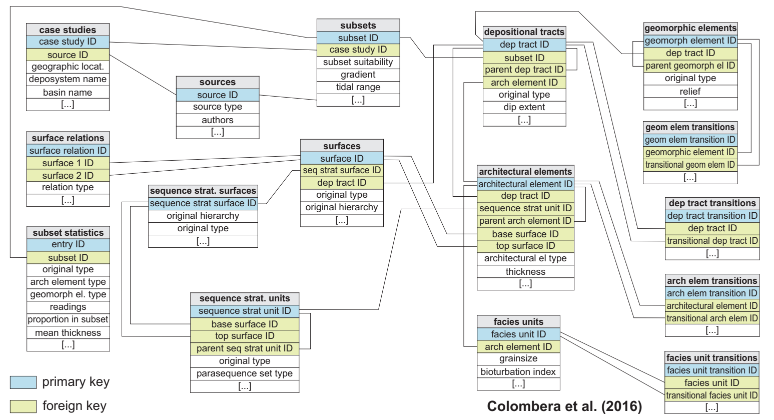
The **Shallow-Marine Architecture Knowledge Store** is a relational database devised to include data on the **sedimentary architecture of shallow marine and paralic ancient depositional systems**, and on the **geomorphic organization of corresponding modern environments**. The database incorporates data on sedimentary bodies and surfaces and geomorphic units, which are classified on descriptive (e.g., grainsize) and interpretive (e.g., sub-environment) categories, and characterized on a variety of attributes (e.g., geometries, spatial relationships, hierarchical relationships). Depositional systems, and stratigraphic intervals or planform segments thereof, are classified on descriptive parameters (e.g. shelf gradient) and controlling factors (e.g. tidal regime) to allow the selection of relevant outcrop or modern analogs.

The **database can be queried to return a quantified characterization of multiple analogs, and data can be synthesized in models** that incorporate uncertainty related to variability in sedimentary heterogeneity.

To illustrate the range of genetic units types, depositional systems, associated data and potential applications, example database output is showcased relating to the following:

- the hierarchical arrangement and scaling relationships of architectural elements that form constructional units in Quaternary deltas of different types;
- the facies organization of nearshore sandstone belts and the geometry of associated parasequences, from the Upper Cretaceous of the Western Interior Seaway in Utah (USA);
- the geometry of modern geomorphic features, and their relations with the geometry of architectural elements interpreted as the preserved product of the morphodynamic evolution of corresponding landforms.

Particular attention is paid to how the **database output can be applied to the construction of accurate, quantitative 3D geological models**.

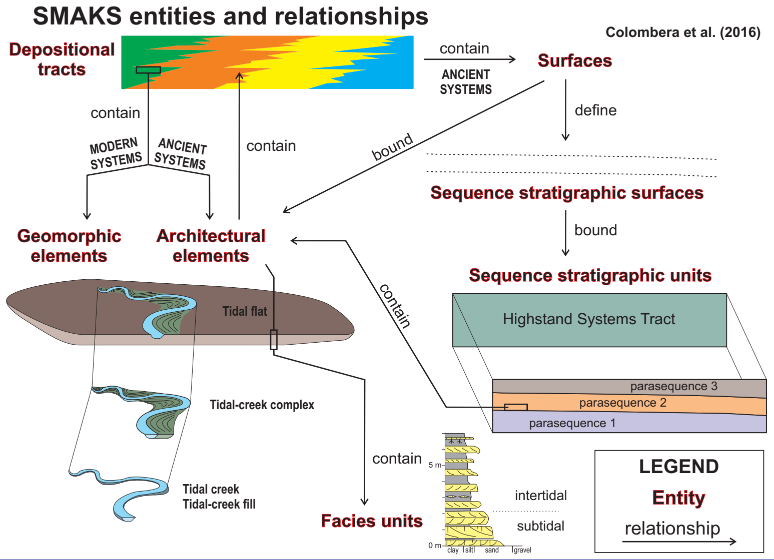


Colombera et al. (2016)

The Shallow-Marine Architecture Knowledge Store

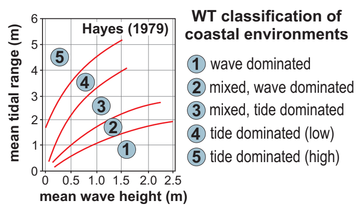
The Shallow-Marine Architecture Knowledge Store (SMAKS) is a relational database devised for storing data on the **sedimentary architecture** of ancient shallow-marine and paralic siliciclastic successions, and on the **geomorphic organization** of corresponding modern environments. The database allows incorporation of data from the **published literature**, uploaded to a common standard to ensure consistency in data definition. SMAKS incorporates data on **geologic entities** of varied nature and scale (i.e., surfaces, depositional tracts, architectural elements, sequence stratigraphic units, facies units, geomorphic elements), and characterizes their type, geometry, spatial relations, hierarchical relations, and temporal significance. SMAKS has been devised to allow translation of different types of datasets in a way that reconciles **different approaches** to analog characterization (e.g., outcrop studies, seismic interpretations, geomorphic mapping).

SMAKS entities and relationships



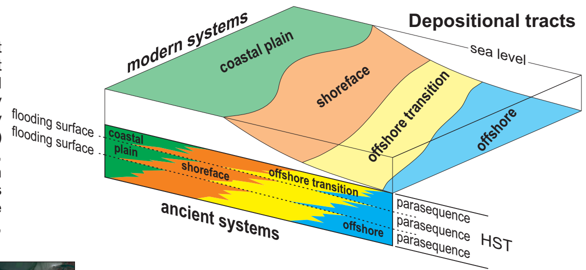
SMAKS depositional systems

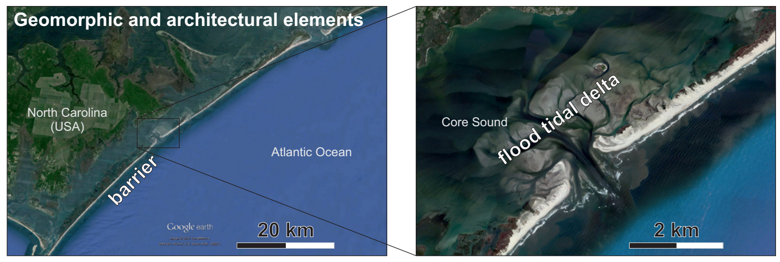
All SMAKS geologic entities are assigned to **case studies**, i.e. datasets on a particular ancient or modern depositional system. All **depositional systems** (or parts thereof, e.g., stratigraphic intervals) are classified on multiple attributes that describe **environmental characteristics and controlling factors** (e.g., basin type, shelf width, tidal range, paleolatitude), tied to case-study **metadata** (e.g., data types, data sources, 'data quality index').
These classifications permit filtering SMAKS in order to obtain sets of output from selected **relevant analogs**.



Classification of SMAKS genetic units

SMAKS **depositional tracts** correspond to plan-form belts that represent **gross depositional settings**, for modern systems, and to their preserved expression in the rock record, in the form of sedimentary bodies that are continuous but potentially architecturally complex, and with boundaries that are time-transgressive and may crosscut stratigraphic surfaces, for ancient systems. Depositional tracts are particularly – but not only – applicable to largest-scale environmental subdivisions. These units enable a lithostratigraphic approach, allowing the characterization of rock domains that represent the preserved product of a sub-environment but embody a potentially complex depositional history. SMAKS depositional tracts largely correspond with the 'facies tracts' of many authors. Depositional tracts can be classified: 1) on categories adopted in the source works (e.g., 'coastal facies belt'), in a text field, and 2) on alternative pre-defined classification schemes (e.g., based on bathymetric zonation of the shoreline profile: 'backshore', 'foreshore', 'shoreface', 'offshore transition zone', 'offshore').





SMAKS **geomorphic elements** are discrete landforms that are characterized by distinctive physiography, resulting from a particular set of depositional and erosional processes, and that represent different sub-environment types.

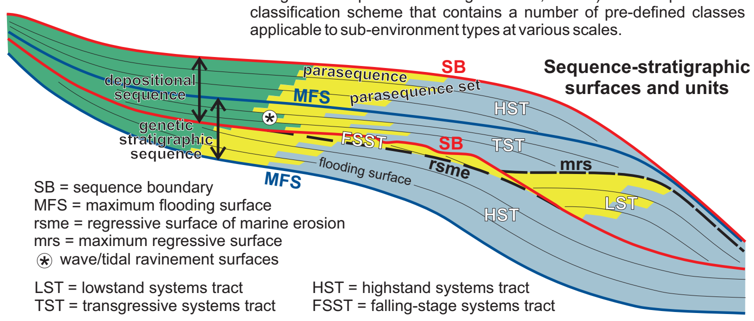
Architectural elements are discrete sedimentary bodies with characteristic facies associations and architectural properties (nature of bounding surfaces, external and internal geometries, stratal trends), interpretable as the preserved product of a sub-environment of deposition. These units enable an architectural approach (cf. Miall 1985), which allows the characterization of rock volumes that typically record the finite morphodynamic evolution of a geomorphic element.

Both architectural and geomorphic elements are classified: 1) on categories adopted in the original work, and 2) on an open-ended classification scheme that contains a number of pre-defined classes applicable to sub-environment types at various scales.

All **bounding surfaces**, including **sequence stratigraphic surfaces**, are classified according to multiple pre-defined classification schemes.

Sequence stratigraphic units are classified on the hierarchical order of units they belong to, and on the type of unit at the particular level. Four pre-defined hierarchical levels are considered: sequence, systems tract, parasequence set, and parasequence. Sequence stratigraphic units are classified according to categories adopted in the source work, which may include informal types. Parasequence sets are classified as 'aggradational', 'progradational' or 'retrogradational'. Systems tracts are classified as 'FSST (falling-stage systems tract)', 'LST (lowstand systems tract)', 'TST (transgressive systems tract)' or 'HST (highstand systems tract)'. Sequences are classified as 'depositional sequence' (cf. Mitchum et al. 1977) or 'genetic stratigraphic sequence' (*sensu* Galloway 1989). Given that sequence stratigraphic units are defined on the basis of the sequence stratigraphic surfaces that define their bases and tops, it is possible for any succession to be described in terms of both depositional sequences and genetic stratigraphic sequences at the same time.

