doi: 10.3304/JMES.2018.003

Journal of Mediterranean Earth Sciences 10 (2018), 129-134

Journal of Mediterranean Earth Sciences

Investigation methods on continental outcrops: developing an upgrade of the architectural analysis method by field tests in well-exposed Sardinian outcrops

Luca Giacomo Costamagna

Dipartimento di Scienze Chimiche e Geologiche, Università di Cagliari, Cagliari, Italy
lucakost@unica.it

ABSTRACT - In order to perfect the analytical procedures used to investigate the continental depositional environments, an upgrade of the architectural analysis method is here proposed in its main lines. The method has been tested in several well-exposed outcrops pertaining to continental environments related to different units of various age outcropping in different parts of Sardinia. The method appears to be promising in determining the fluvial style and the features of the corresponding fluvial network of the investigated units throughout a careful analysis of a discrete number of well-exposed outcrops.

Keywords: Alluvial deposits; Bounding surfaces; Channel-bodies; Depositional architecture; Interchannel areas.

1. INTRODUCTION

In the past thirty years the 3D architectural analysis of the fluvial deposits outcrops by the use of photomosaics and laser telemeters (LIDAR) experienced a significant development. The concepts expressed by Allen (1983), by Ramos and Sopena (1983), but especially developed by Miall (1985, 1988, 1991, 1996, 2014 and references therein) have been largely followed and used in the interpretation and the organic framing of all the successions that presented a significant lateral heterogeneity, but especially of the alluvial sediments. Nonetheless, this method was still far from perfect and its use in the field showed some criticalities: so, each worker on the field felt authorized to erect its own method, fitted to the case study. Thus, we tested several outcrops experimenting several changes to establish a common, straightforward method useful as a shared language in the study of this type of successions.

2. ARCHITECTURAL ANALYSIS

The analytical procedures of the depositional architecture are based on the analysis of wide and well-exposed outcrops by using predefined lithofacies, hierarchically organized boundary surfaces and well-defined depositional physical (architectural) objects. By testing them on the field, the original elements erected and defined by Miall (1985, 1988, 1991, 1996, 2014 and references therein) have been partially revised and modified to resolve some problems that arose during the field work, in order to make them fit to a wider and unequivocal use.

The final purpose of the architectural analysis is to hypothesize the fluvial style of each outcrop, and, in the end, to mark the overall spatial and chronological evolution of the investigated fluvial system by correlating the analyzed outcrops. In this way, the hereby tested method may be used in every similar situation.

3. MODIFICATION OF THE METHOD

In order to use the Miall's method at its best, appropriate outcrops have been divided into genetic units interpreted as being related to different scales of physical events (floods and substages of floods) that led to their deposition. The genetic units are now organized in hierarchies, and separated by bounding surfaces. The bounding surfaces are arranged by their own hierarchy, this latter based on shape, size and reciprocal relationships. The genetic depositional units show diverse styles of accretion over a wide range of scales and the bounding surfaces reflect erosion or non-deposition (or accretion, presumably), at different scales of time and size.

For that purpose, the scheme for the classification of bounding surfaces have been redefined and some of them added to the original Miall's schemes. The architectural elements have been redefined and hierarchically organized, and several new ones have been defined. Besides, and when it has been possible, some of the architectural elements have been subdivided into two types of sub-units, each one representing a sedimentation phase: A) an "active" sedimentation phase, developing during the falling-stage floods of the river: during this phase the main part of the load deposes; B) a "passive" sedimentation phase, developing during the low-water stage: here a minimal part of the load deposited. The involved structures mainly derive from the reworking of the previously formed bedforms. Specific reference tables of lithofacies, bounding surfaces and architectural elements and their hierarchy have been prepared during the field analysis. An idealization of the setting and the relationships of the different units in meandering and braided environments is sketched (Fig. 1), and a table of the hierarchic constituents is showed (Fig. 2).

3.1. Lithofacies Table

Miall's 1996 Lithofacies Table 4.1 is the most recent and updated version of the Lithofacies Table 1 firstly published in the former Miall's 1985 paper. It takes account of some improvements inserted later by Miall itself due to further investigations. In our method a modified Lithofacies Table has been used and considers Bridge's criticisms (1993) (Fig. 3). Further additions at this table have been made recently by other authors.

The only original modification to this table now proposed is the addition of the Lithofacies Bc, which includes very coarse-grained lithologies with chaotic structures usually deposited on slopes and piedmont aprons. This lithofacies often marks the transgressive base of sedimentary cycles.

