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INNOVATIVE AND CLASSICAL FIELD-BASED APPROACH FOR ANALOGUE RESERVOIR MODELLING: THE PRECIPICE SANDSTONE, QLD

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"Io un geologo.
Ho una vaga idea di terra coperta da oceani
di animali del passato
di una lenta forza che spezza la superficie."

Charles Darwin

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ABSTRACT

The Jurassic Precipice Sandstone was studied as a potential oil and gas reservoir unit within the Surat Basin, Queensland. Since the early depletion of its productive fields, the Precipice Sandstone has been recently selected by the ANLECR&D Company as the target unit for the injection of up to 200.000 tons of Greenhouse Gas Stream derived from coal-fired power stations.

The aim of this work is to provide new outcrop-based depositional models for the so called Lower and Upper Precipice Sandstone, with their first application in reservoir characterization.

Trough a classical facies analysis approach, both at the outcrop scale and borehole core-cuts, and the innovative use of 3D Digital Photogrammetry, this study assists the creation of the most reliable geo-cellular reservoir model.

The Lower Precipice outcrop studied at Nathan Gorge National Park shows unit-bar and compound-bar deposits typical of the alluvial architecture of a sandy-braided river system. On the other hand, the Upper Precipice shows lobated bodies comparable to mouth-bar deposits which might be ascribed to a shallow-water delta complex. The recognition of braided-bar deposits in the studied outcrops deals with the well-known fluvial origin the Lower Precipice. However, despite the common thought of the pure fluvial nature of the Precipice Sandstone, the Upper Precipice outcrops might provide new insights on the interpretations of the depositional environment of this unit.

In this framework, the presented detailed facies analysis study, enhanced by the powerful 3D Digital Photogrammetric technique, demonstrates that sedimentary investigations on the Precipice Sandstone reservoir analogue reduces uncertainties in the reservoir characterization and supports the creation of a 3D reservoir model. Nevertheless, the advancement of knowledge of the Upper Precipice depositional environment might have further implications in the understanding of geological evolution of the Jurassic-Cretaceous Surat Basin.

Key words: *Precipice Sandstone*, *reservoir modelling*, *reservoir analogue*, *3D digital photogrammetry*, *depositional model*, *alluvial architecture*, *sandy-braided*, *mouth-bars*

RIASSUNTO

La Precipice Sandstone è una formazione rocciosa sedimentaria di età giurassica situata nello stato del Queensland, Australia. Questa formazione è stata a lungo studiata per il suo interesse economico poiché principale roccia reservoir del Surat Basin, un bacino sedimentario di retro-arco di età giurassico-cretacica. Tuttavia, visto il precoce esaurimento dei giacimenti di petrolio e gas, questa formazione rocciosa è stata recentemente scelta dall'ANLEC *Research & Development Company* come unità target per lo stoccaggio di 200.000 tonnellate di biossido di carbonio prodotto dalle vicine centrali energetiche a carbone.

Il principale scopo di questo lavoro di tesi è quello di supportare con dettagli di interesse geologico lo studio della roccia reservoir nel contesto del progetto dell'*ANLEC R&D Company*. In particolare, l'obiettivo è fornire nuovi modelli deposizionali della *Lower Precipice* e dell'*Upper Precipice* e di studiare le implicazioni che queste due diverse sub-unità possono avere in una roccia reservoir, all'interno del classico studio di *reservoir characterization*.

Attraverso uno studio tradizionale di analisi di facies, sia alla scala d'affioramento sia dei carotaggi, e all'uso innovativo della fotogrammetria digitale 3D, questo lavoro assiste la creazione del modello di reservoir con l'obiettivo principale di limitare l'irresolutezza del modello stesso, in genere dovuta a problemi riguardanti errata interpretazione di dati sismici e di pozzo.

La *Lower Precipice* studiata in Nathan Gorge National Park (QLD) mostra sia singole barre di canale sia barre di canale multiple, tipiche di fiumi a canali intrecciati di origine sabbiosa. Contrariamente, l'*Upper Precipice* mostra dei corpi geologici lobati, comparabili a delle *mouth-bars* e ascrivibili a dei complessi deltizi di acque poco profonde. L'identificazione di depositi sabbiosi di origine fluviale concorda con l'origine - già conosciuta - di tipo braided-fluviale della *Lower Precipice*. Tuttavia, l'identificazione di un sistema deltizio nella *Upper Precipice* differisce completamente dall'origine puramente fluviale da sempre attribuita alla Precipice Sandstone, fornendo quindi una nuova interpretazione di ambiente deposizionale.

In questo contesto, lo studio dettagliato di analisi di facies, affiancato da un altrettanto efficace uso della fotogrammetria digitale 3D, dimostra che una valida indagine sedimentaria effettuata sui *reservoir analogues* della Precipice Sandstone porta a ridurre l'irresolutezza nella caratterizzazione della roccia reservoir stessa e assiste positivamente alla creazione del modello tridimensionale. Inoltre, il nuovo stato di conoscenze nei riguardi dell'*Upper Precipice* può avere importanti implicazioni nello studio dell'evoluzione geologica-bacinale del Surat Basin.

INTRODUCTION

The Jurassic Precipice Sandstone Formation of Queensland, Australia, crops out irregularly along the northern border of the Surat Basin exceeding the length of 300 km with an east-west trend. The Precipice Sandstone is the basal unit of the Surat Basin and was deposited by a sandy-braided river system, interpreted as the Lowstand System Tract of a continental sequence, lying unconformably on the Permian Bowen Basin (Martin, 1976; Exon, 1976; Hoffman et al. 2009; Ziolkowski et al. 2014). The typical aspect of the Precipice Sandstone is easily detectable both in outcrop and in the subsurface and consists of coarse grained sand reach in quartz, forming thick cosets of planar cross stratified and trough cross stratified deposits originated in a fluvial environment as a result of migration of braid channel bars and bedforms (Martin, 1976; Exon, 1976). The use of seismic-exploration and petroleum-exploration wells carried out on the Surat Basin allowed to determine the thickness of the Precipice Sandstone that averages about 60-80 m, although maximum thicknesses of 150 m are recorded in the northern part of the basin (Martin, 1976; Exon, 1976; QGC Report, April 2012).

In the topmost part of the formation the sand-sheet braided channel belt system is waning, grading up in a meandering stream system, passing gradually into the lacustrine Evergreen Formation (Martin, 1976; Exon, 1976). Despite uncertainty it is generally accepted the recognition of two subunits within the Precipice Sandstone (Martin, 1976; Exon, 1976): (i) a “Lower” Precipice, consisting of coarse grained, pebbly sandstone with planar-to-cross bedding and (ii) the “Upper” Precipice, made of fine-grained sand with higher portions of silt and clay layers.

Because of the peculiar features of this sandstone i.e. high porosity, no matrix, textural and compositional homogeneity the Precipice Sandstone was studied for a long time as a potential oil reservoir in the Surat Basin. In the past decade numerous small oil and gas fields were discovered but the reserves were not that sufficient and the majority of the fields were depleted very soon (Exon, 1976).

Since the oil fields were unproductive, in the last few years the Australian Coal Association Low Emission Technology Limited supported projects in order to study the Precipice Sandstone as the principal geosequestration target within the Surat Basin, with the main goal to inject up to 200,000 tons of Greenhouse Gas Stream derived from coal-fired power stations.

Although the Precipice Sandstone has been largely studied in the past decades, several misinterpretations still concern this unit. Firstly, there are still debates on the nature of the so called "Upper Precipice": despite the easily detectable differences with the underlying Lower Precipice in terms of lithology, the depositional environment of the fading system is in discussion even in present days. Some authors propose a meandering system (Exon, 1976) while others prefer to ascribe this change in grain size to a simple local variation in depositional environment that is passing gradational to the overlying lacustrine deposits, although without justifying the lack of transitional environment (Martin, 1976). Secondly, the recent work of Ziowloski et al. (2014) ascribed the lower part of the younger Evergreen Formation to the Precipice Sandstone. This is in contrast with the classical subdivision of the Early Jurassic stratigraphy of the Surat Basin proposed in several studies, include those of Exon (1976), Martin (1976), Fielding (1989) and Hoffmann et al. (2009), and confirms that the enhancing of knowledge of these formation is needed, especially in the transition between the two units.

Concerning the Precipice Sandstone reservoir characterization for CO_2 injection purposes, the construction of the best 3D static and dynamic model of the reservoir must be as accurate as possible in order to better define the potential flow pathways once the fluid is injected into the system, which will be influenced by differences in texture and fabric caused by sedimentary processes. According to Mikes et al. (2006), during the development of the reservoir cellular model, facies interpretation detains among the largest errors concerning the different approximations required for the upscaling procedure, passing from the small-scale heterogeneities up to the definition of the 3D bodies. Thus, in order to obtain the most reliable reservoir model, accurate characterization of the sedimentary facies of the Precipice Sandstone is required both in the Lower and in the Upper Precipice.

This study of the Precipice Sandstone consists of a multilateral approach, with classical and innovative techniques to survey at the outcrop scale and, in addition, investigation of core data. With regarding to the fieldwork activities, a classical sedimentary analysis of the outcrops, using fieldmapping and detailed logging, is adopted in order to determine allostratigraphic units and to reconstruct the succession in terms of paleoenvironment interpretations. On the other hand, the innovative use of Sirovision^{TM} and 3D Photogrammetry permits to create high-resolution 3D virtual models of the outcrop which are suitable for conceptual and geo-cellular reservoir models. Regarding the study of cores, facies analysis is applied on the collected samples in order to put forward interpretations on the environments in the subsurface.

In conclusion the main goals of this thesis are: (i) studying the evolution of dunes and channel bars of the sandy-braided river system in the Lower Precipice, focusing on the geometries and dimension of the geological bodies (ii) to improve the knowledge on the depositional environment of the Upper Precipice, referring to the outcrops observed during the field campaign performed at Nathan Gorge National Park, QLD (iii) try to clarify whereas the facies change observed in the outcrop can be the expression of a marine influenced embayment, dealing with the interpretations of previous studies led by Bianchi et al. (2015) (iv) give a contribution to the characterization of the Precipice Sandstone 3D reservoir modelling and (v) provide a preliminary correlation of the main facies between the outcrop to the subcrop using cores.

GEOLOGICAL SETTING

The Surat Basin

The Surat Basin is a Jurassic-Createaceous intracratonic basin which covers an area of about 300.000 km^2 in the eastern part of Australia, mostly in Queensland and partially in the New South Wales. The Surat Basin interfingers eastward across the Kumbarilla Ridge with the Clarence-Moreton Basin and westward across the Nebine Ridge with the Eromanga Basin, forming collectively the Great Artesian Basin, a Mesozoic intercontinental Basin that covers a widespread area on the eastern Australia (Martin, 1976; Exon, 1976) (Figure 1). The basin is bounded on the eastern side by the Auburn Arch and the New England Fold Belt and between these two basements blocks it intertongues with the Clarence-Moreton basin. In the south, it is delimited by the Central West Folded Belt while, on the western side, it is bounded by the Nebine Ridge. This latter basement high is easterly linked to the Roma Ridge, a shelf-like extension of the same basement which trends south-southeast within the Surat Basin (Figure 1). The northern part of the Surat Basin has been eroded but isolated outliers of its infill (i.e. Precipice Sandstone) located further in the north, suggest that the ancient Surat Basin formerly occupied a greater area than at present (Martin, 1976; Raza et al. 2009).

The Surat Basin is elongated southward and overlies unconformable the Permian-Triassic Bowen Basin, it contains up to 2500 m of flat-lying sediments which are generally undeformed, although in some places they have been mildly folded and/or faulted (Exon, 1976). The sedimentation in the Surat Basin began in the Early Jurassic with the deposition of the Precipice Sandstone and continued till the Early Cretaceous, when the Griman Creek Formation was deposited. During this period, several and cyclic episodes of sedimentation affected more or less continuously the whole basin, forming predominantly continental deposits in the Jurassic and coastal plain and shallow marine deposits in the Cretaceous (Exon, 1976; Hoffman et al. 2009; Raza et al. 2009).

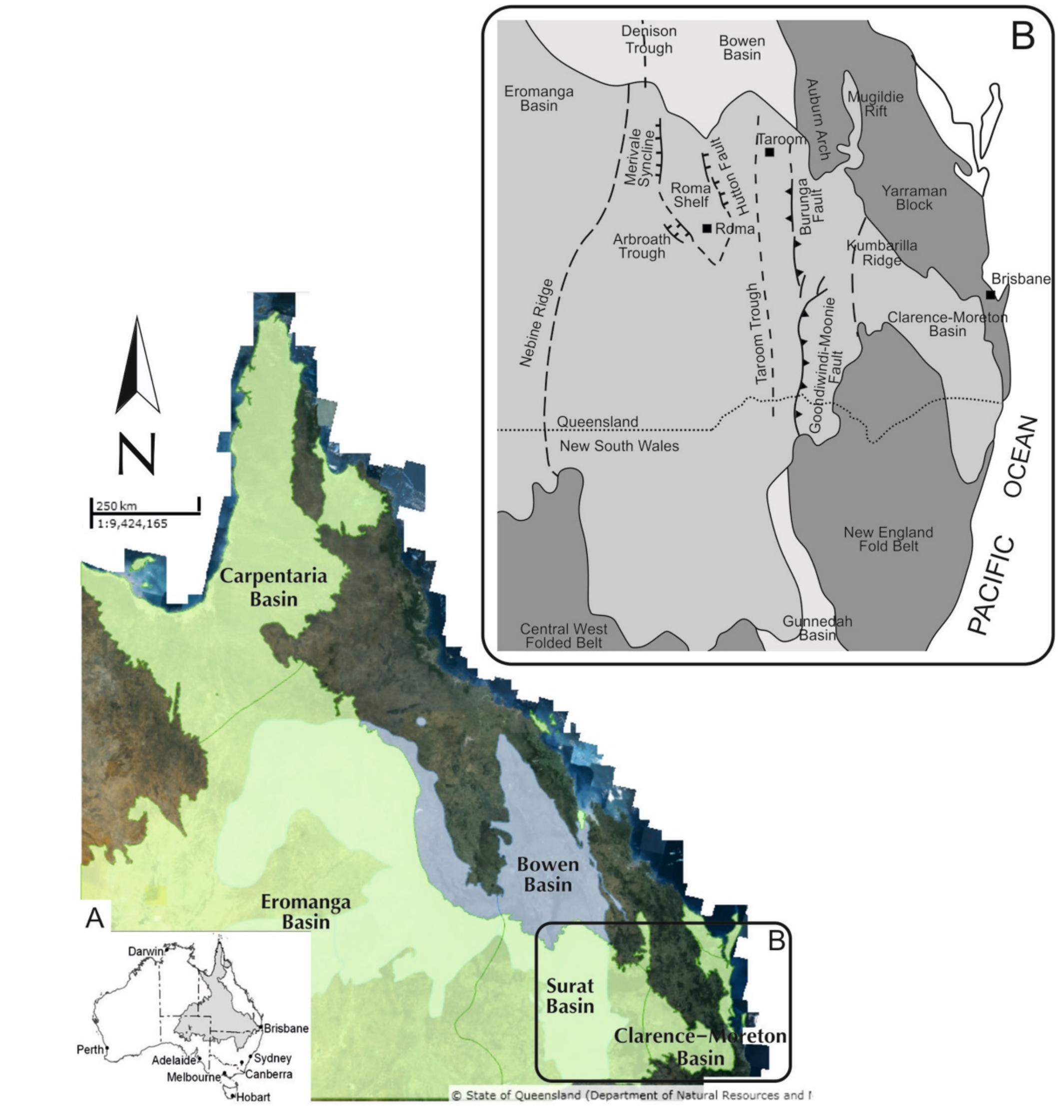


Figure 1: A – Map showing the location of the major Jurassic basins (green) and the underlying Permian-Triassic Bowen Basin (violet) (Source: Mines Online Maps, QLD Government); B – Map showing the major structural elements of the Surat Basin.

Structural Elements

Despite the complex tectonic setting and stratigraphy of the underlying Bowen Basin, the structural contest in which the Surat Basin developed was simpler. Generally, tectonic elements (i.e. faults and/or folds) may have conditioned deposition but rarely affected the Jurassic succession directly. Indeed, the base of the Surat succession cuts nearly all the major faults of the basin, confirming that the main tectonic events predated the beginning of deposition. The few movements that affected the succession after the deposition were due to a reactivation of the thrust fault at depth, which gently folded and rarely faulted the strata (Korsch et al. 2009).

The major tectonic feature in the basin is the Taroom Trough, a meridional long and narrow depression which is overlied by more than 10 km of sediments accumulated during the Permian-Triassic and Jurassic-Cretaceous (Exon, 1976; Brakel et al. 2009; Totterdell et al. 2009). In the northern part of the basin the depression is 10 000 m deep and decreases to about 1600 m in the southern part (Exon, 1976) (Figure 2). In the south, the trough reaches the New South Wales and the Permian-Triassic Gunnedah Basin. Therefore, the Bowen and the smaller Gunnedah Basin are connected by the Taroom Trough and the expression is a shallower depression called Maules Creek sub-basin, one of the main depositional areas within the Gunnedah Basin (Totterdell et al. 2009).

The axis of the Taroom Trough lies on the eastern part and confers asymmetry to the basin. Hence, the Permian-Triassic and Jurassic-Cretaceous succession gradually thickens from west toward the depocentre of the trough, but thins abruptly moving eastward (Martin, 1976; Exon, 1976; QGC Report, April 2012) (Figure 2).

The Taroom Trough is superimposed by the Mimosa Syncline, the main tectonic feature within the Bowen Basin succession. Dickins & Malone, (1973) considered the Mymosa Syncline as a depositional unfolded downwarp and so, the syncline has been always considered as the depocentre of the Bowen Basin, since his axis fairly corresponds to the depression of the Taroom Trough (Martin, 1976; Exon, 1976; QGC Report, 2012). The recent work of Korsch et al. (2009) argued that dips of 25-30° degrees on the eastern flank of the Mimosa Syncline are too steep for a depositional slope and the axis of maximum thickness of the Permian-Triassic succession do not coincide with the axis of the syncline, but it is 10-25 km further east. Therefore, the eastern flank of Mimosa Syncline has been interpreted as a limb which was tilted above a series of west directed thrusts located near the present eastern margin of the Bowen and Surat Basin (Korsch et al. 2009).

Until the Middle Jurassic, both the Taroom Trough and the Mymosa Syncline represented the depocentres of the system and affected with continuity the deposition in the Surat Basin but, later on, the influence of the Bowen Basin on the Surat gradually declined.

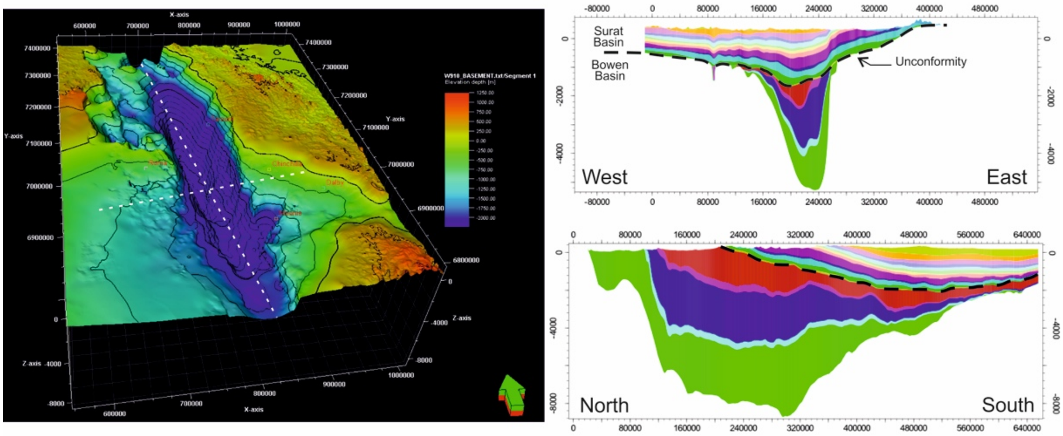


Figure 2: Basement elevation depth (left image) showing the Taroom Trough. Dot lines indicate the transverse and longitudinal section (right images) of the trough, complete of sedimentary units. Vertical scale is exaggerated (Images with the courtesy of Fengde Zhou).

A major N-S-trending fault system is situated on the eastern part of the Bowen-Gunnedah and Surat basin. The Goondiwindi-Moonie-Burunga fault system consists of several discrete faults, the Burunga, Leichhardt, Moonie, Goondiwindi, Mooki and Hunter Faults, disposed approximately along the 150° meridian and separated by gaps and several transfer zones (Exon, 1976; Korsch et al. 2009) (Figure 1, b). The system consists predominantly of low-angle thrust faults with a flat ramp geometry related to the formation of the New England Orogen and the majority of these thrusts are east dipping, except for the Burunga Fault which is the only east verging thrust (Korsch et al. 2009). As already mentioned, few faults cut the first strata of the Jurassic-Createaceous succession, as in the case of the Moonie Fault (Korsch et al. 2009, their figure 6 a) but in general the thrust faults did not affect the Surat Basin.
On the western side of the Surat Basin two major fault system are associated with the Roma Shelf. The Hutton-Wallumbilla fault bounds the eastern side of the Roma Shelf and trends north-northwest, with a westerly downthrown of up to 800 m in the north. On the western and south-western side of the Roma Shelf are located the Merivale and the Arbroath Faults. These two faults may form the western limit of the Roma Shelf on the same line of weakness but the continuity

between them is not well established and they could be two separated structures (Exon, 1976; Martin, 1976). The downthrown of the two faults exceed 1000 m and together define the eastern and the north-eastern edges of two troughs, the Merivale Syncline and the Arbroath Trough, which constitute half-grabens and separate the Roma Ridge from the Nebine Ridge further west (Exon, 1976; Martin, 1976) (Figure 1, b).

Basin phases and fill history

Bowen Basin

As well as the tectonic setting, the geological evolution of the Surat Basin is intimately related to the Bowen Basin. Several tectonic events, spanning from at least the Middle to Late Devonian until the Cretaceous, affected the eastern margin of Australia and allowed the formation of the Bowen-Surat basin. A number of extensional and contractional, intraplate and interplate events produced many subduction and uplift phases that initiated or ceased the deposition into the basins. The backarc tectonic setting in which the Bowen and Surat basin formed, was situated behind (to the west of) the active convergent plate margin of the Eastern Gondwanaland, influenced by a west-dipping subduction system which produced the New England Orogen (Brakel et al. 2009; Korsch et al. 2009; Korsch & Totterdell 2009). The initial Early Permian basin-forming event, the Denison Event, stretched the continental crust and formed the extensional Early Permian East Australian Rift System. A series of half-grabens (i.e. the Denison Trough, Figure 1, b) developed on the western side of the Bowen Basin and thick succession of fluvial and lacustrine sediments were deposited into the graben system (Brakel et al. 2009; Korsch et al. 2009 cum bibl.; Korsch & Totterdell 2009). At the same time, in the Taroom Trough to the east, several episodes of volcanism occurred and the Camboon Volcanincs and associated fluvial sediments were deposited (Brakel et al. 2009). As the subduction zone advanced eastward, the extensional phase ceased and was followed by a period with lower subsidence rates in the Early to Mid Permian, driven by thermal relaxation of the lithosphere (Korsch et al. 2009; Raza et al. 2009; Waschbusch et al. 2009 cum bibl.). In the early Late Permian, the thermal-sag phase was interrupted by the rapid subsidence in the Taroom Trough. This latter basin phase is the long lasting phase if compared to the previous extensional phases and lasted at least 30 Ma and accounted for the greatest accumulation of section with more than 9 km of sediments in some parts (Waschbusch et al. 2009). Although is commonly accepted that the retroforeland thrust belt evolved progressively from internal (eastern New England Orogen) to external (western New England Orogen) and that the effects of the thrust loading spread across the basin from east to west over a period of more than 20 Ma (Figure 3), the recent work of Waschbusch et al. (2009) suggested that, prior to the foreland loading, the dynamic platform tilting was the dominant cause of subsidence in the basin system. Based on geological observation and modelling results the authors concluded that the style of the subsidence recorded by the Bowen Basin in the early Late Permian is consistent with subduction-induced dynamic subsidence (see Mitrovica et al. 1989) and so, the dynamic forces induced from the viscous corner flow over the subducted plate allowed the platform tilting and the subsidence in the backarc setting (Waschbusch et al. 2009). In addition, the platform tilting mechanism proves the differences in amount of sedimentation between the Taroom Trough and the Denison Trough, further on the west. Indeed, this latter depression was filled with a minor amount of sediments because was in the far-field region at about 200 km from the subducted zone (Waschbusch et al. 2009).

Later on, the thickening of the wedge and the relative foreland loading overwhelmed the dynamic platform tilting which probably continued to create subsidence but was not the predominant cause. In the middle-to-late Late Permian the thrust front of the New England Orogen migrated further to the west and the static flexural loading due to foreland loads became dominant (Waschbusch et al. 2009). Till the Middle Triassic the accretionary wedge moved westward, causing cannibalisation of the eastern part of the basin, before the end of deposition (Korsch et al. 2009; Korsch & Totterdell 2009). The final basin phase was one of uplift and erosion, because the thrust front reached the basin and the succession was deformed, uplifted and than eroded, allowing the development of an extensive peneplain, with over 4 km of stratigraphic succession being removed in places (Brakel et al. 2009; Korsch et al. 2009). This prolonged period (about 30 Ma) of non deposition and/or erosion is reflected in the regularity of the base of the Precipice Sandstone, especially by the pronounced angular unconformity and paraconformity which separate the Bowen and the Surat Basin (Korsch et al. 2009).

Subsidence in the Surat Basin commenced in the Early Jurassic but it is doubtful that the process was driven by foreland loading. Indeed, subsidence had a significant different pattern to that of the Bowen and Gunnedah basin in that a thinner succession accumulated over a longer period of time and over a larger area and, furthermore, there is no evidence of thrusting in the New England Orogen from the Early Jurassic to the Early Cretaceous (Korsch et al. 2009; Korsch & Totterdell 2009; Waschbusch et al. 2009). Preliminary models of Waschbusch et al. (2009) suggest that subsidence was controlled once again by dynamic platform tilting, which provides mechanisms for both the near-field (Surat Basin) and far-field (Eromanga Basin) effects. Thus, from the beginning of the Early Jurassic to the early Late Cretaceous the sedimentation in the Surat Basin was controlled by several cycles of deposition and periods of erosion, due to the effect of the corner flow in the atmospheric wedge above the subducted plate. At about 95 Ma, subsidence ceased in the Surat Basin (Korsch et al. 2009; Raza et al., 2009) and the basin became inverted with different amount of denudation, spanning from 1.9 km in the southern-central part, up to 2.5 km in the northern part (Raza et al. 2009). This latter uplift event was associated with a contractional phase, termed the Moonie Event (Korsch & Tottederll 2009 cum bibl.), and is connected with the beginning of seafloor spreading in the southern Tasman Sea (~ 84 Ma) and the rifting of continental fragments such as the Lord Howe Rise, New Caledonia and New Zealand from Australia (Korsch & Totterdell 2009 cum bibl.; Waschbusch et al. 2009 cum bibl.) (Figure 3, a).

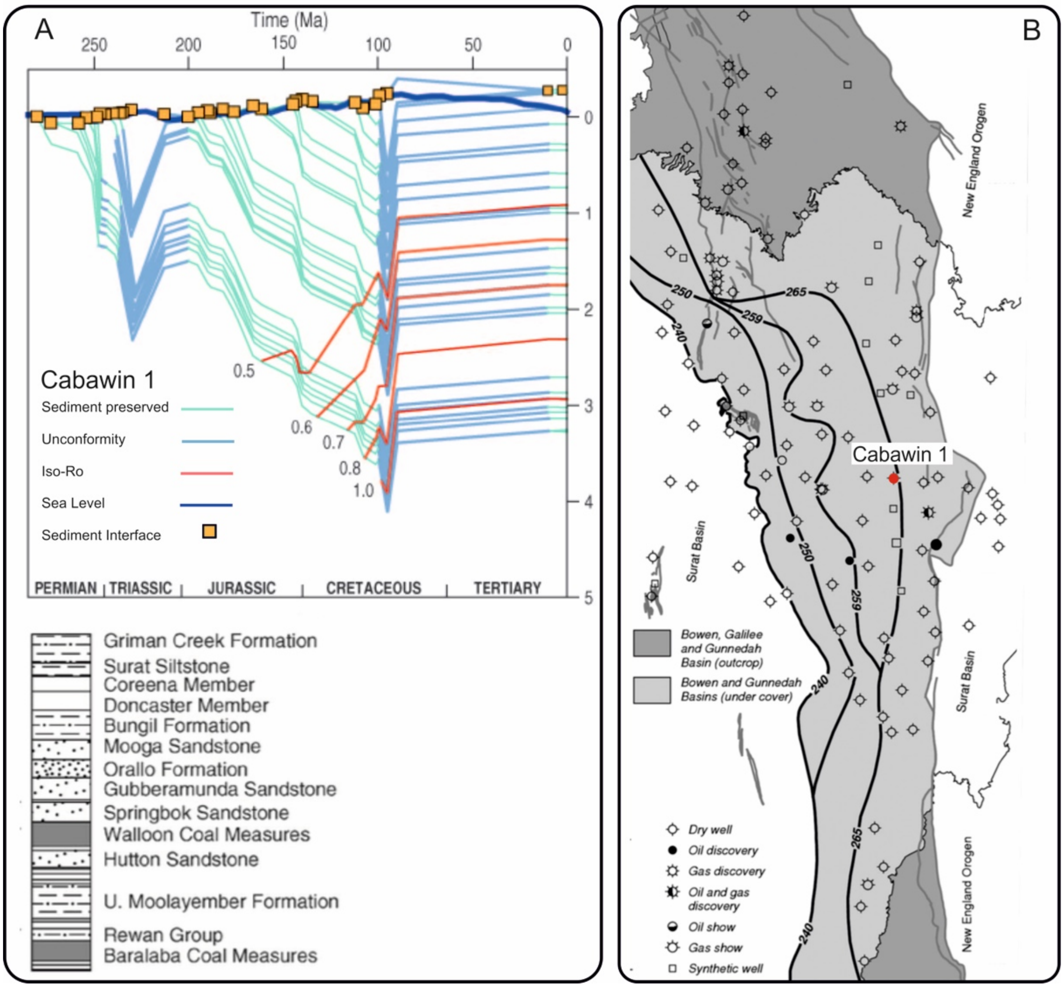


Figure 3: A – Subsidence curves showing the burial and uplift phases of the Bowen and Surat Basin. Note the uplift event prior the deposition of the Precipice Sandstone and the uplift Cretaceous event that produced the widespread erosion of the northernmost part of the Surat Basin (Images from: Raza et al. 2009); B- Map showing the contours (in Ma) delineating the timing of onset of the increase of tectonic subsidence. Subsidence propagated from east to west (Image from: Korsch & Totterdell 2009).

The fill history of the Bowen Basin consists of several basin-fill episodes divided in nine supersequences (A-I) and it is summarised in the work of Brakel et al. (2009).

The Early Permian extensional phase (supersequence A) is characterized by fluviolacustrine deposits. Adjacent to the active extensional faults, alluvial fans, talus slopes and apron braided stream sediments were deposited. On the hinge side of the half-grabens, meandering streams with extensive swampy overbank areas drained into several large lakes and allowed the formation of coal (Brakel et al. 2009, their figure 4). In the subsequent thermal subsidence phase, four marine supersequence (B-E) were generated. The lower part of supersequence B consists of marine shale and minor limestone, as well as deltaic shale sandstone and coal, which form the transgressive part of the cycle. These latter deposits are overlain by a coarser, progradational succession consisting of nearshore-deltaic sandstone, conglomerate and minor coal with interbedded marine (prodelta) shale (Brakel et al. 2009). The marine ingression was assumed to be in the north-eastern part in respect to the basin system, hence the deltaic and coastal deposits in the south propagated northwards into the Taroom Trough and eastwards in the western part of the Denison Trough (Brakel et al. 2009). From the supersequence C to the E the deposition was predominantly marine, consisting of shelf muds deposited offshore, nearshore deposits along the paleocoast and deltaic successions near the eroding upthrust highlands to the east, associated with the inception of the New England Orogen.

The supersequence F began with marine deposits in the west and marine-brackish deposits in the east and ended up with deltaic-fluvial coal measures in all the basin areas. During the marine phase the whole basin was initially under a general condition of anoxia. Successively, delta plain and coal swamps propagated progressively within the sea, forming the most extensive coal measures of Australia. The last remnant of the sea was expelled from the basin in the north-eastern area of the region before the basin became completely non-marine (Brakel et al. 2009). The supersequences G-H-I were deposited predominantly in a fluvial environment, with different values of accommodation rates that differentiated the nature of the river system, complexity and interconnection of the channels between the three supersequences. Paleocurrents measurements indicate a north-to-south axial trunk drainage over most of the basin, with the outlet changed to a southerly position (Brakel et al. 2009). In particular, during the deposition of the last supersequence (I) salt-lake-lacustrine conditions were established in the southernmost part of the basin, with meandering streams, vegetated floodplains and coal measures in the remaining part of the Bowen Basin (Brakel et al. 2009 cum bibl.).

Surat Basin

A period of uplift and erosion spanned from the Late Triassic to the Early Jurassic (Exon, 1976; Hoffmann et al. 2009; Korsch et al. 2009; Raza et al. 2009; Waschbusch et al. 2009) and a new phase of deposition began in the Sinemurian in the eastern Clarence-Moreton Basin, continuing progressively westwards into the Surat and Eromanga Basin (Hoffmann et al. 2009 cum bibl.).