Sequence-stratigraphic surfaces and units

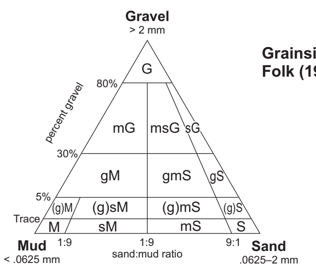


SB = sequence boundary
MFS = maximum flooding surface
rsme = regressive surface of marine erosion
mrs = maximum regressive surface
⊛ wave/tidal ravinement surfaces

LST = lowstand systems tract
TST = transgressive systems tract
HST = highstand systems tract
FSST = falling-stage systems tract

Facies units

Grainsize classes based on schemes of Folk (1980) and Farrell et al. (2012)



other classes:
-G = gravel/conglomerate (generic)
-S = sand/sandstone (generic)
-M = mud/mudstone (generic)
C = clay
Z = silt
G/S = gravel-dominated gravel/sand heterolithic deposits
S/G = sand-dominated gravel/sand heterolithic deposits
S/M = sand-dominated sand/mud heterolithic deposits
M/S = mud-dominated sand/mud heterolithic deposits

Dominant sedimentary structure: classification 1
Massive
Asymmetrical ripple cross-lamination
Symmetrical ripple cross-lamination
Planar horizontal lamination
Low-angle cross-bedding
Trough cross-bedding
Planar cross-bedding
Flaser bedding
Wavy bedding
Lenticular bedding
Swaley cross-stratification
Hummocky cross-stratification

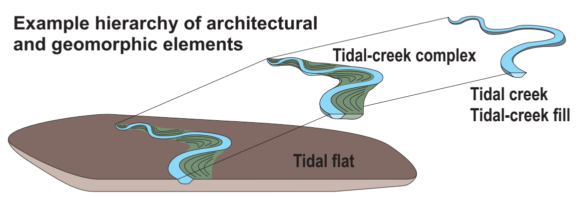
Dominant sedimentary structure: classification 2
Cross-lamination
Horizontal lamination **or** low-angle cross-stratification
Trough **or** planar cross-bedding
Heterolithic structures
Hummocky **or** swaley cross-stratification

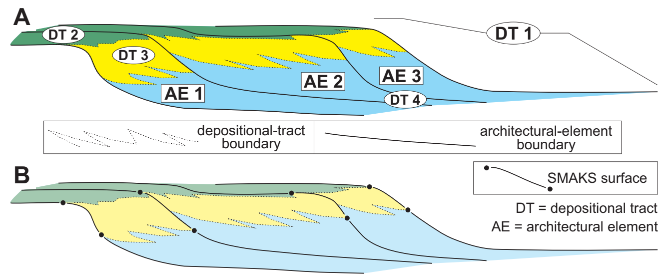
SMAKS **facies units** are elementary lithologic units with sub-bed-scale resolution. The subdivision of deposits into different facies units is based upon identification of changes in sediment texture, structure, paleoflow directions. Facies units are classified on attributes that describe textural characteristics and sedimentary structures (original and predefined classes).

Hierarchy of SMAKS genetic units

Hierarchical relationships **between entities of a different rank** (depositional tracts in subsets or architectural elements, architectural or geomorphic elements in depositional tracts, architectural elements in sequence stratigraphic units, facies units in architectural elements), and **between pairs of genetic units of the same rank** (depositional tracts, architectural elements, or geomorphic elements), but associated with different hierarchical levels, are expressed by means of unique numeric indices used to identify each individual unit. These identifiers are used to relate the tables so that the nature of the containment (nesting) of each unit within higher-scale parent units can be recorded.

Example hierarchy of architectural and geomorphic elements





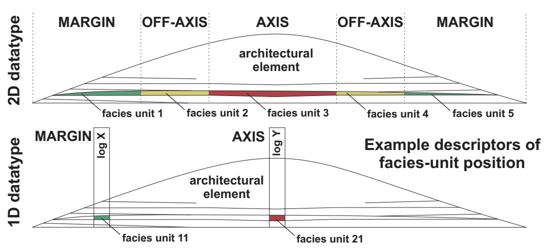
Multiple orders of depositional tracts can be erected for a system, to allow depositional tracts that crosscut different architectural elements to be defined (e.g., delta-front depositional tract that crosscuts several delta-lobe architectural elements; see figure above). Architectural elements are permitted to contain lower-scale depositional tracts and elements themselves may belong to multiple scales, to reflect the hierarchical arrangement of the sub-environments they represent (e.g., tidal channel-fill in tidal-flat deposits; delta lobes within a delta complex).

Spatial relationships and distribution of SMAKS genetic units

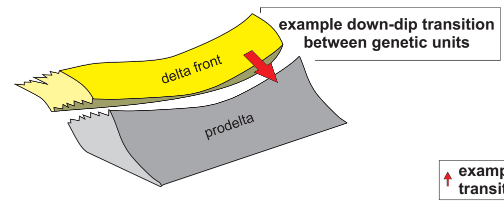
Spatial relationships between pairs of genetic units of the same rank are stored in the form of **transitions along the vertical, strike, and dip directions**. The following conventions are adopted: vertical transitions are upward directed, dip transitions are downdip/offshore directed, strike transitions are right-hand lateral directed, facing offshore.

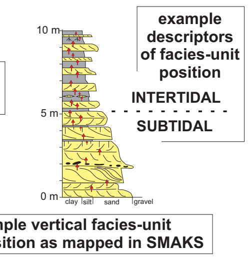
Transitions are expressed by means of the numeric identifiers of the units. Additional attributes used to describe each spatial relationship include the identifiers of the surface across which the transition is recorded, the nature of the transition ('sharp' or 'gradual', for elements and facies units), and the type of stratal termination (e.g., 'updip onlap', 'downlap of upper unit').

In addition, multiple alternative classification schemes are employed to describe the **position of a facies** unit within its parent architectural element, in terms of bathymetric or physiographic setting (e.g., as 'proximal', 'medial', or 'distal').



Example descriptors of facies-unit position





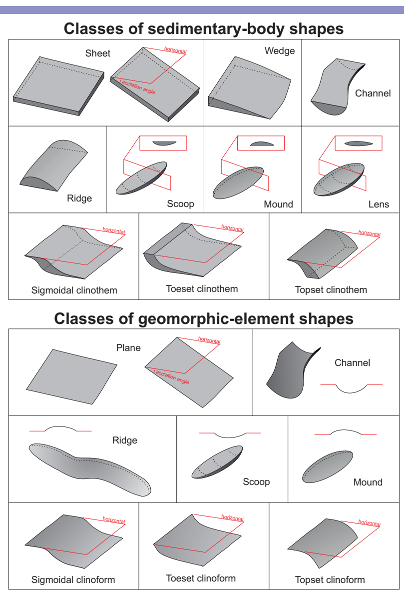
example vertical facies-unit transition as mapped in SMAKS

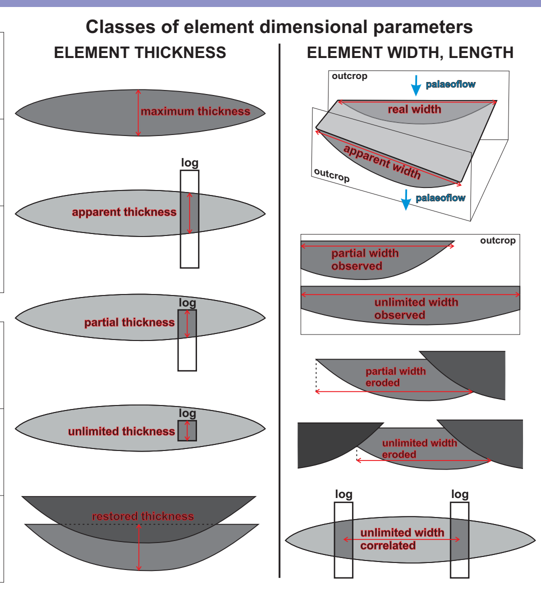
Geometry of genetic units

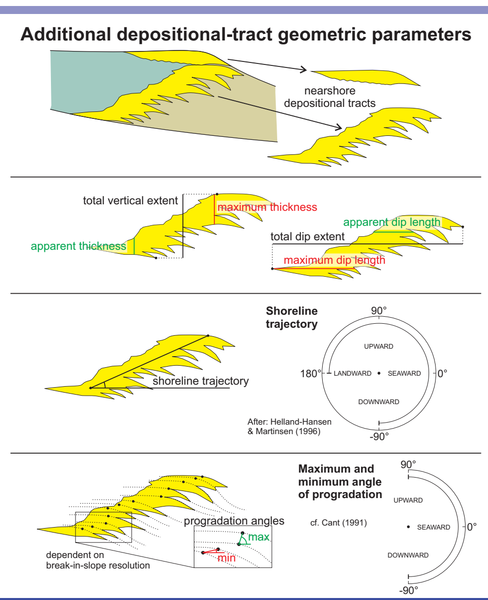
Morphometric parameters describe the geometry of depositional tracts, architectural elements, geomorphic elements and facies units. All these units are characterized in terms of their thickness/height, dip length and strike width, classified by observation type (e.g., as 'real', 'apparent', 'partial', 'unlimited', *sensu* Geehan & Underwood, 1993).

Additional geometric attributes are applicable to particular unit types, for example:

- the 'shoreline trajectory', i.e. the angle that defines the direction of migration of a depositional shoreline-break relative to the paleo-horizontal, cf. Helland-Hansen & Martinsen, 1996;
- 3D volumetric shape of a body;
- 3D surface shape of a landform.







Other attributes

Additional fields characterize attributes of units and store metadata.

These include, for example:

- a 'process category' (interpreted relative importance of wave, tidal and fluvial processes in forming elements; cf. Ainsworth et al., 2011);
- a 'data quality index' used to rank interpretations;
- 'timescale' and 'duration' of a unit;
- 'trace fossil' fields, which specify the presence of ichnogenera in facies units;
- both 'mean aggradation rate' and 'mean progradation rate'.

Bioturbation index (Taylor & Goldring 1993)

Key	BI	% bioturbated
	0	0
	1	1 to 5
	2	5 to 30
	3	30 to 60
	4	60 to 90
	5	90 to 99
	6	100

References

Ainsworth R.B., Vakarelov B.K., Nanson R.A. (2011) AAPG Bulletin 95, 267-297.
Cant D.J. (1991) Basin Research 3, 51-62.
Colombera L., Mountney N.P., Hodgson D.M., McCaffrey W.D. (2016) Mar. Petrol. Geol. 75, 83-99.
Farrell K.M., Harris W.B., Mallinson D.J., Culver S.J., Riggs S.R., Pierson J., Self-Trail J.M., Lautier J.C. (2012) J. Sed. Res. 82, 364-378.
Folk R.L. (1980) Petrology of sedimentary rocks. Hemphill, Austin. 182 pp.
Galloway W.E. (1989) AAPG Bulletin 73, 125-142.
Geehan G., Underwood J. (1993) IAS Spec. Publ. 15, 205-212.
Hayes M.O. (1979) Barrier Islands from the Gulf of Mexico to the Gulf of St. Lawrence, 1-28. Academic Press, New York.
Helland-Hansen W., Martinsen O.J. (1996) J. Sed. Res. 66, 670-688.
Miall A.D. (1985) Earth-Sci. Rev. 22, 261-308.
Mitchum Jr R.M., Vail P.R., Thompson III S. (1977) AAPG Memoir 26, 53-62.
Taylor A.M., Goldring R. (1993) J. Geol. Soc. 150, 141-148.