3.2. Bounding Surfaces Table and Architectural Elements Table

Here the changes proposed in this paper to the Miall's recommendations are many: they are related to the rank, type, scale and number of the bounding surfaces (Fig. 4),

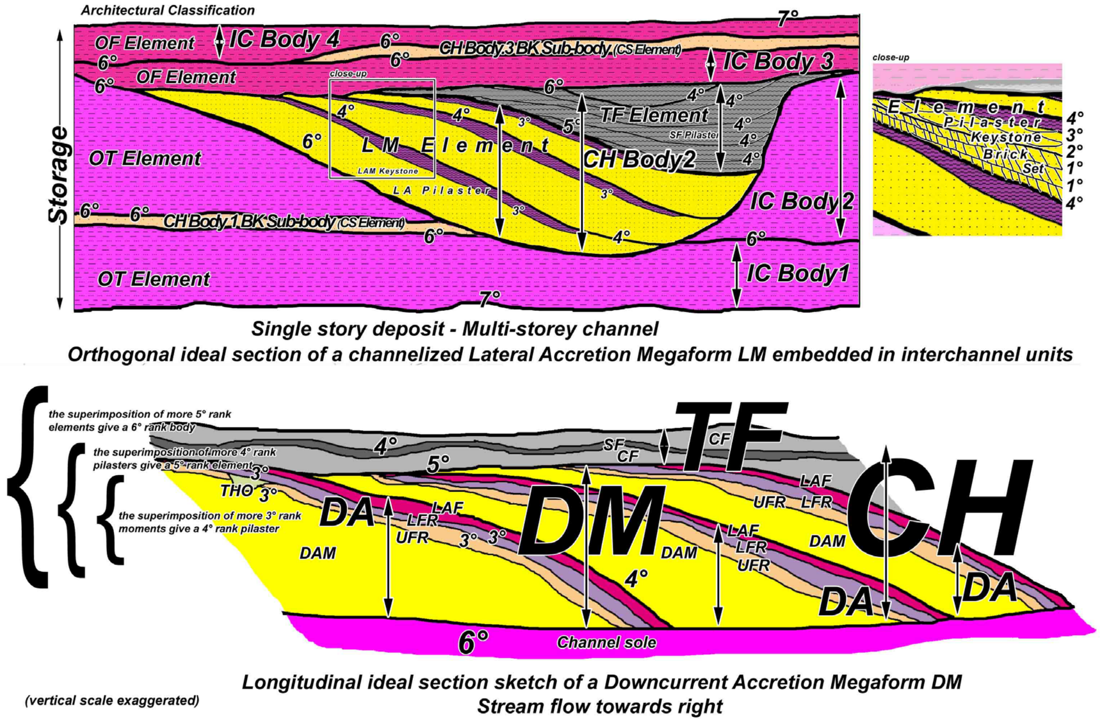
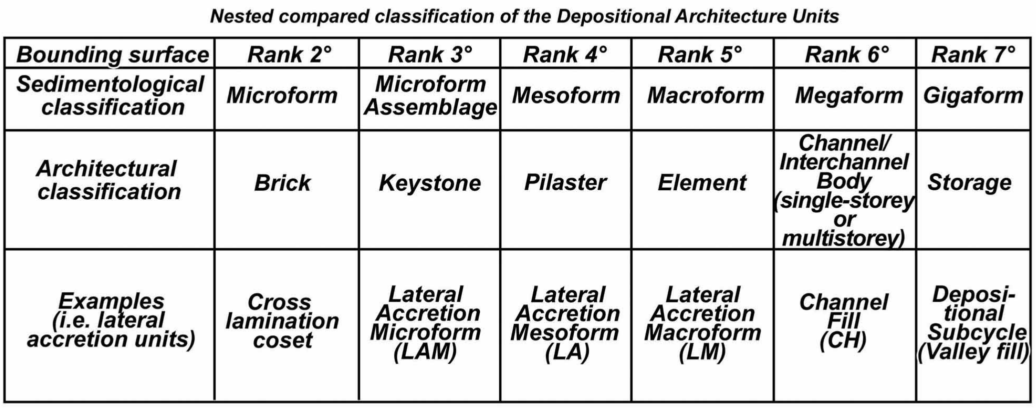