Hoffmann et al. (2009) based his study on the principles of non-marine sequence stratigraphy and recognized three fining-upward cycles within the Surat Basin succession (Figure 4). The cylicity was previously reported by Exon (1976) who identified a lower part of each depositional cycle as being predominantly sandstone with mostly siltstone, mudstone and coals in the upper part. The three cycles recognised by Hoffmann et al. (2009) have the duration of ~ 15-25 Ma and represent second-order supersequences and are named continuing the informal scheme developed by Brakel et al. (2009).

The first supersequence (J) in the Surat Basin consists mainly in two lithofacies that essentially correspond to the Precipice Sandstone and the Evergreen Formation which were deposited over a period of ~ 24 Ma and reach maximum thickness of about 450 m. Palinological data indicate that the base of supersequence J is diachronous and it is younger to the west, and consists of a major angular unconformity which change to a paraconformity in the central-western part of the Taroom Trough (Brakel et al. 2009 figures 15, 16; Hoffmann et al. 2009 cum bibl.). The first lithofacies is the equivalent of the Precipice Sandstone and will be discussed in detail in the following part of this work. In general, it consists of dominantly quartzose, fine to coarse- grained sandstone with common siltstone, shale and coal laminae in the upper part of the formation, and is up to 150 m thick. The Precipice Sandstone grades up into the finer-grained Evergreen Formation which is up to 300 m thick and areally more widespread than the underlying formation. The Evergreen Formation generally overlies conformable the Precipice Sandstone although near to Roma Shelf the formation truncates the underlying strata (Hoffmann et al. 2009) and, beyond the depositional limits of the Precipice Sandstone, it overlies unconformable the Bowen Basin strata or the pre-Permian basement.

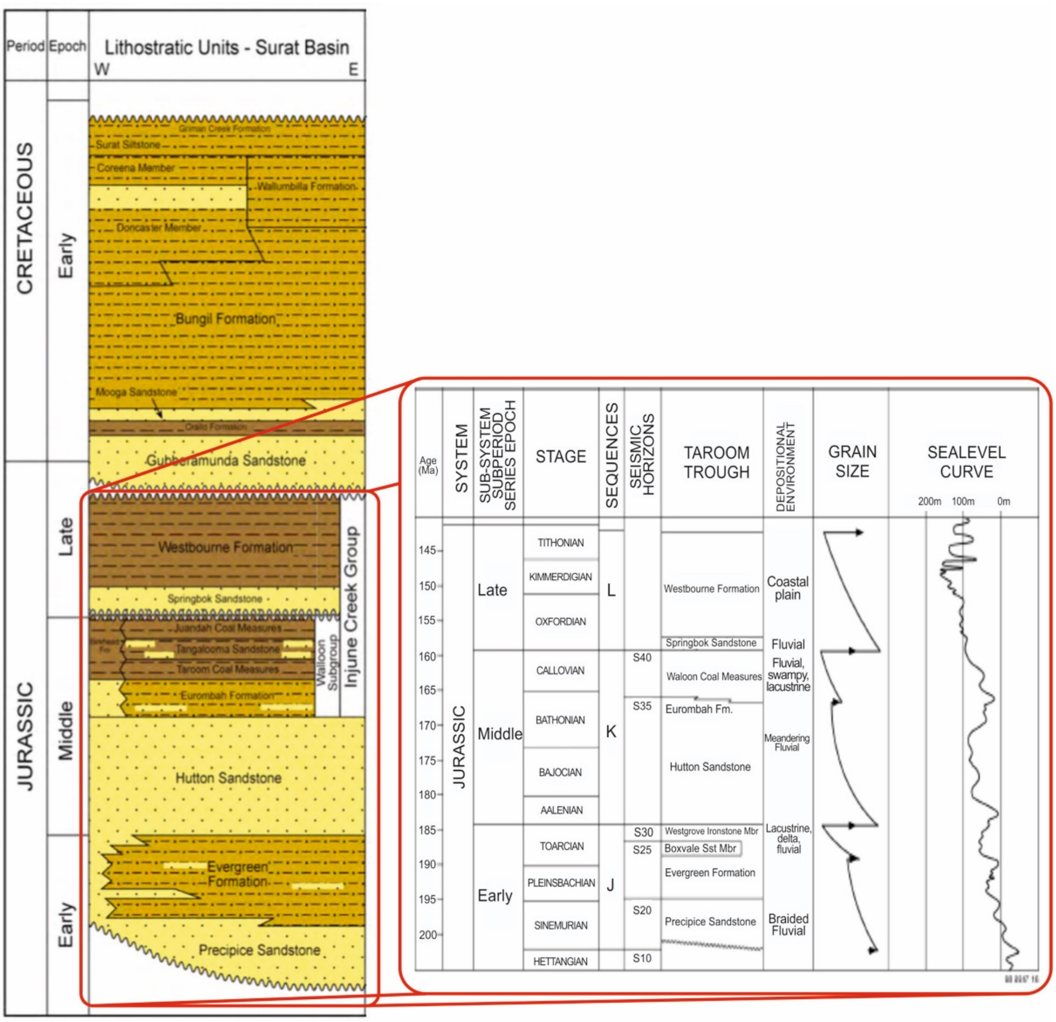


Figure 4: Stratigraphic chart showing the litostratigraphic units of the Surat Basin (Images modified from: Hoffman et al. 2009).

The Evergreen Formation includes the Boxvale Sandstone Member and the Westgrove Ironstone Member and can be informally divided in three intervals (Exon, 1976; Ravestein, 2013): the lower Evergreen Formation, the Boxvale Sandstone Member and the Upper Evergreen Formation with the Westgrove Ironstone Member. The lower part is 100 m thick and consists mainly of carbonaceous siltstone with some horizons of sandstone and shale. Most of the sandstone are impermeable owing the presence of argillaceous matrix and ferruginous cements. The Boxvale Sandstone member (40 m thick) is confined mainly in the north-western part of the region and consists of very fine to fine quartzose sand with argillaceous matrix. Following in the succession, the Westgrove Ironstone Member is 5 m thick and overlies directly the lower Evergreen Formation when the Boxvale is not present. This latter member extends right across the northern part of the basin and consists of mudstone and pellettal ironstone with the composition of the pellets and oolites ranging from chamosite to siderite and possibly glauconite (Exon, 1976). The upper shaly part of the Evergreen formation consists of 12 m of siltstone and mudstone (Exon, 1976).

The depositional environment attributed to the Evergreen Formation was of lacustrine setting (Martin, 1976) although interpretations differ on weather a meandering stream system interacted with the freshwater lake or formed part of a coastal plain with deltas (Exon, 1976). In addition, the Boxvale Sandstone Member is well sorted, fine- to medium-grained sandstone with symmetrical ripples, hummocky cross-stratification and massive sand beds that are consistent with a shoreline facies. Thus, the degree in marine influence on the Evergreen Formation is uncertain. However, Fielding et al. (1989) suggested that these beds accumulated in a lake rather than a marine setting and concluded that the presence of hummocky cross-stratification, wave ripples and coarsening upward nature of succession simply indicated a prograding lacustrine delta system. Furthermore, the chamositic, oolite and mudstone beds of the overlying Westrgrove Ironstone Member maybe were the result of gentle wave action coupled with sediment starvation, as in a lacustrine environment (Hoffmann et al. 2009 cum bibl.).

With the deposition of the upper part of the Evergreen Formation the first supersequence is concluded. Hence, the Lowstand System Tracts (LST) is represented by the Precipice Sandstone while the Trasgressive System Tracts (TST) and the High Stand System Tracts (HST) are represented respectively by the lower and upper part of the Evergreen Formation (Hoffmann et al. 2009).

After the deposition of the supersequence J the second fining-upward cycle started at the beginning of the Middle Triassic. The supersequence K includes the basal Hutton Sandstone, the Eurombah Formation and the Walloon Coal Measures, which accumulated over a period of ~ 19 Ma. The Hutton Sandstone reaches a maximum thickness of 266 m and consists of fine- to medium-grained quartzose to lithic sandstone, which is both thick-bedded and cross-bedded, although some siltstone and mudstone are also present. The overlying Eurombah Formation consists of lithic conglomeratic sandstone with some conglomerate, siltstone and mudstone beds that were deposited by meandering streams. The formation lies conformable between the Hutton Formation and the Walloon Coal Measures and is up 100 m thick. Toward the top of the supersequence, the Walloon Coal Measures forms extensive deposits and reaches a maximum thickness of 650 m. The contact with the underlying Eurombah formation is transitional and the deposits consist of sandstone, siltstone, mudstone and rare to very abundant coal seams laid down in poorly drained floodplains. This supersequence (K) extends well to the southwest of the underlying formation, reaching the New South Wales in the south. The maximum deposition occurred in the northern part of the Taroom Trough and the axis of the depocentre trends north-westerly, if compared with the more northerly trend of the older Surat units (Hoffmann et al. 2009). The LST of the supersequence K is represented by the Hutton Sandstone, which were deposited in a meandering stream system during a period of low base-level rise. The deposition of the Eurombah Formation occurred in sluggish meandering streams, while the Walloon Coal Measures are the products of floodplain sedimentation (Exon, 1976; Hoffmann et al. 2009). These latter units represent respectively the TST to the early HST phase of the supersequence (Hoffmann et al. 2009).

The last supersequence L was deposited during the Late Jurassic and equates the Springbok Sandstone and the finer-grained Westbourne Formation, which together form the last fining-upward cycle of the Jurassic Surat Basin. The units were accumulated over a period of ~ 19 Ma and constitute up to 450 m of the Surat succession. The Springbok Sandstone consists of feldspathic to lithic sandstone with minor siltstone, mudstone and few coal seams forming medium to very thick beds with scours and planar-cross beds also present (Exon, 1976; Hoffmann et al. 2009). The Westbourne Formation has maximum thickness of 200 m and consists of interbedded mudstone, siltstone, coal and very fine-grained quartzose to lithic-feldspathic sandstone. Because of the presence of glaucony, heavy-mineral concentrations, acritarchs and barite, Exon (1976) suggested that during the deposition of this unit there may were some shallow marine incursions but, based on geological implications, Hoffmann et al. (2009) argued that, if the incursion existed, was negligible. In general, the Springbok Sandstone was deposited by high-energy streams that became less vigorous through the time allowing overbank and swamp sediments to accumulate. Several depocentres in the central part of the basin with an approximate east-west trend, suggest that the underlying Bowen Basin no longer had a controlling influence on deposition (Hoffmann et al. 2009). The Westbourne Formation was deposited in a coastal-plain setting although freshwater conditions are also consistent with the geological observations. Thus, the fluvial Springbok Sandstone represent the LST and initial TST phase of supersequence L and the possible coastal-plain deposits of the Westbourne Formation constitute the finer-grained part of the TST-HST phases of the last supersequence of the Jurassic.

The deposition in the Surat Basin continued during the Cretaceous and, in a time span of ~ 46 Ma, continental and marine deposits filled progressively the Surat Basin forming: the Blythesdale Group, the Wallumbilla Formation, the Surat Siltstone and the Griman Greek Formation, the last unit of the Surat sequence. Detailed study on the geology of the Cretaceous Surat Basin was carried out by Exon (1976) and his further works.

The end of deposition occurred in the Albian and it is supported by subsidence curves by Raza et al. (2009) who registered around 95 Ma the onset of uplift and denudation along the entire eastern margin, with consequent loss of more than 2.5 km of sediments in the northern Bowen and Surat Basin (Figure 3).

The Precipice Sandstone

The Early Jurassic Precipice Sandstone is a quartzose sandstone which constitutes the basal formation of the Surat Basin (Exon, 1976; Martin, 1976). It overlies unconformable or disconformable on older rocks of the Bowen Basin and it is absent only in some parts of the Roma Shelf, Nebine and Kumbarilla Ridge, because of the presence of topographic highs in the basement. To the south, it wedges out below the boarder of the New South Wales and, to the north-east, terminates against the Auburn Arch and the Yarraman Highs. The Precipice Sandstone crops out in a (~ 350 km long) sinuous east-west belt which defines the northern limit of the Surat Basin and in the outcrop it is easily recognisable because of its typical cliffs which are up to 50 m.

Since the late ‘60s the Precipice Sandstone has been of economical interests because was the most important producer of hydrocarbons in the basin, acting as the main reservoir unit for the Permian (i.e. Back Creek Group) and Jurassic (Evergreen Formation) source rocks (Exon, 1976). Because of its interest, it has been largely studied by several authors including Martin (1976, 1981) and the following part of this work refers mostly to the latter author.

Over the most of its extent, the formation consists in medium-to-coarse, porous, quartzose sandstone with kaolinitic matrix and contains only a minor amount of lithic, feldspathic, micaceous and carbonaceous material. In the outcrop it is typically cross-bedded with high-angle, medium scale, planar cross-stratification and trough cross-stratification, being the predominantly bedding form. The basal contact of the Precipice Sandstone is generally marked by a thin bed of siliceous pebbles although a basal and extensive thick layer of conglomerate is not developed. However, intercalated to the cross-bedded strata thin beds and lens of pebbles are common, as well as thin beds of shale or flaggy fine sandstone. Toward the top of the formation the grain size decreases and the sandstone tends to become horizontally bedded and flaggy rather than cross-stratified, the content of kaolinitic matrix increases considerably, and the unit passes gradually to the carbonaceous and micaceous siltstone of the Evergreen Formation. In some parts this passage is discontinuous, hence more thin and irregular beds of permeable sandstone may be found within the basal sequence of the Evergreen Formation.

The Precipice Sandstone is 60-80 m thick in averages but reaches up to 150 m of thickness in some parts. The maximum thicknesses are found where also the Bowen Basin succession is thickest, hence immediately to the west of the Goondiwindi-Moonie-Burunga fault over the axis of the Taroom Trough the maximum section is measured (Figure 5).

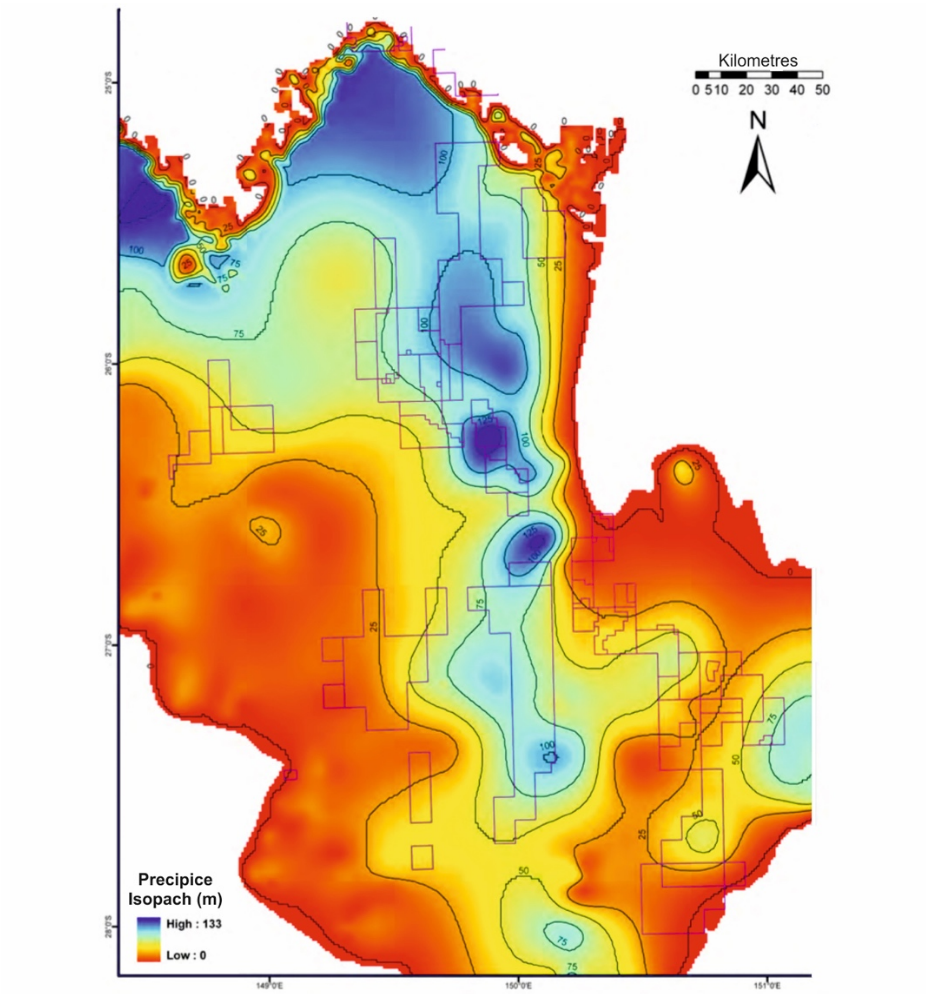


Figure 5: Isopach map of Precipice Sandstone. Note the major depocentres dislocated along the Taroom Trough axis (Image from: QGC Report, April 2912).

The isopach map shows three different depocentres that can be distinguished above the Mymosa Syncline and one largely eroded depocentre on the north-west. Sediment thickness generally increases toward the north of the basin but several incongruities affect the northernmost part of the basin, where exploration wells are fewer and computational models tend to be inaccurate. In example, Exon (1976) and later on the Queensland Gas Company (2012), reported several isopach maps in which the Precipice Sandstone reaches the thickness of more than 100 m from the north of Taroom city till the outcrops of the Precipice Sandstone Belt further north. In contrast, the interpretation of Martin (1976) is that the Precipice Sandstone reaches up to 100 m of thickness in the vicinity of Taroom city but decreases to 40 m toward the northern outcrop on the eastern side of the

Taroom Trough, where a section of only 32 m is present. It should be taken in account, however, that in the same area (near the location of Forest Hill) Bianchi et al. (2015) found only incomplete sections and may the Precipice Sandstone does not crop out completely in this part of the sandstone belt. In the outcrop, thicknesses ranging from 100 up to 120 m are situated in the westernmost part of the sandstone belt, near Carnavorn Gorge and in Isla Gorge and in Nathan Gorge, on the opposite side. On the east of the latter location, the section thins abruptly to 37 m, to the south of Cracow. Thus, the Precipice Sandstone appears to wedge out onto the Auburn Arch. On the western and south-western side of the Taroom axis, the formation is slightly thinner before it thickens again toward west and Carnavorn Gorge (locations in Figure 6).

It is widely accepted that within the Precipice Sandstone formation two informal subunits are distinguished: the "Lower" Precipice and the "Upper" Precipice. This division is a source of confusion because authors and reports give their personal interpretation with the regarding to the boundaries between the "Lower" and "Upper" and the "Upper" and the Evergreen Formation. To complicate things further, in the basal part of the Evergreen Formation a coarse-grained sandy interval can be present. Martin (1976) argued about the subdivision and concluded that, even if thin and fine-grained intervals occurred in the upper part of the Precipice Sandstone and were recognized in many sections, they simply indicate local variations in depositional environment within a fluviatile system and so it is doubtful whether they are regionally significant or correlatable.

In the framework of a Geosequestration Reservoir 3D model it is of fundamental importance distinguishing different facies within the reservoir unit because facies interpretation detains the largest errors in the upscaling procedure (Mikes et al. 2006). Thus, the subdivision between the Lower and the Upper Precipice is accepted because does not simply record a gradual waning of the system and the passage to the upper Evergreen Formation unit, but implies that within the reservoir unit two different facies are present with differences in bottomset permeability and continuity, relativity permeability curves and capillarity pression curves (Mikes et al. 2006). The two sub-units are discussed below.

Lower Precipice

The Lower Precipice is easily recognizable both in outcrop and in cores cuts and represents the typical facies of the formation. It is generally white to grey when fresh and it is mostly quartzose, with minor lithic grains and coaly fragments. In some places it is pebbly while, in other parts, interbeds of conglomerate may be present. The matrix consists of authigenic clay and silica, with little calcite, siderite or pyrite (Exon, 1976).

At the outcrop scale, the most striking and widespread feature of the unit is the cross-stratification. This is the typical bedform of the sandstone throughout the succession and horizontal bedding characterises only a minor part of the formation. Cross-sets are generally planar, although trough cross-stratification might be present in some part of the succession. Sets of cross-stratification range from the small scale (up to 5 cm) to the very large scale (up to 8 m), highlighting differences in stream power and water column during sedimentation. However, most of the relatively thin sets (up to 10 cm thick) simply represent remnants of much large dunes which were almost obliterated by erosion during the falling stage phases. Bases of the sets are mostly erosional, from relatively flat or gently undulated to concave downwards scours infilled by cross stratification. It is common to find quartzose pebble lags scattered on the erosion surfaces or in some case forming thin beds and lenses of pebbles conglomerate. Horizontal bedding or ripple marked beds may occur between the cross-stratified sets and over the crests of dunes.

The laminae forming the sets are planar and rarely exceed the thickness of 1.5 cm and the typical depositional angles range from 24° up to 30° (Martin, 1976). The layers are typically well sorted and the mean grain size differs between one each other, suggesting that some sorting mechanism were acting on the crests of dunes and this was probably in the horizontal and ripple marked bed which is preserved sometimes between sets of dunes.

The Lower Precipice Sandstone is thought to have been deposited in a sandy braided stream system (Exon, 1976; Martin, 1976, 1981) similar to the braided Brahmaputra River and the big cosets (up to 10 m) of planar cross-stratification and trough cross-stratification are the result of downstream migration of transverse/diamond braided channel bars. As in the Brahmaputra River, the fine sediments of the Precipice Sandstone were deposited in a very low gradient area (1 m/km) and the large volume of fine grained bedload exceeded the transportation capacity and the river system was choked with sediment, giving a typical braided pattern (Martin, 1976). Paleocurrents measurements are only possible in the outcrop of the "Sandstone Belt" and were carried out by Martin (1976) who stated that rivers flowed in a general easterly direction (northeast to southeast). In the Mulgildie Rift there is a general northerly trend but the data were limited. However, this trend, together with the south-south-easterly trend to the south of Cracow may indicate that rivers possibly swung to the south and flowed around the southern end of the Auburn Arch and than north to the Mulgildie Rift. Thus the Auburn Arch may have constituted at least a partial barrier to easterly stream flow during the deposition of the Precipice Sandstone. Finally, Exon (1976) suggested that the source rocks for the Precipice Sandstone were probably: (i) the southwestern block and the St. George slope (Central Western Fold Belt) (ii) the New England Fold belt, on the southeast-east and (iii) the Auburn Arch and Yarraman Block on the north-eastern part, even if Martin (1976) stated that these latter highs contributed little sediment to the Precipice Sandstone.

Further in this work a ~60 m thick section of the Lower Precipice will be studied and discussed, allowing to focus on the processes that generated the braided stream deposits.

Upper Precipice

Despite the large knowledge and studies on the Lower Precipice little is know with the regarding of the Upper Precipice. Because of its patchy distribution, the minor thickness and the incongruities in the definition of the lower and upper boundaries, both in outcrop and in cores, it is generally considered simply as the waning part of the braided stream system, but no specific studies have been carried out in the past decades.

Exon (1976) ascribed the Upper Precipice Sandstone to a meandering stream system and described the upper formation as a thinly bedded sandstone and siltstone, generally laminated and micaceous but commonly carbonaceous, in which ripple marks, worm trails and leaf impression are common. In addition, various prospection wells of several oil and gas companies report that carbonaceous cement is strongly present in the upper formation, together with high content of kaolinitc matrix, highlighting the different nature of deposits within the same formation. However, following the study of Bianchi et al. (2015), further geological observations have been put forward concerning the Upper Precipice. In particular, the (i) drastic change in paleocurrents toward the north in the Upper Precipice, (ii) the presence of a "cave-facies", which corresponds to a thinning-upward and fining-upward of the sequence, with high content of siltstone and kaolinitic matrix, symmetrical ripple, horizontal and vertical burrowing and (iii) the presence of lobe-shaped bodies might suggest that, despite the common thought about the pure fluvial nature of the Precipice Sandstone (Exon, 1976; Martin, 1976; Ziolkowski et al. 2014), the Upper Precipice Sandstone may prove a major complexity in the nature of its deposition and might involve a different depositional environment.

STUDY AREA AND METHODS

One of the main aim of the ANLEC Project is to investigate with multidisciplinary approach the Precipice Sandstone which is the geosequestration target unit within the Surat Basin. Where low seismic resolution and wide well spacing cannot afford a good characterization of the reservoir complexity (i.e. heterogeneities), a good geological and petrophysical description of reservoir analogues can overcome in some part the lack of relevant data needed for the construction of the 3D reservoir model. In this framework the studied outcrops represent an excellent analogue and the outcrop-based information allow to transfer and incorporate data into operational practice.

This work is based on sedimentological outcrop investigation integrated with well data provided by the ANLECR&D Company. Field investigation were based on integration between facies analysis and Terrestrial Digital Photogrammetry.

Study area

The study area is located in the easternmost part of the "Precipice Sandstone Belt" in the north eastern part of the Surat Basin, Queensland. The outcrops are situated ~20 km south of Cracow, in the Precipice Sandstone National Park (see location map, Figure 6). This fieldwork follows the previous campaigns led by Bianchi et al. (2015) in Carnavorn Gorge, Forest Hill, Flagstaff and Isla Gorge, and focuses on the eastern side of the Precipice Sandstone belt because it is closer to the leasing terrain owned by the company. Nevertheless, the eastern part of the belt is situated between the Taroom Trough axis and the Burunga-Moonie-Goondiwindi fault system and so the formation it is not significantly deformed.

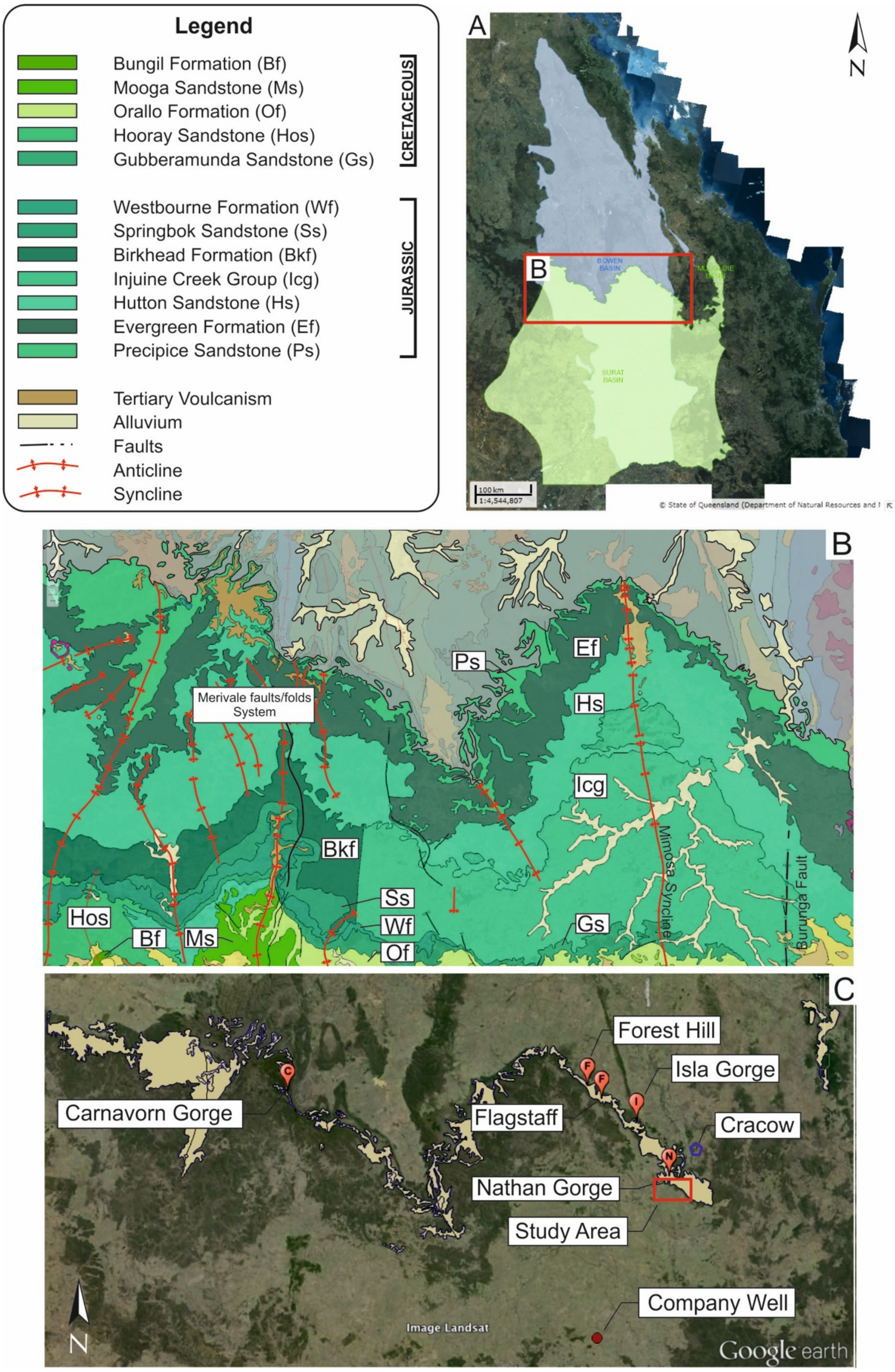


Figure 6: A – Image showing the Surat and the Bowen Basin; B – Geological map of the Jurassic and Cretaceous Surat Basin. Major tectonic elements are present; C – Image showing the "Precipice Sandstone belt" and locations of outcrops studied by Bianchi et al. 2015 (Source: Mines Online Maps, QLD Government).

Before the field campaign commenced, an accurate planning phase was conducted together with the surveyors in order to select the best targets in the outcrop suitable both for facies analysis and photogrammetry. Preliminary GIS analysis was carried out in order to find out the steepest areas (ideal for photogrammetry) and several contour lines maps were performed using maps available from the Web Map Services (WMS). The planning phase included also the analysis of practicable off roads and the request submitted to the rangers of the National Park and the owners of the farms to drive trough the different areas. All this issues strongly constrained the selection of the outcrops and areas that could be object of studies.

After the planning phase four outcrops were chosen in order to conduct analysis and are shown in Figure 7.

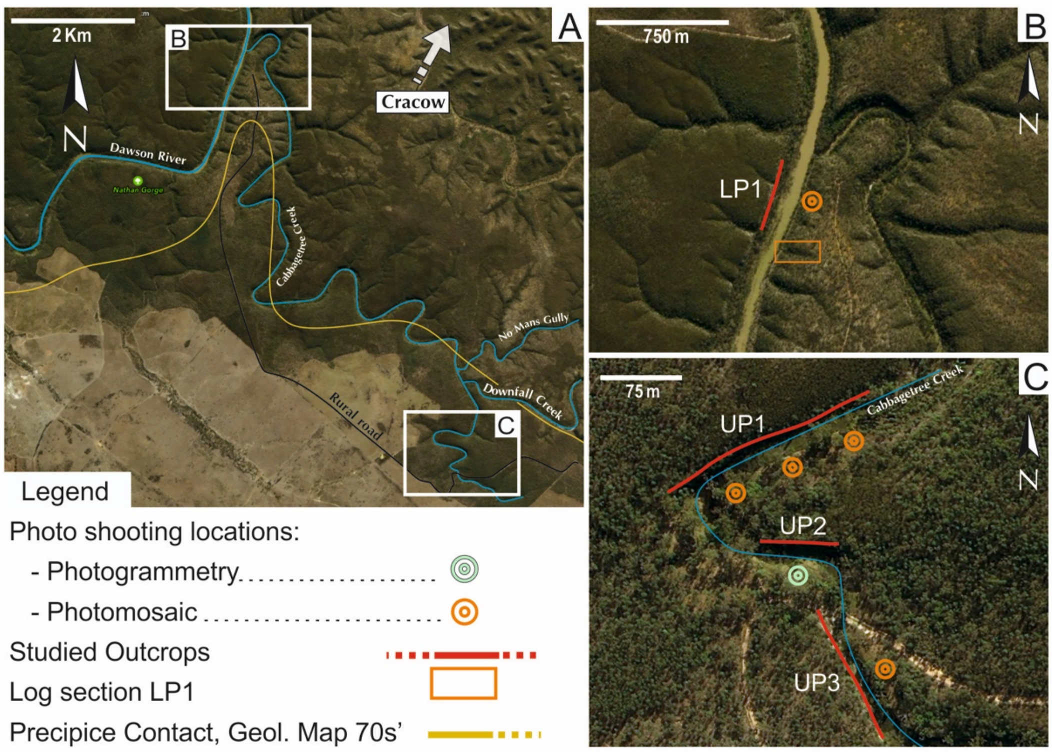


Figure 7: A – Study Area; B – Location of the Lower Precipice Outcrop; C – Location of the Upper Precipice outcrops.

The first outcrop (LP1) is in proximity of Nathan Gorge. Here, the Lower Precipice crops out and forms steep cliffs of about ~50 m and exceeds the length of 200 m. These cliffs are delimited by a river and the succession was studied from the opposite side, firstly using long focus 28 mm lens for the photomosaic shooting and than doing facies analysis on a patchy outcrop which is situated on the same side in the vicinity of a gully.

The Upper Precipice has been recognized in proximity of Cabbagetree Creek, where three outcrops are dislocated along the creek path (UP1, UP2 & UP3). The outcropping area is located less than 1 km outside of the mapped Precipice area in the 70s' geological map, but it is still Precipice Sandstone. The assertion is possible on the base of the topographic height: the location of the latter outcrops indeed, is at minor height (~ 230 m asl) in respect to the outcrops mapped in the 70s' which are just to the north (~ 255 m asl). Because of the Surat Basin is slightly tilted 2° toward south, it is possible to reach the Precipice Formation further south if this is at minor height, as in the case of the incised valley of the Cabbagetree Creek. The three outcrops provide a 3D view of the system, allowing a detailed study in terms of facies analysis and 3D photogrammetry.