PetroleumLeeds

Shallow-Marine Research Group
School of Earth and Environment
University of Leeds
Leeds LS2 9JT UK

contact: Luca Colombera
email: l.colombera@leeds.ac.uk
mobile: +44 (0)7554096074
URL: http://smrg.leeds.ac.uk

This research was funded by: NERC SCIENCE OF THE ENVIRONMENT

SMRG is sponsored by: De Beers ENGIE

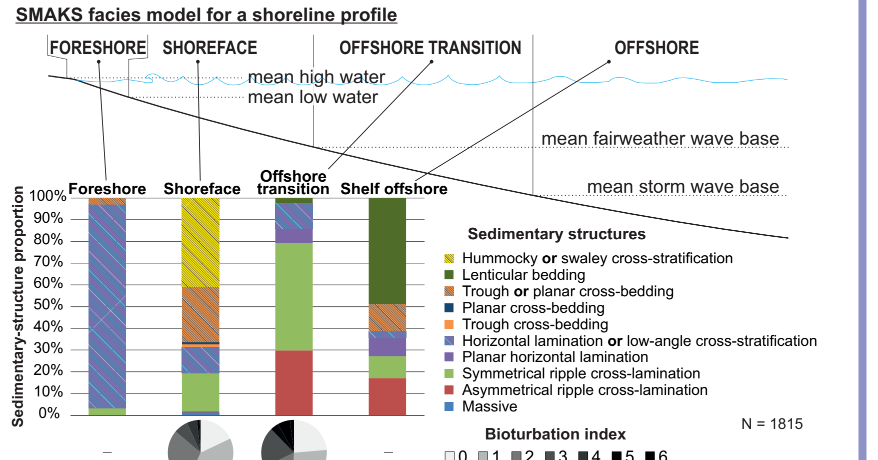
SMRG
Shallow-Marine Research Group
UNIVERSITY OF LEEDS

Quantitative characterization of the sedimentary architecture of shallow-marine and paralic reservoir analogs: a database approach

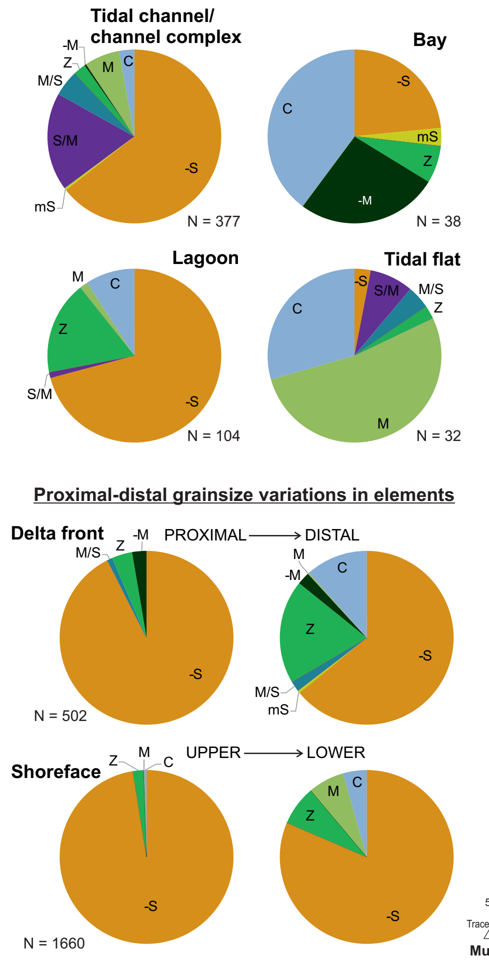
Luca Colombera, Nigel P. Mountney, David M. Hodgson, William D. McCaffrey
Shallow-Marine Research Group, University of Leeds, UK

Facies models for paralic and shallow-marine sub-environments

SMAKS can be queried for proportions of genetic units in higher-scale parent units. For example, it is possible to compute the proportion of different facies-unit types in depositional tracts, or of architectural-element types in sequence stratigraphic units. This type of information can be employed to build base-case facies models, which can describe the likelihood of occurrence of different grain-size categories and associated sedimentary structures in various sub-environments. These proportions could be based on the total measured thickness of facies units, and could relate SMAKS grain-size categories (see figures below), the types of internal sedimentary structures seen in sand-prone facies units (see figures at bottom left, and on the right), or classes of lithofacies bioturbation index (see figure on the right). Spatial variations in facies organization can be characterized in terms of changes within genetic units of a given type, and across genetic units of a given rank. Effective integration of many datasets can be achieved when interpretive classes of sub-environments can be attributed based on SMAKS criteria and definitions, which may differ from the ones adopted in the original source works, even when a corresponding nomenclature is used. Re-classification of units is undertaken only when a match with SMAKS criteria and definitions can be established.

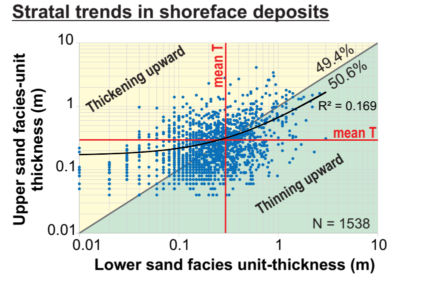


Proportion of grainsize classes in paralic elements

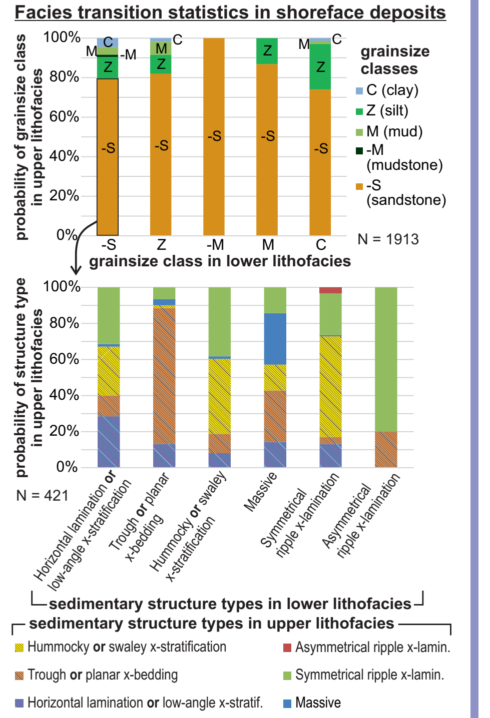


SMAKS can be queried for statistics that describe the spatial relationships between genetic units of a given rank. For example, vertical transition statistics could be obtained for grain-size categories, or for the types of internal sedimentary structures seen in sand-prone facies units (see figures on the right). SMAKS allows transition statistics to be computed at any order, to elucidate the internal facies organization of particular types of units, to quantify the degree of development of stratal trends (e.g., rate of thickening upward of shoreface deposits; see figure below), or to constrain reservoir models based on Markov chains.

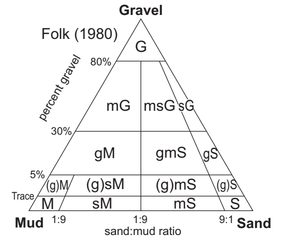
Stratal trends in shoreface deposits



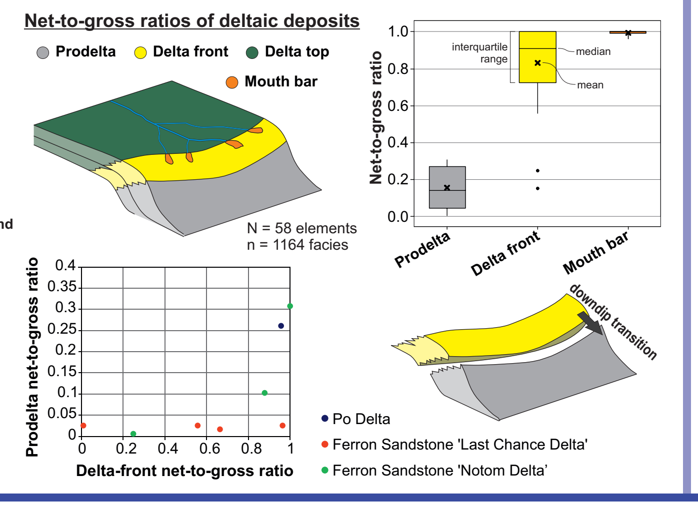
Facies transition statistics in shoreface deposits



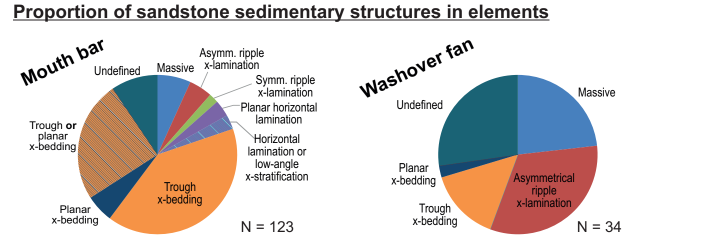
SMAKS can be applied to determine ranges of net-to-gross ratios for types of deposits, based on genetic-unit proportions and on user-defined specifications of net categories. Such data, compiled from multiple analogs, could be applied to make predictions of uncertainty in net-to-gross ratio for reservoir sandstones in sand-prone facies units (e.g., delta front) or for objects that may be below seismic resolution (e.g., mouth bars). Because SMAKS records spatial relationships between units, net-to-gross output can be retrieved for spatially related units (e.g., delta-front and prodelta deposits; see figure below). Such information could be applied to attempt predictions of net-to-gross ratios away from wells.