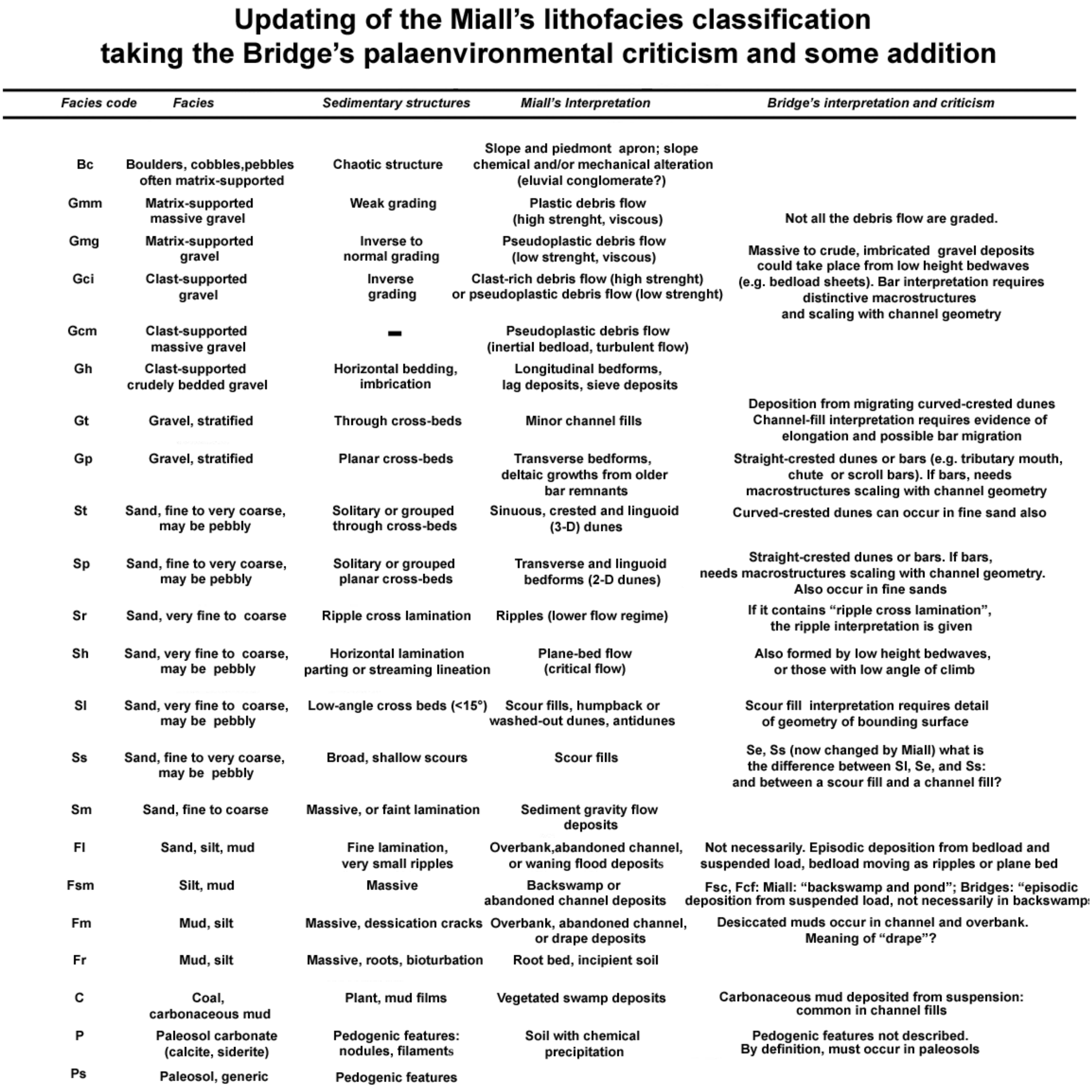
Fig. 1 - Demostrative, idealized sketch of architectural analysis in meandering (up) and braided (down) environments.



Nested compared classification of the Depositional Architecture Units

Bounding surface	Rank 2°	Rank 3°	Rank 4°	Rank 5°	Rank 6°	Rank 7°
Sedimentological classification	Microform	Microform Assemblage	Mesoform	Macroform	Megaform	Gigaform
Architectural classification	Brick	Keystone	Pilaster	Element	Channel/ Interchannel Body (single-storey or multistorey)	Storage
Examples (i.e. lateral accretion units)	Cross lamination coset	Lateral Accretion Microform (LAM)	Lateral Accretion Mesoform (LA)	Lateral Accretion Macroform (LM)	Channel Fill (CH)	Deposi-tional Subcycle (Valley fill)

Fig. 2 - Nested compared classification of the Depositonal Architecture Units.