The overall geographical and geomorphological setting have made extremely challenging the acquisition of data. The alluvium and the covering of vegetation often blocked both the possibility to do facies analysis and also 3D photogrammetry, in terms of (i) GPS acquisition signal (ii) on-field logistical complexity for the acquisition of pictures that allow the 3D photogrammetric reconstruction (iii) quality of 3D models where the outcrop is covered by vegetation. Natural barriers such as rivers and spiders/snakes made pleasant the wild campaign.

Facies analysis

Field and outcrop investigations have been carried out on several natural cliffs which are dislocated along the Cabbagetree creek (Figure 7). The study deposits have been analysed trough a sedimentological approach based on facies analysis principles. Each succession has been characterized via bed by bed logging and distinguished on the base of facies associations, those consist of assemblages of

spatially and genetically related facies that are the expression of different depositional environments.
The deposits have been divided in sedimentary units or allostratigraphic units (from the Greek *allo*: "other, different."), which are defined as mappable body of rocks that are identified on the basis of their bounding discontinuities, both unconformities or correlative-conformities (North American Commission on Stratigraphic Nomenclature, 1983). There is no implication of lithology within the definition and so, internal characteristics (i.e. physical, chemical and paleontological) may vary laterally or vertically throughout the unit. The using of allostratigraphic units detains a wider applicability if compared to the use of depositional sequences or synthems and allows to easily define the history and the basin-scale geometry of the sedimentary succession within heterogeneous, confined basins which are characterized by erosional, non-depositional and correlative-conformities surfaces.
The data set consists of 2D and 3D photo-mosaics and line drawings integrated with several sedimentary logs. The outcrops architectural panels have been made in order to reconstruct geometries and temporal evolution of macroforms (i.e. channel bars) and complex compound bodies. Where possible, paleo-currents measures were calculated based on the dip of laminae from cross-bedded strata or inferred from direction of asymmetrical ripple crests.
Study deposits are affected by an overall tectonic tilting toward south of 2 degrees, which is not considered a significant tectonic tilting that requires a correction of the palaeocurrent data.

Terrestrial Digital Photogrammetry (TDP)

One of the main aim of this project is the application of 3D ground based photogrammetric models to capture digital images that can be archived and analysed for sedimentary and structural features that will impact on reservoir properties. The term photogrammetry means the science and technique of interpreting and evaluating the form, dimension and position of objects by analysing and measuring images of them and the result of photogrammetric procedure is a precise three-dimension geometric reconstruction of the object that can be orthogonally projected onto a plane (i.e. normally, horizontally or vertically) at a certain scale (Bianchi et al. 2015; Redweik, 2013). In this framework and within the ANLEC project, the goal has been to create several 3D models of cliffs which are most representative of the typical planar-to-trough cross-bedded Precipice Sandstone, in order to detect architectural elements in the outcrop and trace bedding in 3 dimension. The workflow proposed by Jackson et al. (2005) (Figure 8, a) might be a useful and indicative example wherein photogrammetric 3D models could be a great implementation for the reservoir characterization and where is shown the potential applicability of the technique concerning reservoir studies.

Before the undertaking of the field campaign and in order to create the best and accurate models, it has been necessary to consider some essential planning components, including: (i) setting the resolution (ground point spacing) necessary for the purpose of a project (ii) specifying the required accuracy and precision (iii) defining the area to be mapped, taking into account physical/topographic constraints. The interplay between these points/questions plays an important role during the elaboration of the 3D photogrammetry model and are briefly discussed hereinafter because of fundamental relevance when this method is used.

The ground point spacing (or ground resolution) depends on the instantaneous angular field of view or IFOV (i.e. the area covered by one pixel on the ground) and by the step size, which quantifies the number of pixels used, both horizontally and vertically, to generate one spatial point (typical step sizes range between 4 and 8 pixels). The ground pixel size (IFOV) should be multiplied by step size to obtain the ground point spacing and so, areas closer to the scanner have a closer ground point spacing rather than distant objects which have a wider ground point spacing.

The ground point spacing used in digital photogrammetry surveys is an average value and several software provide "planning tools" that enable the user to estimate the correct values.

The accuracy and precision depend on: (i) calibration of the lenses (made by the software – for processing correctly the images acquired which depends by the physical characteristics of the lens) (ii) automated stereo-couple matching (depending on the powerful of the software) (iii) ground resolution and (iv) network geometry. The network geometry operates primary on the depth accuracy, which depends on the geometric relationship between the camera positions (baseline) and the object being photographed at a certain distance, according to the following equation:

$$\text{Depth accuracy} = \text{Planimetric Accuracy} * \text{Distance/Baseline}$$

This equation suggests that a large distance/baseline ratio provides a better depth accuracy. However, a large distance/baseline ratio results in difficulties for the image matching process causing several errors. Consequently, a ratio situated between 5/1 and 8/1 is recommended.

The third and last point that needs to be set - before and during the field campaign - concerns the physical and topographical constraints in which ability and experience of the surveyor play the most important role. In general, depending on the size of the area to be mapped, several sets of photographs will need to be taken. When there are major changes in perspective, such as around a corner, the area should be split into smaller windows and when there is a potential for occlusion and/or orientation bias (prospective errors), separated pairs of photographs should be taken from different angles. Furthermore, obstructions (like tall trees or shrubbery) and occlusions in front of the outcrop spoil the good construction of a correct and reliable model. All this issues strongly affect the completion of a useful and precise 3D model, because easily and accessible outcrops are unlikely to be found.

Concerning the fieldwork activity, during the images acquisition procedure several points needed to be set in order to obtain the best data for the most reliable 3D photogrammetric model. In particular, these concerned (i) the camera/lens set up and (ii) the Global Positioning System (GPS) registration approach. Firstly, camera has been set up keeping in mind that the image sharpening and focus is the most important target to achieve during the shooting for a 3D digital model. Thus, for the creation of this model a 50mm lens has been chosen and pictures have been shot left to right with f/8 aperture and ISO sensitivity of 100, trying to capture the frames at the same light conditions. Since the models can be registered in a variety of coordinate systems, including Universal Transverse Mercator (UTM) or Geographic Coordinate System, the outcrop is georeferenced and to every single pixel of the 3D model a coordinate couple is associated. The GPS point acquisition, should be as accurate as possible when a georeferenced 3D model is required. Position is determined following the Differential Global Positioning System (DGPS) concept, in which 4 satellite positions are needed in order to have the coordinates of a unique receiver. When single receivers are used (e.g. like commercial handheld GPS, integrated or external camera GPS) the accuracy is in the order of metres or tens of metres while, using two ore more receivers (as in this case), an accuracy of a few meters to millimetres can be obtained. During the campaign, the main receiver (the base) was left on a fixed point for a few hours so that its position could be recorded with accuracy while the second receiver (the rover) was placed at the position which needed to be surveyed (i.e. photo-shoot location and rock-wall). By simultaneously tracking the same satellites, the base and rover are subject to the same errors and bias and these allowed us to get a series of geographic points with an average 3D quality of about 3 cm. To survey the UP2 outcrop has been necessary to take 44 pictures from 15 different positions for a total of 22 stereo couples (Figure 8, b). The geographical constrain represented by the presence of a large creek just in front of the outcrop forced us to capture images following the bank, trying to maintain an average distance of 20 meters. Accuracy on the outcrop surface (ground pixel size) is 1.8 mm. 3D models have been created for every stereo couple thanks to powerful Sirovision^{TM} (by CSIRO) algorithm. When necessary, spikes generated automatically because of perspective errors (outliers) or deformations at image borders have been cleaned (Figure 8, c). All single stereo couple have been then merged together by manually digitizing anchor points between them to form a unique big virtual model (see the Results section).

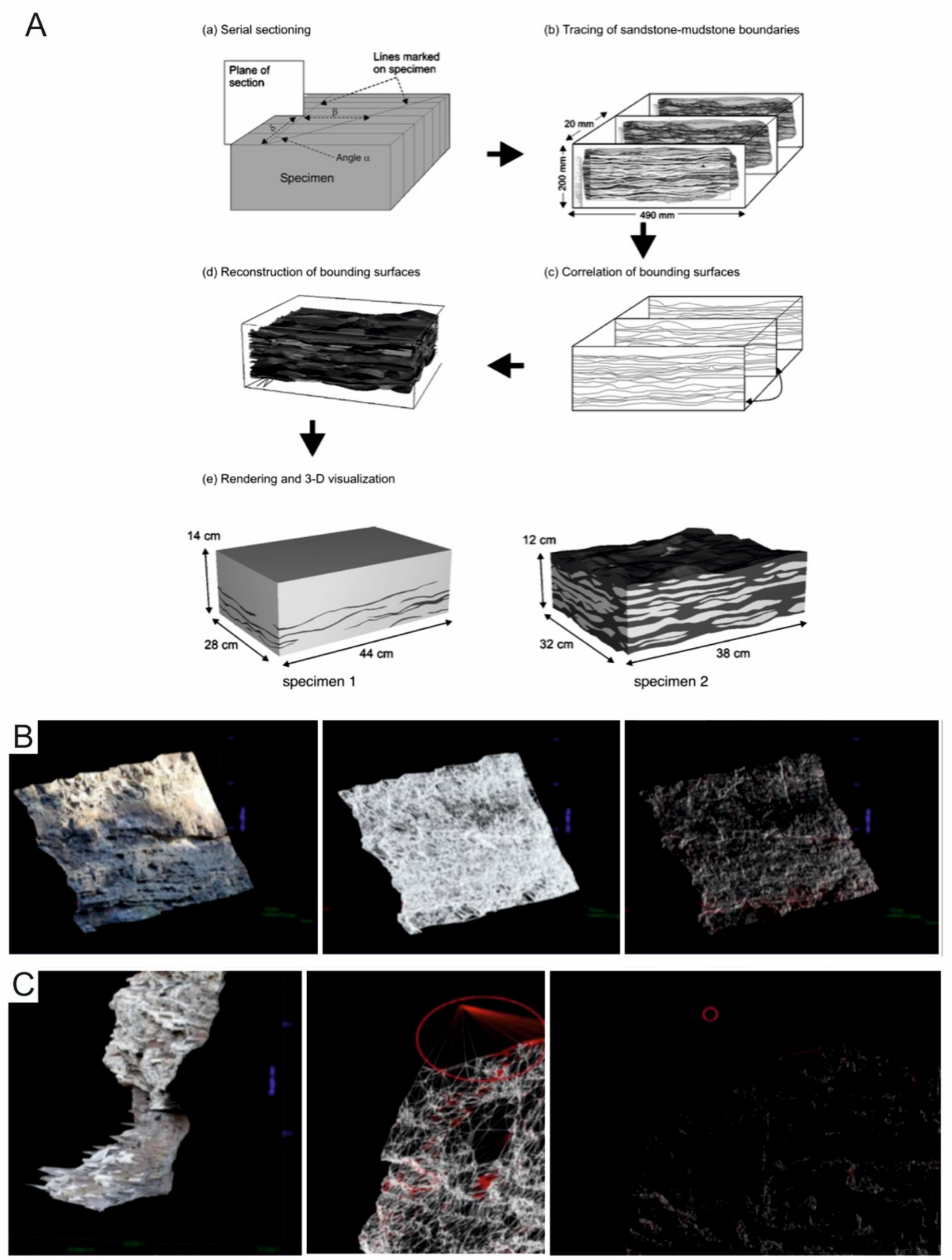


Figure 8: A – image showing the workflow proposed by Jackson et al. (2005). Note the construction of a grid-cell by the correlation of the bounding surfaces (Image from: Jackson et al. 2005); B - Stereo couple model views, from left to right: textured mesh, wireframe and pointcloud. Area approximately 5m square; C – Spikes and artefacts cleaning on the stereo couple.

Borehole data

Before the beginning of the fieldwork campaign the Precipice Sandstone has been studied using core data provided by the ANLECR&D Company or collected at the Exploration Data Centre in Zillmere, Queensland. The main aim of the studying was to do core logging of the Precipice Sandstone in order to characterize facies of both the Lower and the Upper units before the fieldwork began. The studied core was recovered in the Woleebee Creek GW4 borehole (hereinafter GW4), and was drilled by QGC (Queensland Gas Company) to assist in understanding the regional aquifers in the Surat Basin. Furthermore, ANLECR&D Company provided useful data from the closer West Wandoan 1 well (hereinafter WW1), thus allowing the comparison between the two cores. In particular, WW1 is owned by the company and is supposed to be the injection well from where CO2 will be shot underground. Since the WW1 is located ~150 km south to the Precipice Sandstone belt, the core logging of the closer GW4 is useful in order to investigate whether abrupt changes in facies occur within the Surat Basin and also how the Upper Precipice looks like farther south from the studied outcrop. When possible, public data and reports (QPED 2015 database) from various wells have been taken in account and obtained from open sources in order to enhance the knowledge of the Precipice Sandstone geology.

The core was studied using facies analysis principles, keeping in mind that in core analysis lateral continuity is not appreciable. Where possible, texture, colour, composition, sorting, bedding/lamination, bioturbation and other distinguishing features were described. Particular attention was put on changes in grain size and significant surfaces, if any.

RESULTS

In the following part of this work are shown the outcomes of the studies performed during the aforementioned internship in Australia. Since the goals were mainly to (i) characterize the Lower Precipice and provide data relevant for the creation of a geocellular 3D reservoir model and (ii) to investigate on the nature of the Upper Precipice in terms of facies distribution, depositional environment and thicknesses, the studied outcrops are therefore described separately and the results are shown based on the principle of superposition, from the older Lower Precipice to the younger Upper Precipice. The workflow is equivalent for both the units and these are studied based on the facies analysis principles.

Lower Precipice outcrop study

Facies Analysis

Four sedimentary facies (see Table 1) have been identified in the study area via bed by bed logging (see Logged section in the Appendix). These facies are characterized by well-defined sedimentary features (i.e. grain size, sedimentary structures, bed geometry and stratal terminations) that are the expression of well-defined depositional processes. Five facies associations (see Table 2) have been successively identified, which represent genetically related facies deposited in different sedimentary environments. It is important to note that some facies are exclusive to one depositional setting whereas others might be recognized in several environments and subenvironments and, because ubiquitous, they could not act as a target in the recognition of the depositional setting. However, the well known, sandy-braided nature of the Lower Precipice Sandstone is helpful in the understanding of the geometries of the bodies recognized in the outcrop.
The hierarchical classification in micro-, meso- and macro-forms refers to the terminology used by Jackson (1975) and it will be largely adopted hereinafter because of its useful applicability, especially in facies characterization of sandy braided river systems. Defined TE as the time interval between successive

dynamic events, the hierarchic units are easily differentiable in (i) macroforms, relatively insensitive to the local flow conditions and with life much grater than TE (ii) mesoforms, which respond to variations in flow conditions throughout each dynamic event, with time life scaled with TE and (iii) microforms, which respond to short-lived fluctuations of flow regime and life time much lower than TE (Jackson, 1975). A typical example might be: a point bar (i.e. compound bar) which is the macroform; the dunes, sand waves or transverse /longitudinal unit bars, which are mesoforms and finally, small scale ripple cross lamination or upper plane parallel stratification which are microforms. It is worthy specify that the single unit bars, which form a compound bar, are mesoforms and, therefore, they could be modified during a single dynamic event, modifying the macroforms (i.e. compound bars) too.

Facies Association (FA): 2D and 3D dunes

Description

Facies association A is made up of 6 cm up to 1 m thick sets of planar to trough cross-stratified sandstone (Facies 3), which is the most striking and widespread sedimentary structure in the outcrop (Figure 9, 11). The sets present both flattened and scoured erosive bases and pebble lags (Facies 4) are common in between each set, or in minor pockets at toe of lamination. The laminae making up the cross stratification are planar and rarely exceed 1.5 cm and consist of well sorted and very porous sandstone with up to 90% of quartz. The mean grain size is medium sand but both fine and coarse sand is common. The cross-strata deep at generally ~23-24° and at bottom they might be reworked by secondary currents, being tangential with the bounding surfaces. However, the relative geometry between the lamination and the basal surfaces is generally angular. When preserved, minor ripple cross lamination (Facies 1) is present on top of the cross-strata.

Interpretation

Facies association A is interpreted as the result of the downcurrent migration of ‘trains’ of dunes which were formed under tractional conditions in a stream system with frequent changes in flow velocity.

Table 1: Table showing the main facies recognized in LP1

Facies	General description	Lithology	Sedimentary structures	Bounding surfaces	Bed thickness	Other features
1	Planar-to-trough cross laminated Sandstone	Well sorted quartzose sand, fine to medium, rarely coarse.	Thin laminae forming small sets of 2D and 3D ripples. Deposited under tractional conditions due to unidirectional currents. Deposits move on the stoss side and settle down on the lee side.	Gradational bases and erosive tops.	Individual sets are up to 6 cm. Beds rarely exceed 15 cm.	-
2	Plane parallel laminated sandstone	Well sorted quartzose sand, medium to coarse, rarely fine.	Plane parallel lamination, sediments are deposited under tractional conditions in upper flow regime	Gradational bases and tops.	Individual laminae are up to 2 cm. Cosets made of plane parallel lamination rarely exceed 20 cm.	-
3	Planar-to-trough cross stratified Sandstone	Well sorted quartzose sand, generally medium to coarse but sometimes fine grained.	High angle (from 24° up to 30°) laminae (cross-strata) forming big cosets of 2D and 3D dunes. Deposited under tractional conditions in high flow regime (up to 1 m/s).	Erosive sharp bases or scoured bases. Tops are both erosive or gradational.	Sets range in thickness from few centimetres up to 3m or more.	At the bases pockets of pebbles or mud clasts might be present.
4	Pebble lag	Quartzose whitish pebbles and granules, subrounded to rounded and in general spheroidal. Matrix between clasts is present.	Lag of pebbles and granules are structureless, rolled according to their momentum.	Generally erosive bases. Tops are gradational.	Pebble lags are up to 15 centimetres.	_

Table 2: Table showing the principal Facies Associations recognized in LP1

Facies associations	Brief description	Component lithofacies	Facies interpretation	Subenvironment
FA	Long and thin (6cm up to 1m thick) sets of planar to trough cross-stratified sandstone. Sets are separated by erosive sharp-to-scoured surfaces. Pebble lags are common.	3 (dominant) 4-1 (subordinated)	Minor 2D and 3D dunes formed under tractional conditions.	Cannel talweg and channel flanks; cross-channel bar top and flank.
FB	Thick (up to 3m) sets of planar cross stratified sandstone with dip angle of ~27-30°. Orientation of cross-strata is unidirectional. Sets are separated by erosive sharp-to-scoured bases. Pebble lags are common.	3 (dominant) 4-1 (subordinated)	Large 2D dunes which form mesoforms ascribed to cross-bar channel accretionary front.	Transverse unit-bar
FC	Large sets of planar and trough cross-stratified sandstone (up to 4m high). Orientation of cross-strata is random. Sets are separated by erosive sharp-to-scoured bases. Pebble lags are common.	3 (dominant) 4 (subordinated)	Large 2D and 3D formed under tractional conditions.	Compound bar
FD	Near symmetric erosive wide scours filled by massive, strutureless deposits and by planar-to-cross stratified sand. Tabular lamination occurs in the topmost part of the channel.	3 (dominant) 4-2 (subordinated)	Deposit infilling of channelized feature.	Cross-bar channels
FE	Flat-lying sand sheet beds with little cross-stratification or upper plane parallel lamination. Beds are tens of metres long and laterally continuous.	3-2-1	Minor dunes and ripples deposited under lower stage flow.	Sand flat

The different grade of reworking at the bases of the dunes (tangential vs angular geometry), the different erosion and preservation rate between each set and the wide range of height (measured on preserved and complete dunes where possible) suggest that the depth of the water column changed frequently during the deposition of the bedforms. The distinction between 3D (linguoid or lobate) and 2D (straight-crested or slightly sinuous) dunes is not easily appreciable because the majority of bedforms are obliterated by erosion. However, in section transverse to the flow the differences are easily recognisable (Figures 9 a, b; 11).
Dunes are present in all the active parts of a sandy braided river system (Ashworth et al. 2000, 2001; Bridge & Lunt 2006; Cant & Walker 1978; Horn et al. 2012; Lunt et al. 2013) and this implies that wherever the main channel and the anabranches flow, sediment is reworked and deposited mostly as dunes. Dunes are present: (i) in channel talweg and channel flanks (ii) superimposed on flanks of compound bars (scrolling dunes) (iii) on the top of unit bars and compound bars and (iv) as fundamental/architectural element within the major unit bars and compound bars. Nevertheless, morphology and preservation rate is strongly dependent and differs between each depositional subenvironment, e.g. dunes formed on bar tops are frequently exposed during low stages rate flow and thus mostly reworked and/or eroded.

Facies Association (FB): Transverse unit-bars

Description

Facies association B (Figure 10) typically consists of thick (up to 3 m) sets of planar cross stratified sandstone (Facies 3) which generally dip with an average angle of about ~27-30°. The cross-strata making up the laminae are planar and consist of alternation of sand layers well sorted but with different mean grain size, suggesting some sorting mechanism prior and during the frontal accretion. However, the deposits are generally composed of medium to coarse sand and fine sand is rare. Within the laminae it is possible to recognize the dominance of inverse grading (grainflow deposits) that is the result of the avalanching process (Figure 9 c). Alternated to the inverse graded layer there are the grainfall deposits, which represent the fallout of finer grained sediments over the accretion front. The relative geometry between the cross-strata and the basal surface is generally angular, but tangential or concave geometry may occur. Thus, the bounding surfaces are generally erosive, usually fairly flat or undulating, even if scours also occur. Pebble lags (Facies 4), mud clasts (Figure 9 d, f) or isolated groups of pebbles could be found at the base of sets. Minor dunes or ripple stratification (Facies 1) are sometimes present onto the flattened top of the cross-stratified strata (Figure 9 e; 10).

Interpretation

Facies association B is interpreted as extensive mesoforms, ascribed to transverse unit-bars. In particular, the cross-strata represent the channel bar accretionary front. Transverse bar migrate downcurrent similarly to longitudinal bars but are characterized by an avalanching front transverse to the main flow. The sediment is transported under tractional conditions on the top of the bar and avalanches once the crest is attained, forming the inverse graded grainflow deposits which are the building blocks of the cross-stratified strata. The larger clasts roll downslope according to their momentum and form a pebble lag directly at the toe of the slope. More pebbles might accumulate in the scours which are due to the secondary currents associated with a re-circulation cell in front of the dune. When the bar top is preserved, minor dunes or ripples might be found. These latter bedforms modify the bar top during reduced flows and migrate toward the crest allowing a sort of pre-sorting mechanism prior the avalanching phase (Figure 10, 13).

Large transverse bars are common in sandy braided river systems (e.g. in the Platte River, see Horn et al. 2012) and are equant to elongate barforms with an arcuate to straight frontal surface, exceeding 90 m in width. However, minor transverse bars are common and have width of 33-88m. When several transverse bars are active they might be coalesced to form large compound bars hundreds of meter wide and over 1 km long (Asworth et al. 2000, 2011; Horn et al. 2012) (Figures 12, 14).

Facies Association (FC): Compound bars

Description

Facies association C is made up of large sets of planar and trough cross-stratified medium to coarse sand (Facies 3). The cross strata can locally be up to 4 m high and extend laterally for ten of metres (Figure 11, 12). The range in dip angles reflects both the orientation angle of the outcrop section with respect to the cross-strata and also the different morphologies present in a braided river system, ranging from ~ 30° to 10-15° (Figure 11, 12). Quartz- pebble lags (Facies 4) are common at the toe of the cross-strata, in scours and between each set of cross-stratified sandstone. Bounding surfaces are erosional, usually fairly flat or undulating but not necessarily parallel to the upper surfaces of the sets of cross-strata. Consequently, erosion surfaces may truncate sets of cross strata by cutting across them at low angles.

Interpretation

Facies association C is interpreted as the typical facies arrangement which characterises large compound bars (*sensu* Bridge, 2003). Compound bars are common elements within a sandy braided river system and are largely described by several authors whose studied analogue sedimentary elements in modern rivers (Ashworth et al. 2000, 2011; Best et al. 2003; Bridge & Lunt 2006; Lunt et al. 2013; Sambrook Smith et al. 2009). Dunes dominate much of the deposits of the compound bars, especially in the bar head and central regions. The largest trough cross-stratification are found at the bar head and the scale of these sets decreases vertically towards the bar surface (Sambrook Smith et al. 2009) (Figure 12). Large scale, high angle planar stratification is mostly found at bar margins, as the result of lateral migration or frontal accretion of the compound bar. Minor cross-bar channel (FD) or bar top hollows (Best et al. 2006) might be found on the top of the compound bars.

Several and really different models are proposed by various authors (e.g. Cant & Walker 1978, Ashworth et al. 2000 and finally Horn et al. 2012) for mid-channel bar growth in large sand-bed braided rivers. When a central bar nucleus is built, conditions for a single unit bar formation is reached. As the flow regime fluctuates, the unit bar growths and bar-top aggradation continues trough both dunes superimposition and development of accretionary front on bar margins or bar tail. When major perturbation of the flow occurs (i.e. large floods or ebb conditions), channel belt and anabranches change their pattern, reshaping and modifying the existing unit bar or creating new unit bars on the relict of the pre-existing bodies. Thus, compound bar in sandy-braided system might consist of three to seven unit bars (Lunt et al. 2013 cum bibl.) and form the largest macroforms within the river system.

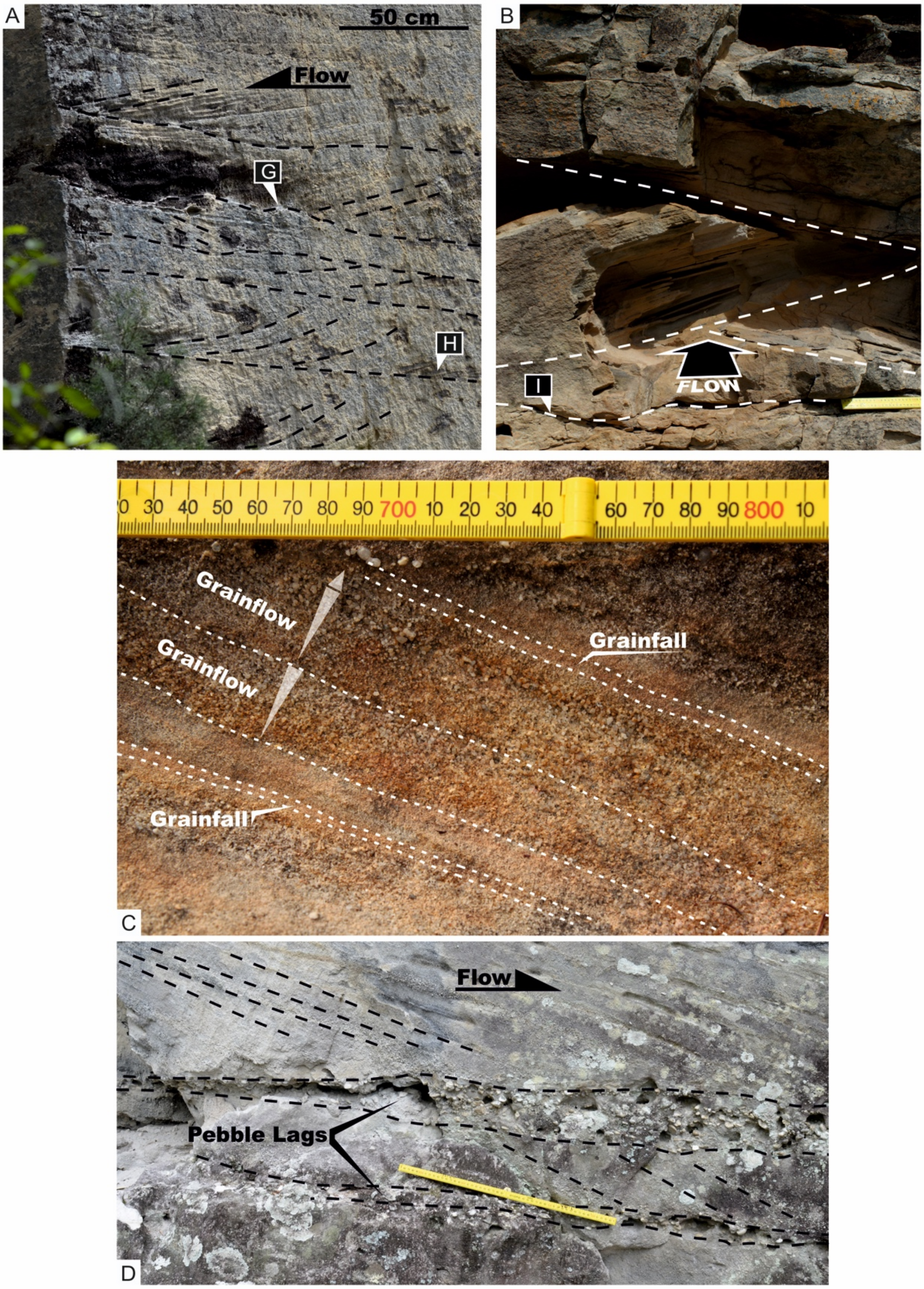
Facies Associations (FD): Cross-bar channels

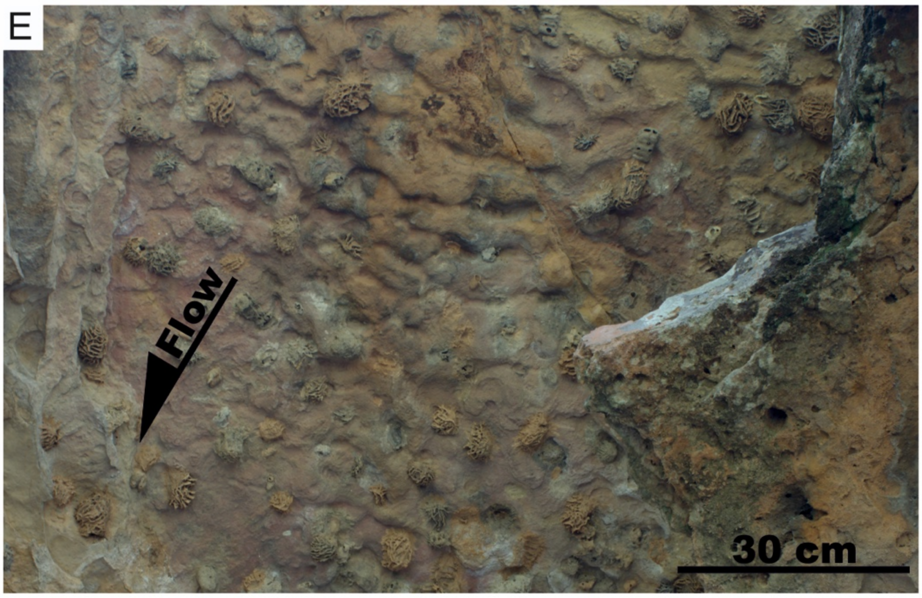
Description

Facies association D is mainly composed of sandy deposits with a higher percentage of fine sediment in respect with facies associations A, B and C. The FD sandy deposits infill gently concaved erosion surfaces (if viewed in cross-section) which are ~ 1.5 high and 8 metres width and typically truncate the underlying FC deposits (Figure 12). The sequence infilling of these scours usually begins with a layer of rounded quartz-pebbles lags (Facies 4) overlain by (i) coarse - very coarse sandstone which usually appears to be massive and structureless and by (ii) cross-strata with a planar-to-trough cross geometry sandstones identical to those of the surrounding sequence (Facies 3). The trend is generally fining-upward, with very fine sand on top of the scour fill (Facies 2).

Interpretation

Facies association D is interpreted as the result of the abandonment and infilling of channels which cross the bar top of individual transverse bar (FB) or major compound bars (FC). Cross-bar channels and minor channels (slough) are occupied during any stage of over-bar flow but they are more likely to form during the falling water stages, as water exposes the lower-lying areas while the headward erosion from the bar edges might trigger channel growth (Sambrook Smith et al. 2009). Thus, frequent fluctuations in flow stage provide more opportunities for such cross-bar channels to form. However, it is worthy to note that there is little modification of the bar morphologies by cross cutting minor channels during waning and low flows.