Net-to-gross ratios of deltaic deposits

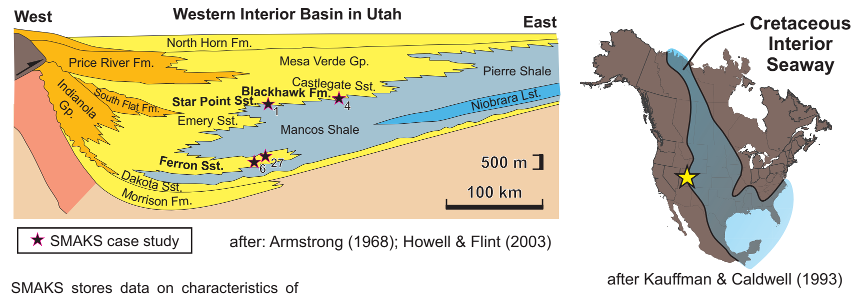


Proportion of sandstone sedimentary structures in elements



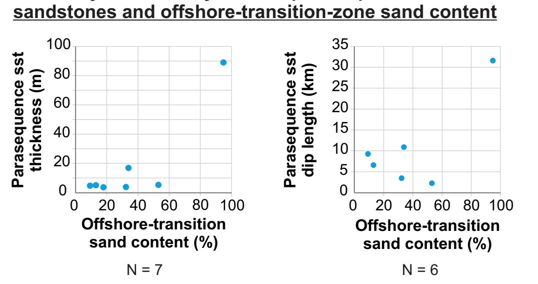
Characterization of parasequence-scale shallow-marine sandstones of the Cretaceous Western Interior Seaway (Utah, USA)

ID	Case study	Location	Age	Data source
1	Star Point Sandstone	Utah, USA	Santonian-Campanian	Hampson et al. (2011)
4	Composite database (includes Blackhawk Formation data)	- (Utah, USA)	- (Campanian)	Reynolds (1999)
6	Ferron Sandstone, 'Notom Delta'	Utah, USA	Turonian	Li et al. (2010)
				Li et al. (2011a)
				Li et al. (2011b)
				Li et al. (2012)
				Zhu et al. (2012)
27	Ferron Sandstone, 'Last Chance Delta'	Utah, USA	Turonian-Coniacian	Garrison & van den Bergh (2004)
				Van den Bergh & Garrison (2004)

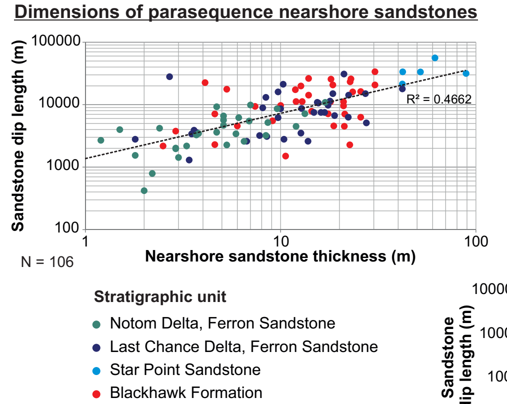


SMAKS stores data on characteristics of parasequence-scale sandstones. These sandstone units represent nearshore sand belts, but no specific genetic significance is implied for their definition (e.g., in bathymetric terms). Also, no sand-to-mud threshold is considered in the SMAKS standard for the definition of these units. The geometries of these units are based on lower and upper boundaries and pinch-outs of the sand-prone segments of the parasequences, as mapped in each of the original source works from which the data are derived. To assess the degree to which these units reflect the sub-environment of deposition, data on the geometry of parasequence sandstones can be related to the proportion of sandy facies units in deposits that represent a preserved record of the offshore transition zone in the same parasequences, as shown on the right.

Geometry of arbitrarily defined parasequence sandstones and offshore-transition-zone sand content



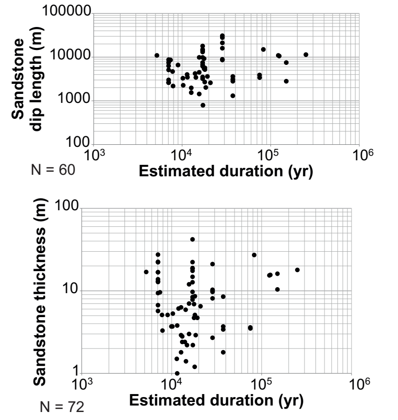
Dimensions of parasequence nearshore sandstones



The figure on the left illustrates output on the geometry of nearshore sandstone belts from Upper Cretaceous parasequences of the Western Interior Seaway of Utah (USA), based on data derived from published outcrop studies of the Ferron Sandstone, Star Point Sandstone and Blackhawk Formation (see table above). The scatter-plot relates the dip length (horizontal distance between the up-dip and down-dip boundaries) and thickness of parasequence-scale nearshore sandstones. A power-law regression curve is fitted to the data.

Temporal significance of parasequences

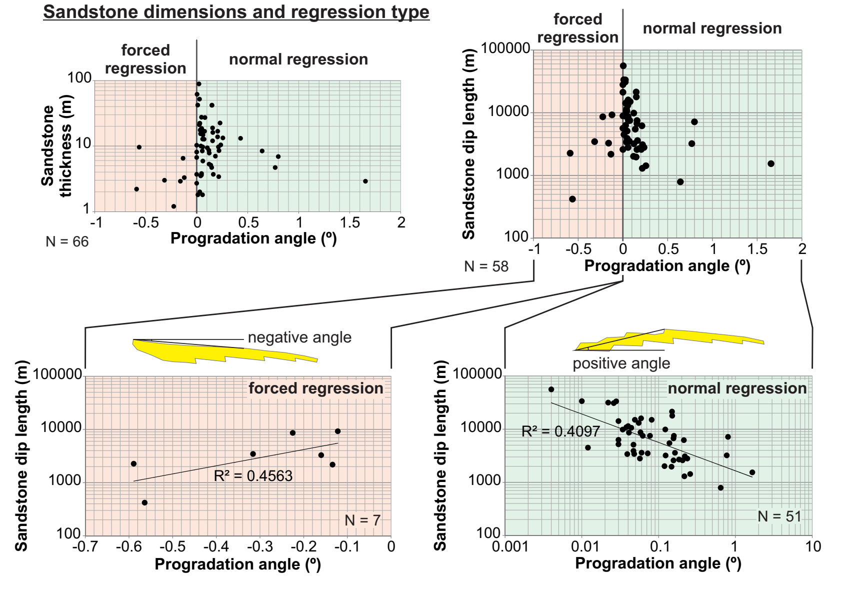
The temporal significance of sequence stratigraphic units is characterized in SMAKS in terms of their timescale, i.e., the order of magnitude of the time embodied by the unit (e.g., 10^4 yr), and of their duration, i.e., the length of time embodied by the unit (e.g., 150,000 yr); both attributes are based on existing temporal constraints. The studied parasequences are inferred to record deposition at timescale of 10^3 yr to 10^5 yr. Weak positive relationships are seen (i) between the thickness of a nearshore sandstone and the inferred timespan embodied by the corresponding parasequence (Pearson correlation coefficient of 0.183; p-value 0.123), and (ii) between the dip length of the sandstone and the timespan of the parasequence (Pearson correlation coefficient of 0.126; p-value 0.339).



The progradation angle is the angle that tracks the direction of progradation of the regressive evolution of a parasequence (i.e., its regressive shoreline trajectory; Helland-Hansen & Martinsen 1996), relative to the paleo-horizontal, corrected for structural dip. Below, scatterplots relate the dip length of parasequence shallow-marine sandstones to their progradation angle. The field of negative progradation angle (forced regression) and of positive progradation angle (depositional regression) are expanded in separate graphs, in which exponential and power-law regression curves are respectively fitted to the data. The dip length of parasequence nearshore sandstones appears to increase as the progradation angle approaches 0º.

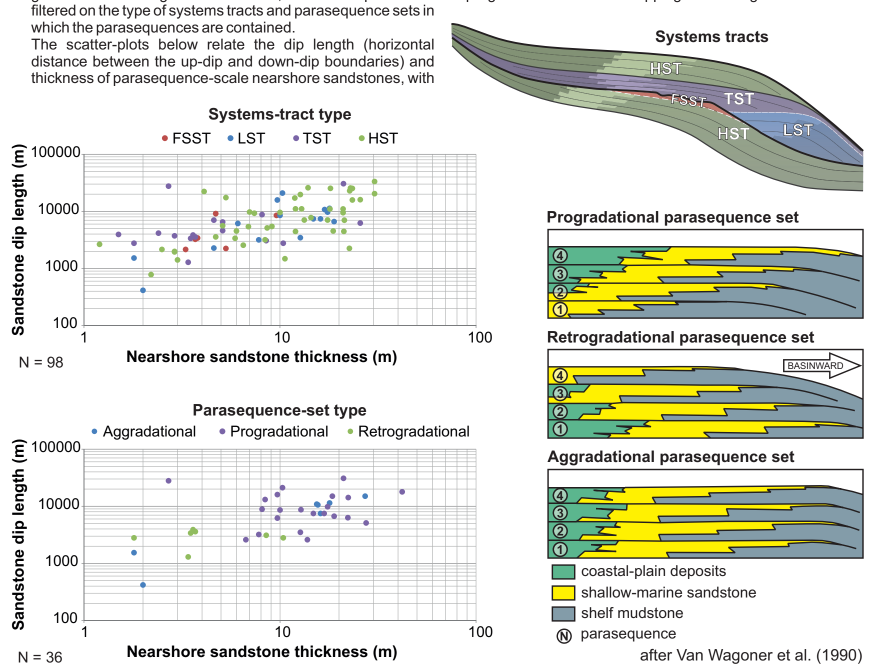
Information on the geometry of parasequence-scale sandstones are suggestive of possible controls on deposition in nearshore areas. A positive relationship is seen between the thickness and the dip length of parasequence sandstone units (Pearson correlation coefficient of 0.686; p-value 0.000), which may be interpreted in terms of a control by the source and supply rate of sand to the nearshore (cf. Niedoroda et al. 1984; Cowell et al. 1999; Helle & Helland-Hansen 2009), whereas the down-dip lateral continuity of shallow-marine sandstones tend to be highest under conditions where the ratio between the rate of accommodation generation and sediment supply is closest to zero.

Sandstone dimensions and regression type



Sandstone dimensions and type of parasequence set or systems tract

The SMAKS output above provides insight into the way parasequence sandstones may be controlled by the ratio between rate of accommodation creation and rate of sediment supply (A/S), at the temporal scale of the parasequence. To assess potential relationships between parasequence geometries and longer-term A/S ratio, SMAKS output can be filtered on the type of systems tracts and parasequence sets in which the parasequences are contained. The scatter-plots below relate the dip length (horizontal distance between the up-dip and down-dip boundaries) and thickness of parasequence-scale nearshore sandstones, with data points color-coded on the different classes of (i) systems tract and (ii) parasequence sets that host each parasequence. The dimensions of parasequence sandstones do not seem to be controlled by the systems tract types. Additional data are required to assess whether the apparent differences between progradational and backstepping sets are significant.