Updating of the Miall's lithofacies classification taking the Bridge's palaenvironmental criticism and some addition

Facies code	*Facies*	*Sedimentary structures*	*Miall's Interpretation*	*Bridge's interpretation and criticism*
Bc	Boulders, cobbles,pebbles often matrix-supported	Chaotic structure	Slope and piedmont apron; slope chemical and/or mechanical alteration (eluvial conglomerate?)	
Gmm	Matrix-supported massive gravel	Weak grading	Plastic debris flow (high strenght, viscous)	Not all the debris flow are graded.
Gmg	Matrix-supported gravel	Inverse to normal grading	Pseudoplastic debris flow (low strenght, viscous)	Massive to crude, imbricated gravel deposits could take place from low height bedwaves (e.g. bedload sheets). Bar interpretation requires distinctive macrostructures and scaling with channel geometry
Gci	Clast-supported gravel	Inverse grading	Clast-rich debris flow (high strenght) or pseudoplastic debris flow (low strenght)	
Gcm	Clast-supported massive gravel	–	Pseudoplastic debris flow (inertial bedload, turbulent flow)	
Gh	Clast-supported crudely bedded gravel	Horizontal bedding, imbrication	Longitudinal bedforms, lag deposits, sieve deposits	
Gt	Gravel, stratified	Through cross-beds	Minor channel fills	Deposition from migrating curved-crested dunes Channel-fill interpretation requires evidence of elongation and possible bar migration
Gp	Gravel, stratified	Planar cross-beds	Transverse bedforms, deltaic growths from older bar remnants	Straight-crested dunes or bars (e.g. tributary mouth, chute or scroll bars). If bars, needs macrostructures scaling with channel geometry
St	Sand, fine to very coarse, may be pebbly	Solitary or grouped through cross-beds	Sinuous, crested and linguoid (3-D) dunes	Curved-crested dunes can occur in fine sand also
Sp	Sand, fine to very coarse, may be pebbly	Solitary or grouped planar cross-beds	Transverse and linguoid bedforms (2-D dunes)	Straight-crested dunes or bars. If bars, needs macrostructures scaling with channel geometry. Also occur in fine sands
Sr	Sand, very fine to coarse	Ripple cross lamination	Ripples (lower flow regime)	If it contains "ripple cross lamination", the ripple interpretation is given
Sh	Sand, very fine to coarse, may be pebbly	Horizontal lamination parting or streaming lineation	Plane-bed flow (critical flow)	Also formed by low height bedwaves, or those with low angle of climb
Sl	Sand, very fine to coarse, may be pebbly	Low-angle cross beds (<15°)	Scour fills, humpback or washed-out dunes, antidunes	Scour fill interpretation requires detail of geometry of bounding surface
Ss	Sand, fine to very coarse, may be pebbly	Broad, shallow scours	Scour fills	Se, Ss (now changed by Miall) what is the difference between Sl, Se, and Ss: and between a scour fill and a channel fill?
Sm	Sand, fine to coarse	Massive, or faint lamination	Sediment gravity flow deposits	
Fl	Sand, silt, mud	Fine lamination, very small ripples	Overbank,abandoned channel, or waning flood deposits	Not necessarily. Episodic deposition from bedload and suspended load, bedload moving as ripples or plane bed
Fsm	Silt, mud	Massive	Backswamp or abandoned channel deposits	Fsc, Fcf: Miall: "backswamp and pond"; Bridges: "episodic deposition from suspended load, not necessarily in backswamp
Fm	Mud, silt	Massive, dessication cracks	Overbank, abandoned channel, or drape deposits	Desiccated muds occur in channel and overbank. Meaning of "drape"?
Fr	Mud, silt	Massive, roots, bioturbation	Root bed, incipient soil	
C	Coal, carbonaceous mud	Plant, mud films	Vegetated swamp deposits	Carbonaceous mud deposited from suspension: common in channel fills
P	Paleosol carbonate (calcite, siderite)	Pedogenic features: nodules, filaments	Soil with chemical precipitation	Pedogenic features not described. By definition, must occur in paleosols
Ps	Paleosol, generic	Pedogenic features		

Fig. 3 - Lithofacies Classification.