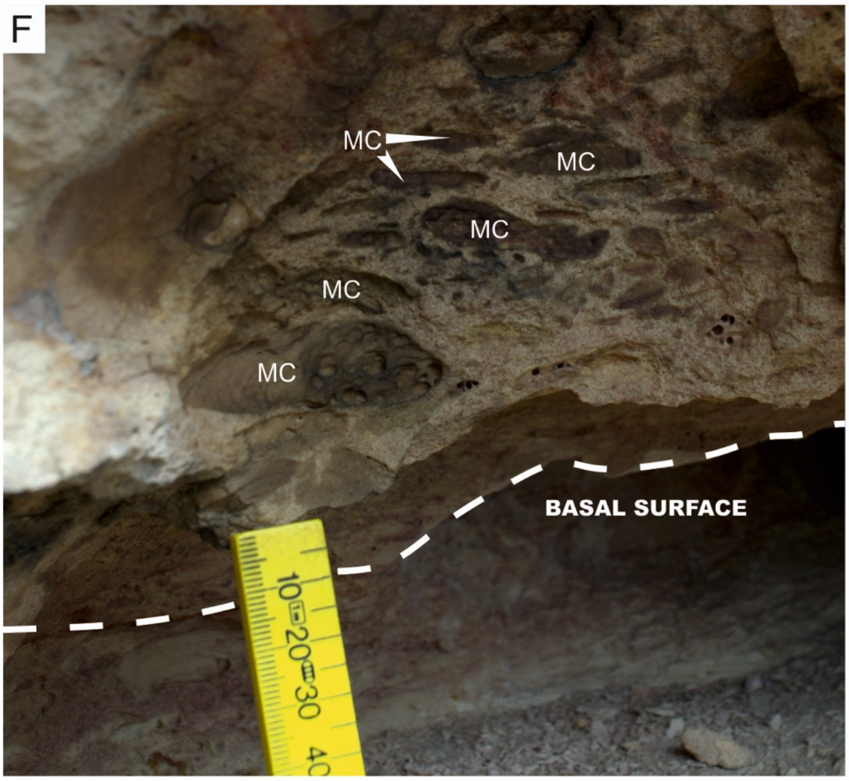


Figure 9: A (PREVIOUS PAGE) – Rock wall showing sections of 2D dunes and planar-cross stratified strata, bases are both strongly eroded and reworked (G) or nearly flat and sharp (H); B (P.P.) – Cross section of trough cross-stratified dunes. Note the troughs with different dipping directions and marked erosional base (I); C (P.P) – Detailed image showing alternated grainflow and grainfall deposits forming the avalanche front of a dune; D (P.P.) – Pebble lags at the bottomset of dunes; E – Bottomset view of ripple cross-laminated strata situated at the top of a large transverse unit-bar. Ripples present complex crests due high flow velocity; F – Mud clasts at the bottomset of a dune.

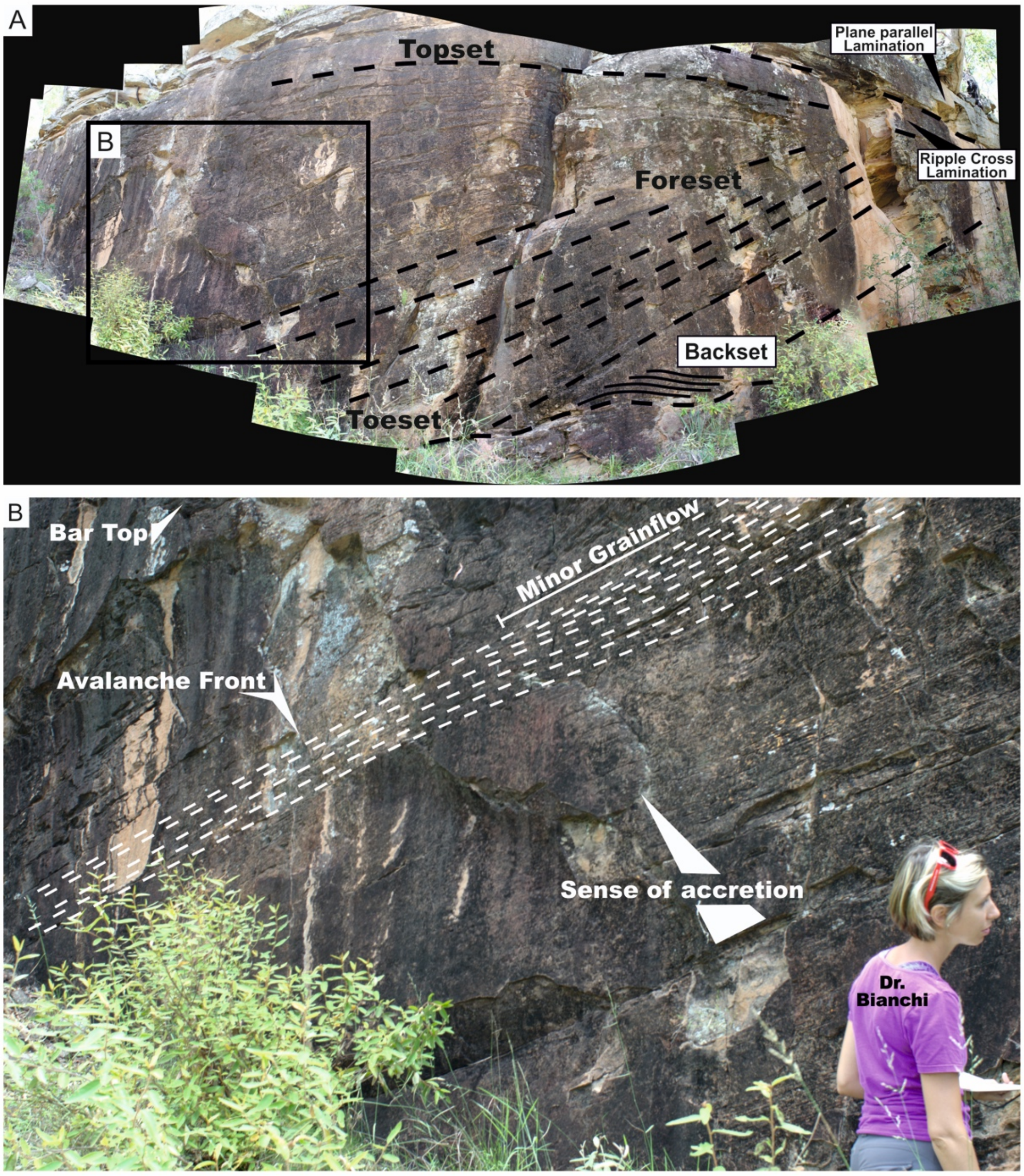


Figure 10: A – Photomosaic showing a nearly 3D section of a large transverse unit-bar. Note that highness of the avalanche front (Dr. Bianchi for scale) produces backset deposits at the base of the bar up to 0.50 m high; B – Detail showing the avalanche front of the transverse unit-bar made up of predominantly grainflow deposits. Minor grainflow deposits are present and do not reach the bottomset, stopping halfway.

Facies Association (FE): Sand flats

Description

Facies association E is typically composed of medium to coarse sand with higher content of finer component in respect with the facies described above. Deposits consist of 30 cm thick beds, wherein minor sets of planar cross stratification

(Facies 3) and planar to trough cross lamination (Facies 1) are present. Furthermore, upper plane parallel stratification (Facies 2) also occur. Geometry of strata is fairly flat and beds are in general laterally continuous for tens of metres (Figure 12) while bounding surfaces and bases between each set are erosive and sharp respectively.

Interpretation

Facies association E deposits are the expression of long and narrow flat-lying sand sheet defined the first time as 'sand flat' by Cant & Walker (1978). These, are large areas of sand accumulation which emerge at low to moderate river stage and can be relatively simple (as a single exposed top of cross-channel bar) or very complex (when several bar top of cross-channel bar or various compound bars become coalescent), even dissected by complex nets of cross-bar channels (FD). Sand Flats might range from 50m to 2km in length, and 30 to 450m in width and could be submerged or emerged dealing with the range of maximum and minimum flood of the rivers system; occasionally water depth over the sand flat can reach 1m (Cant & Walker 1978). After recession of the flood, sand flats are usually covered by dunes of various eight, ripples and horizontal lamination.

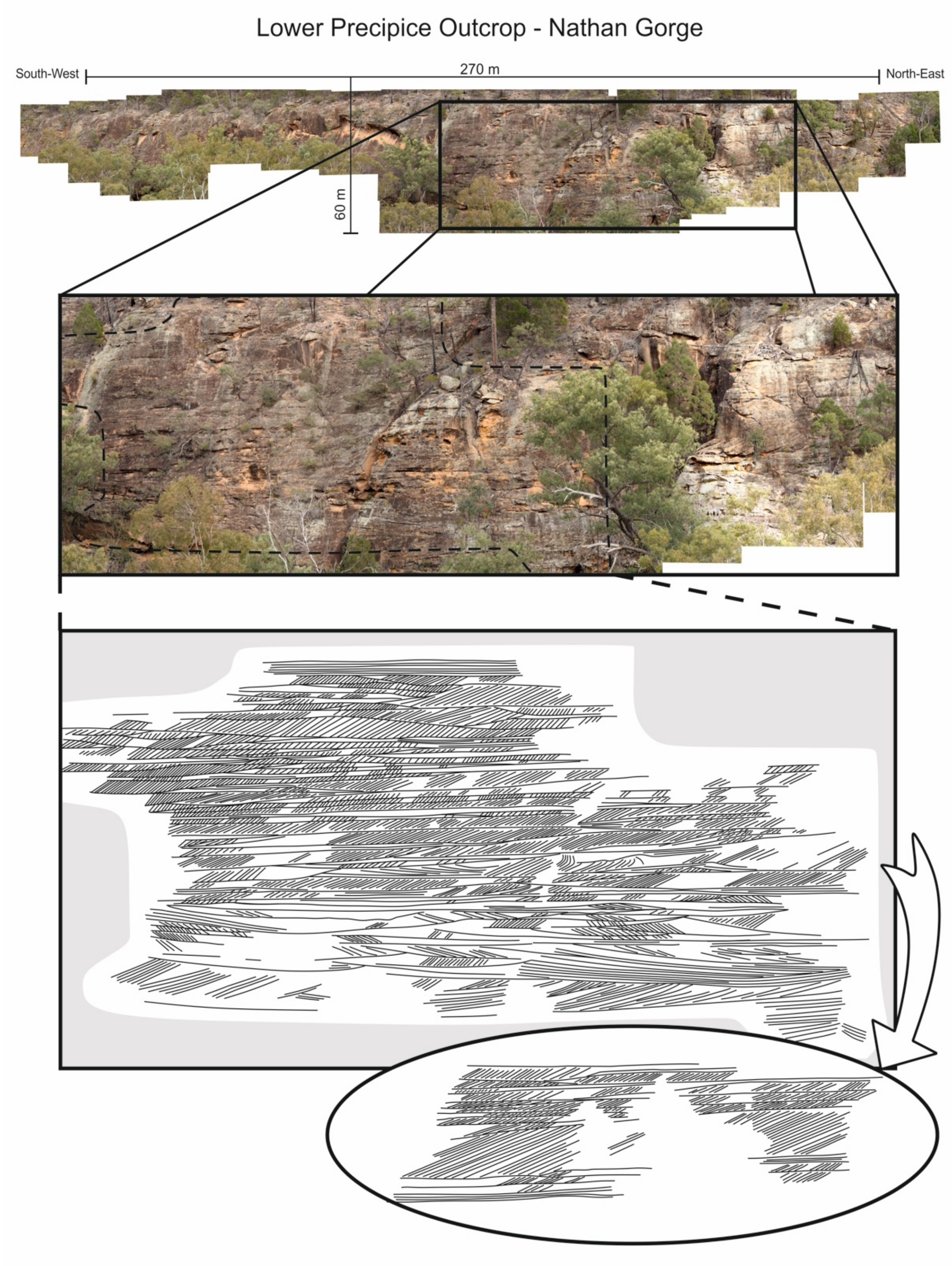
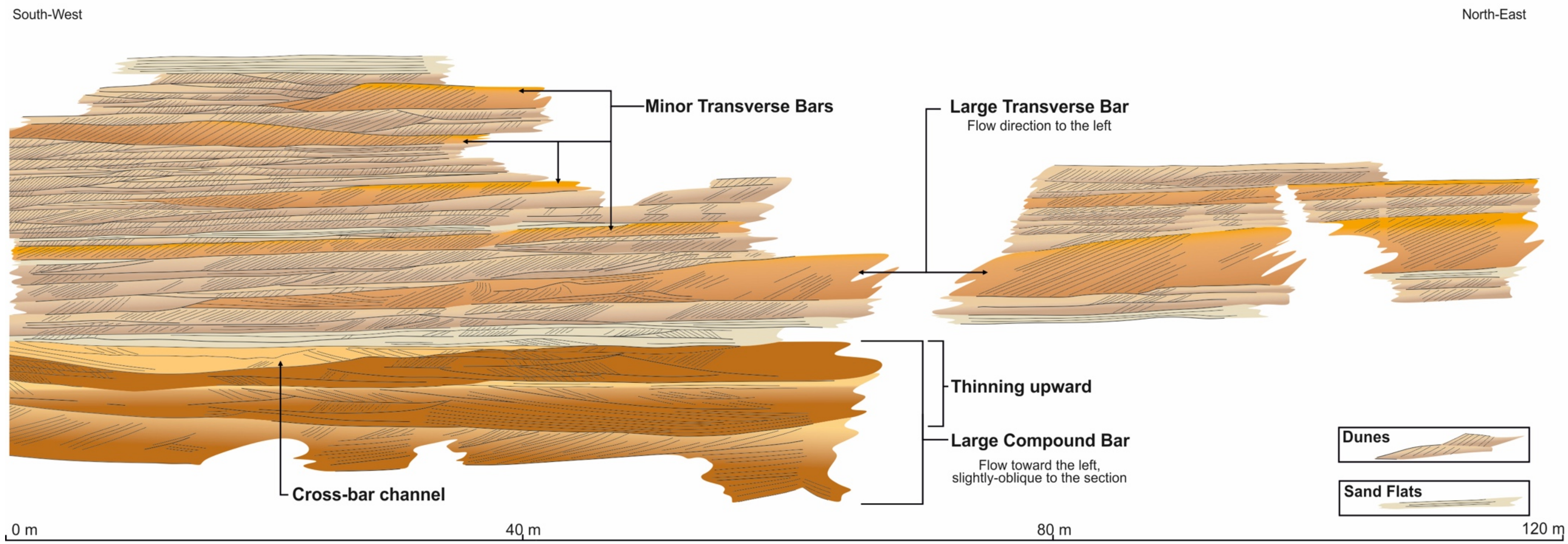


Figure 11: Panoramic view of the Lower Precipice Outcrop complete of outcrop-based linedrawing showing an overall thinning upward of the strata. Paleoflow direction inferred from the outcrop is predominantly toward south. Note the numerous dunes reworked and eroded by currents.



Lower Precipice Outcrop - Facies Associations

Figure 12: (PREVIOUS PAGE) Outcrop based interpretation of the LP1 outcrop showing major Facies Associations of the sandy-braided alluvial architectural elements (see Table 2).

Depositional model and sequence characterization

The Lower Precipice outcrop (LP1, Figure 11, 12) studied in Nathan Gorge National Park is an extensive rock wall that is ~55 m high and exceeds 100 m in length. The entire succession is made up of large sets of cross-strata which are the result of downstream migration of both 2-dimensional and 3-dimensional dunes, unit bars (ascribed to transverse bar, Figure13, panel a) and minor preserved section of major compound bars.

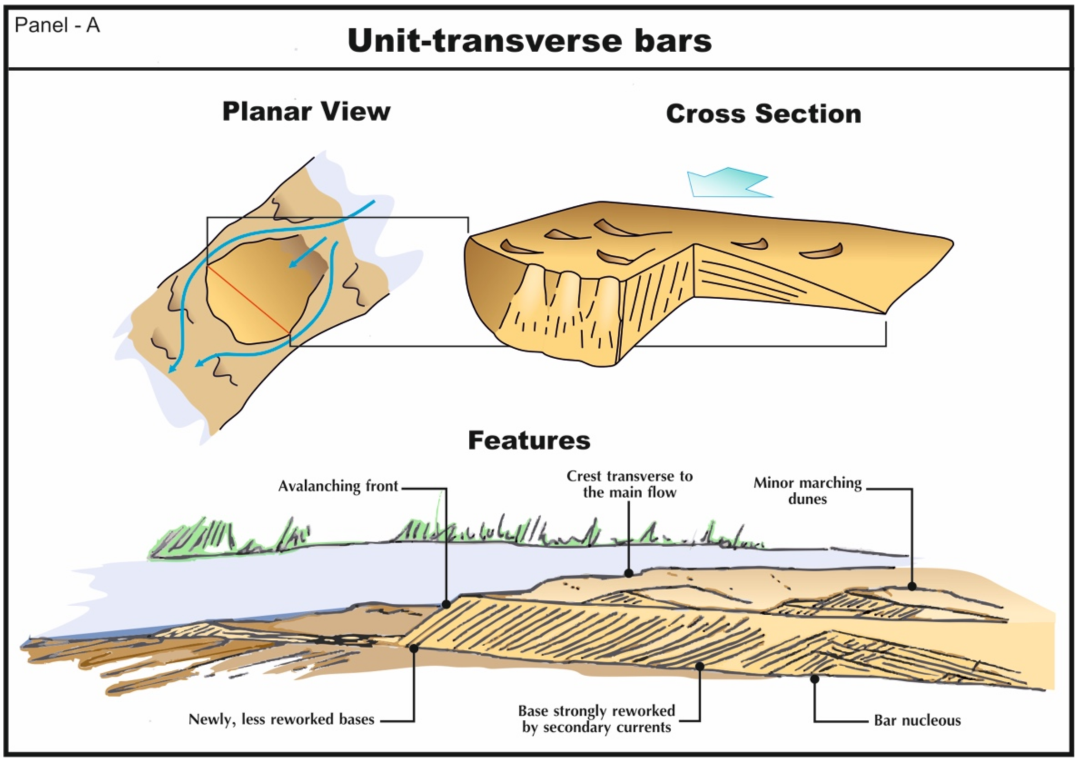
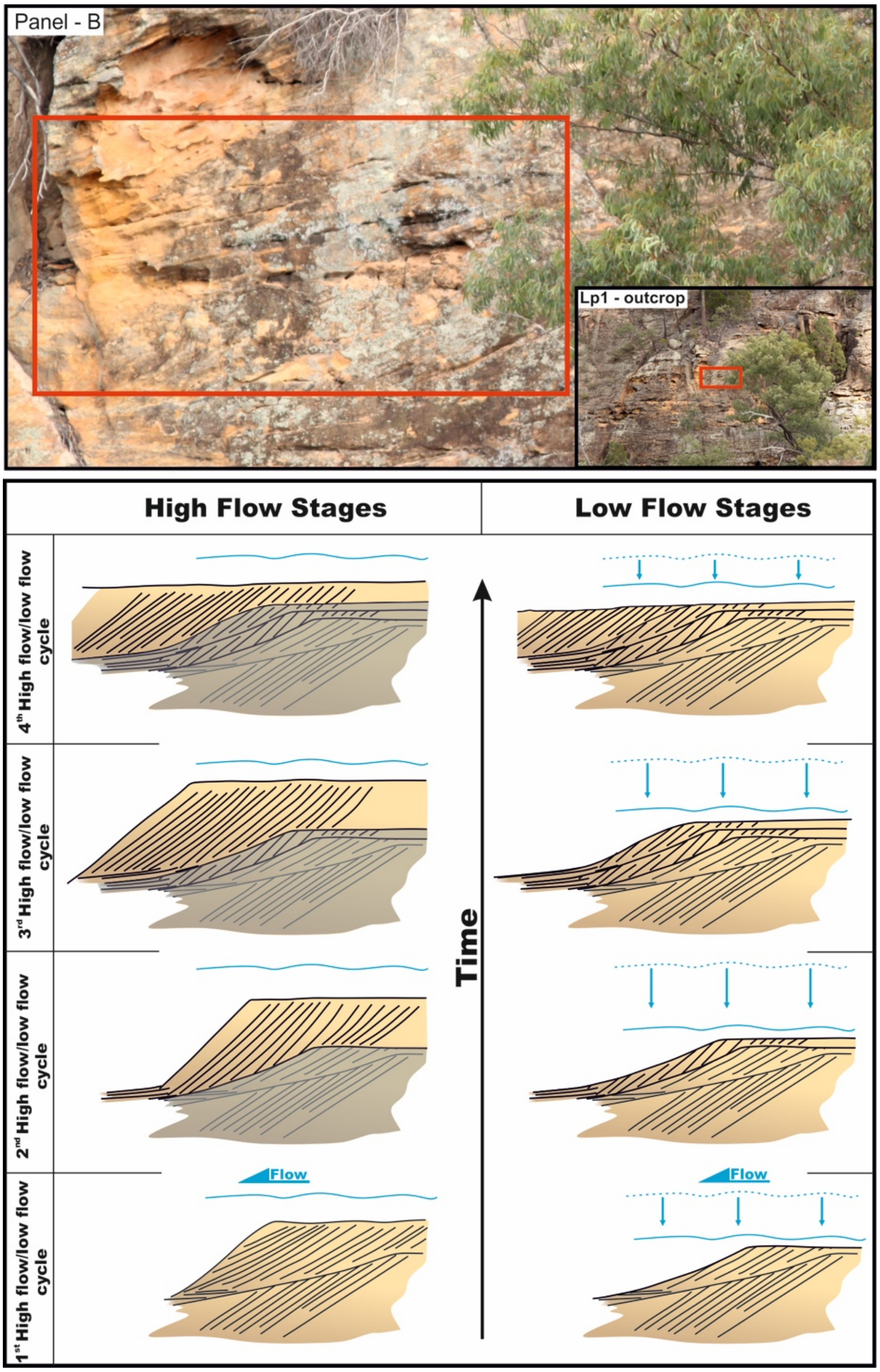


Figure 13: PANEL A shows the main features of transverse braided bars to which are ascribed unit bar deposits recognized in LP1; PANEL B (NEXT TWO PAGES) shows the evolution phases of dunes deposits affected by several phases of currents oscillations. The rock-wall pictures is taken from the LP1 outcrop and shows the geometries derived from the process.

The succession shows an overall thinning trend, meaning that sets and bedforms tend to reduce their thickness toward the topmost part of the formation, suggesting that the mean channel depth of the system diminished with the time. However, during a detailed study of the formation, it has been highlighted that several oscillations in the flow river discharge occurred during the deposition of dunes and the succession experienced repeated episodes of erosion and deposition. The wide range of dunes height (measured when possible on complete dunes) and the different erosion and preservation rates suggest that the water column reached different heights, alternating low and high flow rate phases that produced both reworked-eroded bedforms and avalanche fronts up to 3 m high. To support the hypothesis of continuous river flow oscillations in some parts of the outcrop the peculiar geometry of bedforms and beds testifies the phases of waxing and waning of the river system, as shown in Figure 13, panel b.

Paleocurrents are inferred both from the logged section and from the photomosaic shown in Figure 11 and exhibit a consistent southerly trend. However, different palecurrent directions are expected to be found, especially in the case of compound bars as in the lowermost part of the outcrop section, in which large set of cross-strata show random paleoflow directions. As stated by Ashworth et al. (2000) nucleus of large braided bar, such as compound bars, is made up of amalgamated dunes that usually exhibit different paleoflow directions. Successively, with the growth of the bar, preferential sense of accretion is established allowing the formation of sets of dunes that still show different paleocurrent directions but with a minor dispersal pattern. Concerning the first part of the outcrop succession, this is supposed to be a section of a compound bar nucleous. Nevertheless, it is hard to state which section of the compound bar is representing the outcrop, mostly because the section is too small if compared to the large extensions that these macroforms can reach (up to 2 km in length and 5 km in width, see Figure 14). Since the uppermost part of the succession is clearly longitudinal to the channel system, showing tangential section of dunes and transverse unit bars, the section is supposed to be tangential too. However, it is important to note that the chance of the section of being slightly transversal to the flow system could not be avoided.

According to Sambrook Smith et al. (2009) toward the topmost part of the compound bar, sets tend to decrease their thicknesses (Figure 12) and palocurrents directions still show a dispersal pattern. A cross-bar channel is recognized in a slight transversal section at the top of the compound bar. These erosional features



are common during the waning stages of the system (Ashworth et al. 2011) and could easily show a different flow direction in respect with the general flow pattern (Figure 14). Onto the compound bar complex, long and narrow beds with minor bedforms represent the very end of a compound bar formation and are defined as sand flat deposits. At this stage, the bar complex is as high as the flow section and thus only major floods overpass the bar top, allowing the formation of this laterally continuous and narrow beds. With the going on of the deposition alternated phases of minor and major river floods led the deposition of thick successions of dunes while, during the major flooding events, the largest transverse bar progrades onto the channel talweg or large bar-tops forming unit bar deposits.

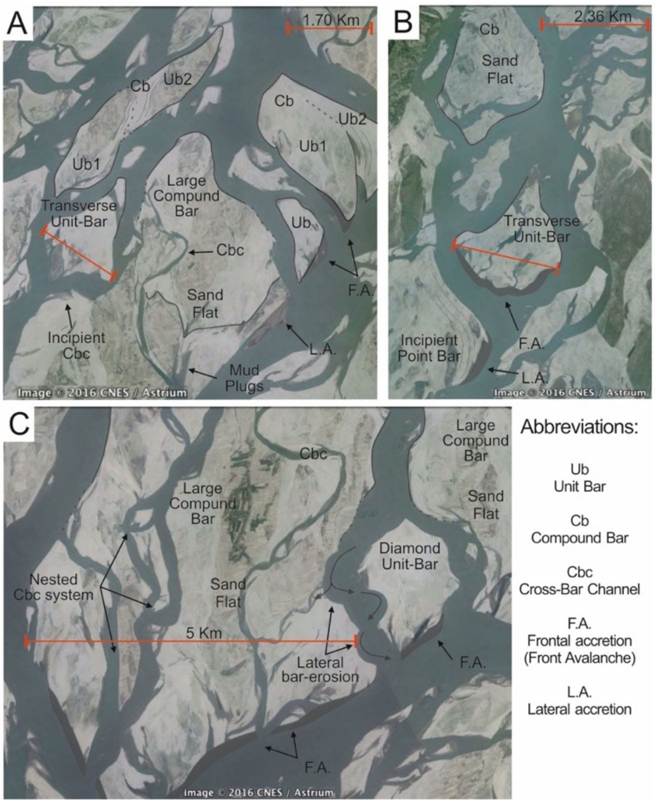


Figure 14: Satellite image taken from the Brahmaputra river which shows the main architectural elements in the active channel belt of the modern sandy braided river.

The main phases representing the evolution of the system inferred by the outcrop study are shown in Figure 15. The model emphasises the phases in which major and relevant sedimentary bodies were deposited.

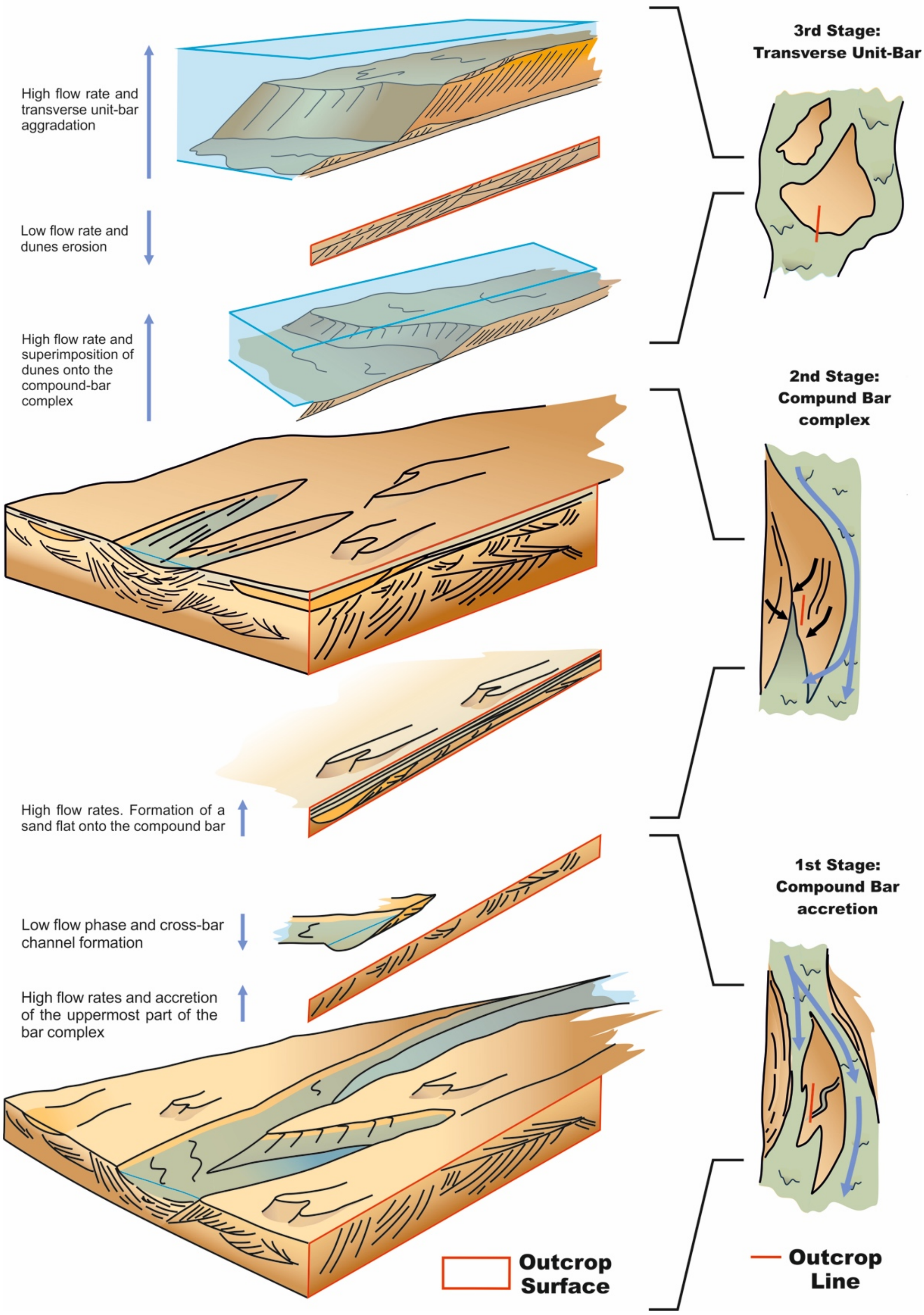


Figure 15: Depositional model inferred after the study of the LP1 outcrop. Main phases of erosion and accretion are emphasized along with their representative deposits at the outcrop scale (red rectangle). See text for details.

Upper Precipice outcrop study

Facies Analysis

In this studying of the Upper Precipice Formation, five facies association (Table 4) have been recognized with respect to the three outcrops dislocated in the field (Figure 16, 19, see Appendix for logged section) and have been ascribed to different portions of deltaic mouth bars (sensu Postma, 1990). Five different sedimentary facies (Table 3, Figure 17) have been identified in the study area and each facies has been recognized on the base of peculiar sedimentary features, such as grain size, sedimentary structures, bed geometry or strata termination. Beds are formed as the result of well-defined depositional process and together form group of genetically related facies which collectively constitute different facies associations.