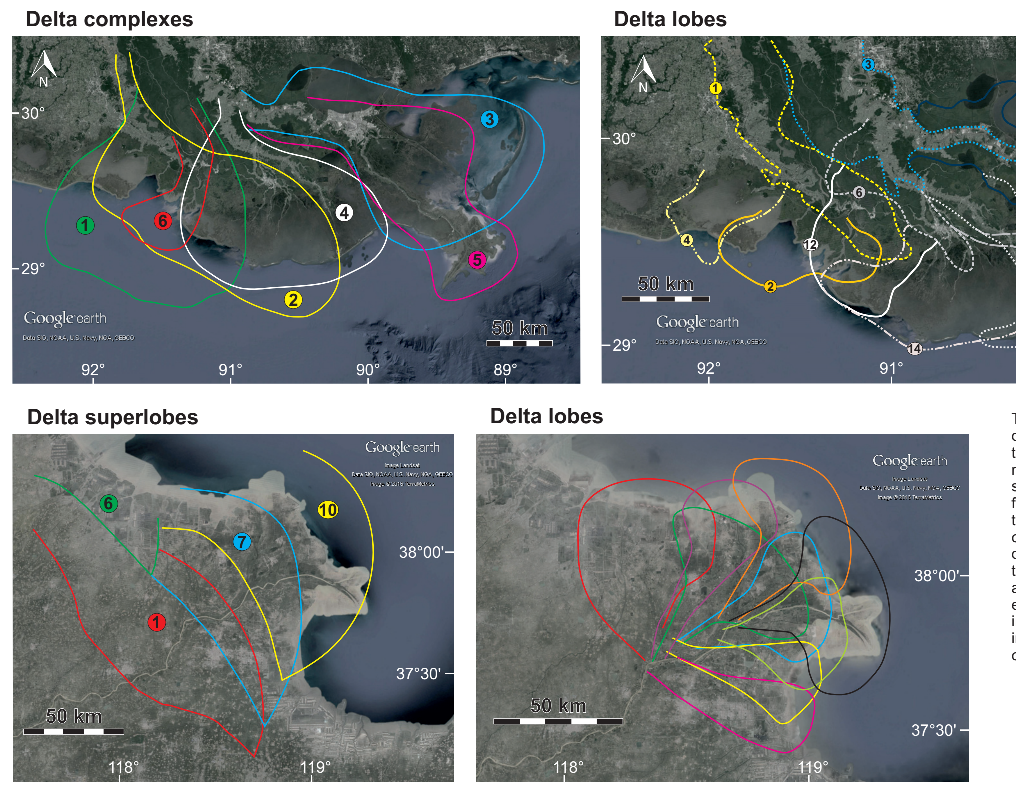


Characterization of hierarchically arranged architectural elements in Quaternary deltas

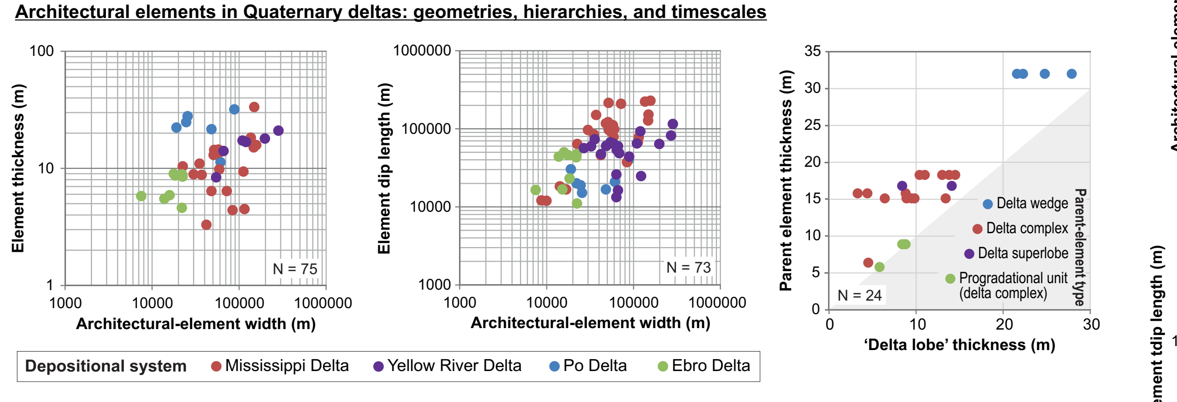
ID	Case study	Location	Data source
2	Po Delta	Italy, Adriatic Sea	Correggiari et al. (2005a)
			Correggiari et al. (2005b)
3	Mississippi Delta	USA, Gulf of Mexico	Frazier (1967)
			Roberts (1997)
5	Ebro Delta	Spain, Mediterranean Sea	Somoza et al. (1998)
26	Yellow River Delta	China, Bohai Sea	Xue (1993)
			Van Gelder et al. (1994)
			Li et al. (1998)
			Wang et al. (2015)

SMAKS allows derivation of output information on the properties of architectural elements at multiple hierarchical levels, corresponding to different scales of observation, because hierarchical relationships are tracked in terms of the containment of lower-order elements in higher-order parent elements.
Also, SMAKS can be queried for output on units that are solely classified following nomenclatures adopted in the source publications or field studies, i.e., for which no equivalent sub-environment type or architectural-element designation exists in SMAKS at the time of data entry (the classification of sub-environments is expandable and can accommodate units at many levels).

Here, data are presented that relate to building blocks of deltas at multiple scales, and which are originally categorized following different nomenclatures. The studied elements, from four different Quaternary depositional systems (Po, Mississippi, Yellow River, and Ebro deltas), are all recognized in the original source works based on interpretations of suitable subsurface datasets.
Quantified database output on spatial scales, temporal scales, and hierarchical relationships of relative containment is presented; this information is directly relevant to the characterization of hierarchy in the organization of the depositional units, as recognized within and across depositional systems.

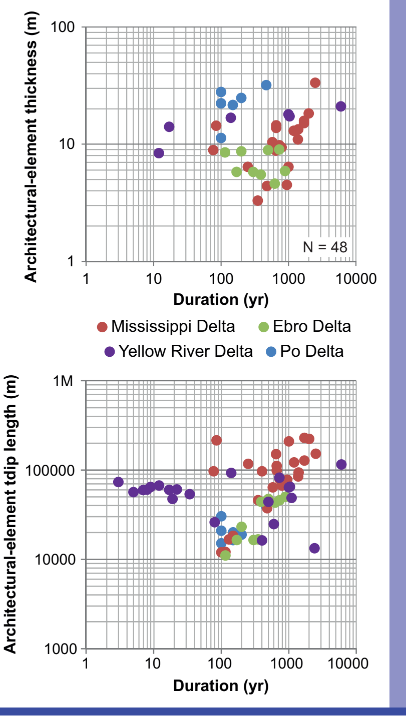


Architectural elements in Quaternary deltas: geometries, hierarchies, and timescales



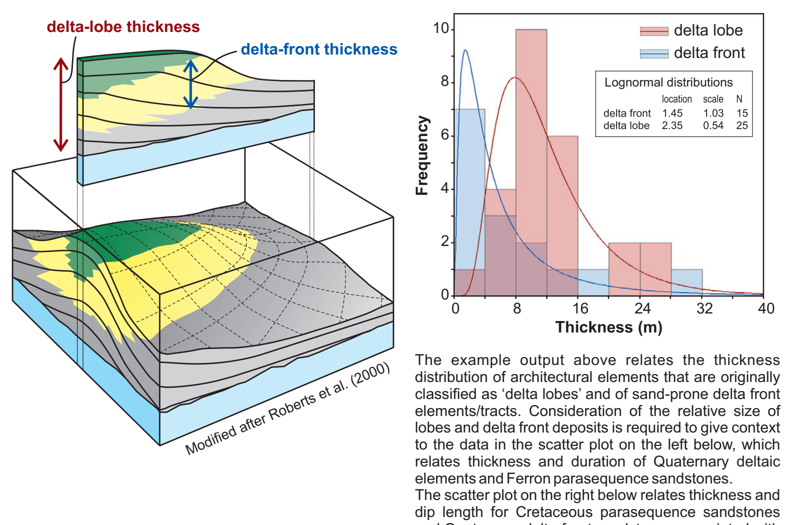
The analyzed literature studies recognized a hierarchy of deltaic constructional units, and each of these studies erected a nomenclature of its own for units belonging to the different orders. This analysis highlights the use of a common term: the 'delta lobe'. A delta lobe is not defined on widely established criteria, such as the drainage order of the distributary whose inception in response to channel avulsion triggered deposition, or their absolute or relative size, or their timescale. The flexibility in the way that SMAKS accommodates genetic-unit classifications enables this type of analysis, which permits comparisons of hierarchical and classification schemes for depositional units, some of which may use terms that are broadly adopted but perhaps loosely defined in genetic terms. Thus, this example output offers an indication of the value of SMAKS as a tool with which to undertake comprehensive analyses of the hierarchical organization in the sedimentary architecture of clastic depositional systems, and of the terminology associated with hierarchical schemes. SMAKS can facilitate the review and analysis of the varied terminology adopted in the published literature, and may therefore find application in highlighting terminological pitfalls in current sedimentological practice.

The scatter plots presented below relate strike-oriented width, dip-oriented length, thickness and temporal duration for architectural elements that represent deltaic constructional units at multiple scales, and which were originally categorized following different nomenclatures. Additionally, for the architectural elements originally classified as 'delta lobe' is shown against the thickness of the higher-scale architectural elements in which the 'lobes' are hosted; the spots are colored according to the classification of the higher-scale elements, as in legend. The duration of deposition, inferred from temporal constraints, provides an indication of the timescale of deltaic 'lobe'-switching cycles for the different orders of depositional units.

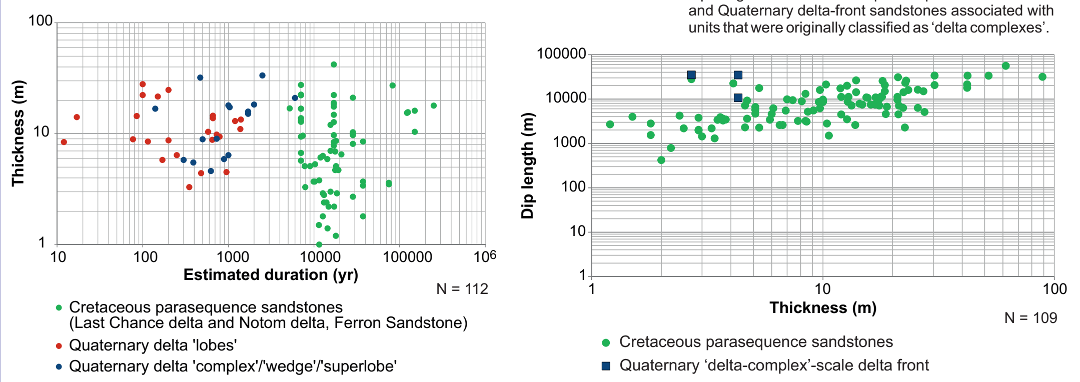


Comparing deltaic constructional units and parasequences

In the shallow-marine realm, the development of parasequences is commonly interpreted in terms of (i) variations in relative sea level, whereby flooding surfaces are generated by positive eustatic fluctuations or increases in subsidence, or (ii) in terms of delta lobe-switching processes, whereby avulsion of the genetically related distributary channel causes lobe abandonment and subsequent drowning (Van Wagoner et al. 1990). The latter mechanism is expected to be active in the context of river-dominated coasts, such as the interpreted setting of the Cretaceous Ferron Sandstone Member of the Mancos Shale of Utah (USA). Here, we compare the temporal and spatial scales of genetic units from Quaternary deltas with those of parasequence shallow-marine sandstones from the Last Chance and Notom deltas of the Ferron Sandstone, which accumulated in the context of a retroarc foreland basin subject to greenhouse wet climate.