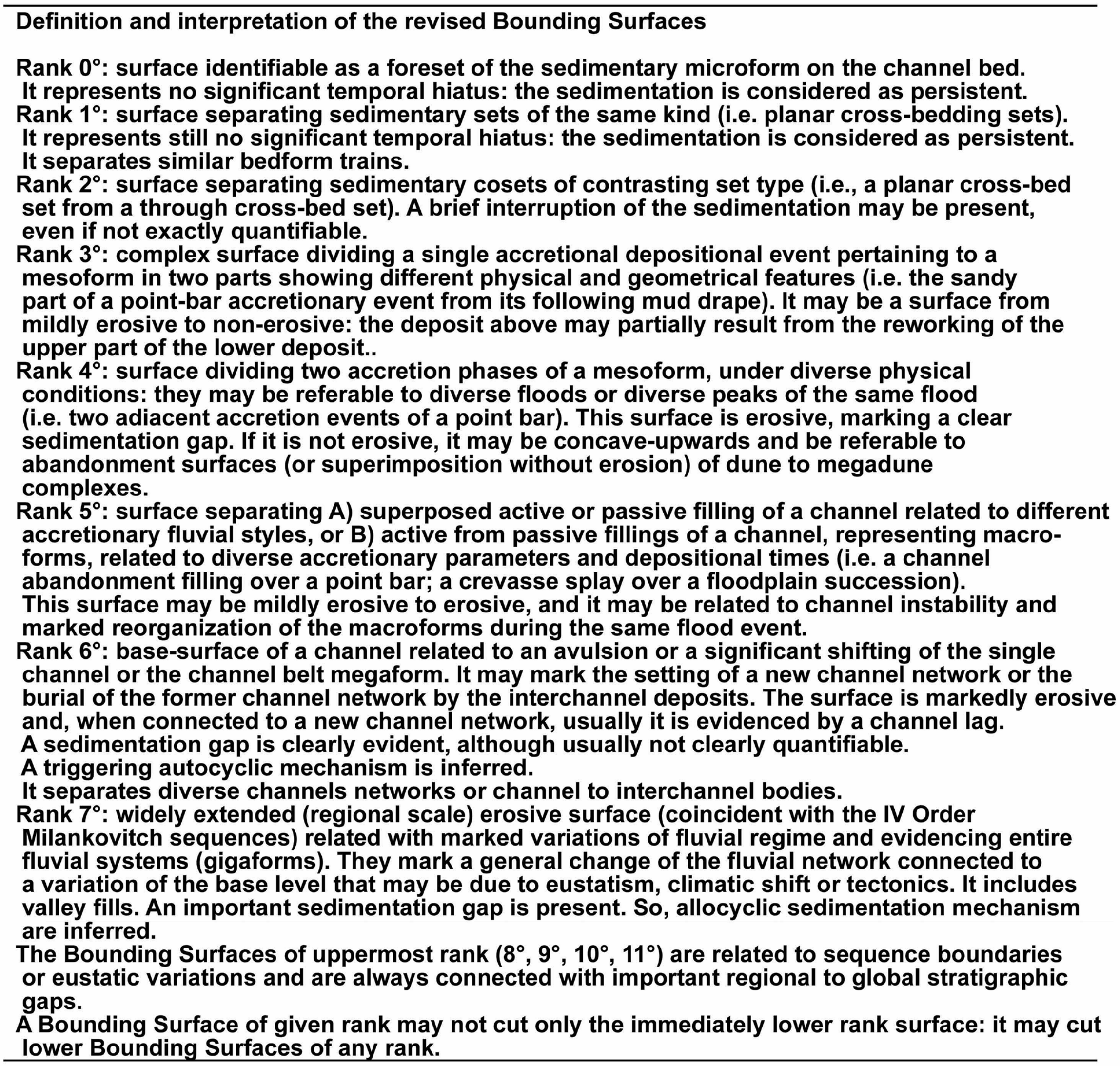
the definition of the architectural units, and their framing in hierarchically organized objects related to two different but strictly correlated types of classification (Fig. 5). There are: A) Sedimentological classification and B) Architectural classification (Fig. 2). Evidently, the architectural elements are related to physical mechanisms of deposition.

The addition of some bounding surfaces and their redefinition allowed to conciliate the geometrical features of the fluvial sedimentation bodies with the physical architectural units.

The hierarchization of the diverse depositional elements permitted their univocal, easy use at all the different temporal and spatial scales. This makes possible the definition of hierarchized base units (each one of them featured by specific lithofacies), by which evidence and identify precise fluvial tyles and build their architectural structure.

Architectural and sedimentological units belonging to the same rank (the rank being related to their size: macroforms, mesoforms, microforms) may be separated in the field using one or more parameters. Those parameters are: 1) Grain size; 2) Type of depositional process involved (tractional or massive; settling; pedogenesis); 3) Accretionary geometry (vertical, frontal or lateral); 4) Pertinence to different active or passive sedimentation phases (see also below).