Table 3: Table showing the main Facies recognized in UP1, UP2 & UP3

Facies	General description	Lithology	Sedimentary structures	Bounding surfaces	Bed thickness	Other features
1	Laminated siltstone and sandstone.	Alternation of medium to fine sand and silt, reddish and grey in colour. Moderately sorted sand with argillaceous matrix.	Plane parallel lamination, formed under tractional conditions in upper flow regime. Alternation of silt and sand points out the waxing and waning of a pulsating system.	Gradational bases and tops.	Individual laminae are up to 0.5-2 cm, individual beds more than 30 cm.	Small plant fragments are present as plant debris at the base and within the laminae, small roots might be present.
2	Cross laminated sandstone and siltstone.	Alternation of medium to fine sand and silt, reddish and grey in colour. Moderately sorted sand with argillaceous matrix.	Asymmetric ripples including climbing ripple. Deposited under tractional conditions due to unidirectional currents fed by pulsating flows.	Generally gradational, rarely sharp but not erosive base and tops.	Cross-strata organised as thin cosets from few centimetres up to 10 cm, individual beds are up to 100 cm thick.	Ripples might be capped by silt or finer sediment dealing with a diminishing of stream power, small plant fragments are present as plant debris at the base of the sets.
3	Cross laminated sandstone formed under wave influence.	Medium to fine sand, whitish in colour, well sorted.	Asymmetric near symmetric ripples with internal lamination showing opposite dipping due to oscillatory currents.	Generally gradational, rarely sharp bases and tops.	Sets of symmetric ripples are up to 3 cm high, individual beds up to 30 cm.	–
4	Cross stratified sandstone.	Moderately sorted, medium sand reddish in colour.	Low angle cross stratification formed by 2D and 3D irregular crested dunes from unidirectional currents.	Generally erosive bases reworked by the flow deflected during the building up of the dune front, cross strata show a tangential basal contact. Gradational to sharp tops.	Sets of dunes up to 90 cm, beds are 2 meters thick.	–
5	Strctureless sandstone and mudstone.	Both moderately sorted, medium sand and grey mud.	No bedforms or structures are recognizable, mud is settle down because of gravity force.	Gradational bases and tops, erosive tops are also present.	Beds are up to 30 cm.	–

Table 4: Table showing the principal Facies Associations recognized in UP1, UP2 & UP3

Facies associations	Brief description	Component lithofacies	Facies interpretation	Subenvironment
FA	Near symmetric channels (approximately: 5-meter-wide, 1.20-meter-high) filled by channelized deposits showing roughly normal grading.	4 – 2 (dominant) 5 (subordinated)	Distributary channels that feed the main mouth bar or form new incipient lobate deposit building up a compound mouth bar.	Distributary channel
FB	Inclined (~20°) beds with scrolling dunes marching toward the top of the strata along with FC deposits dipping in the opposite direction.	4 – 2 (dominant) 3 (subordinated)	Channel lobe transition highlighted by the opposite dipping of the strata which represent the transition between back-bar, bar crest and distal bar.	Channel lobe transition
FC	Gently inclined tabular beds with alternation of plane parallel stratification (dominant) and ripple cross stratification (subordinated) thinning and fining laterally passing into the distal lobe.	2 – 1	The bar crest is overpassed by the jet-flow which discharges the most part of bed load in the proximal lobe, where the friction diminishes in relation with the understanding body.	Proximal mouth-bar lobe
FD	Gently inclined to sub-planar tabular beds formed by the alternation of ripple cross stratification (dominant) and plane parallel stratification (subordinated) thinning and fining laterally toward the distal part of the body.	2 – 1 (dominant) 3 (subordinated)	Distal lobe area, where the flow has lost the majority of the inertia and deposits the finest part of the bed load and suspended load.	Distal mouth-bar lobe
FE	Tabulare and lateral continuous beds formed by mud. Deposits are structureless or slightly parallel laminated	5	Mud settled in a low-energy subenvironment thought to be restricted embayment within the delta system.	Interdistributary bay

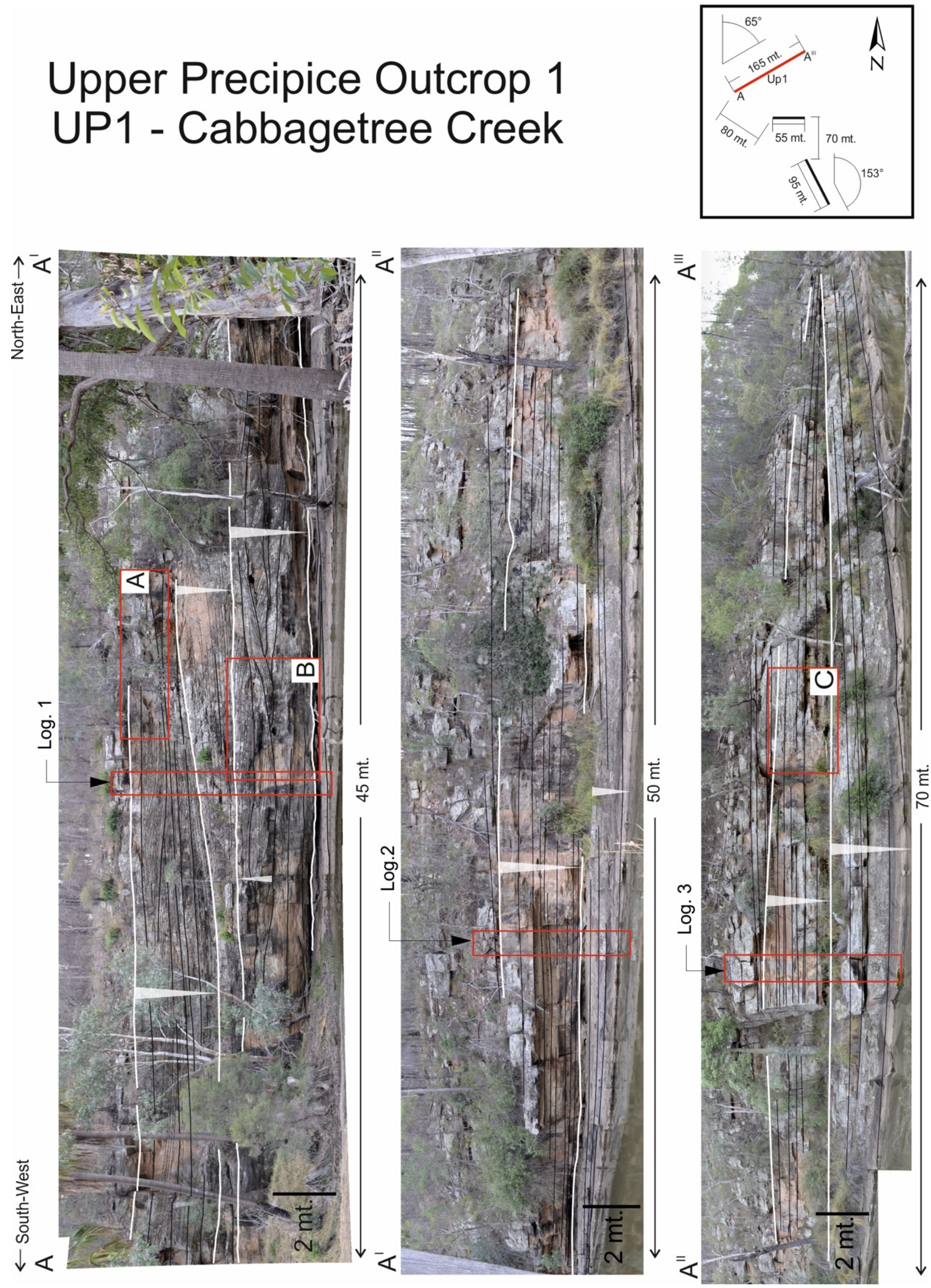
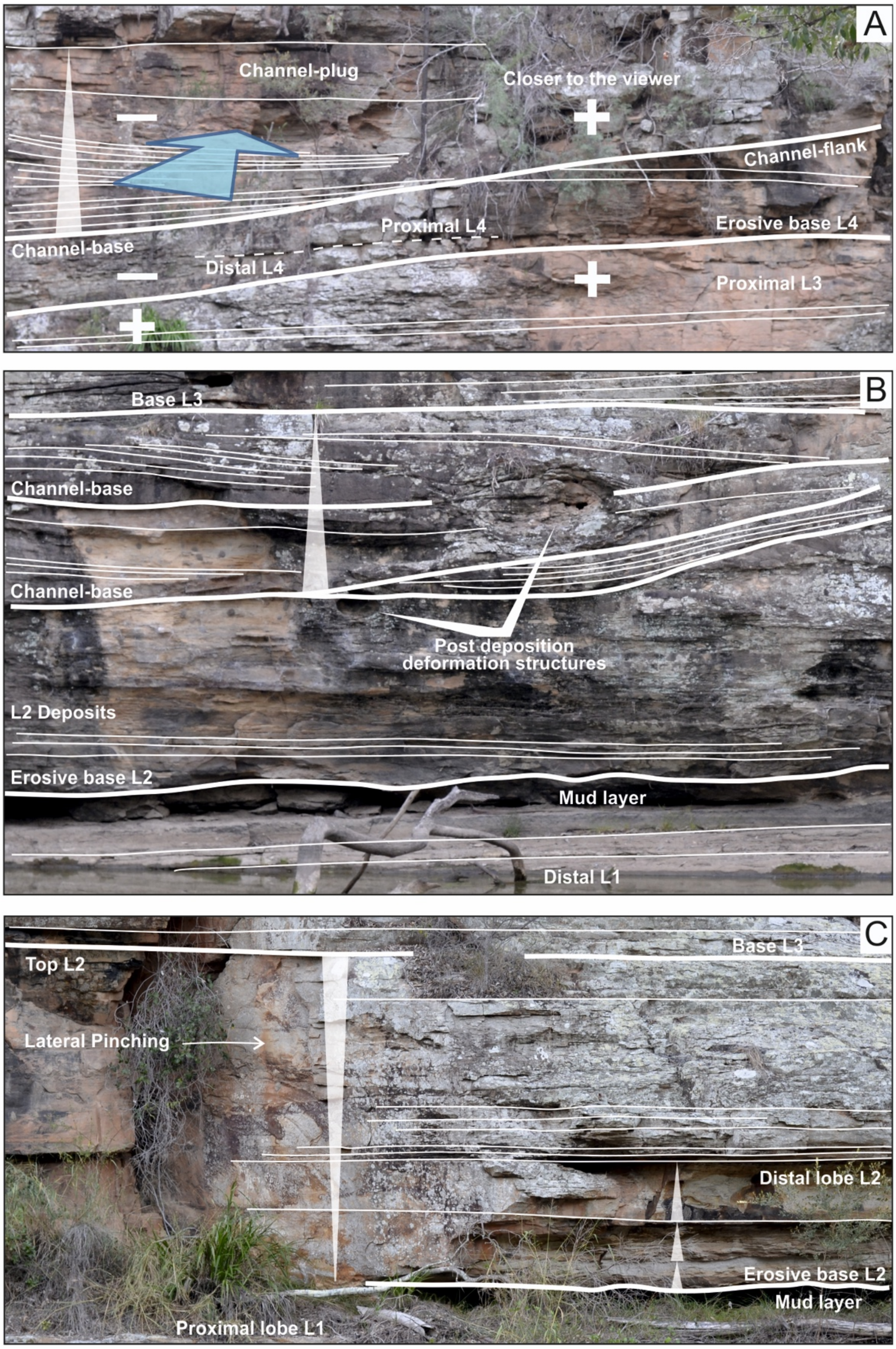
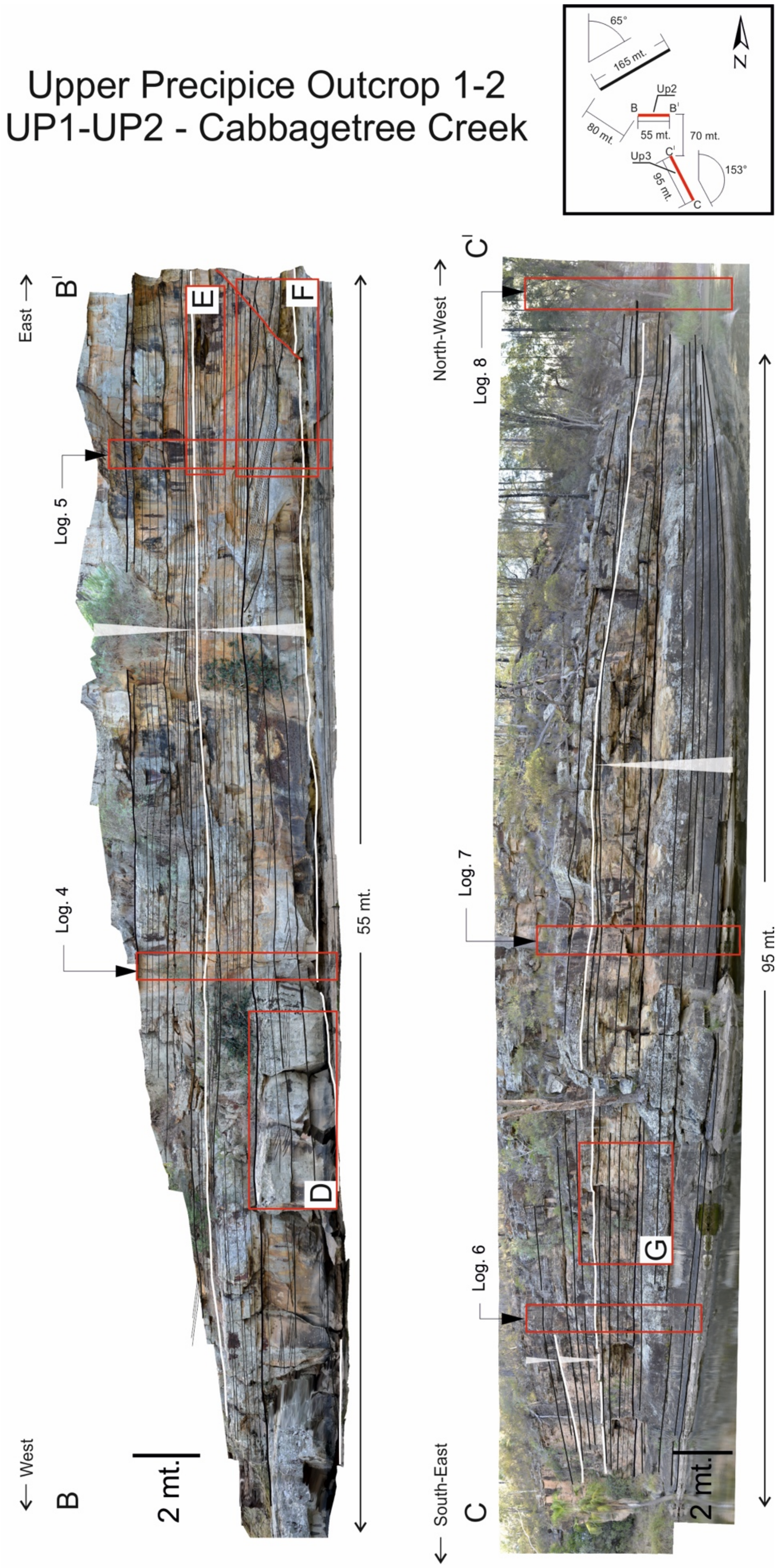
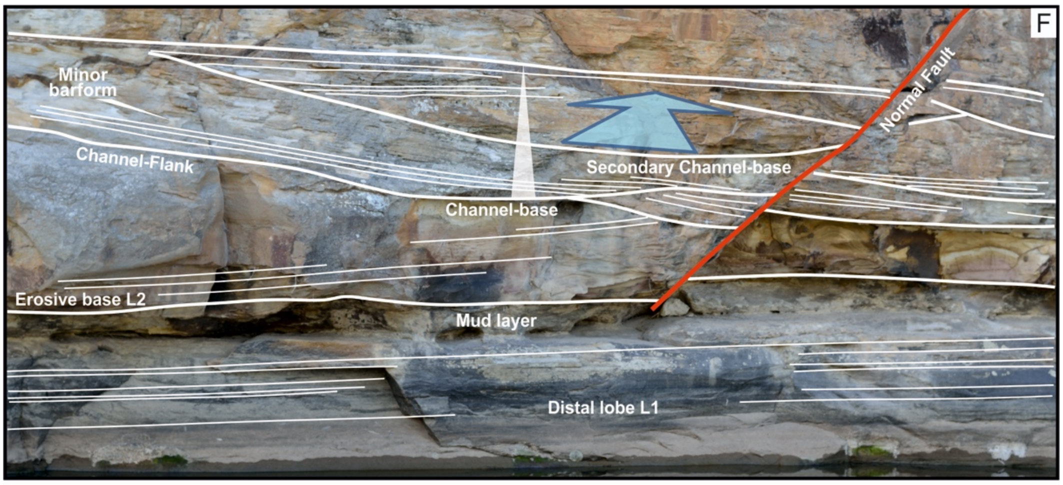


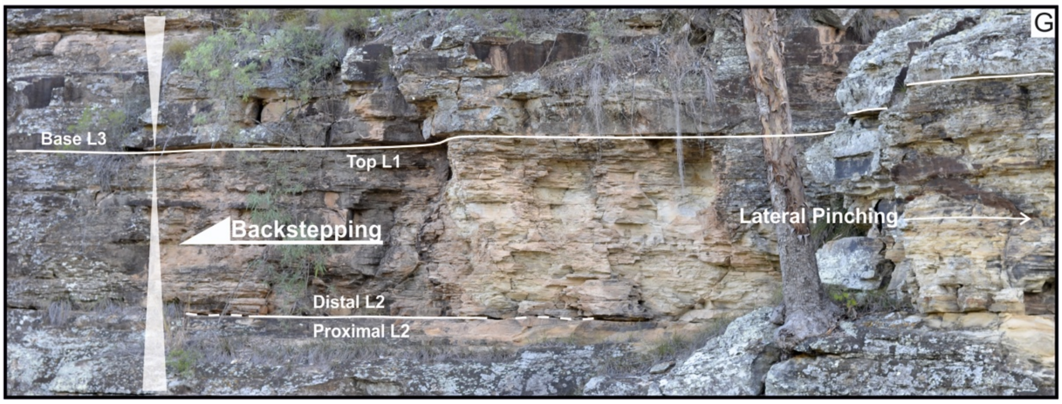
Figure 16: (THIS PAGE) Photomosaics complete of linedrawing showing the UP1 outcrop divided in three main section, from south-west to north-east. Schematic planar view of the study area is provided above. Enlargements showing peculiar features are provided next page; (NEXT PAGES – SEE TITLES) Photomosaics complete of linedrawing of UP2 and UP3 outcrops.


A
Channel-plug
Closer to the viewer
Channel-flank
Erosive base L4
Proximal L4
Channel-base
Distal L4
Proximal L3
B
Base L3
Channel-base
Channel-base
Post deposition
deformation structures
L2 Deposits
Erosive base L2
Mud layer
Distal L1
C
Top L2
Base L3
Lateral Pinching
Distal lobe L2
Erosive base L2
Mud layer
Proximal lobe L1

Upper Precipice Outcrop 1-2
UP1-UP2 - Cabbagetree Creek




F
Minor barform
Normal Fault
Channel-Flank
Secondary Channel-base
Channel-base
Erosive base L2
Mud layer
Distal lobe L1


G
Base L3
Top L1
Backstepping
Lateral Pinching
Distal L2
Proximal L2

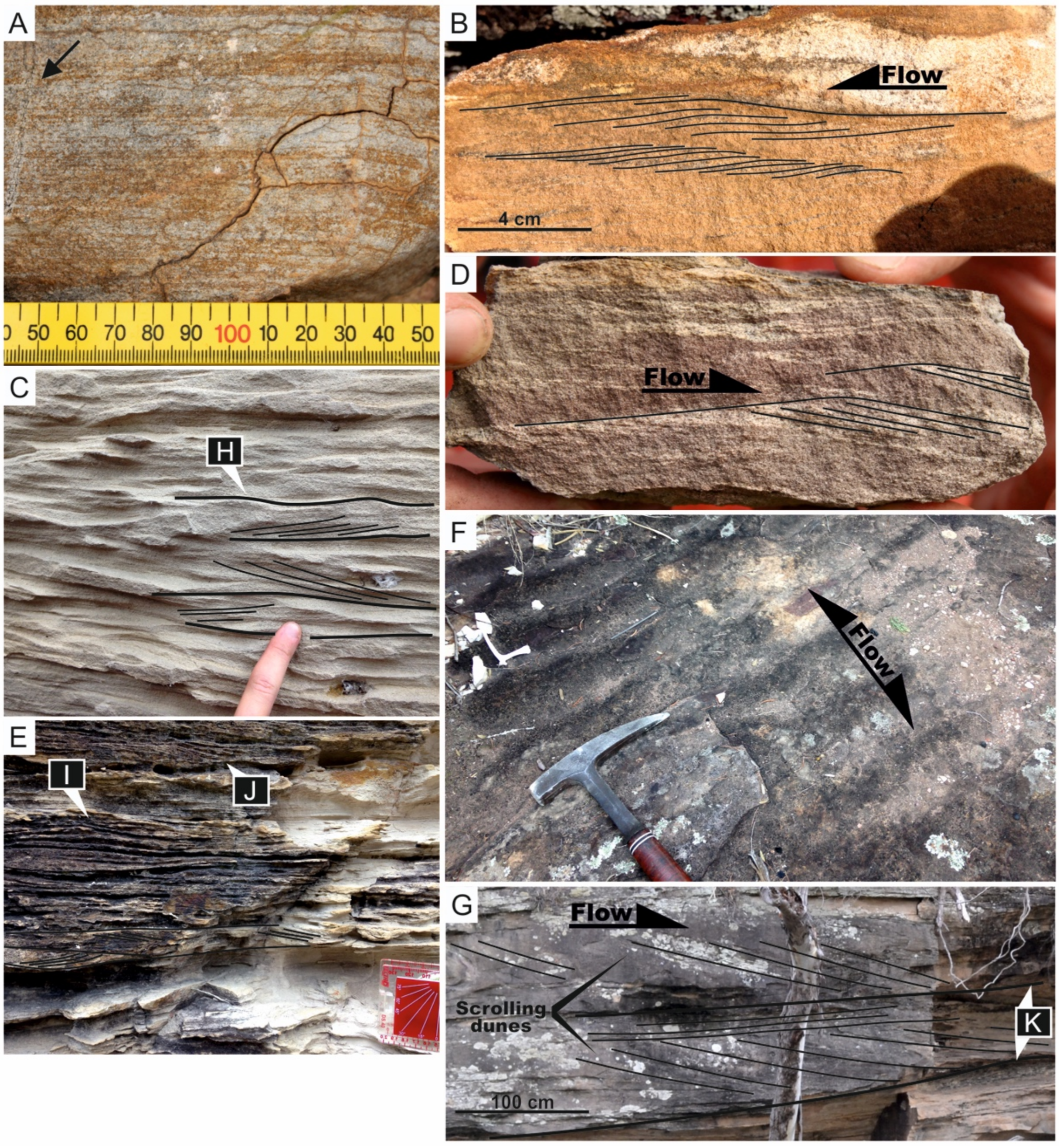


Figure 17: A – Plane parallel lamination in medium to fine sand. Arrow points bioturbated strata; B – Climbing ripples in fine to very fine sand; C – Near symmetric double dipping ripples with crests gently reworked by bidirectional currents (H); D – Ripple cross lamination in medium sand; E – Ripple cross lamination showing bidirectional dipping (bottom part) and near symmetric crests reworked by bidirectional currents (J; I); Symmetric wave reworked ripples in planar view; G – Scrolling dunes with minor ripple cross-strata on top. Note the dunes move onto strata showing opposite dipping directions (K).

Figure 18: A – External mold of wood fragments (arrowed); B – Strata reach in plant debris deposits. View from the bottom; C – Detailed image of vegetate fragments; D – Bioturbation (arrowed) in fine sand deposits; E – Wood fossil; F – Plant seed (arrowed).

Facies Associations (FA): Distributary channel

Description

Facies association A is made of medium to fine sand deposits which infill concave-up erosional surfaces, generally symmetric to near-symmetric in shape if viewed in cross-section (Figure 16, 19). The FA infill deposits exhibit near-horizontal upper bounding surfaces and typically truncate the FB and FC deposits, even if FD deposits might be present below the erosional surfaces. The sandy succession consists predominantly of both low and high angle planar-to-trough cross-stratified sandstone (Facies 4), planar-tabular cross stratified sandstone (Facies 1) and ripple cross-laminated sandstone (Facies 2), commonly building body of complex internal organization (Figure 16 enlargements a, b, f). Plugs composed of finer grain component with minor internal organization and/or structureless (Facies 5) might me present in the uppermost part of the infill sequences. Paleocurrent directions inferred by the cross-stratified strata and basal scours are almost perpendicular to slightly oblique to the outcrop section, even if considerable oblique sections in respect to the flow are also present (Figure 16 a). The infill deposits show slightly fining-upward trend and the grain-size pattern is commonly accompanied by a change from dominance of stratified sandstone in the lower part to dominantly ripple cross-laminated sandstone in the uppermost part of the deposits.

Interpretation

Facies A association is interpreted as the sediment infilling of shallow and wide (from ~ 1.5 m high up to 8 m wide) channelized features which are filled up with a complex network of bedforms formed by the combination of both fluvial and basinal processes. The presence of planar-to-trough cross-stratification and ripple cross stratification on the topmost part of the infill sequences, suggests that sediment is accumulated under tractional condition, probably in a subaqueous environment beyond the shoreline. The lack of subaerial features like red beds, desiccation structures or paleosols, also points on an origin in a delta front area, as terminal distributive channels to mouth bars. As highlighted by Martini &

Sandrelli (2015), the absence of coarse-grained lags at the base of channels suggests that these deposits were formed by erosion and sediment bypass generated by river-related jet flows, whose erosive capacity may extend several kilometres into the basin. In addition, bank-attached minor barforms situated along the channel flank (Figure 16 f) might testify localized area prone to accumulation of sediment (e.g. major accommodation space, slight sinuosity of the channel) within the distributary channel system.

Similar channelized erosional features are described by Olariu & Bhattacharya (2006) as being at the very end of distributary channel system in river-dominated shallow-water deltas, starting at the last subaerial bifurcation and extending to the last channelized expression on the subaqueous delta front. These are generally shallow channelized features intimately associated with mouth bars which generally have a large variability in orientation in respect with the trunk channel, even if they could be also perpendicular to the paleo-shoreline (Olariu & Bhattacharya, 2006; Schomacker et al. 2010).

Facies Association (FB): Channel-Lobe transition zone

<u>Description</u>

Facies association B consists of generally medium to coarse sandy cross-stratified deposits (Facies 4) which form sets up to 90 cm (Figure 16, 19). Boundaries between these sets are generally erosive and they might be reworked by secondary currents, altering the lamination at toe and forming tangential geometries in respect with the bounding surfaces. However, sharp bases are also common and these are generally associated with low inclined cross-strata that show angular geometries at the base (Figure 16, d). In the topmost part of the beds, 20 cm thick sets of ripple cross lamination (Facies 2) are common and ripple crests are might be reworked by secondary currents which conferred a symmetrical shape (Facies 3). Cross-strata show an opposite dipping in respect with the general beds attitude and this is the most striking feature within Facies B deposits. In general, cross-strata overcome the erosive and reworked bases which dip in the opposite direction and this result in a clear double-dipping orientation between the 1st (i.e.

internal lamination) and the 2nd (i.e. base and top beds boundaries) order surfaces (Figure 17 g). FB deposits are intimately related to FC ones, which differ completely in terms of sedimentary facies and bedding attitude.

Interpretation

Facies association B deposits are interpreted as the result of deposition of scrolling dunes formed in the channel-lobe transition zone (hereinafter CLTZ), in particular at the transition from confined channels to unconfined lobes (Postma et al. 2015). The CLTZ is characterized by strong bed-load deposition and marks the transition between: (i) the relatively confined scoured region, an area of erosion/bypass which is mainly affected by the turbulence of the jet flow and (ii) the conformable surface formed by the suspended loads deposits which form a radial apron seaward the scour pool (i.e. the lunate mouth-bar lobe) (Hoyal et al. 2003; Wellner et al. 2005). In particular, jet flows generated at the outlet of the river system, are characterized by strong turbulence which erodes the substrate and create flute-like erosional scour pools. The scour pool widens and deepens downstream the region of maximum turbulence and then merges with the depositional surfaces represented by the CLTZ deposits. As the jet flow continue to discharge sediment, deposits start to form a flat ramp which gently ascend toward the basin, forming the back bar complex. The back bar is strongly affected by tractional currents along with bed load deposition and this promote the formation of trains of dunes which moves downstream over the ramp (i.e. scrolling dunes, figure 16, 19). Dunes move toward the topmost part of the CLTZ, which represents the bar crest, and they might be associated with ripples and ripple reworked by secondary currents. Bar crest marks the transition between bed-load deposition region to suspended load depositional area, which fines and thins away from the terminal end of the scour. It is worthy to note that the scour-pool, back-bar and bar-crest complex might have large differences between each lobe of the same delta system in terms of evolution, formation, spatial distribution and dimension. As stated by Edmonds & Slingerland (2007), the distance between the river outlet and the mouth bar complex is proportional to the jet momentum flux and inversely proportional to the grain size. This implies that, the more mouth bars deposits are far from the main outlet which has major inertia, the more mouth bars are closest to the distributary channel outlet and both CLTZ and lobe are smaller in size.

Facies Association (FC): Proximal mouth-bar lobe

Description

Facies association C is made up of thick succession (up to 3 m) of medium to fine sand deposits organized in 30 cm sets of tabular, plane-parallel laminated (Facies 1) or ripple-cross laminated (Facies 2) sand, and it is characterized by the presence of climbing ripple or plant debris deposits at the base of each major strata (Figure 17, 19). Major fossilized wood or plant seeds are also common (Figure 18). Each set present sharp base and gradational top and might exhibit partial Bouma sequence, highlighted by the slight normal grading and the change in bedforms, which are passing from typical high velocity bedforms (i.e. upper flow regime beds, Facies 1) to typical lower velocity bedforms (i.e. climbing ripple and ripple lamination, Facies 2) generally due to the waning of a pulsating flow. However, the overall trend of the entire succession is coarsening upward (Figure 16, c) and, as a whole, FC shows both erosional and depositional boundaries.

In section parallel to the transport direction these deposits are gentle dipping (~2-5°) and extend tens of metres along the outcrop section, showing tabular geometries with marked lateral continuity. On the whole, FC (along with FD deposits) fines and thins away from the terminal end of FB deposits and are characterized by lateral pinching, which lends a typical fan-lobate shape if viewed in transversal section.

Interpretation

Facies association C consists of several packages of tabular beds made up of mostly planar and ripple-cross laminated deposits, interpreted as the result of suspension-load deposition and successive reworking under tractional condition in

a proximal mouth-bar region (Wellner et al. 2005; Wright, 1977) (Figure 19). In the mouth bar front, deposits are rapidly delivered because jet streams are forced to flow trough a shallower water column, caused by the presence of the bar crest which reduces the water section and minimizes the flow capacity-load. This hydraulic jump produces a low-velocity wake behind the bar, allowing the dropping of sediments which can be successively reworked by the overriding sustained flow (Wellner et al. 2005; Wright, 1977; Edmonds & Slingerland 2007). The internal strata show a lateral fining/pinching toward the distal part of the lobe and this suggests both the general fading of the stream flow which is overriding the mouth bar front and the gradual passage to the distal mouth-bar (FD) deposits.
As already mentioned, proximal mouth-bar deposits show both erosional and depositional boundaries. In detail, erosive bases are the product of the basinward progradation of the mouth bar complex which generally scours and reworks the underlying FE deposits while, depositional boundaries, are generally represented by downlap terminations between various portions of different and genetically unrelated mouth-bars (Figure 20). Because spatial distribution of deltaic mouth bars is commonly controlled by the attitude of the system to fill available spaces, when a new mouth bar progrades basinward or tends to overcome the space between two pre-existing lobes it generally aggrades over them and this result in downlapping strata between each body. The stratal architecture shows the typical compensational stacking pattern (Ilgar & Nemec, 2005) in which coalescent lobe are built stacked one upon another forming as a whole a shallow water mouth-bar delta system.

Facies Association (FD): distal mouth-bar lobe

Description

Facies association D consists of tabular and horizontal beds of generally fine to very fine sand deposits which are alternated to consistent portions of silt. These deposits are generally thin laminated and show plane-parallel stratification (Facies 1) and ripple-cross lamination (Facies 2) which sometimes consist of both climbing ripples and wave reworked ripples with clear symmetrical shape and opposite dipping due to the action of bidirectional currents (Facies 3) (Figure 17). Plant debris along with major plant fragments are common within the whole succession and biouturbated beds might be present. Beds are typically 15 cm thick and are laterally continuous for tens of metres, even if they pinch and thin at their edge. The overall FD deposits are up to 2 m thick and show a general coarsening upward trend and lateral fining. However, beds that exhibit partial Bouma sequence and normal grading within the succession are common, as in the case of FC deposits.

Interpretation

Facies association D is interpreted as the distal portion of mouth bar deposits. In this area the last remaining finest sediments are dropped down from the waked jet flow and are reworked under tractional condition because of the overriding sustained flow (Wellner et al. 2005). When the flow rate is waning, the silt is deposited forming the distal bar that is generally linked to the prodelta deposits (Wright, 1977; Postma, 1990) which are not exposed in the studied section. Wavy bedded deposits and bioturbated beds highlight that the flow dynamics and river discharge begin to have a minor control while the dynamics of the basin system play a dominant role on the distant lobe deposits.

Facies Association (FE): Interdistributary bay

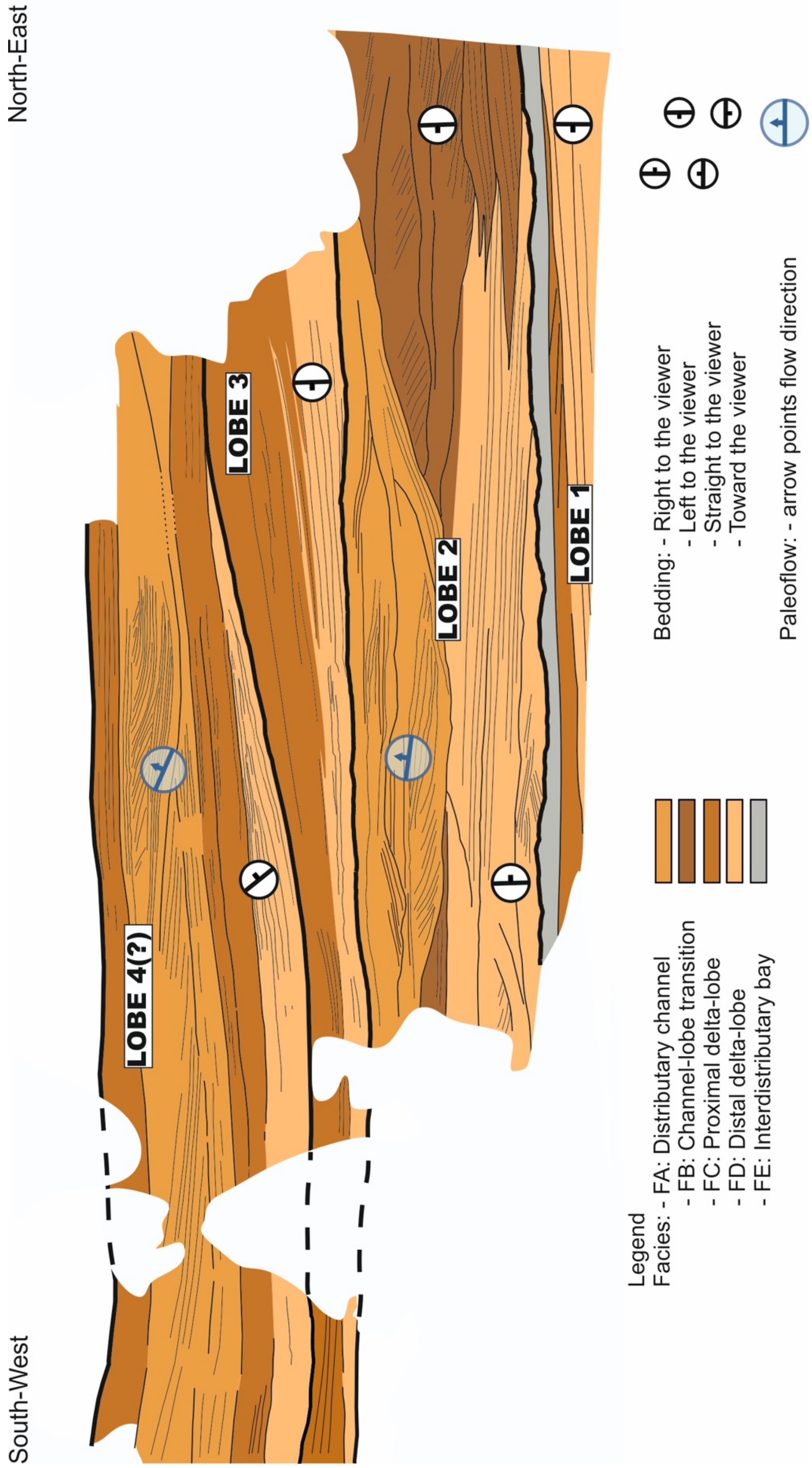
Description

Facies association E consists of up to 30 cm thick mud which generally overlain both the FC and FD deposits. Beds are structureless (Facies 5) and it is hard to recognize if parallel lamination due to mud settling in a low energy realm is present. FE deposits typically present sharp bases and erosive tops and are laterally continuous for tens of metres without any facies variation.