The example output above relates the thickness distribution of architectural elements that are originally classified as 'delta lobes' and of sand-prone delta front elements/tracts. Consideration of the relative size of lobes and delta front deposits is required to give context to the data in the scatter plot on the left below, which relates thickness and duration of Quaternary deltaic elements and Ferron parasequence sandstones.
The scatter plot on the right below relates thickness and dip length for Cretaceous parasequence sandstones and Quaternary delta-front sandstones associated with units that were originally classified as 'delta complexes'.



Summary

SMAKS is a database that is being populated **with data on the sedimentary organization of shallow-marine and paralic depositional systems**. The database design and standard have been structured with **consideration of the variety of approaches and data types** that are taken in studying the sedimentary geology of shallow-marine and paralic depositional systems. The database allows for a convergence of **datasets from studies of outcrops, of the subsurface and of the modern seabed**, and permits the reconciliation of **facies analysis, architectural-element analysis, sequence stratigraphy and geomorphology** in the same framework.

SMAKS can be interrogated to **select suitable outcrop or modern analogs**, based on knowledge of depositional-system boundary conditions or sedimentological characteristics, or to build quantitative facies models based on the integration of many studied examples, as well as composite analogs.

SMAKS output can be **employed in a range of applications**, and particularly in subsurface studies. For example, SMAKS can be used for:

- guiding **rock-record interpretations**, and the development of conceptual models of reservoir heterogeneity;
- conditioning **stochastic reservoir models**;
- informing **inter-well correlations** of sedimentary bodies;
- attempting **predictions of reservoir characteristics** (e.g., for geophysically imaged units, or away from well coverage);
- assessing **seismic resolvability** of genetic units;
- **predicting stratigraphic traps**, in terms of potential occurrence and size.

Additionally, SMAKS is a tool that can be employed to **assist fundamental research** that may benefit the hydrocarbon E&P industry. For example, SMAKS can be used to investigate controls on deposition through comparative analyses of multiple depositional systems, and hence to assess the value of depositional-system parameters as predictors of sedimentary architecture, or to test the value of modern forms as analogs to preserved ancient deposits.

References

Armstrong R.L. (1968) GSA Bull. 79, 429-458.
Colombera L., Mountney N.P., Hodgson D.M., McCaffrey W.D. (2016) Mar. Petrol. Geol. 75, 83-99.
Correggiari A., Cattaneo A., Trincardi F. (2005a) SEPM Spec. Publ. 83, 365-392.
Correggiari A., Cattaneo A., Trincardi F. (2005b) Mar. Geol. 222, 49-74.
Cowell P.J., Roy P.S., Cleveringa J., de Boer P.L. (1999) SEPM Spec. Publ. 62, 371-380.
Folk R.L. (1980) Petrology of sedimentary rocks. Hemphill, Austin. 182 pp.
Frazier D.E. (1967) Trans. Gulf Coast Assoc. Geol. Soc. 17, 287-315.
Garrison Jr. J.R., van den Bergh T.C.V. (2004) AAPG Studies in Geology 50, 125-192.
Hampson G.J., Gani M.R., Sharman K.E., Irfan N., Bracken B. (2011) J. Sed. Res. 81, 159-184.
Helland-Hansen W., Martinsen O.J. (1996) J. Sed. Res. 66, 670-688.
Helle K., Helland-Hansen W. (2009) Basin Res. 21, 620-643.
Howell J.A., Flint S.S. (2003) In: Coe A (ed.) The sedimentary record of sea-level change, 158-178. Cambridge University Press, Cambridge.
Li G., Wei H., Yue S., Cheng Y., Han Y. (1998) Mar. Geol. 149, 113-131.
Li W., Bhattacharya J.P., Campbell C. (2010) J. Sed. Res. 80, 529-549.
Li W., Bhattacharya J., Zhu Y. (2011a) Mar. Petrol. Geol. 28, 1517-1529.
Li W., Bhattacharya J.P., Zhu Y., Garza D., Blankenship E. (2011b) Sedimentology 58, 478-507.
Li W., Bhattacharya J.P., Zhu Y. (2012) AAPG Bull. 96, 415-438.
Niedoroda A.W., Swift D.J., Hopkins T.S., Ma C.M. (1984) Mar. Geol. 60, 331-354.
Reynolds A.D. (1999) AAPG Bull. 83, 211-229.
Roberts H.H. (1997) J. Coast. Res. 13, 605-627.
Somoza L., Barnolas A., Arasa A., Maestro A., Rees J.G., Hernandez-Molina F.J.
(1998) Sed. Geol. 117, 11-32.
Van den Bergh T.C.V., Garrison Jr. J.R. (2004) AAPG Studies in Geology 50, 451-498.
Van Gelder A., van den Berg J.H., Cheng G., Xue C. (1994) Sed. Geol. 90, 293-305.
Van Wagoner J.C., Mitchum R.M., Campion K.M., Rahmanian V.D. (1990) AAPG Methods in Exploration Series 7. AAPG, Tulsa, 55 pp.
Wang Y., Liu X., Li G., Zhang W. (2015) Geol. Soc. London Spec. Publ. 429, article SP429-8.
Xue C. (1993) Mar. Geol. 113, 321-330.
Zhu Y., Bhattacharya J.P., Li W., Lapen T.J., Jicha B.R., Singer B.S. (2012) J. Sed. Res. 82, 723-746.

PetroleumLeeds
Shallow-Marine Research Group
School of Earth and Environment
University of Leeds
Leeds LS2 9JT UK
contact: Luca Colombera
email: l.colombera@leeds.ac.uk
mobile: +44 (0)7554096074
URL: http://smrg.leeds.ac.uk

This research was funded by: NERC SCIENCE OF THE ENVIRONMENT
SMRG is sponsored by: De Beers ENGIE

Quantitative characterization of the sedimentary architecture of shallow-marine and paralic reservoir analogs: a database approach

Luca Colombera, Nigel P. Mountney, David M. Hodgson, William D. McCaffrey

Shallow-Marine Research Group, University of Leeds, UK

Abstract

Shelf tidal sand ridges are large (up to over 200 km long and over 50 m high) depositional landforms underlain by co-genetic sedimentary bodies. Depending on their size and internal characteristics, sand ridges may form excellent hydrocarbon reservoir units. Observations from Quaternary and modern depositional systems indicate that the development of tidal sand ridges is common in tide-dominated shallow seas under transgressive conditions, and that the resulting ridges may be buried by mud-prone deposits (e.g. prodelta mudstones) during the subsequent sea-level highstand. In this context, and depending on co-occurring factors, sand-ridge architectural elements may form elongated stratigraphically trapped reservoirs of significant size. Sedimentary facies models provide constraints to guide interpretations of tidal sand-ridge deposits in the subsurface rock record. However, predictions of their reservoir characteristics or trapping potential are largely qualitative and based on individual, well-documented examples.

This study integrates sedimentological data from ancient and Quaternary deposits interpreted as preserved tidal sand ridges with geomorphological data from modern seas. A composite dataset has been compiled from a number of published case studies to offer a quantitative characterization of the sedimentary architecture of tidal sand-ridge deposits. All data have been included in the Shallow-Marine Architecture Knowledge Store (SMAKS), a relational database designed to accommodate data on the architecture of shallow-marine and paralic depositional systems, coded to a common standard. Qualitative information on the studied examples is considered together with quantitative SMAKS database output that describes the geometries and facies properties of tidal sand-ridge architectural elements and geomorphic units, and their relationships with associated units.

This work assesses the value of modern sand-ridge landforms as analogues for stratigraphic traps and reservoir units, by assessing the roles of morphodynamic evolution and preservation potential in controlling the architecture of preserved stratigraphic products. The results of the analysis highlight the uncertainty in considering modern forms as representative analogues to depositional products, in particular with respect to their preserved morphometry and notably in relation to the compound depositional-erosional nature of forms whose height is only partially related to build-up of depositional relief.

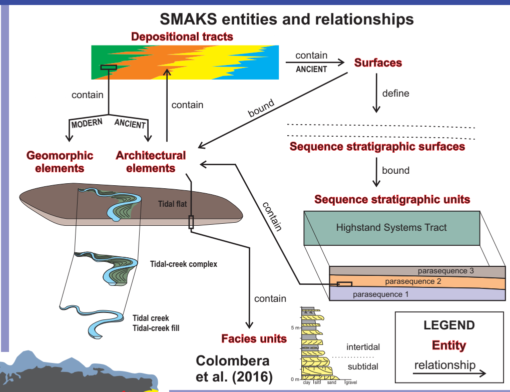
This study demonstrates the sensitivity of sand-ridge morphometry to plausible controlling factors, thereby enabling predictions of likely reservoir continuity or trapping potential from knowledge of depositional boundary conditions including shelf-edge depth, tidal range and transgression rate.

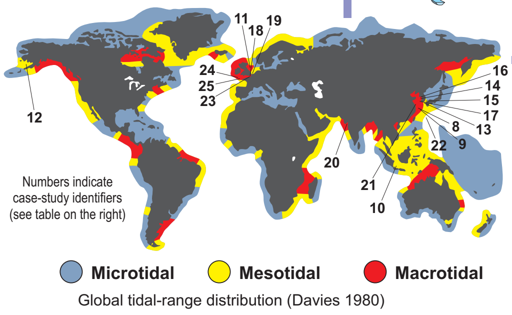
SMAKS database and case studies

The Shallow-Marine Architecture Knowledge Store (SMAKS) is a relational database devised for storing data on the sedimentary architecture of ancient shallow-marine and paralic siliciclastic successions, and on the geomorphic organization of corresponding modern environments. The database allows incorporation of data from the published literature, uploaded to a common standard to ensure consistency in data definition. SMAKS incorporates data on geological entities of varied nature and scale (i.e., surfaces, depositional tracts, architectural elements, sequence stratigraphic units, facies units, geomorphic elements), and characterizes their type, geometry, spatial relations, hierarchical relations, and temporal significance. All geological entities are assigned to depositional systems (or parts thereof) classified on multiple parameters (e.g., shelf width, tidal range) tied to metadata (e.g., data types, data sources).