Architectural objects of uncertain classification because of poor or limited outcropping conditions or faint or missing sedimentary structures and/or textures may be framed as general units specifically designed for this use (Fig. 5). In



Definition and interpretation of the revised Bounding Surfaces

Rank 0°: surface identifiable as a foreset of the sedimentary microform on the channel bed. It represents no significant temporal hiatus: the sedimentation is considered as persistent.

Rank 1°: surface separating sedimentary sets of the same kind (i.e. planar cross-bedding sets). It represents still no significant temporal hiatus: the sedimentation is considered as persistent. It separates similar bedform trains.

Rank 2°: surface separating sedimentary cosets of contrasting set type (i.e., a planar cross-bed set from a through cross-bed set). A brief interruption of the sedimentation may be present, even if not exactly quantifiable.

Rank 3°: complex surface dividing a single accretional depositional event pertaining to a mesoform in two parts showing different physical and geometrical features (i.e. the sandy part of a point-bar accretionary event from its following mud drape). It may be a surface from mildly erosive to non-erosive: the deposit above may partially result from the reworking of the upper part of the lower deposit..

Rank 4°: surface dividing two accretion phases of a mesoform, under diverse physical conditions: they may be referable to diverse floods or diverse peaks of the same flood (i.e. two adiacent accretion events of a point bar). This surface is erosive, marking a clear sedimentation gap. If it is not erosive, it may be concave-upwards and be referable to abandonment surfaces (or superimposition without erosion) of dune to megadune complexes.

Rank 5°: surface separating A) superposed active or passive filling of a channel related to different accretionary fluvial styles, or B) active from passive fillings of a channel, representing macroforms, related to diverse accretionary parameters and depositional times (i.e. a channel abandonment filling over a point bar; a crevasse splay over a floodplain succession). This surface may be mildly erosive to erosive, and it may be related to channel instability and marked reorganization of the macroforms during the same flood event.

Rank 6°: base-surface of a channel related to an avulsion or a significant shifting of the single channel or the channel belt megaform. It may mark the setting of a new channel network or the burial of the former channel network by the interchannel deposits. The surface is markedly erosive and, when connected to a new channel network, usually it is evidenced by a channel lag. A sedimentation gap is clearly evident, although usually not clearly quantifiable. A triggering autocyclic mechanism is inferred. It separates diverse channels networks or channel to interchannel bodies.

Rank 7°: widely extended (regional scale) erosive surface (coincident with the IV Order Milankovitch sequences) related with marked variations of fluvial regime and evidencing entire fluvial systems (gigaforms). They mark a general change of the fluvial network connected to a variation of the base level that may be due to eustatism, climatic shift or tectonics. It includes valley fills. An important sedimentation gap is present. So, allocyclic sedimentation mechanism are inferred.

The Bounding Surfaces of uppermost rank (8°, 9°, 10°, 11°) are related to sequence boundaries or eustatic variations and are always connected with important regional to global stratigraphic gaps.

A Bounding Surface of given rank may not cut only the immediately lower rank surface: it may cut lower Bounding Surfaces of any rank.

Fig. 4 - Bounding Surfaces Table.

this case, the parameter utilized for the classification has been the grain size: it is frequently the only parameter clearly identifiable.

From this classification it derives that the lower-rank architectural units frequently are entirely formed by only one single lithofacies.

Besides, in our methodology we interpreted a multistorey channel as a channel body composed of several depositional events, but related to the same, persistent fluvial network. Conversely, a compound channel body is a channel body formed by the superimposition of different, single- or multistorey channels bodies related to different superimposed fluvial networks. Thus, the renewing of the fluvial network is related to an autocyclic cause (eg. river avulsion) but not to an allocyclic one (sea level variations, tectonics, represented by a 7° rank BS) (Fig. 2).

3.3. Main subdivisions of the architectural units

The architectural classification of the physical fluvial sedimentary bodies subdivides them into three main categories (Fig. 6), that in their turn are hierarchically organized (Fig. 5). They are, respectively:

1) Channelized Megaforms (CH);
2) Bank Megaforms (BK);
Interchannel Megaforms (IC);

The Channelized Megaforms CH form the sediment distribution main network, while the Interchannel Megaforms IC extend in between the fluvial network and mainly are characterized by overbank deposits. Conversely, the Bank Megaform BK plays a special role: it performs a chronological and geometrical connection, allowing correlations between the Channelized Megaforms CH and the Interchannel Megaforms IC, as between channel and overbank deposits.