Interpretation

Facies association E deposits are interpreted as the result of mud settling in low-energy sub-environments which are thought to be constrained embayments within the mouth bar delta system, usually called interdistributary bays. The lack of bedforms and tractional structures suggests that water column is almost static and is not affected by stream currents, allowing the deposition of mud which is settled down because of gravity force. These sub-environments are common in many delta systems (e.g. Apalachicola delta, Escambia delta, etc.) and their formation is due to the abandonment or lateral shifting of mature lobes, promoting the development of an embayed region between the mouth bar and the shoreline. This region is no more affected by currents due to the stream flow coming from the outlet and thus mud settling continues until a new lobe emplaces, filling the accommodation space in the embayed region and thus promoting the formation of a new mouth bar stacked on the others.

Upper Precipice Outcrop 1 - Facies Associations
Section A-A'



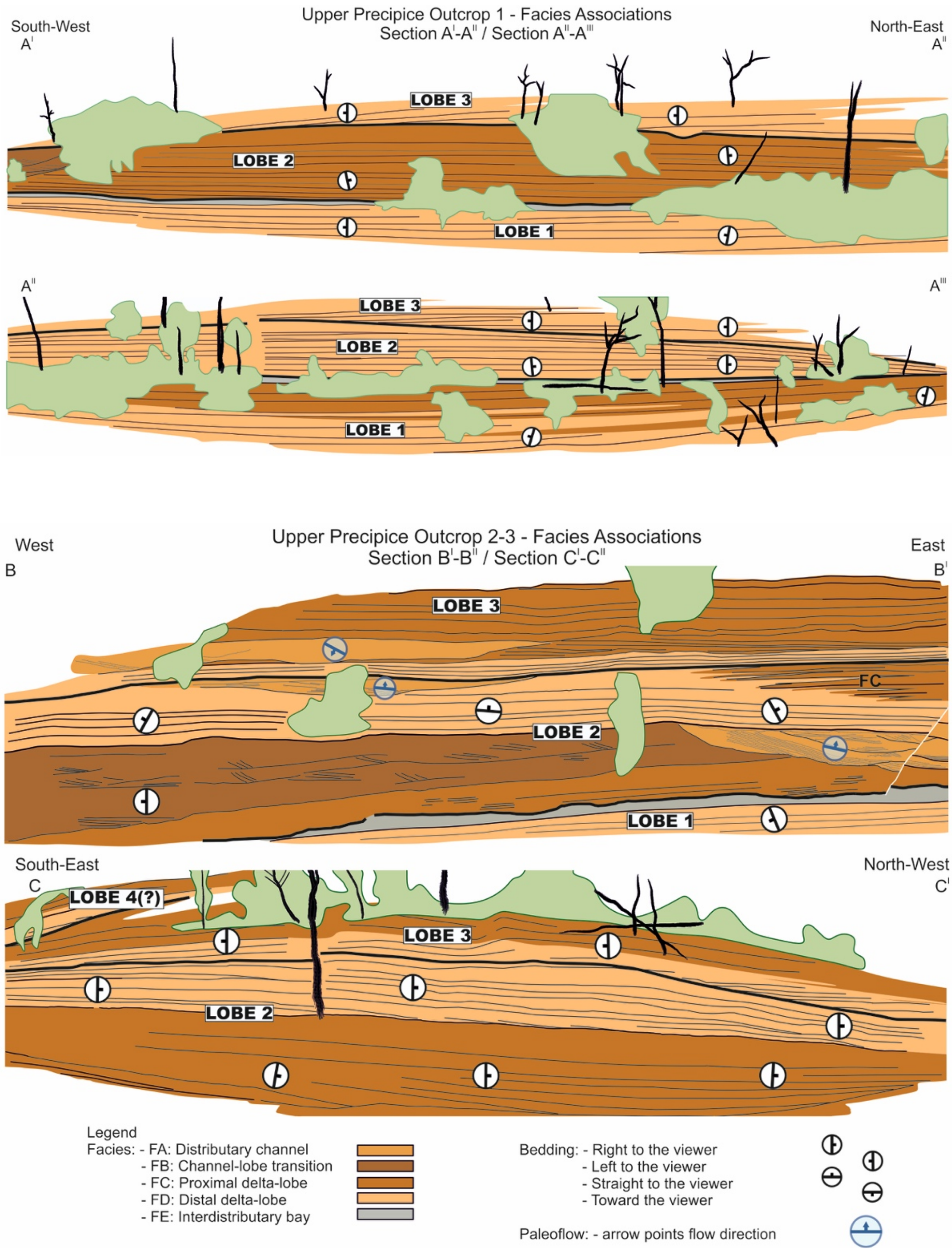


Figure 19: Linedrawings showing facies associations recognized in UP1 (section AA' in previous Page), UP2 & UP3 outcrop. See text for details.

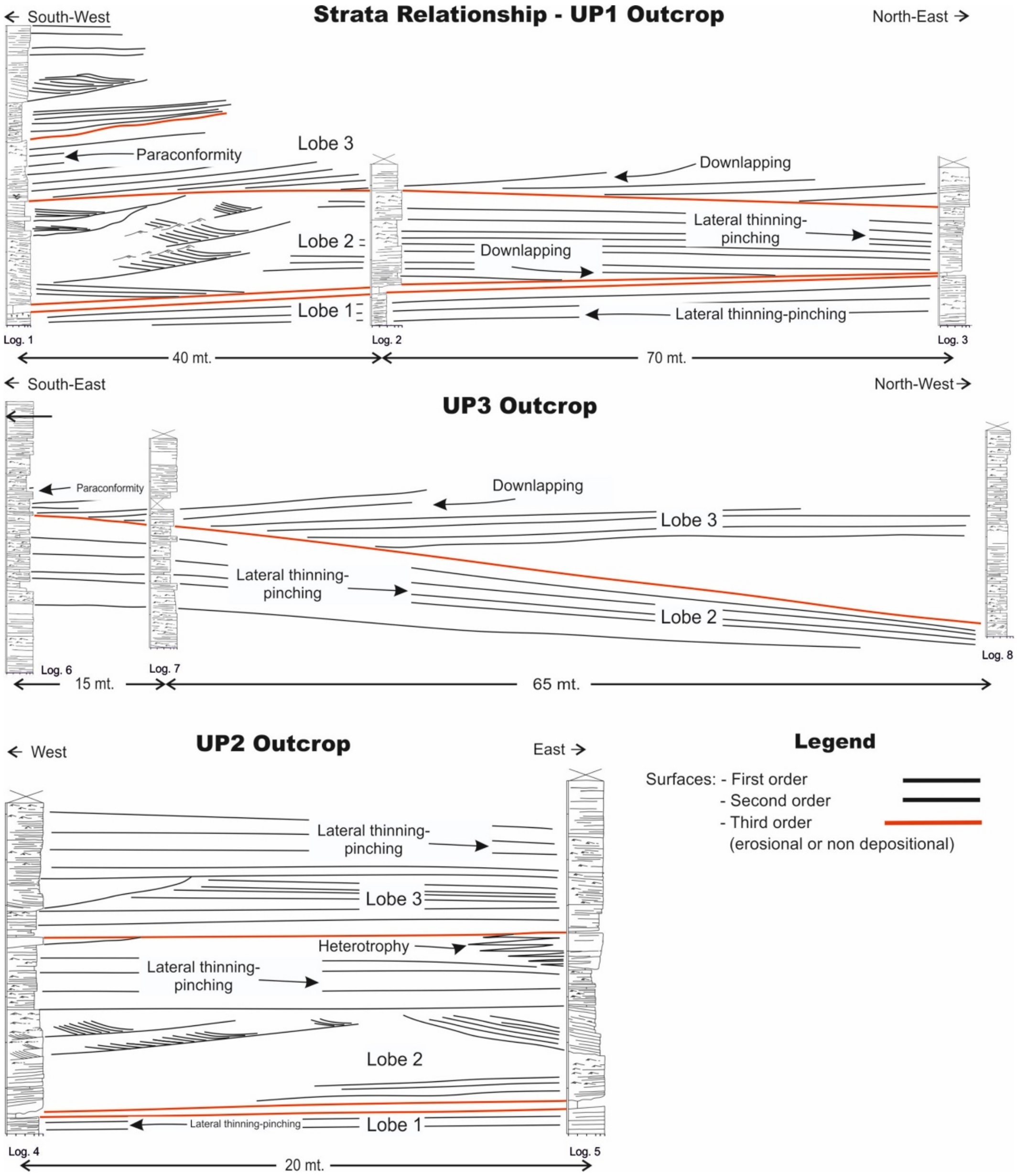


Figure 20: Simplifed sketch representing the three main lobes recogognized in the study area. The image emphasizes the strata relationship between the different bodies.

Depositional model and sequence characterization

Among the three outcrops dislocated along the Cabbagetree Creek (UP1 – UP2 – UP3) three main sedimentary bodies have been recognized within the stratigraphic succession while a fourth and uppermost body is incomplete and thus hard to characterize. The bodies have been ascribed to shallow-water deltaic mouth-bars deposits (sensu Wright, 1977; Postma 1990). Mouth-bar deposits form at the outlet of distributary channels of river-dominated deltas, as a result of fully turbolent inertia-dominated jet flow which enters in a generally shallow water basin (Wright, 1977; Postma, 1990; Wellner et al. 2005). As a sediment-laden channelized flow at capacity exits into a standing body of water, the flow slows because of its rapid expansion in cross sectional area during transition from confined to unconfined flow. During the deceleration of the flow, the gravity force overcomes the inertia force and the sediment is dropped down, commonly promoting formation of massive, normal graded deposits, which can be successively reworked under tractional conditions. In this framework, at the outlet of a stream system, the effluent behaviour and consequent sediment dispersal and accumulation patterns (i.e. mouth-bars), are governed by three basic effluent forces, which are: (i) outflow inertia (ii) turbolent bed friction and (iii) outflow buoyancy (Wright, 1977). The interplay between each of the latter controlling factors regulates the dynamic conditions in which different mouth bars can form, in terms of morphologies and depositional pattern (see Wright, 1977). Hereinafter is presented a depositional model inferred after the studying of the three outcrops situated in Nathan Gorge National Park which allowed a 3-dimensional interpretation of the sedimentary bodies. The model focuses on the main evolution phases that are recognized based on facies analysis studies. Modern analogues, such as the Apalachicola river delta complex (Florida), have been taken as an example to refer in the understanding of the stages that characterized the formation of the lobated-delta system and mouth bar deposits.

The first lobe is recognized in only two outcrops, UP1 and UP2 and is shown in Figure 21, a. In both the successions, sediments show an overall lateral fining and thinning while in UP1 also a coarsening upward trend is recognized. The unit in UP1 is supposed to be a transversal section of a proximal- to distal-lobe that might testify a progradational phase of the mouth-bar because of the coarsening upward trend. On the very end of the UP1 outcrop (see bottom-left part of the AA^{I} section, Figure 19) minor strata made up of coarser sediments downlap the distal-lobe deposits and might testify the stacking of another lobe coming from south-west. However, data are not enough to confirm this hypothesis. On the other hand, the UP2 is supposed to be a slightly oblique section of the lobe. Because the presence of a mud layer onto the Lobe 1, it is supposed that a possible abandonment or a shifting of the Lobe 1 created the condition of an embayment (i.e. interdistributary bay) in which mud settling was possible.

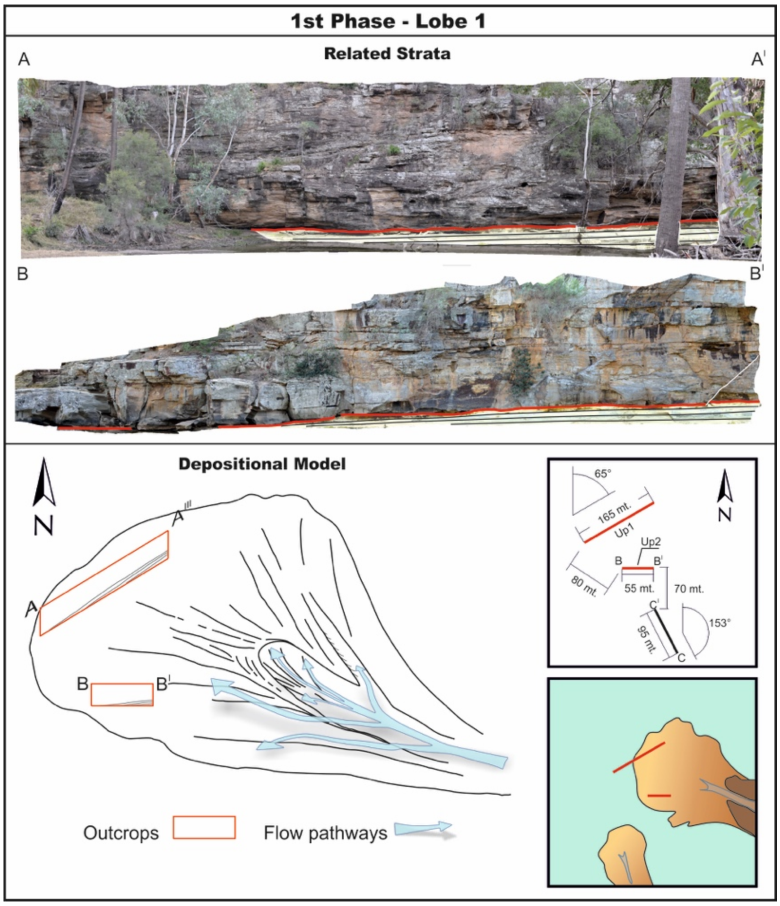


Figure 21, a

In the successive evolution phase the Lobe 2 prograde onto the Lobe 1 (Figure 21, b) and this is highlighted by the erosive surface at the base of the lobe. This phase is recognizable only in UP1 and UP2 but deposits belonging to Lobe 2 are probably under the water table in UP3. Unit in UP1 shows a partial transverse section of the lobe, and from the section AA^{I} to the section A^{II}A^{III} the channel-lobe transition deposits, proximal-lobe and distal-lobe deposits are recognizable.

In the UP2 outcrop the section is oblique in respect to the sense of the lobe accretion and thus geometries are flattened if compared with UP1 outcrop. On the right side of section BB[I] a channelized feature cuts almost transversal the CLTZ deposits and this is supposed to be a secondary channel that might build up a new lobated deposit onto the flank of the major one, according to the typical compensational stacking processes of mouth-bars.

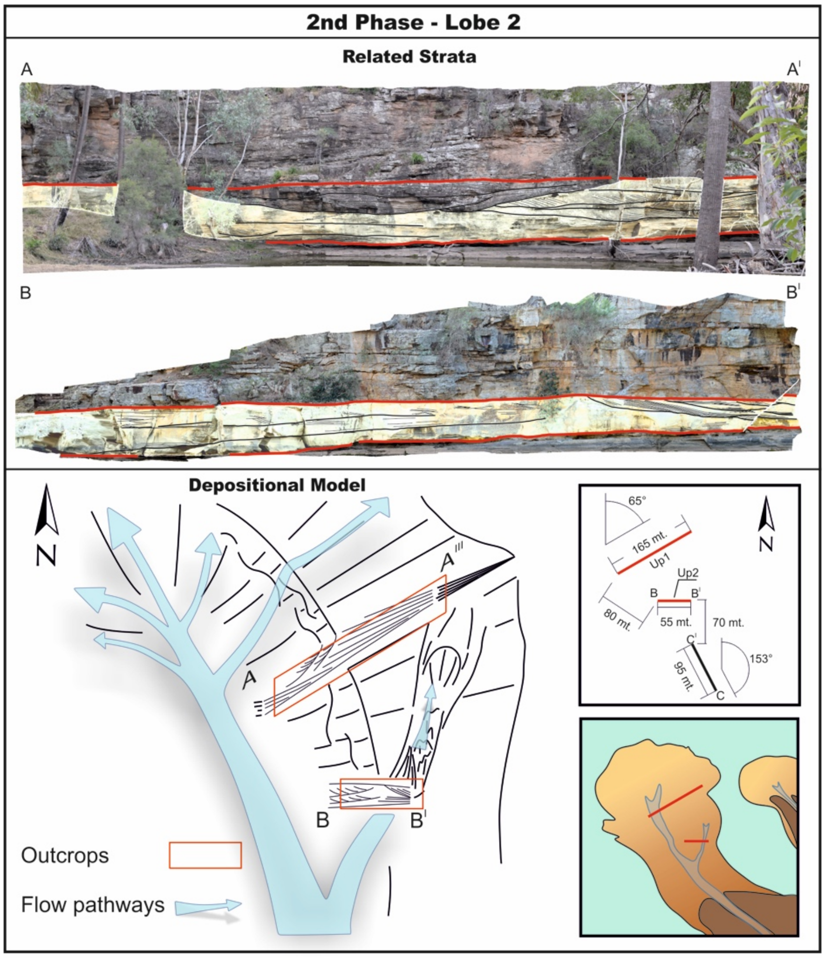


Figure 21, b

The third phase is shown in Figure 21, c and consists mainly in the back-stepping of the major lobe. This stage is detectable only in UP1 and UP3 outcrops and it is inferred that probably deposition shifted in the lobe juxtaposed the major one trough the channel situated in UP2. The back-stepping is well identified in UP3 in which the beginning of the fining upward trend coincides with the first 2~3 metres of the outcrop. On the other hand, the back-stepping phase within the major lobe (UP1) is supposed to be represented by the infilling of the CLTZ due to the last input discharges that were not able to overpass the bar crest and remained behind it, in the back-bar complex.

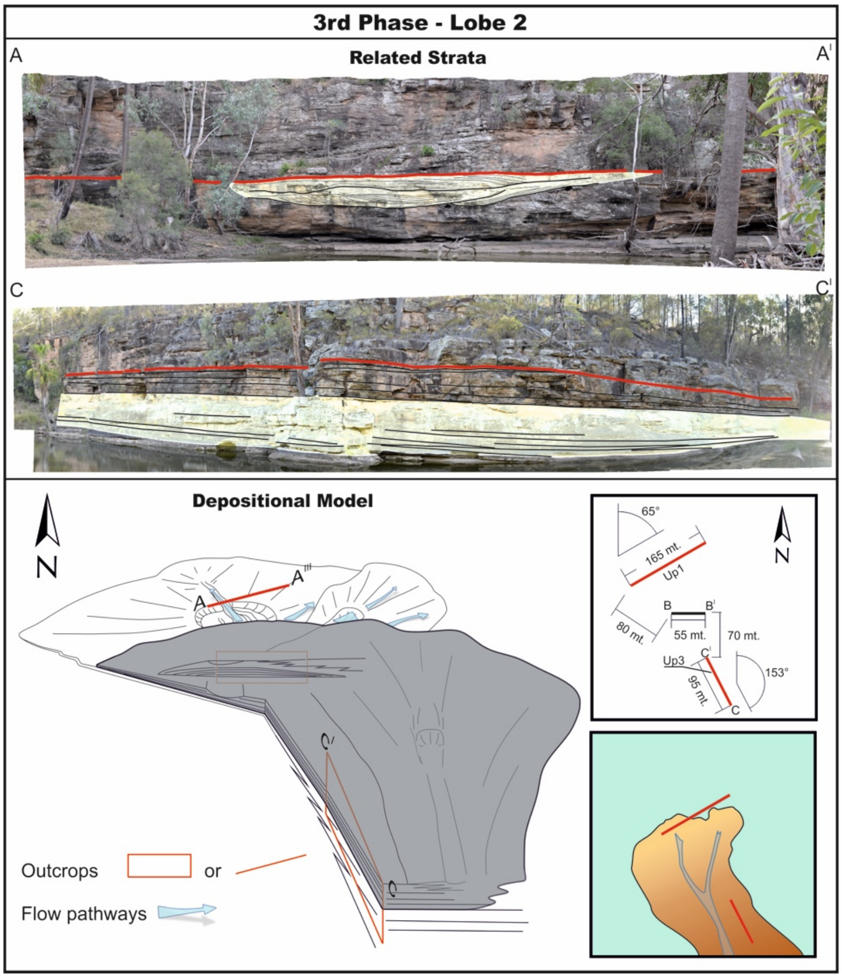


Figure 21, c

In the fourth phase (Figure 21, d) the back-stepping of the major lobe, along with the minor lobe on its right-side, is still going on. This phase is recognized only in UP2 and UP3 while the absence of strata representing this stage in UP1 might highlight the abandonment of the major lobe. The lacking of mud deposits onto the Lobe 2 in UP1 might is due because no embayment developed during this phase. In UP2 very fine deposits identify the retrogression of the lobe-system and are characterized by minor channelized features that represent the very end of distributary channels. At this stage, in the right part of the BB^I a coarser input of sediments is in heterotrophy relation with the back-stepping deposits and this might suggest the presence of another closer mouth-bar body within the system. In UP3, alternated very-fine sand deposits with silt deposits represent the final part of the fining upward sequence.

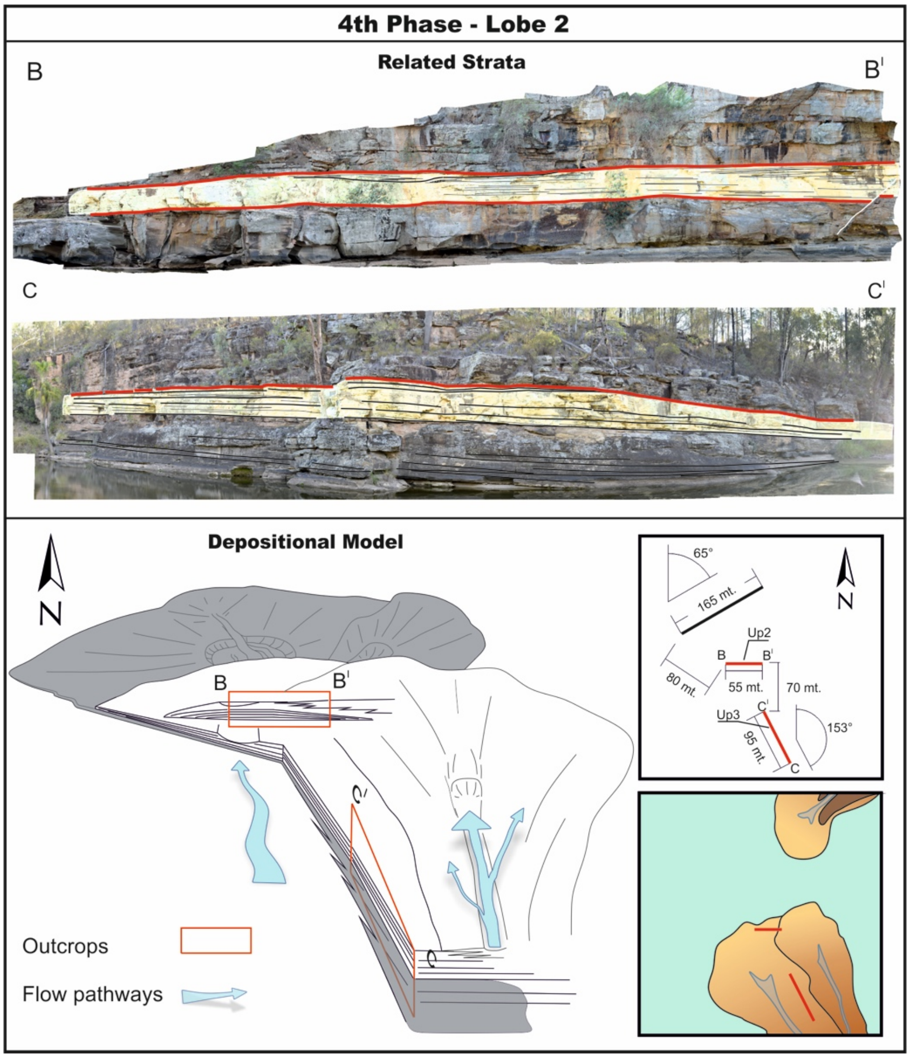
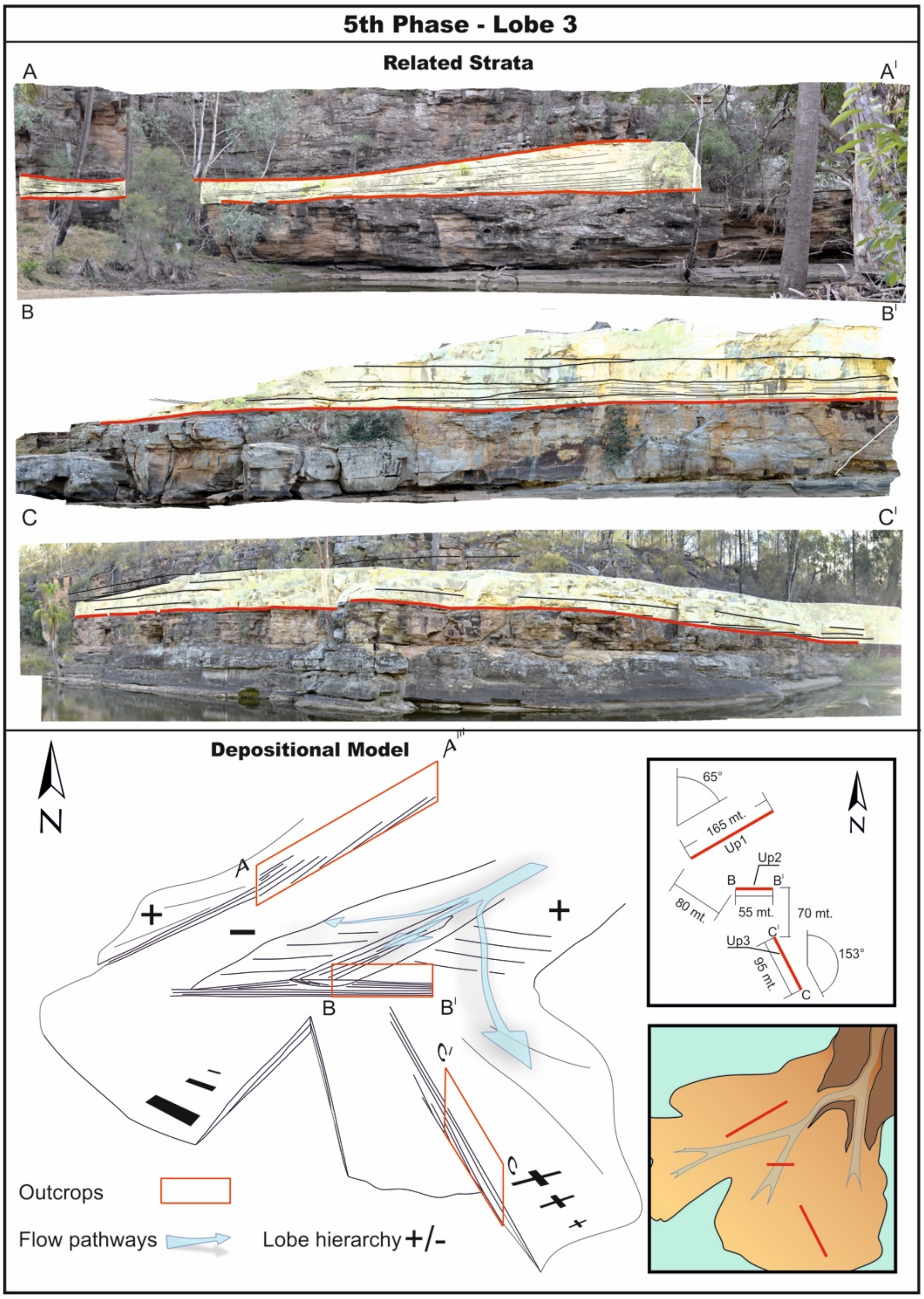


Figure 21, d

The final and last evolution phase recognized between the three outcrops consists in the progradation of the Lobe 3 onto the above-mentioned bodies and is detected in UP1, UP2 and UP3 outcrops (Figure 21, e). A major downlapping surface characterizes this progradational phase and is easily detectable in UP1 and UP3 which are supposed to be slight longitudinal sections of the Lobe 3. In detail, the downlapping surface of both AA^{III} and CC^{I} sections is on the right side but it becomes almost flattened and parallel to the underlying strata moving toward the left, in paraconformity relation with Lobe 2 sediments. Since the uppermost part of UP2 is supposed to be a section almost transversal to the body, the downlapping surface is not appreciable in this outcrop. Progradation of the lobe is not simultaneous, starting from the very northern part toward the south and with Lobe 3 downlapping progressively onto the Lobe 2. Thus, the strata that are parallel in AA^{I} are supposed to be the first downlapping strata situated on the right side of CC^{I} while the horizontal strata which form a paraconformity on the left side of CC^{I} represent the last phase of progradation of the lobe. This relationship is inferred also because the back-stepped Lobe 2 body in UP3 is thicker in respect to the Lobe 2 deposits in UP1 and thus strata that are sub-parallel in AA^{I} form a downlapping surface in CC^{I}. A lateral fining and thinning of the strata is recognized in UP3, highlighting the progressive shifting in distal-lobe deposits. In UP2 deposits, the presence of a channelized feature and levee deposits is recognized in slight transversal section and this is supposed to be a portions of the central part of the Lobe 3.

A sixth phase is inferred because of the erosive scours that are recognized in the upper-left part of both UP1 and UP3 outcrops. Identification of different portions of a lobe has been made based on facies interpretation and thus this is supposed to be Lobe 4. However, data are not enough because of the position of the outcrops and their exposure and thus interpretation on the fifth phase would be inaccurate.

After the studying of the 3 outcrops a 3D sketch has been made which represents the different phases that summarize the depositional history of the sequence and is shown in Figure 22.



5th Phase - Lobe 3
Related Strata
A
A'
B
B'
C
C'
Depositional Model
65°
165 mt.
Up1
Up2
B
B'
80 mt.
55 mt.
70 mt.
Up3
C'
95 mt.
C
153°
N
Outcrops
Flow pathways
Lobe hierarchy +/-

Figure 21, e

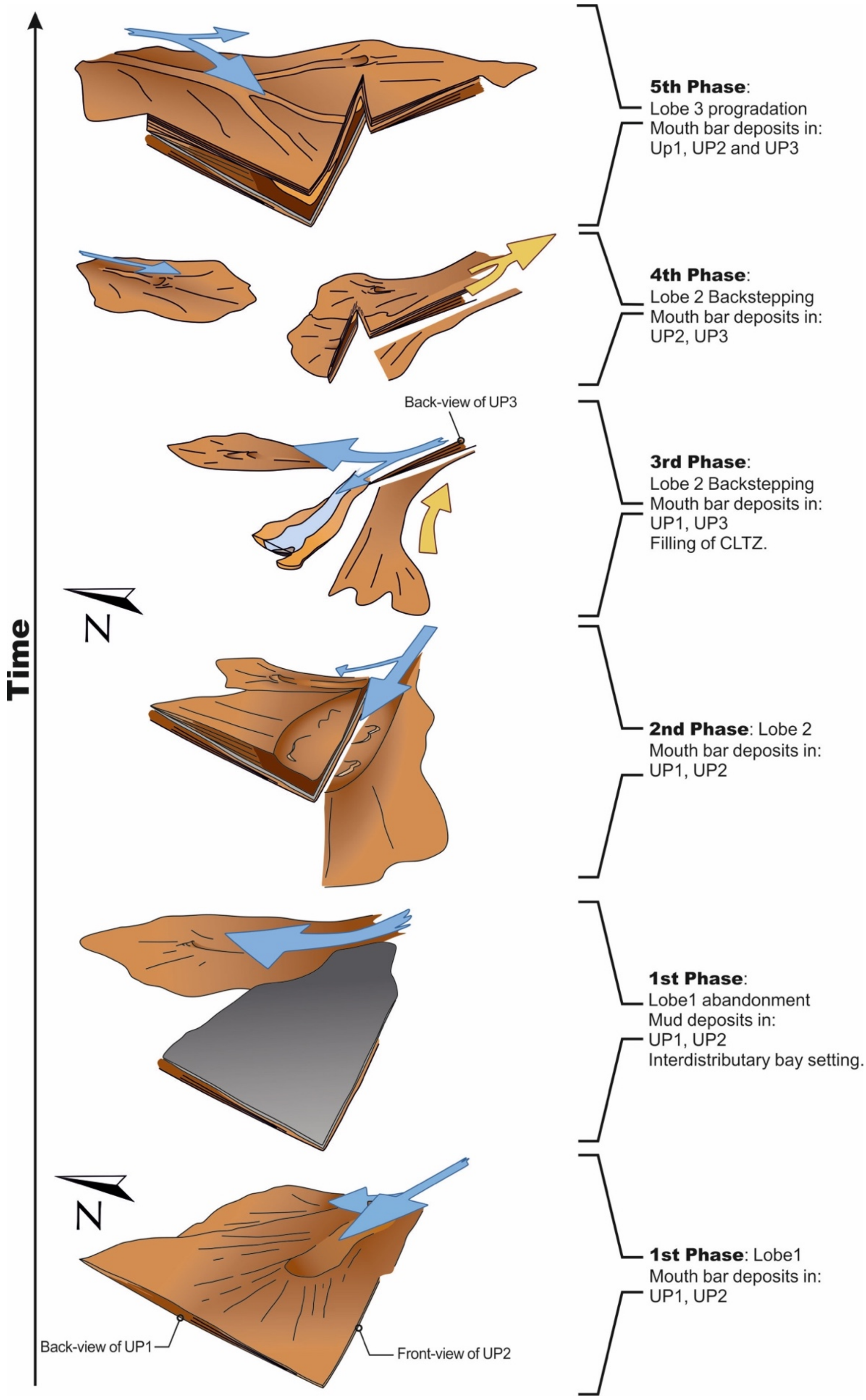


Figure 22: 3D depositional model inferred after the studying of the Upper Precipice.