SMAKS includes datasets of ancient, Quaternary and modern tidal sand ridges, which are here (i) synthesized in a facies model that offers a quantitative characterization of the sedimentary architecture of tidal sand ridges, and (ii) analysed with the scope of establishing rules for guidance of subsurface predictions in tide-dominated transgressive systems tracts.

SMAKS entities and relationships





Global tidal-range distribution (Davies 1980)

ID	Case study	Data source	Type
7	Composite database	Off (1963)	Modern
8	East China Sea	Liu et al. (2000)	Modern + Quaternary
		Berné et al. (2002)	
		Liu et al. (2007)	
9	East China Sea	Yang (1989)	Quaternary
10	Upper Cibulakan Fm.	Posamentier (2002)	Ancient (Miocene)
11	East Bank, North Sea	Davis & Balson (1992)	Modern + Quaternary
12	Bering Sea	Nelson et al. (1980)	Modern + Quaternary
13	Eastern Yellow Sea	Park & Lee (1994)	Modern + Quaternary
14	Korea Strait	Park & Lee (1994)	Modern + Quaternary
15	Korea Strait	Park et al. (2003)	Modern + Quaternary
16	Eastern Yellow Sea	Park et al. (2006)	Modern + Quaternary
17	Eastern Yellow Sea	Klein et al. (1982)	Modern + Quaternary
18	Southern North Sea	Trentesaux et al. (1994)	Modern + Quaternary
		Berné et al. (1994)	
		Trentesaux et al. (1999)	
19	Southern North Sea	Houbolt (1968)	Modern + Quaternary
		Caston (1972)	
20	Gulf of Khambhat	Saha et al. (2007)	Modern
21	Western Yellow Sea	Liu et al. (1989)	Modern + Quaternary
22	East China Sea	Yoo et al. (2002)	Modern + Quaternary
23	Southern North Sea	Tessier et al. (1999)	Modern + Quaternary
24	Celtic Sea	Bouysse et al. (1976)	Modern
		Evans et al. (1984)	
		Pantin & Evans (1984)	
		Scourse et al. (2009)	
25	Celtic Sea	Berné et al. (1998)	Modern + Quaternary
		Marsset et al. (1999)	
		Reynaud et al. (1999)	
		Reynaud et al. (2003)	

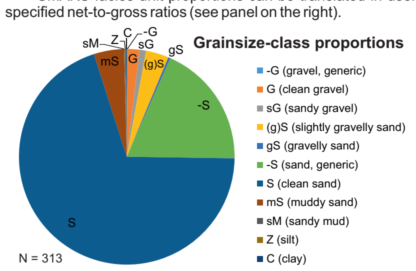
Sand-ridge lithofacies

SMAKS data on grainsize and thickness of facies units from tidal sand-ridge elements are used to derive the following:

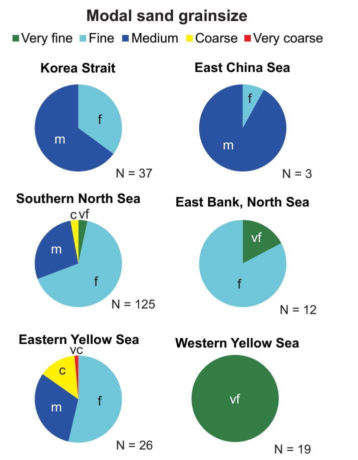
- base-case proportions of grainsize classes in sand-ridge elements (below);
- proportions of granulometric classes of sandy facies units for tidal sand ridges from six different locations (on the right);
- grain-size mean and standard deviation for sandy facies units from shelf tidal sand ridges (far right).

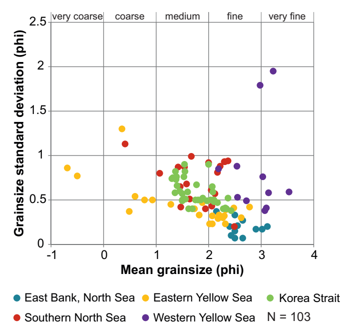
SMAKS facies-unit proportions can be translated in user-specified net-to-gross ratios (see panel on the right).

Grainsize-class proportions



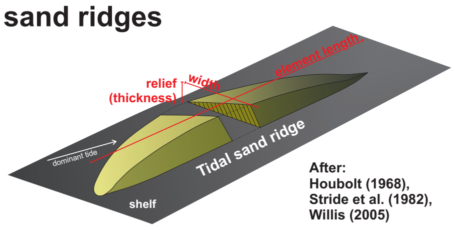
Modal sand grainsize

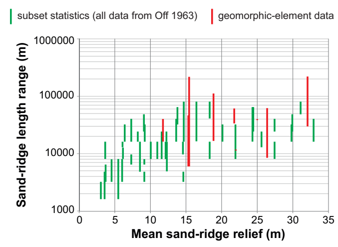


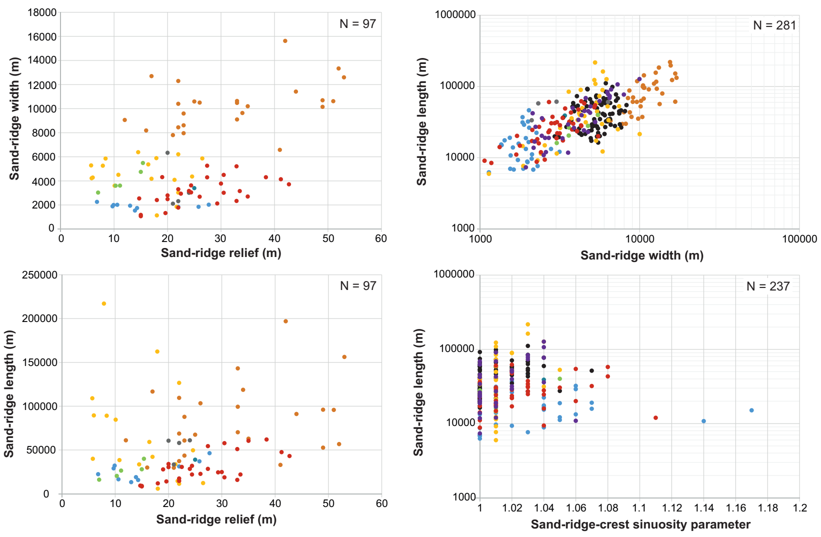


Morphometry of modern sand ridges

SMAKS elements are characterized in terms of their thickness (architectural elements) or relief (i.e., height; geomorphic elements), dip length (horizontal distance between the up-dip and down-dip boundaries of a unit, as measured within the unit) and strike width (horizontal distance between the boundaries of a unit as measured along strike). The element length is referred to the direction of elongation of some geomorphic or architectural element types, which may be oriented at an angle to the regional dip direction and/or with the shoreline, including sand ridges.







- East Bank, North Sea
- Southern North Sea
- Eastern Yellow Sea
- Western Yellow Sea
- East China Sea
- Korea Strait
- Gulf of Khambhat
- Bering Sea
- Celtic Sea

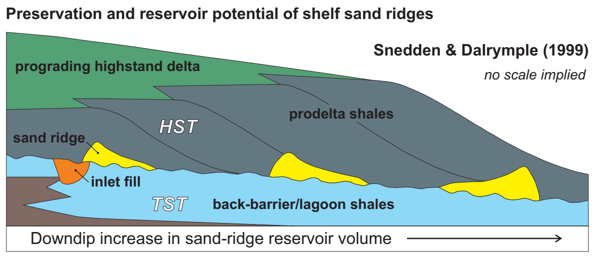
On the assumption that analogy can be drawn between the geometry of modern forms and that of ancient deposits (discussed below), SMAKS data on the morphometry of modern sand ridges, based on bathymetric datasets from a range of tidal seas, provide indication of the likely size of stratigraphic traps or reservoir units, applicable to predict volumes, the likelihood of seismic resolvability of sand-ridge elements, and to guide interwell correlations.

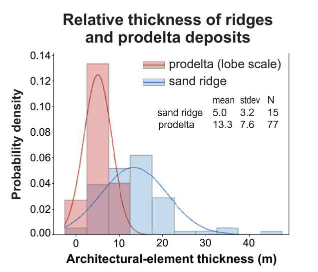
SMAKS output indicates the following:

- a strong positive relationship between sand-ridge width and length (Pearson's $R = 0.68$);
- a positive relationship between sand-ridge relief and width ($R = 0.49$);
- a weak positive relationship between sand-ridge relief and length ($R = 0.23$);
- a very weak positive relationship between sand-ridge relief and crest sinuosity ($R = 0.11$);
- a weak negative relationship between sand-ridge width and crest sinuosity ($R = -0.19$);
- no relationship between sand-ridge length and crest sinuosity ($R = 0.04$).

Stratigraphic trapping potential

Preservation and reservoir potential of shelf sand ridges



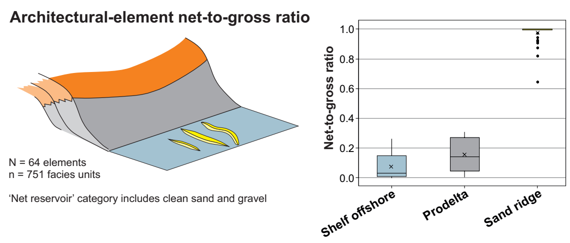


Tidal sand ridges that have accreted in tide-dominated shallow seas under conditions of transgression may be buried by mud-prone deposits, possibly during the subsequent sea-level highstand, thus resulting in the formation of potential stratigraphic traps of significant size. Stratigraphic trapping may be determined by the emplacement of sealing shelf mudstones (cf. Posamentier et al. 2002), or highstand prodelta fines (cf. Snedden & Dalrymple 1999; Berné et al. 2002).

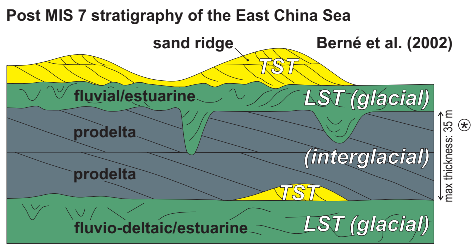
As a tentative quantitative assessment of the trapping potential of tidal sand ridges, output from SMAKS is presented to illustrate:

- the relative thickness of preserved sand-ridge architectural elements and delta-lobe-scale prodelta deposits, based on the entire database; this information suggests that sealing by delta progradation may be unlikely, but it is based on limited data and thus should be used with caution;
- a facies-unit-based estimate of the net-to-gross ratio of prodelta and offshore shelf deposits, which relates the potential quality of these deposits as seals;
- the relative size of sand ridge elements and (i) stacked prodelta deposits or (ii) transgressive sand-sheets, seen in the shallow subsurface of the East China Sea and of the Korea Strait, respectively.