As previously stated before, it is also necessary to define some concepts, like the "active" and "passive" fluvial sedimentation notion as intended here. The rationale on which the architectural elements are based on is this: whatever the temporal/dimensional scale is, every phase of fluvial activity from the lowest to the highest rank can be subdivided and reported to a major "active" sedimentation phase and a minor "passive" one: these together build a

DEPOSITIONAL ARCHITECTURE: HIERARCHICAL SUBDIVISION

Gigaform	Megaform	Macroform	Mesoform	Microform Ass.	Sedimentological Class.
Bound.Surf. 7°	Bound.Surf. 6°	Bound.Surf. 5°	Bound.Surf. 4°	Bound.Surf. 3°	Bounding Surfaces
Storage	Body	Element	Pilaster	Key-Brick	Architectural Class.
CH+BK+IC	CH (Channelized)	SR (Sand Ridge) ►	SB±SB±SB... ►	SB=SS±LFR±LAF	
		DM (Down.Accr.Macr.)	DA±DA±DA±...	DA=DAM±THO±UFR±LFR±LAF	
		LM (Lat.Accr.Macrof.)	LA±LA±LA±..	LA=LAM±LFR±MD	
		GC (Gravel Cover)	GB±GB±GB±...	GB=GS±UFR±LFR±LAF	
		SGC (Sed.Grav.Cover)	SGB±SGB±SGB±...	SGB=SGS±UFR±LFR±LAF	
		TF (Terminal Filling)	SUF+SUF+...±CF±LP (rare)		
		H (Hollows)			
		SB (Slope Breccias)			
	BK (Bank)	LS (Levee Seq.) ►	LU ±LU.......... ►	LU=±UFR±LFR±LFF	
		CS (Crev. Splay Seq.)	CSU±CSU±.........	CSU=±UFR±LFR±LFF	
		CR (Crev. Channel Seq.)	CRU±CRU±.........	CRU=±UFR±LFR±LFF	
		PS (Paleosoils)			
	IC (Interchannel)	OT (Overbank Terrig.) ►	OF (Overbank Fines) {OF = ±LFR±LFF} ±OD (Overland Floods) {OD = ±UFR±LFR±LFF} ±WB (Wind-blown Dust & Sand - Eolian)		
		OI (Overbank Indig.) ►	general LP (Playas-Lacustrine-Palustrine) or PY (Playa)±LK (Lake)±PL (Mire-Marsh-Swamp)±.....		
		PS (Paleosoils) ►	different climatic or mature paleosoils		
	General, unspecific units	SF (Sand Flat) ►	SB (Sand Body) ►	GSB (Generic Sand Bar)	
		GF (Gravel Flat) ►	GB (Gravel Body) ►	GGB (Generic Gravel Bar)	
		FF (Flood Fines)			

LEGEND

Geometrical forms (in alphabetical order)

CF = Coarse filling; CRU = Crevasse Channel Unit; CSU = Crevasse Splay Unit;
DA = Downstream Accretion Mesoform; DM = Downstream Accretion Microform Association;
GB = Gravel Bar; GS = Gravel Sheet; LA = Lateral Accretion Mesoform; LAF: Limited Abandonment Fines;
LAM = Lateral Accretion Microform; LFF = Extension-Limited Flood Fines;
LFR = Lower Flow Regime sheets, lens, scour fills and bedforms;
LP = Lacustrine-Palustrine; LU = Levee Unit; MD = Mud Drape;
SB = Sand Bar; SUF = Subtle Filling; SF = Sand Flat; SGS = Sediment Gravity Sheet;
SGB= Sediment Gravity Bar; SS = Sand Sheet; THO = Top Bar Hollow;
UFR = Upper Flow Regime sheets, lens, scour fills and bedforms;

Specifical forms: LB = Longitudinal bar; TB = Transverse Bar; PB = Point Bar;
SDB = Side bar; MB = Mouth Bar; DB = Diagonal bar (= TB?);

Fig. 5 - Hierarchic subdivision of the architectural units.

tangible generic fluvial unit with a beginning and an end. Considering i.e. the intermediate scale of the river activity (producing mesoforms, as dunes), the "active" sedimentation takes place in the waning energy environment following the bankfull stage, as the falling stage of the single fluvial flood: here the main, coarser-grained part of the river load depose, and the higher-energy tractional sedimentary structures develop. The "passive" sedimentation takes place during the low-flood stage, between a flood end and the next one, until the start of the next rising stage of a flood, and is characterized by fine-grained sediments and rare sedimentary tractional structures, together with reworking of the previously deposed sediments and localized erosion phenomena. Besides, between the start of the rising stage of the flood and the bankfull stage, erosive phenomena take place. Conversely, taking into consideration all the possible physical scales of sedimentation, these phases may be hierarchized relatively to the micro-, meso- and macroforms of sedimentation (ripples and their "passive" deposits, dunes and their "passive" deposits, megadunes and their "passive" deposits), each one related to longer sedimentation periods.