3D Photogrammetry and Preliminary processing of allostratigraphic flow units

The using of 3D Photogrammetry and its preliminary application to reservoir flow modelling has been proposed by the ANLECR&D Company whom requested the using of specific software (i.e. Sirovision™ by CSIRO, Petrel2014™ by Schlumberger) to perform the studies on the reservoir unit.

The employing of Digital Terrestrial Photogrammetry allowed us to create accurate 3D virtual models for the Upper Precipice 2 (UP2) outcrop which is located E-W in the proximity of Cabbagetree Creek. This latter outcrop was the unique suitable for photogrammetry shooting in terms of rock exposure, geographical constraints and vegetation. Successively, thanks to the powerful Sirovision™ algorithm, 3D models have been created for each stereo couple and all single models have been then merged together by manually digitizing anchor points between them to form a unique, big and georeferenced virtual mosaic (Figure 23).

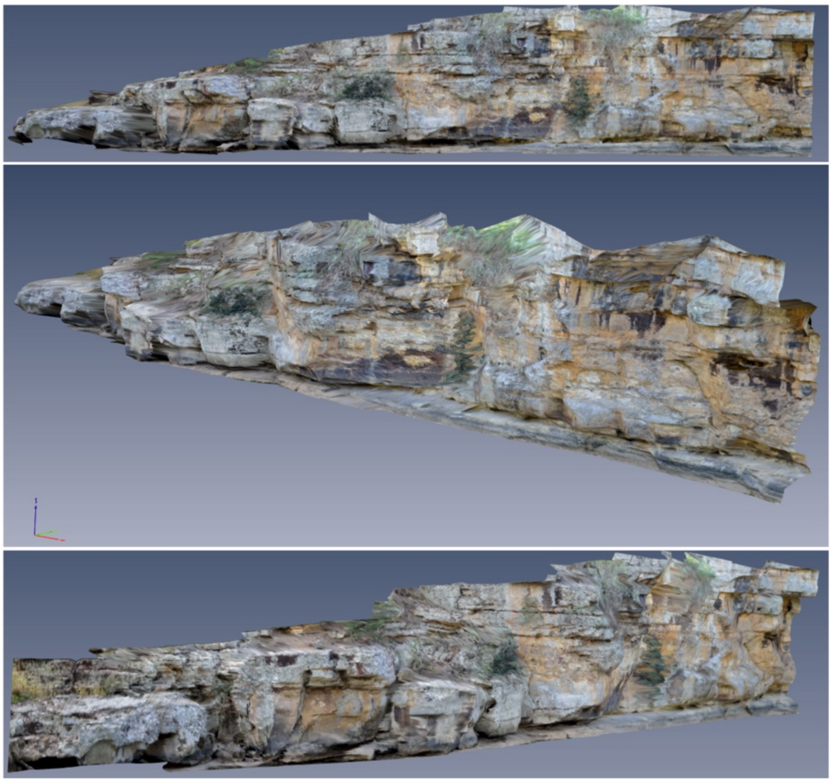


Figure 23: Image representing the 3-dimensional virtual model of the UP2 created in Sirovision™.

Based on the surveyed outcrop, several erosional or non depositional surfaces have been selected and traced as polylines onto the UP2 virtual model in Sirovision^{TM} (Figure 24, a). When possible, polylines can be traced between one or more 3D models forming two-dimensional surfaces which can be ascribed to sedimentary boundaries (e.g. base or top of beds). However, since a single 3D model has been created in this work, polylines do not represent real surfaces between two or more outcrops but are assumed to be a hypothetical prosecution of the erosional or non depositional surfaces recognized in the succession.

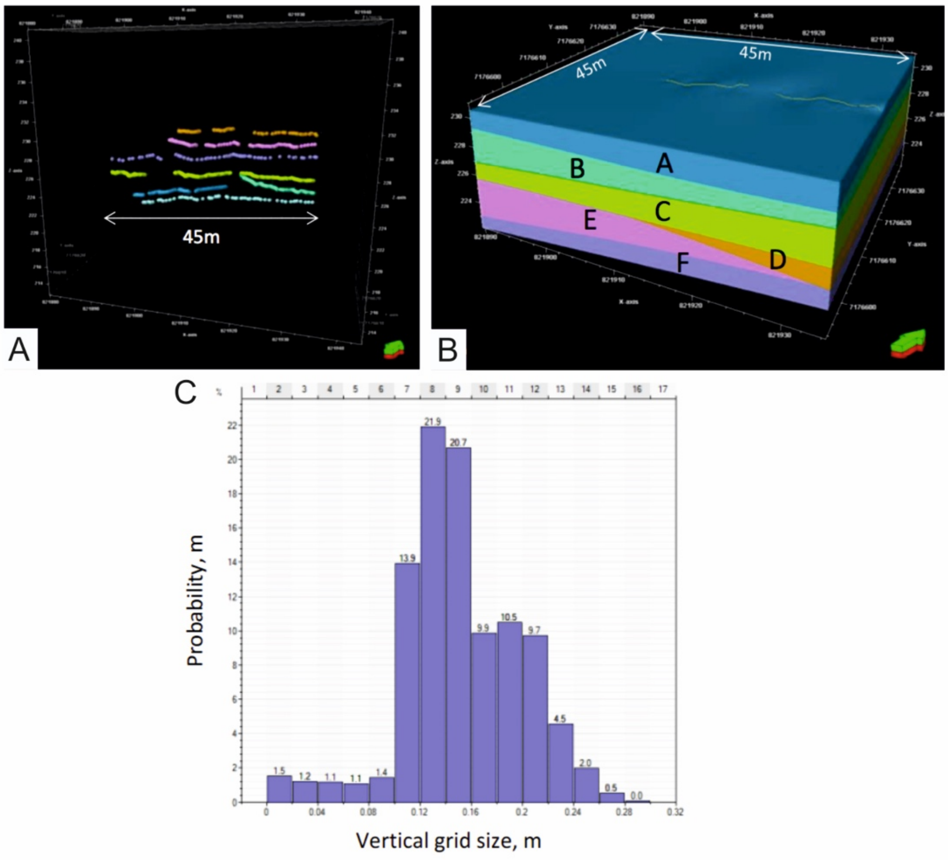


Figure 24: A – Image showing the polylines representing the main surfaces recognized in UP2 and traced in Sirovision^{TM}; B – Grid-cell created in Petrel2014^{TM}starting from the 3D virtual model. Note that the model is georeferenced also in Petrel2014 ^{TM}; C – Histogram showing variation in vertical scale of each zone.

Georeferenced polylines were created, exported and than imported in Petrel2014^{TM} as shown in Figure 24, b. Based on these lines, a 3D unit construction model was built with x- and y- range of 45m: grid size in x- and ydirection is 0.25m while vertical scale is varied (Figure 24, c) because all zones are layered in proportion to each other (Bianchi et al. 2015). However, the average grid size at vertical scale is 0.15 m. Grain size depends on the logged section and thus is related with the proprieties of the sandstone. The rock type for units A to D (Figure 24, b) were classified as medium sand, fine to medium sand, very fine sand, medium to fine sand, respectively while medium to coarse sand has been assigned for both E and F units. Based on the classes of rock type, a mean grain size of 0.4mm, 0.27mm, 0.1mm, 0.062mm, 0.4mm, and 0.4mm was used in modelling for units A to F respectively (Bianchi et al. 2015). With the regarding of the grain size for the x- and y- 45m grid, this is based on a sequential Gaussian simulation, using a variogram with a major and minor range of 50m and 20m and orientation of EW. This procedure was necessary because no information came from this part of the unit. Standard deviations of grain size were assumed as 0.1mm, 0.3mm, 0.1mm, 0.1mm, 0.2mm and 0.1mm for Units A to F, respectively. The 9 realisations are shown in Figure 25 and these differs because the sequential Gaussian algorithms can produce a range of realisations that capture the uncertainty of a regionalized variable (i.e. porosity and/or permeability).

However, it is important to note that the outcomes from these preliminary studies on 3D flow cell simulation are not sufficient for a basin-scaled utilisation and, furthermore, the work must be sustained by more data, especially in the definition of the relationship between grain size and porosity/permeability. This might be done using portable permeameter for micro-permeability analysis directly on the field. Nevertheless, the results show that implementation of classical facies analysis carried out on field, 3D photogrammetry and 3D models created in Sirovision^{TM}, are powerful tools that can be useful in the understanding and definition of geological bodies and facies variations in the framework of a reservoir unit characterisation.

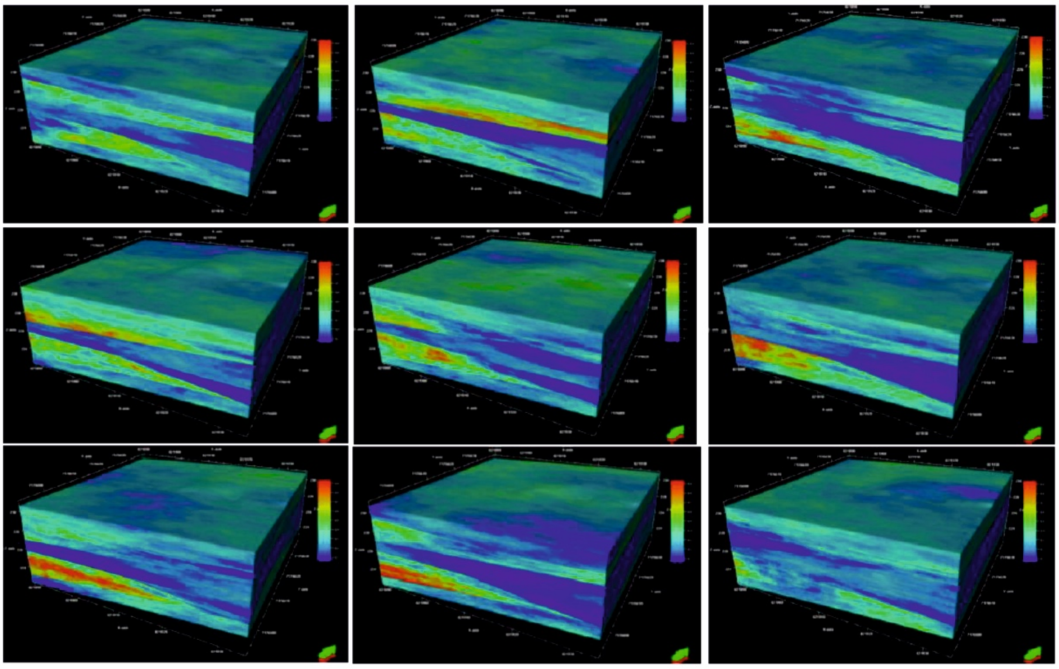


Figure 25: Generated 9 realizations of grain size by Sequential Gaussian Simulation.

Borehole data and core logging

The last part of this work focuses on the studying and facies description of the Woleebee Creek GW4 core (hereinafter GW4) along with the comparison with the borehole data provided by the company. These latter data concern the West Wandoan 1 well, which is supposed to be the injection well for the CO_2 storage (see location in Figure 26). The study was performed with the aim to describe the Lower and Upper Precipice Sandstone before the commencement of the field campaign and the main goals were to (i) get familiar with the different facies of the formation and (ii) characterize the Precipice Sandstone 150 km south from the Precipice Sandstone belt. After these preliminary studies some useful considerations might be put forward in the interpretation of the Precipice Sandstone and will be discussed later on in this work.

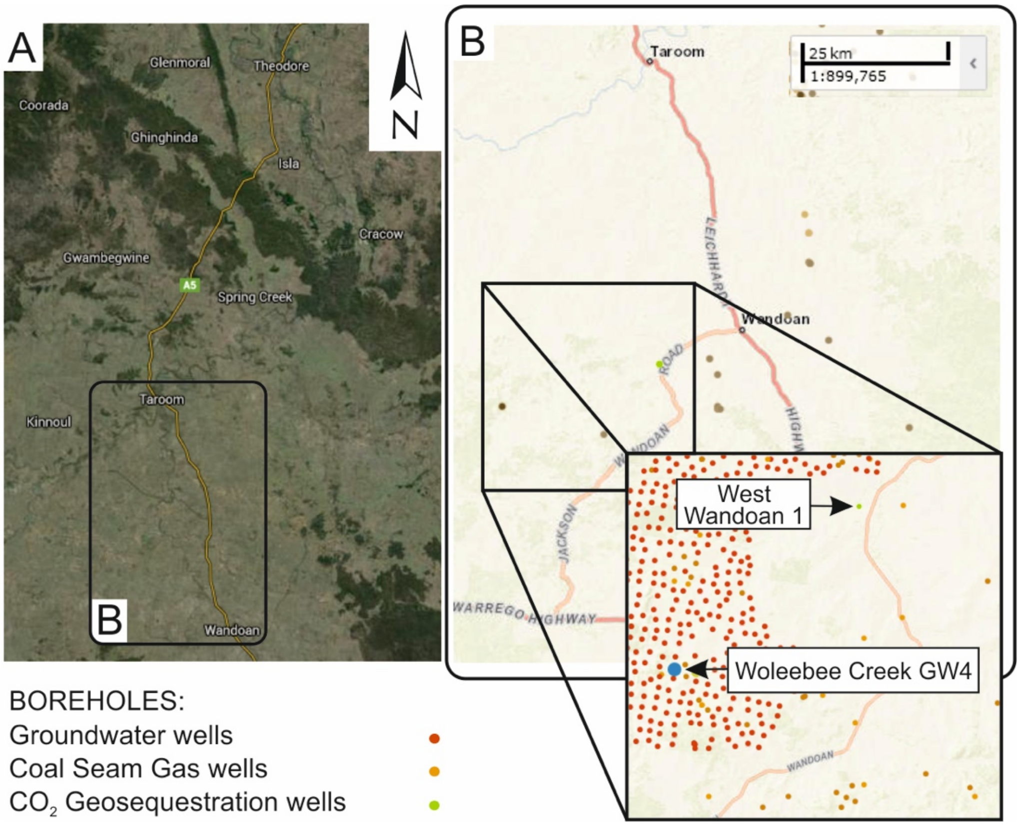


Figure 26: Location map showing the position of the boreholes studied in this work.

Core description

The core is made up of 139 m thick deposits representative of the Precipice Sandstone Formation. The Basal unconformity with the underlying Bowen Basin is at - 1574.12 m (Figure 27) while the core intersects the base of the Evergreen Formation at – 1435 m. The contact between the Lower and Upper Precipice is situated at – 1468 m. However, since the contact between the two different subunits is transitional, it is not possible to give a precise depth measure. Cores were described via bed by bed logging, focusing on significant erosive surfaces, changes in grain size and other key features such as texture, colour, composition, lamination, etc. Since the lateral continuity is not appreciable in core analysis, especially in the case of a unique core study, interpretation on environments and subenvironments is at the beginning, because more data from closer well are necessary. Nevertheless, fieldwork campaign and successive studies applied to core logging aided in the primary interpretation of the subenvironments.

Facies analysis

Concerning the core facies recognized during the studying of the Lower Precipice, those are mostly similar to the facies of the Lower Precipice outcrop (LP1) shown in Table 1. There are no significant variations between the southern Lower Precipice and the outcrop further in the north. However, in some parts high portions of silt and mud are present (Figure 27) and this is not recognized in the outcrop. Furthermore, coal fragments and little slumps are rarely seen in the outcrop while in the core are quite common. Facies associations might be the same of the outcrop succession. When possible, compound or transverse bars are recognized on the base of the bounding surfaces, minor erosive bases within the same strata (i.e. unit bars forming major compound bars), avalanching front, etc. When grain size diminishes and smaller bedforms are found these are interpreted as the waning of the channel system and might represent abandoned cross-bar channels, sand flats or proximal part of floodplains. On the other hand, the Upper Precipice quite differs in respect with the outcrop observed in the field campaign. In this case, the upper portion of the core presents high rates of mud and silt deposits along with roots and minor bioturbated beds. Bedforms such as ripples are commonly capped or alternated with silt and mud, and this suggest that during deposition low-energy conditions were common. As a whole, facies distribution and trends in grain size might suggest a continental setting, such as a floodplain, where levees and crevasse splays associated with meandering streams are frequent.

The GW4 core was stored for a few days in the Exploration Data Centre in Zillmere, Brisbane. Unfortunately, the access to the samples was limited, thus collecting of data was restricted in terms of time. Figure 27 shows peculiar aspects of the Precipice Sandstone in cores while the log-section (see Figure in

Appendix) shows the 139m thick section of the GW4 well, integrated with facies description and preliminary facies interpretations.

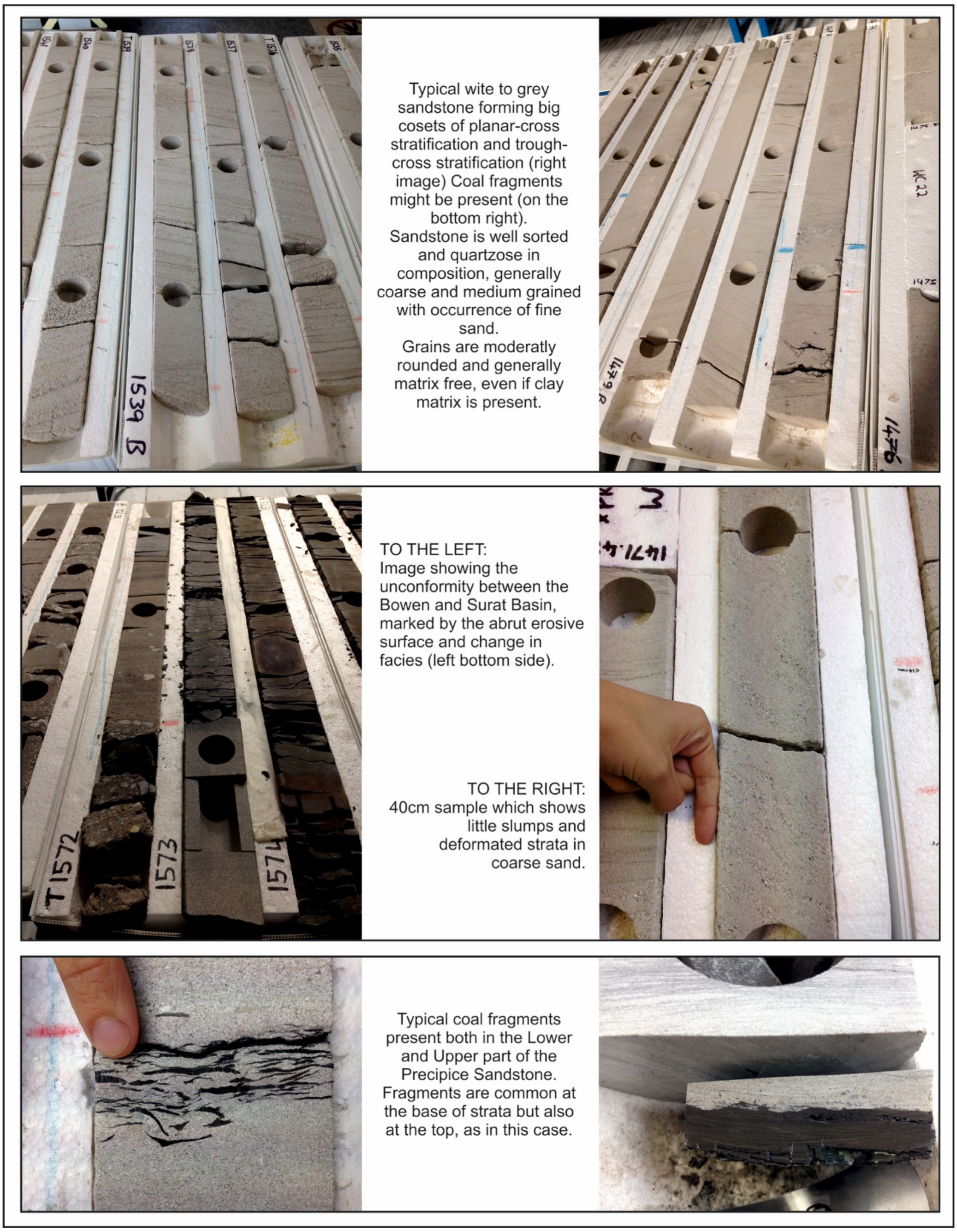
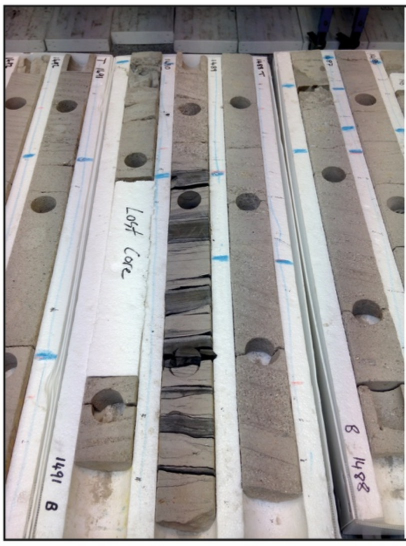
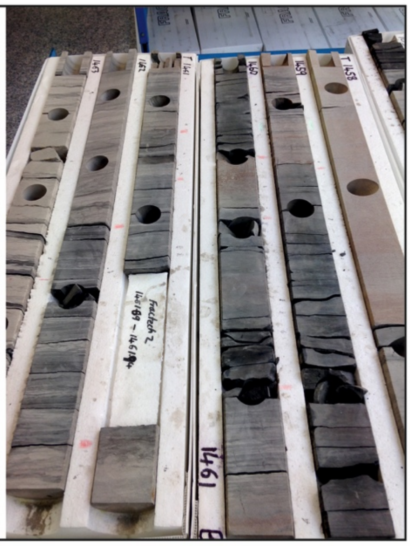


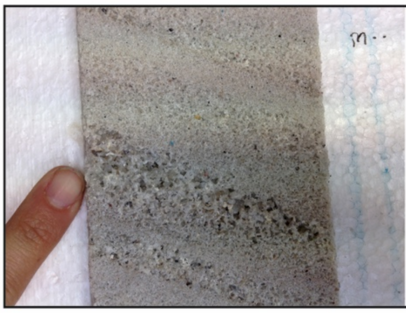
Figure 27: Panels (see also next page) showing the peculiar features recognized during the studying of the GW4 borehole.



TO THE LEFT:
50 cm thick deposits of fine sand and silt with mud intercalations in a dominant planar-cross stratified sandstone. Small ripples are presents.

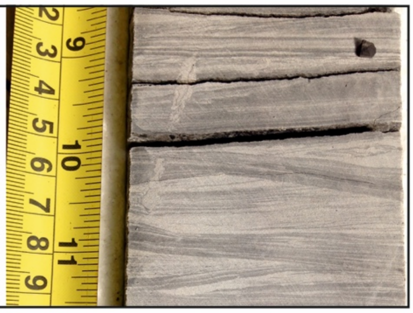
TO THE RIGHT:
Typical facies of the Upper Precipice in core samples. Sediments are organic reach and made up of very fine sand and silt with common mud intercalations. Ripples and bioturbations are dominant

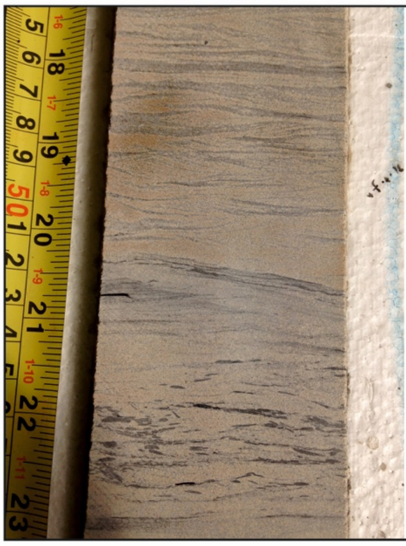




TO THE LEFT:
Typical inverse graded deposits (grainflows) alternated with finer grainfall sediments.

TO THE RIGHT:
Trough-cross laminated fine to very fine sand with silt. 3D ripples are in cross section.
Note the burrow on the top-left part.





TO THE LEFT:
Very fine to fine ripple-cross laminated sandstone (Upper Precipice). Ripples are capped by silt, minor mud and coal chips are present (bottom part).

TO THE RIGHT:
Very fine to silty deposits showing ripple cross lamination.
Ripples are gentle reworked by bydirectional currents showing symmetric crests.

DISCUSSIONS

The Lower Precipice Sandstone

Despite the well known nature of the sandy-braided Precipice Sandstone (Exon, 1976; Martin, 1976; Hoffman et al. 2009, Ziowloski et al. 2014; etc.) less studies have been carried out concerning the sedimentology and the facies associations of the Early-Jurassic formation. The study led by Martin (1976) is the main work in which an extensive and accurate characterization on the petrology and the sedimentary facies is completed. However, no depositional models are proposed by the author and the absence of sedimentary bodies characterization (i.e. braided bars) based on outcrop observations represents a consistent lacking in the mentioned study. Nevertheless, the estimation of fluvial geobody morphology and dimension is a notoriously difficult problem in reservoir modelling. During the building up of a reservoir model, one of the main aim is to reduce uncertainties in terms of 3D facies reconstruction and rock proprieties in order to determine flow-pathways or flow-baffles. It is understandable that, within a sandy-braided reservoir model characterization, the nested river pattern and the wide range of morphologies that characterize such types of environment represents the main barrier for the completion of a reliable reservoir reconstruction.

Over the past decades, numerous studies have been led on modern sandy-braided rivers, as in the case of the Brahmaputra, South Saskatchewan and Platte River (Ashworth et al. 2000, 2001; Bridge & Lunt 2006; Cant & Walker 1978; Horn et al. 2012) and thanks to the using of new techniques (e.g. GPR technique or acoustic Doppler current profiler), new models for sand-bed and gravel-bed braided rivers are now developed and improved (Bridge & Lunt 2006). Although sedimentary bodies differ in terms of preservation rate between modern analogue and ancient deposits, the study of Lunt et al. (2013) suggests that these differences in preservation rate are negligible and the comparison with modern analogues is faithful. This means that, at the state of the art, better interpretations can be put forward in the studying of ancient sandy-braided rivers both in outcrop and in the subsurface, allowing a better characterization of reservoir units and the diminishing of reservoir uncertainties.

This studying of the Lower Precipice Sandstone allowed both the recognition of several braided channel bars and the definition of an ideal depositional model for the braided system (see Result section). The main goal is to give a contribution in the understanding of the wide range of bedforms and barforms (i.e. dunes, unit-bars and compound-bars) that commonly represent the sandy-braided river systems in the rock record and to put forward few important considerations on the implications that dimensions and morphologies (e.g. the length-to-thickness ratio) of geological bodies usually have in the framework of a reservoir characterization study.

Implication on reservoir modelling

The depositional model inferred from the LP1 outcrop can be used to improve scaling relationship in subsurface studies as well as being applied to predict fluvial heterogeneities. The dimensions (i.e. length, width and height) of geological bodies can be defined statistically in stochastic models and enhanced thanks to outcrop or modern analogues studies. In general, the recognition of parameters such as the formative channel depth (d) and mean bankfull depth (dm) in sandstone fluvial bodies is the key requirement for the application of experimental procedures which allow to determine body dimensions from the rock record (see Bridge & Mackey, 1993). However, in order to determine such parameters, it is necessary to observe the full width of fluvial deposits in sections nearly normal to paleoflow directions (Bridge & Mackey, 1993) but this is not the case of the studied outcrop which is tangential to the stream system. Nevertheless, the work of Lunt et al. (2013) describes in detail the morphology and geometry of bedforms and channels in sandy braided river, providing some practical points that allow to establish the likely scale of the fluvial channel (i.e. mean bankfull depth, dm) even when transversal sections of the system are not available.

The mean bankfull depth can be estimate both from mean dune cross-sets thickness and from mean unit bar height, while maximum bankfull depth can be estimated from cross-bar channels (Lunt et al. 2013 cum bibl.). Mean bankfull depth might be inferred also from compound bar deposits however, since the studied outcrop shows only little portions of compound bars, dm is estimated exclusively on dunes and unit bars. It is important to note that these assumptions are possible because differences in mean set thickness of dune cross-strata and bedforms between ancient and modern systems are negligible and thus estimation of body dimensions from the rock record is reliable. The latter assertion is possible because of the above-mentioned work of Lunt et al. (2013) in which the authors compared channel-fill deposits above and below the channel base in the modern Saskatchewan river, allowing the comparison between preserved sediments above and below the erosional surface. Discussions below refer mostly to this work.

In the studied section at Nathan Gorge National Park, two different mean bankfull depths are estimated according to the major and minor flooding events. During minor flooding events, dunes height spans from 0.15 up to 0.90 m and the formative flow depth inferred by the mean cross-sets thickness is slightly 3 times the average value, meaning formative flow depth of ~1.60. Lunt et al. (2013) demonstrated as the dune heights preserved in the rock record are more appropriate to represent the mean bankfull depth of the system and thus 1.60 m is supposed to be dm. Mean unit bar height should also be broadly equivalent to average flow depth meaning that, during low flow rates, unit transverse bars ranging from 1.40 m up to 1.75 m were deposited in a mean bankfull depth of ~1.55 m which is very similar to the dm assumed from dune cross-sets thickness. On the other hand, when major transverse bars of more than 3.20 m were deposited, mean bankfull depth is assumed to be almost 3.10m. The maximum bankfull depth is estimated from the cross-bar channel situated in the middle-lower part of the outcrop section (see Figure 12). The maximum channel fill depth is a third or a quarter of the maximum bankfull channel depth meaning that for a inferred channel section of 1.75 m the maximum bankfull depth is ~6 m (see Lunt et al. 2013 and related works). The definition of the mean bankfull depth allow to estimate also the channel-belt width (cbw) which has a fundamental control on the connectedness of sandstone bodies. Using the estimate of 3.10 m and the empirical equation of Bridge and Mackey (1993)

$$cbw= 192\ dm^{1.37}$$

channel-belt width (cbw) is estimated to be 900m, although this value is slight underestimated of ~100 m. Unit bar deposits generally scale with formative flow width and generally have lengths of between 3 and 7 times the channel width. Using the typical ranges of flow depth (3.10 m) to channel width of 1:200 (Bridge, 2003), the formative channel width is estimated at ~620 m, which implies unit bar lengths of 1860 m to 4340 m. However, it is worthy to note that the extension of preserved unit bars (i.e. width and length) in the rock record is strongly affected by the aggradation rate, the rate of lateral channel migration and variability of bedforms dimensions, which depend mostly on the attitude of the river system and might vary between different sandy-braided systems. The longitudinal preservation potential of unit bars suggested by Lunt et al. (2013) is around 10%, meaning that transverse bars which represent the rock record might have length from ~180 m to 440 m, which is faithful if compared to the length of the major transverse bar recognized in the outcrop. In high aggradational settings the preservation rate is higher. Since cross-strata observed in the outcrop are largely obliterated by erosion, aggradation is supposed to be low and thus preservation rate of 10% is preferred.

In conclusion, allowing for intersection of high permeability basal lags between 2 o 3 adjacent unit bars, a potential high permeability thief zone might be present between wells spaced 300 m to 960 m apart.

Thanks to the work of Lunt et al. (2013) it has been possible to assess the mean flow depth which is than used to estimate scale relationships and predict the range of bedforms and channel widths.

Prediction of geobodies on the length-scale of unit bars is important because such bedforms might have huge impact on reservoir drainage system. Indeed, it has been demonstrated that in the case of adjacent unit-bars the pebble lags present at the bottomset of the bodies represent a preferential flow-pathway that might extend up to ~1000 m in length and 300 m in width. However, given the inherent variability within rivers, these estimates must be taken with caution. On the other hand, they are sufficiently reliable to gain a satisfactory estimate of the overall scale of the alluvial channel.

New insights on the nature of the Upper Precipice

As already discussed in the preceding chapters little is know on the nature of the upper part of the Precipice Sandstone and no detailed facies analysis have been performed on field in order to enhance the knowledge on the geology in the upper unit. As a whole, it is generally deemed that it represents the fluvial waning phase of the stream system prior to the deposition of the lacustrine Evergreen Formation (Exon, 1976; Martin, 1976). However, the unclear presence of a transitional environment between the two different units it is still matter of discussions.