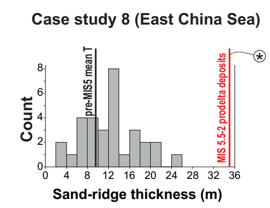
Architectural-element net-to-gross ratio



Post MIS 7 stratigraphy of the East China Sea

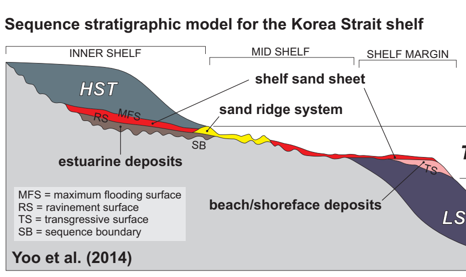


Case study 8 (East China Sea)

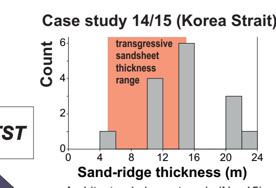


Architectural elements only (N = 31)

Sequence stratigraphic model for the Korea Strait shelf



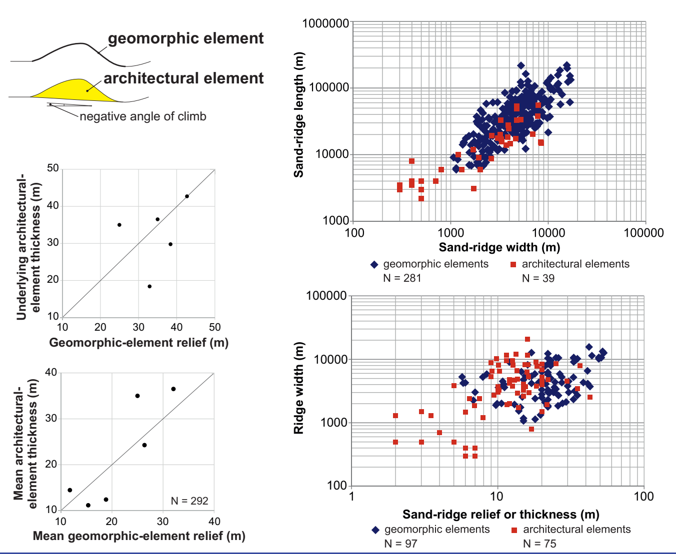
Case study 14/15 (Korea Strait)



Architectural elements only (N = 15)

Depositional units vs. modern landforms

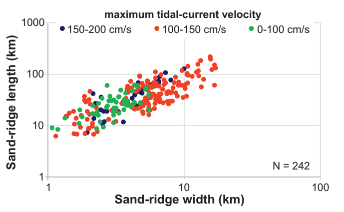
If sand supply-limited conditions subsist on a tide-dominated shelf, on which sand ridges typically develop from tidal cannibalization of the transgressed substrate, similarity might be seen between the morphology of sand ridges as landforms and the morphology of the architectural elements resultant from their migration and preservation. However, a number of factors may influence the supposed similarity, such as the compound depositional-erosional nature of the ridge topography (cf. Berné et al. 2002), element amalgamation expressed by downlap relationships seen for the foresets of an external (downdrift) ridge onto bottomsets of the directly internal (updrift) ridge (cf. Liu et al. 2007), or the existence of palimpsest landforms underlain by deposits that blanket the ridges smoothing their topography.

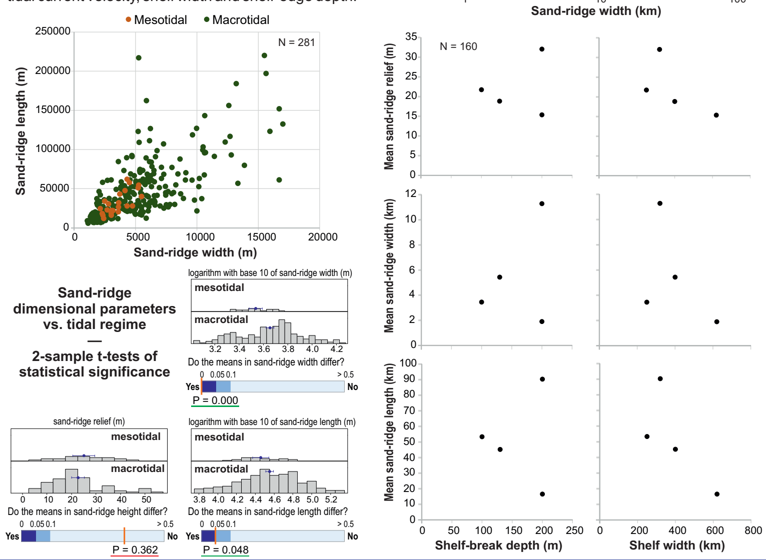


Controls on ridge size

SMAKS facilitates investigations of relationships between sand-ridge properties, such as dimensional parameters, and plausible controlling factors, thereby enabling predictions of likely reservoir continuity, volume or trapping potential from knowledge of boundary conditions of depositional systems.

Results are presented that show the value of tidal regime as a predictor of mean sand-ridge width and length, and how the morphometry of modern sand ridges relates to maximum tidal current velocity, shelf width and shelf-edge depth.





Conclusions

Based on the analysis of several case studies of modern tide-dominated shallow seas and corresponding preserved ancient deposits, enabled by the application of the SMAKS database, quantitative information has been used to show the following:

- tidal sand ridges form potential hydrocarbon-reservoir units with limited lithological heterogeneity and significant volume;
- the size of modern sand ridges can provide an indication of the likely size of isolated sandstone bodies within transgressive systems tracts;
- with consideration of modern analogues, the thickness of tidal sand-ridge architectural elements may not be a good predictor of their lateral extent;
- emplacement of prodelta deposits during highstand progradation of delta lobes may not provide sufficient in determining seal formation;
- transgressive sand sheets and sand veneers are seen to act as likely connectors between ridge units, possibly reducing trapping potential but increasing sandstone connectivity;
- relationships between sand-ridge dimensional parameters and possible controlling factors (tidal regime, maximum tidal current velocity, shelf width and shelf-edge depth) have been assessed; although the considered geomorphic elements typically represent relict or moribund features produced under Holocene transgression, the width and length of sand ridges show statistically significant differences when grouped by present-day coastal tidal regime.

Some of the quantitative SMAKS output presented here can be readily employed in subsurface studies, for example for conditioning reservoir models or guiding well-to-well correlations.

References

Berné S., Trentesaux A., Stolk A., Missiaen T., de Batist M. (1994) Mar. Geol. 121, 57-72.

Berné S., Lericolais G., Marsset T., Bourillet J.F., De Batist M. (1998) J. Sed. Res. 68, 540-555.

Berné S., Vagner P., Guichard F., Lericolais G., Liu Z., Trentesaux A., Yin P., Yi H.I. (2002) Mar. Geol. 188, 293-315.

Bouysse P., Horn R., Lapierre F., Le Lann F. (1976) Mar. Geol. 20, 251-275.

Caston V.N.D. (1972) Sedimentology 18, 63-78.

Colombera L., Mountney N.P., Hodgson D.M., McCaffrey W.D. (2016) Mar. Petrol. Geol. 75, 83-99.

Davies J.L. (1980) Geographical variation to coastal development. Longman London.

Davis Jr R.A., Balson P.S. (1992) J. Sed. Petrol. 62, 116-121.

Evans C.D.R., Hughes M.J. (1984) J. Geol. Soc. 141, 315-326.

Houbolt J.J.H.C. (1968) Geol. en Mijnb. 47, 245-273.

Klein G.D., Park Y.A., Chang J.H., Kim C.S. (1982) Mar. Geol. 50, 221-240.

Liu Z., Huang Y., Zhang Q. (1989) J. Sed. Petrol. 59, 432-437.

Liu Z.X., Berne S., Saito Y., Lericolais G., Marsset T. (2000) J. Asian Earth Sci. 18, 441-452.

Liu Z., Berné S., Saito Y., Yu H., Trentesaux A., Uehara K., Yin P., Liu J.P., Li C., Hu G., Wang X. (2007) Cont. Shelf Res. 27, 1820-1834.

Marsset T., Tessier B., Reynaud J.Y., De Batist M., Plagnol C. (1999) Mar. Geol. 158, 89-109.

Nelson C.H., Dupré W.R., Field M.E., Howard J.D. (1980) USGS Open-File Report 80-979.

Off T. (1963) AAPG Bull. 47, 324-341.

Pantin H.M., Evans C.D.R. (1984) Mar. Geol. 57, 259-293.

Park S.C., Lee S.D. (1994) Mar. Geol. 120, 89-103.

Park S.C., Han H.S., Yoo D.G. (2003) Mar. Geol. 193, 1-18.

Posamentier H.W. (2002) AAPG Bull. 86, 75-106.

Reynaud J.Y., Tessier B., Proust J.N., Dalrymple R., Marsset T., De Batist M., Bourillet J.F., Lericolais G. (1999) Sedimentology 46, 703-721.

Reynaud J.Y., Tessier B., Auffret J.P., Berné S., Batist M.D., Marsset T., Walker, P. (2003) J. Quatern. Sci. 18, 361-371.

Saha S., Ghosh A., Burley S., Banerjee S., Saraswati P.K. (2007) AAPG Search & Disc., article #50050.

Scourse J., Uehara K., Wainwright A. (2009) Mar. Geol. 259, 102-111.

Snedden J.W., Dalrymple R.W. (1999) SEPM Spec. Publ., 64, 13-28.

Stride A.H., Belderson R.H., Kenyon N.H., Johnson M.A. (1982) Offshore tidal sands: Processes and deposits, 95-125. Springer Netherlands.

Tessier B., Corbau C., Chamley H., Auffret J.P. (1999) J. Coastal Res. 15, 593-606.

Trentesaux A., Stolk A., Tessier B., Chamley H. (1994) Mar. Geol. 121, 43-55.

Trentesaux A., Stolk A., Berné S. (1999) Mar. Geol. 159, 253-272.

Willis B.J. (2005) SEPM Spec. Publ., 83, 87-129.

Yang C.-S. (1989) Mar. Geol. 88, 97-116.

Yoo D.G., Lee C.W., Kim S.P., Jin J.H., Kim J.K., Han H.C. (2002) Mar. Geol. 187, 313-328.

Yoo D.G., Kim S.P., Lee C.W., Chang T.S., Kang N.K., Lee G.S. (2014) Quatern. Internat. 344, 143-155.

Shallow-Marine Research Group
School of Earth and Environment
University of Leeds
Leeds LS2 9JT UK

contact: Luca Colombera
email: l.colombera@leeds.ac.uk
mobile: +44 (0)7554096074
URL: http://smrg.leeds.ac.uk

This research was funded by: NERC SCIENCE OF THE ENVIRONMENT

SMRG is sponsored by: De Beers, ENGIE