Consequently, each active or passive unit of the depositional architecture scheme derives from the superposition of active and passive units of lower rank: the active elements are dominated by active sub-units, while the passive elements are dominated by passive sub-units.

The testing of the modified procedures allows to place all the investigated alluvial deposits in well-defined schemes and to infer with a certain extent of confidence their fluvial style.

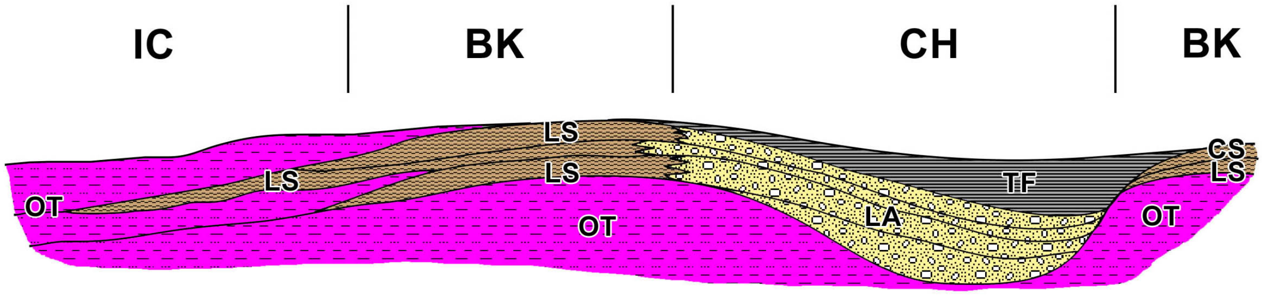


Fig. 6 - Channel (CH), interchannel (IC) and bank (BK) associations and relative elements: LA: Lateral accretion element; TF: Terminal Filling; OT: Overbank Terrigenous; LS: Levee Sequence; CS: Crevasse splay.

As previously stated, the surveyed features of the physical bodies may be so poor that they do not allow a precise framing in the scheme: in prevision of that, some general units were defined in order to manage the classification of the uncertain cases.

4. CONCLUSIONS

The rationale at the base of an experimental improvement of the architectural analysis method has been presented. The method has been tested in several well-exposed Sardinian outcrops of continental units from Carboniferous to Early Miocene age. The results are promising. Further studies are in development in Sardinia. They could allow to outline with good confidence the type of fluvial network and its channel pattern in all the continental units.

ACKNOWLEDGEMENTS - Research was financed by FBS (CAR L.G. Costamagna, 2014).

REFERENCES

Allen J.R.L., 1983. Studies in fluviatile sedimentation: bars, bar complexes and sandstone sheets (low-sinuosity braided streams) in the Brownstones (L. Devonian), Welsh Borders. Sedimentary Geology 33, 237-293.

Bridge, J.S., 1993. Description and interpretation of fluvial deposits: a critical perspective. Sedimentology 40, 801-810.

Miall A.D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. Earth-Science Reviews 22, 261-308.

Miall A.D., 1988. Reservoir heterogeneities in fluvial sandstone: lessons from outcrop studies. American Association of Petroleum Geologists Bulletin 72, 682-697.

Miall A.D., 1991. Hierarchies of architectural units in terrigenous clastic rocks and their relationships with the sedimentation rate. In: Miall A.D, Tyler N. (Eds.), The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and Its Implications for Hydrocarbon Discovery and Recovery. SEPM (Society for Sedimentary Geology) Special Publication 3, 6-12.

Miall A.D., 1996. The geology of fluvial deposits: sedimentary facies, basin analysis, and petroleum geology. Springer, Berlin, pp. 582.

Miall A.D., 2014. Fluvial depositional systems. Springer, Berlin, pp. 320.

Ramos A., Sopena A., 1983. Gravel bars in low-sinuosity streams. In: Collinson J.D., Lewin J. (Eds.). Modern and Ancient Fluvial Systems. IAS (International Association of Sedimentologists) Special Publication 6, 301-312.