According to Van Wagoner et al. (2003), opens systems (i.e. systems through which energy and matter are transmitted), such as stream systems (i.e. braided system ascribed to the Lower Precipice), attempt to return to equilibrium, a state in which gradients are minimized. In order to minimize gradients, the system is asked to create dissipative structures to dissipate both energy and entropy to the surrounding environment. As stated by Hoyal et al. (2003) the fundamental dissipative structure in the fluid is the jet flow which produces peculiar sedimentary bodies, the jet deposits. These deposits are scale invariant, lobate in shape and, from the scale of delta mouths to deepwater fans, exhibit one or more specific mutual proprieties. These shared proprieties are: (i) point-source planform expanding outwards (expansion angle is controlled by jet velocity field and grain size) (ii) near orifice erosion/incipient channel formation surrounded by levees (iii) progression of facies with decreasing velocity (i.e. erosion region – bedform region – pure suspension deposition region) (iv) thickness decreasing exponential-linear and gaussian-like downstream and across-stream respectively and (v) in large scale deposits with paleo-flow indicators, vectors will be spreading from point source orifice (Hoyal et al. 2003).

The mouth bars deposits recognized in the Upper Precipice outcrops (UP1 – UP2 – UP3, see Result section) deal with the theory in which, at transitional environments, such as at the outlet of a river system, or between the fluvial Precipice and the lacustrine Evergreen Formation, the system attempts to dissipate energy trough the building of fan-shaped jet flow deposits (i.e. mouth bars). These fan-shaped deposits detain large implications in the framework of a reservoir characterization study and will be discussed as follow.

Implication on reservoir modelling

In the framework of reservoir unit studies, analogue reservoir modelling and outcrop characterization is of fundamental importance when there is lack in relevant data from seismic survey or wells. During the upscaling procedure, several simplifications might run into errors and the model represents the reservoir inadequately, performing upscaling on inaccurate data. Flow cells are simplified and petrophysical characters are average values, meaning that small-scale heterogeneities, lamina permeability or capillarity are not realistic values or they are even avoided in the estimations. According to Mikes et al. (2006) among the errors due to the upscaling procedure, facies interpretations (e.g. uncored facies, misinterpretation) and bottomset characteristics (e.g. bottomset permeability and continuity) are the largest errors that usually occur. In addition, core plug studies and measurements of permeability are unlikely to yield representative values at the scale of reservoir model grid block, because the connectivity and the continuity of permeable or impermeable layers varies significantly with length scale (Jackson et al. 2005). Thus, it is clear that classical facies analysis of analogue outcrops assists the "scale up" and "scale out" of reservoir proprieties, allowing the development of reliable geo-cell in which lateral and vertical variations of facies could be defined with high accuracy.

Concerning this work, the definition of geological bodies allowed the construction of a geo-cellular 3D model in which rock proprieties were assigned after the characterization of the delta mouth-bar deposits (See Result section). Nevertheless, as stated by Wellner et al. (2005), the definition of geological bodies and the characterization of the depositional environment is of fundamental importance also when the net-to-gross evaluation is approached in reservoir quality studies. Different delta systems show mutual architectural elements which are typical of each system (i.e. delta-plain, delta-front and prodelta) but might have completely different character according to the dominant energy processes (i.e. wave or tide dominated), basinal characteristics (i.e. deep water or shallow water) and, finally, nature and rates of sediments supply (see Postma, 1990). All these features variations, strongly affect the net-to-gross evaluation and the behaviour/quality of the reservoir once CO_2 is injected into the system. Thus, sandy reach and high-energy deltaic systems, as in the case of Panther Tongue Sandstone, Upper Cretaceous of north central Utah (see Wellner et al. 2005, their figure 41), result in high net-to-gross rate, meaning that high percentage of the rock thickness is permeable and capable of flowing water and CO_2. On the other hand, lower energy finer grained systems which show a complex network of stacked lobes and thus more complicated reservoir connectivity, are characterized by minor net-to-gross rate and a limited reservoir quality.

After the definition of a 3D geo-cell and based on the work of Wellner et al. (2005) it might be inferred that, concerning the studied area, the quality of the upper portion of the reservoir unit in the proximity of Cracow in terms of net-to-gross rate is low and could act as a consistent flow baffle within the reservoir unit. However, as already discussed, more data are necessary in the study case for the achievement of the best possible reservoir model, also when net-to-gross evaluation and study on reservoir rock qualities are approached. Nevertheless, the proposed model can be considered end member for the subsurface or can be used to explain some of the flow simulation behaviour encountered in the 3D dynamic modelling.

Preliminary interpretation of borehole data

The GW4 and WW1 boreholes are situated near the city of Wandoan, in the central part of the Surat Basin and are only 20 km distant. The studying of the GW4 through core-logging facies analysis allowed firstly the recognition of the lithologies and facies that characterize the deep formation and secondly a preliminary comparison with WW1 core data. Since these latter data are confidential, only a brief summary of the WW1 core is provided in the appendix.

The Lower Precipice in GW4 is 105 m thick and is mainly composed of large sets of planar and trough cross-strata, which is the typical facies representative of the lower unit. However, some aspects might be highlighted and discussed below because of interest.

In the lowermost part of the core (first ~9 metres), the formation does not present the typical characters that are recognized in the following core cuts. In particular, the strata are thin and relatively fine grained with mud fragments which are common especially in the last meters. The absence of considerable bedforms, such as thick dunes, suggests that water table was significantly lower in respect with the successive phases, when the sandy braided channel belt was established. Thus, it is supposed that the first metres of core represent the onset of the incipient fluvial system, in which the drainage system is progressively setting up, from a wandering fluvial pattern to a well developed channel belt system.

The following part of the succession is made up of channel-fill deposits in which compound-bars, unit-bars, minor dunes and sand flats are recognized. Channel-fill deposits are defined on the base of major erosive surfaces and generally show fining upward trends, suggesting that meso- or macroforms are abandoned because of a lateral shifting of the channel. However, erosive bases might be due to the low-flow stages of the stream system which permits the depletion of the meso- and major macroforms situated within the channel belt. Coal fragments are common at the top of the fining upward sequences or eventually present as rip up coal chips over the erosive bases, suggesting that minor vegetate fragments were frequent during sediment deposition.

The Upper Precipice is 34 m thick and is supposed to be separated from the Lower Precipice by a 20 cm thick strata made up of mud deposits, suggesting a sort of prolonged period of low-energy in the fluvial system. Core samples in this upper part are wholly finer if compared to the underlying deposits and generally consist in fine-sand to silt and mud sediments with high percentage of organic matter, bioturbations, roots, mud and/or coal fragments, ripples and mud capped ripples. These latter features are completely in discordance with the high porous, cleaned quartzose sandy deposits of the Lower Precipice and this highlights the abruptly change in facies and in depositional environment. Several normal- and inverse-graded trends are recognized and are supposed to be floodplain and crevasse-splay deposits. Single splay-deposits show generally a fining upward trend, dealing with the progressive diminishing of energy of the flooding event. On the other hand, when various flooding episodes are preserved, coarsening upward trends might be recognized and testify the aggradational/progradational stacking of successive crevasse splays. Coarser sandy deposits are present within the succession and these are supposed to be channel fill deposits of both crevasse channels or major channels (e.g. meanders). Concerning the sandy deposits, the longest depositional sequence is made up of cross-stratified sand with high percentage of mud fragments and this might suggest that erosion along the outer bank of the stream system was frequent.

The high percentage of mud in the uppermost part of the core highlights the general fading of the stream system. Furthermore, the high presence of roots, bidirectional ripples, footprints and high laminated siltstone might imply the onset of a different environment in which the influence of stream current is overcame by a relative calm and low-energy system in which decantation of finer and organic reach sediments reworked by minor waves might are the expression of a shallow water lacustrine or lagoon environment.

The West Wandoan 1 borehole is situated ~20 km north-east to the GW4 and it closely resembles the above-mentioned well in terms of facies and facies associations. However, two main differences have been pointed out after the examination of the report-well (see Appendix) and these regard the thicknesses of both the Lower and Upper Precipice. Concerning the lower unit thickness, this is only 75 m in WW1 and thus it is 30 m thinner than the GW4 core. This difference in thickness may is due to a simple local variation in the depositional setting (e.g. channels depth, bank height, etc.) or because the different attitude of the system to avulse or maintain the same position within the channel belt, changing from erosional to depositional tendency. However, the observation deals also with the structural arrangement of the basin and this might be of fundamental importance for the thickness distribution in this area. In particular, the thicker GW4 well is situated closer to the Taroom Trough axis meaning that, at the time of deposition, major accommodation space was provided in that area. Furthermore, with the going on of deposition and during the successive tectonic events, the magnitude of subduction was major closer to the Taroom Trough, which was the main depocentre of the system.

With the regarding to the upper part of the WW1 core, the first occurrence of shale and siltstone deposits has been ascribed to the Evergreen Formation, hence no Upper Precipice has been recognized in this borehole. Nevertheless, the facies described in the report and their summary interpretations are the same of the GW4. These consist of floodplain, crevasse and levee deposits and the core cuts show the same lithology observed in GW4. Thus, it is supposed that they simply represent the deposits of the same unit. Since the Evergreen Formation is made up of predominantly siltstone and mudstone sediments which represent a lacustrine environment, it is important to note that the very fine sand deposits with silt and mud intercalations found in the upper part of WW1 might be ascribed to the Upper Precipice Sandstone because they still belong to a fluvial system.

CONCLUSIONS

This thesis enhanced the knowledge on the geology of the Jurassic Precipice Sandstone Formation in the Surat Basin (Queensland, Australia) and consists in the first outcrop-based study which focuses on the definition of sedimentary depositional models with implications in reservoir modelling, in the framework of the major geosequestration project led by the ANLECR&D Company.

The work focused on both the Lower and the Upper Precipice with the main goal to improve the knowledge on the depositional environment at the transition zone between the Precipice Sandstone and the Evergreen Formation and to provide 3D data relevant for the construction of the most reliable 3D reservoir model, using 3D Photogrammetric principles. Thanks to a multidisciplinary approach, it has been possible to enhance the resolution of the Precipice Sandstone reservoir unit, using classical facies analysis, at the outcrop scale and from core data, and 3D Photogrammetry virtual models, which can be used as a template for the construction of 3D geo-cellular model.

In particular, on the base of the results discussed in the preceding chapters, the outcomes of these thesis are summarized as follow:

1) The Lower Precipice at Nathan Gorge National Park site shows the typical aspect of the Precipice Sandstone Formation described by Martin (1976). The high porous and permeable sandstone is made up mainly of cross-stratified strata which form cliffs up to 55 m high.
Cross-strata are the result of downstream migration of dunes and major meso-/macroforms deposited in a sandy-braided fluvial environment. In particular, five main architectural elements have been recognized in the LP1 outcrop and these are: (i) 2D and 3D dunes, formed in all the active section of the stream system, (ii) minor transverse unit-bars (iii) large compound bars (iv) sand flats (*sensu*, Cant & Walker, 1978) and (v) minor cross-bar channels.

2) The presence of eroded and reworked dunes and cross-strata, along with well-preserved bedforms, suggests that the river system was affected by several phases of alternated high-flow and low-flow rates. Three main evolution phases of the sandy braided river system are inferred: (i) the formation of the compound bar, with thinner cross-stratified sets toward the bar-top, accompanied by the incision of a cross-bar channel formed during low-flow stages (Ashworth et al. 2001), (ii) the evolution of the compound bar complex, with formations of large sand flats onto the bar-top and (iii) a following minor aggradation phase of the system with the formation of minor transverse unit-bars.

3) All the architectural elements recognized in the reservoir analogue at Nathan Gorge National Park would affect the fluid flow in the case of fluid injection, with the behaviour depending on rock proprieties such as grain size, presence or absence of finer matrix and beds attitude. In particular, high porous basal pebble lags present at the base of major unit and compound bar deposits represent the main flow pathways which can significantly affect the fluid flow. Assuming for transverse unit-bars a longitudinal preservation potential around 10% (Lunt et al. 2013), pebble lags of 2 or 3 adjacent unit-bars might extend up to 960 m and this can have consequences during the 3D Dynamic Flow Simulation in the case of wide spaced wells.

4) The study of the Upper Precipice led at Nathan Gorge National Park allowed the recognition of four geological bodies ascribed to mouth-bar deposits of a shallow water delta (*sensu*, Postma 1990) which might enter in a standing water body such as a lake or a sea (Bianchi et al. 2015). These bodies developed following the classical compensational stacking pattern of delta mouth-bars, creating a delta complex in which several episodes of progradation and retrogradation of lobes are recognized.

5) The low-energy finer grained shallow water delta system shows a complex reservoir connectivity because of the compensational stacking pattern of lobes (Wellner et al. 2005). This complexity diminishes the net-to-gross rate and the quality of the reservoir unit. Thus, in Cracow study site, the Upper Precipice Sandstone shows nested heterogeneities which might act as consistent flow baffles that must be taken in account during reservoir 3D flow simulations.

6) Following the identification of mouth-bar lobes suggests an opening toward the north of a lacustrine or shallow water marine embayment in which such mouth-bars deposits were entering in. This latter interpretation proves the presence of a transitional environment prior the deposition of the lacustrine Evergreen Formation and it is strongly in contrast with the commonly thought of the pure fluvial nature of the Precipice Sandstone (Exon, 1976; Martin, 1976).

7) The 3D Photogrammetry virtual models created with Sirovision^{TM} and than imported in Petrel2014^{TM} show that the implementation of digital photogrammetric technique is a powerful tool when the reconstruction of a geo-cellular 3D model is needed. This responds positively to the requirements submitted by the ANLECR&D Company. The grid cell has been created starting from the 3D Photogrammetric model of the outcrop. Successively, the rock proprieties have been assigned to a single geo-cell basing on the lateral and vertical variations of facies detected in the field.

8) The study of the Woleebee Creek GW4 Core, situated 150 km further south to the study area, allowed the comparison between the facies recognized in the Precipice Sandstone belt and the subsurface. The Lower Precipice in core cuts shows almost identical features if compared to the LP1 outcrop, while the Upper Precipice shows a different nature if compared to the UP1, UP2 and UP3 outcrops: the samples studied in the core cuts are supposed to be those of meandering stream and floodplain deposits. In terms of time, these deposits

might be the equivalent of the Upper Precipice shallow-water delta deposits situated further north, suggesting that in the southern part of the Surat Basin the deposition was in a pure continental setting.

9) The core-logging study of the West Wandoan 1 and the GW4 core cuts allowed the comparison between two close boreholes. In both the cores the Lower Precipice shows the same features and facies associations. However, the Lower Precipice is thicker in the GW4 borehole and this is might due because its closeness to the Taroom Trough axis. The floodplain and meandering stream deposits of the Upper Precipice are ascribed to the Evergreen Formation in the WW1 borehole. On the other hand, since the nature of these deposits is not lacustrine, it should might be suggested to consider the first metres of the Evergreen Formation in WW1 as the equivalent of the Upper Precipice Sandstone deposits recognized in GW4 because they still represent deposits belonging to a fluvialtile system.

At the end of this work new insights on the nature of the Upper Precipice have been proposed at the transition zone between the Precipice Sandstone and the overlying Evergreen Formation. In addition, the characterization of the morphology and geometry of geological bodies of both channel-fill deposits and mouth-bar deposits, of the Lower and Upper Precipice respectively, can have large implications in the reservoir unit characterization or can be used as end members for the definition of the rock units in the subsurface. The powerful application of 3D Photogrammetry technique to a detailed facies analysis study and 3D reservoir modelling demonstrates that sedimentary investigation on reservoir analogues can be a key element for reducing uncertainties during the characterization of the Precipice Sandstone as a reservoir unit.
Finally, the workflow proposed in this thesis for the studying of the Precipice Sandstone in Cracow area can be used in further investigations across the 300 km

long sandstone belt, enhancing the knowledge of the sandy braided river which was flowing along the northern boarder of the Surat Basin, Queensland.

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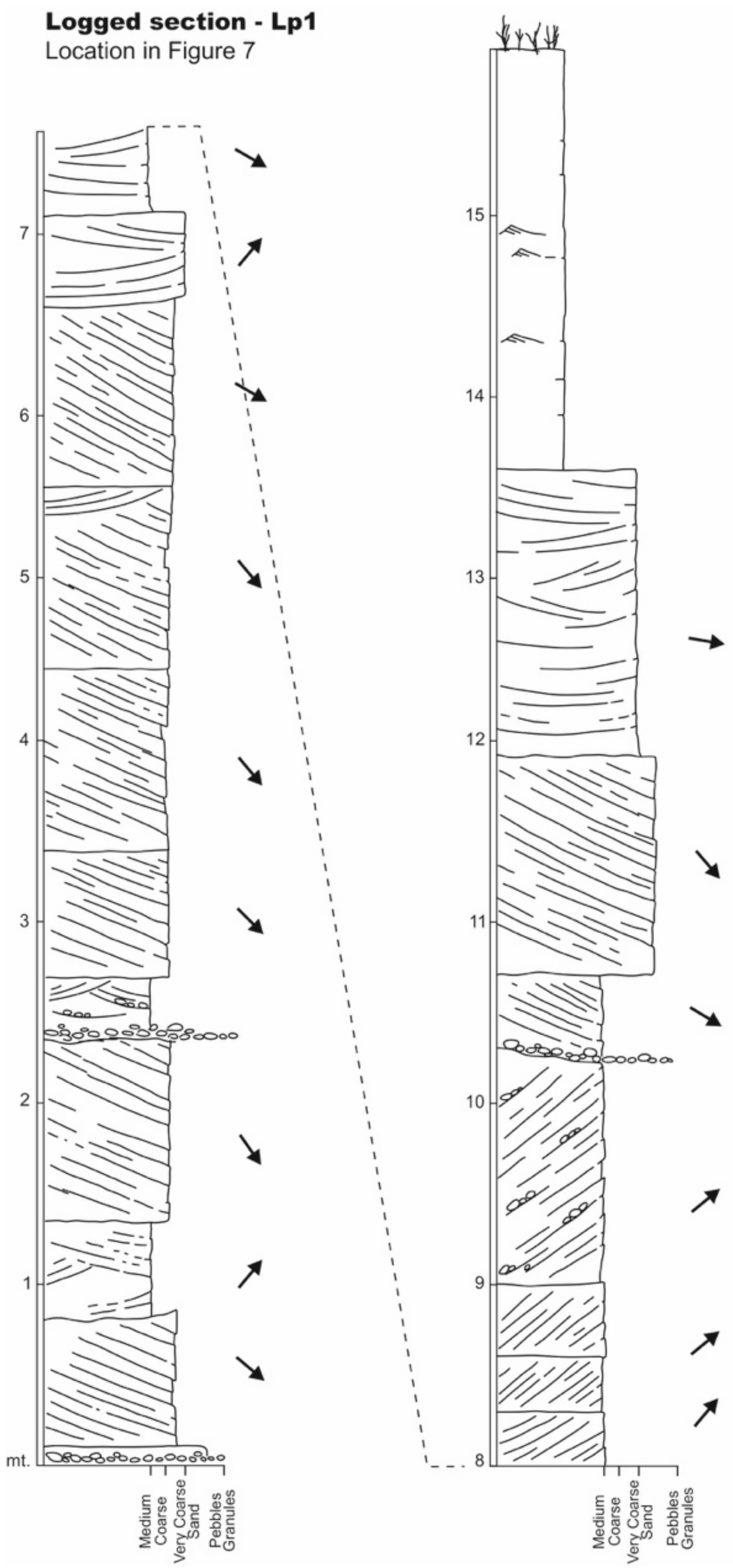
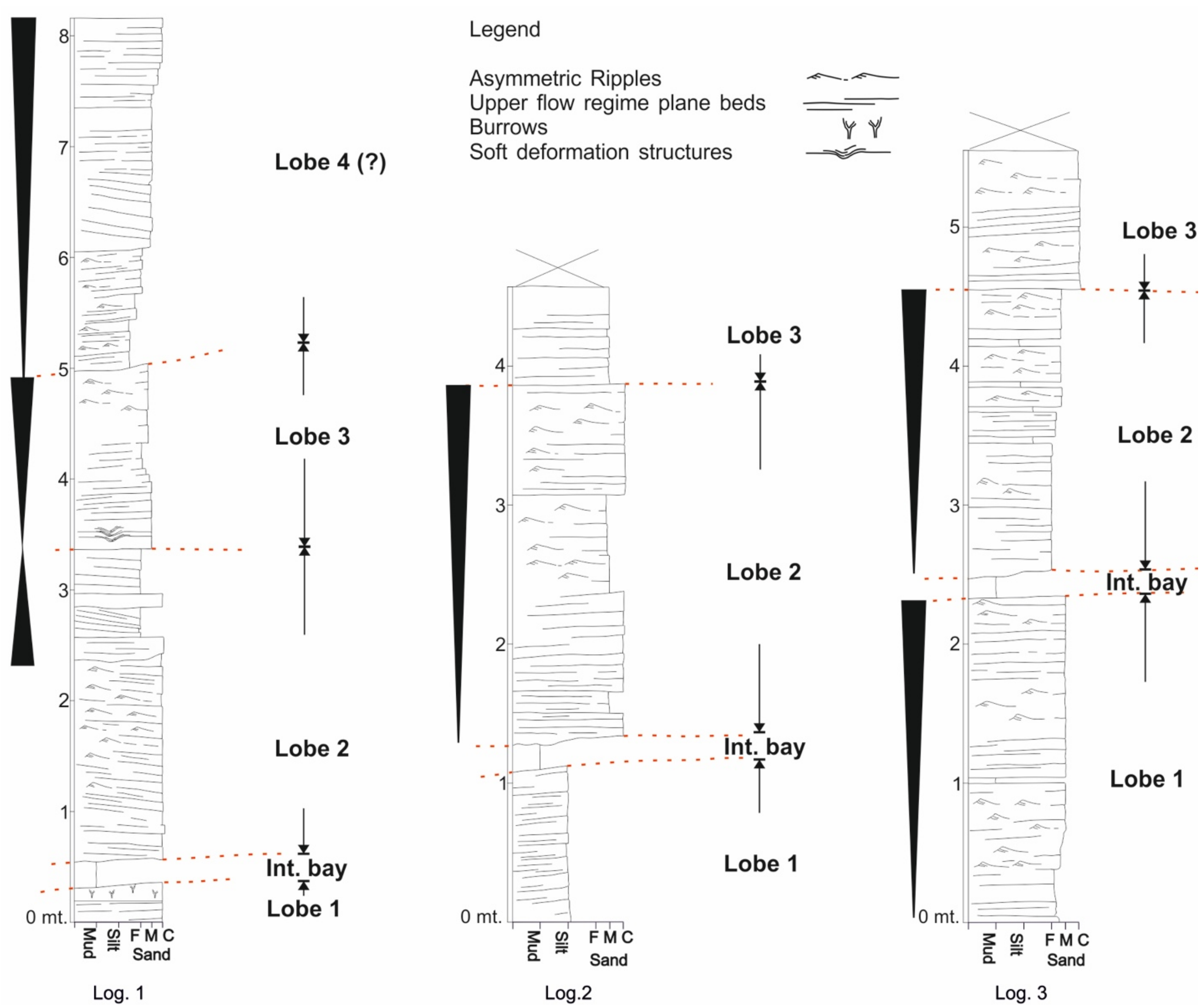
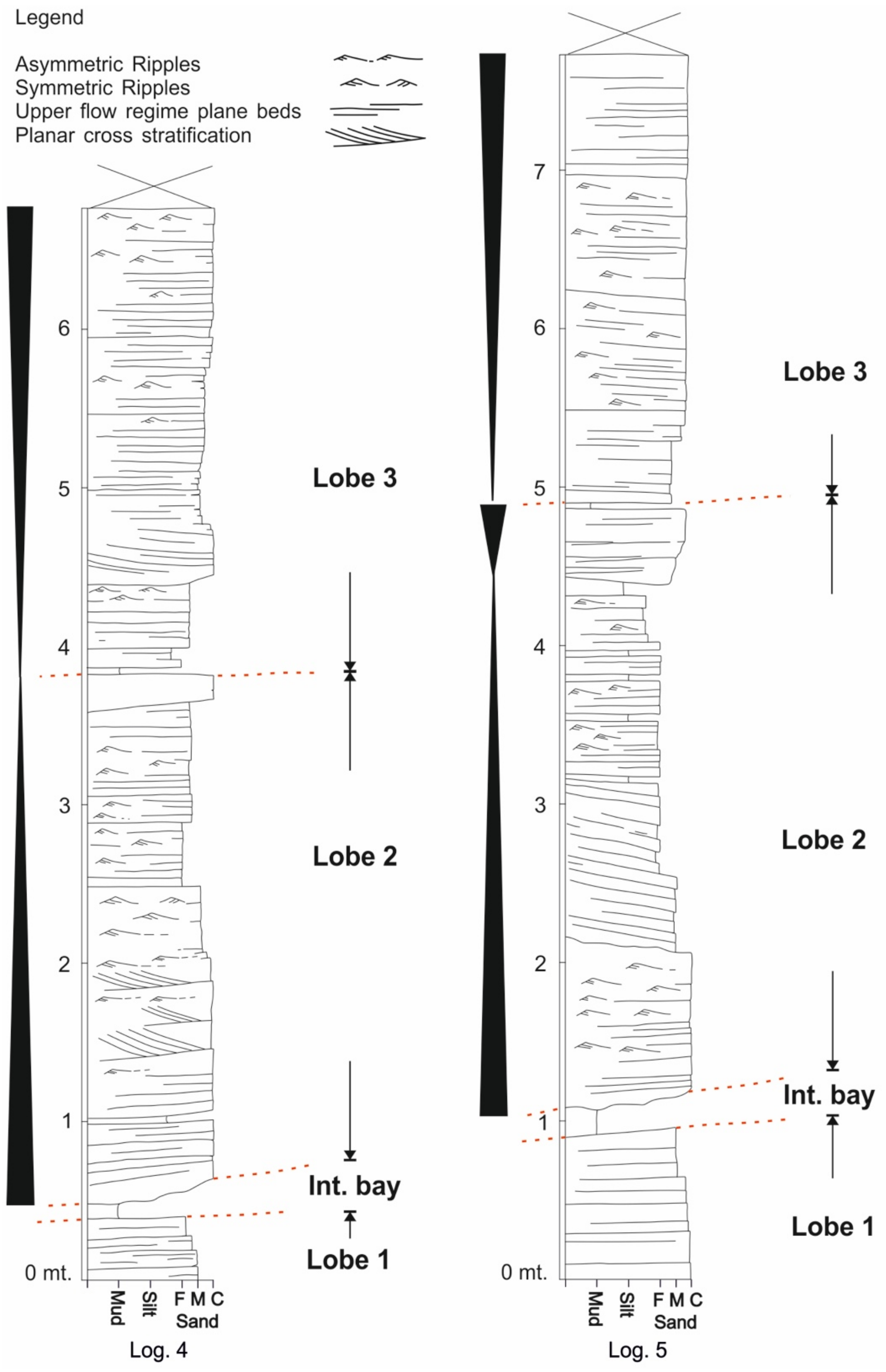
APPENDIX

LOGGED SECTION – LOWER PRECIPICE 1

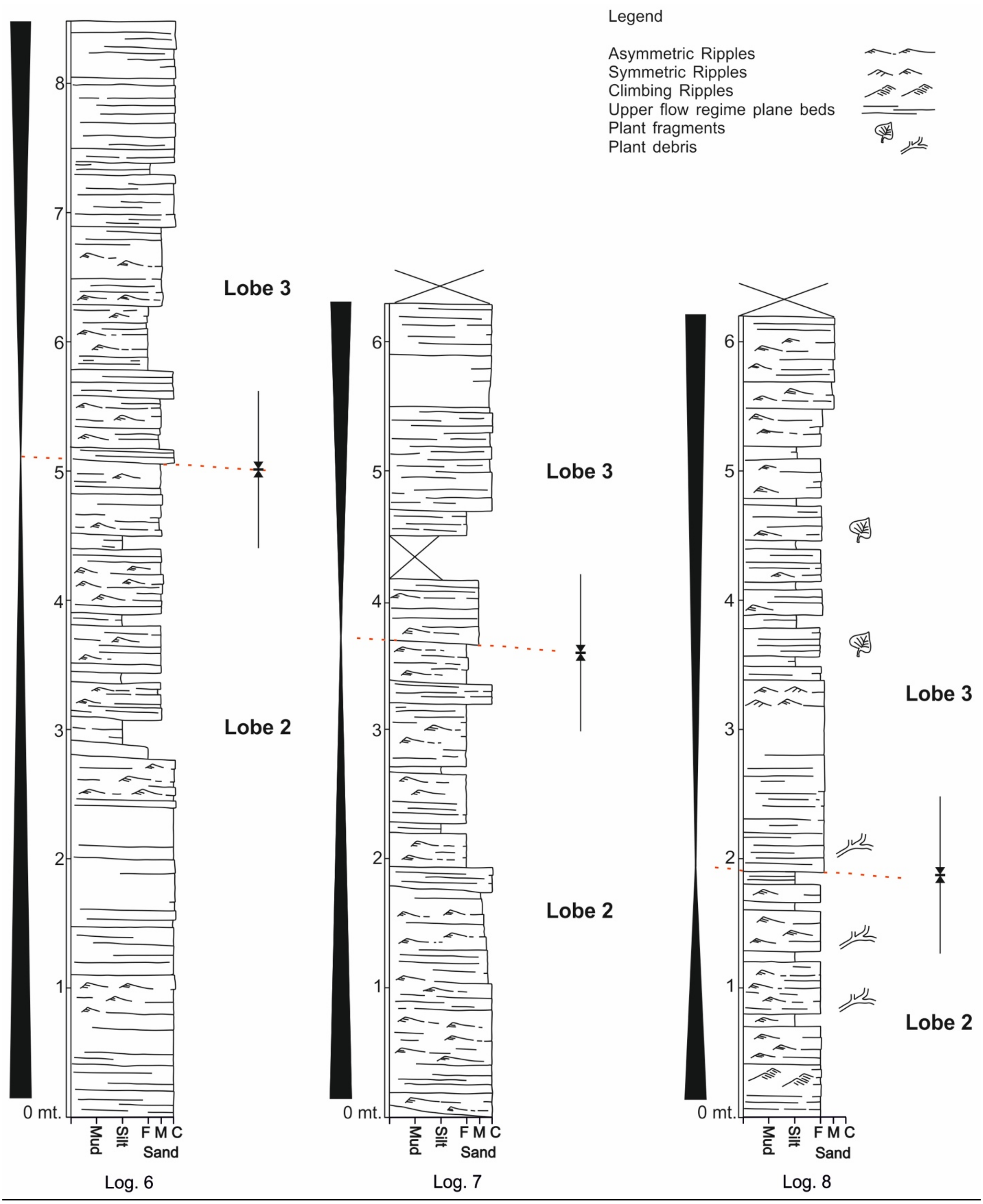


LOGGED SECTION – UPPER PRECIPICE 1, 2 AND 3



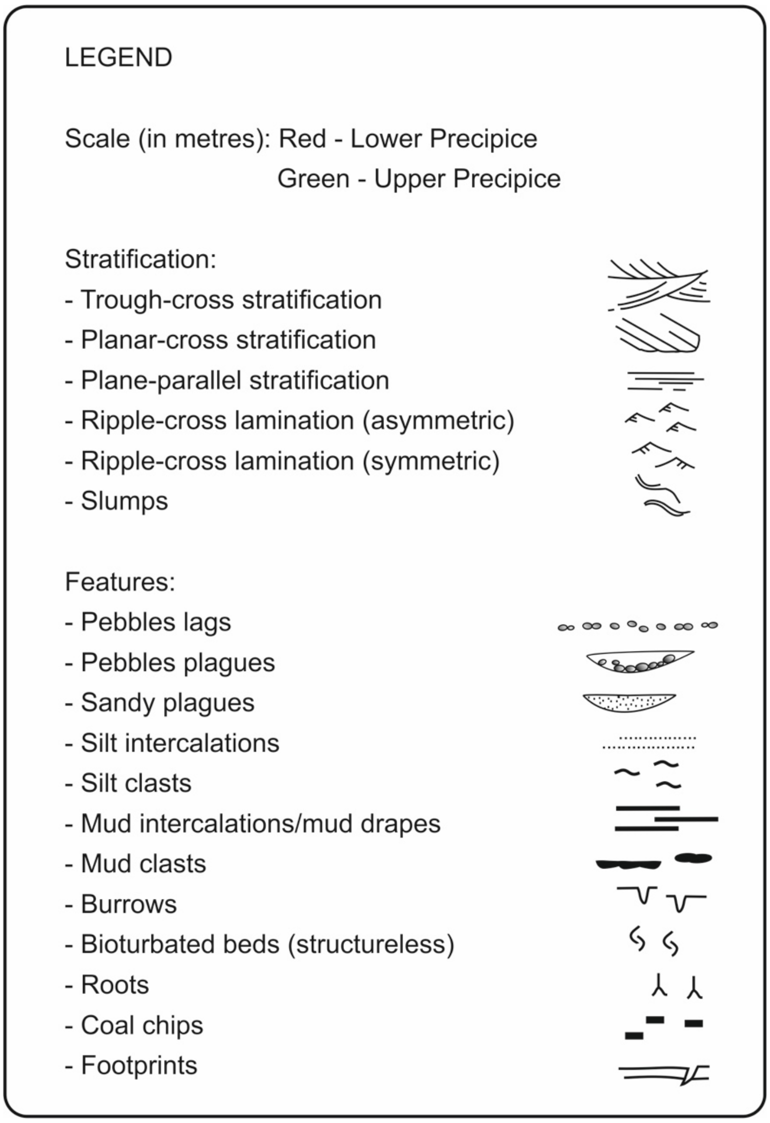


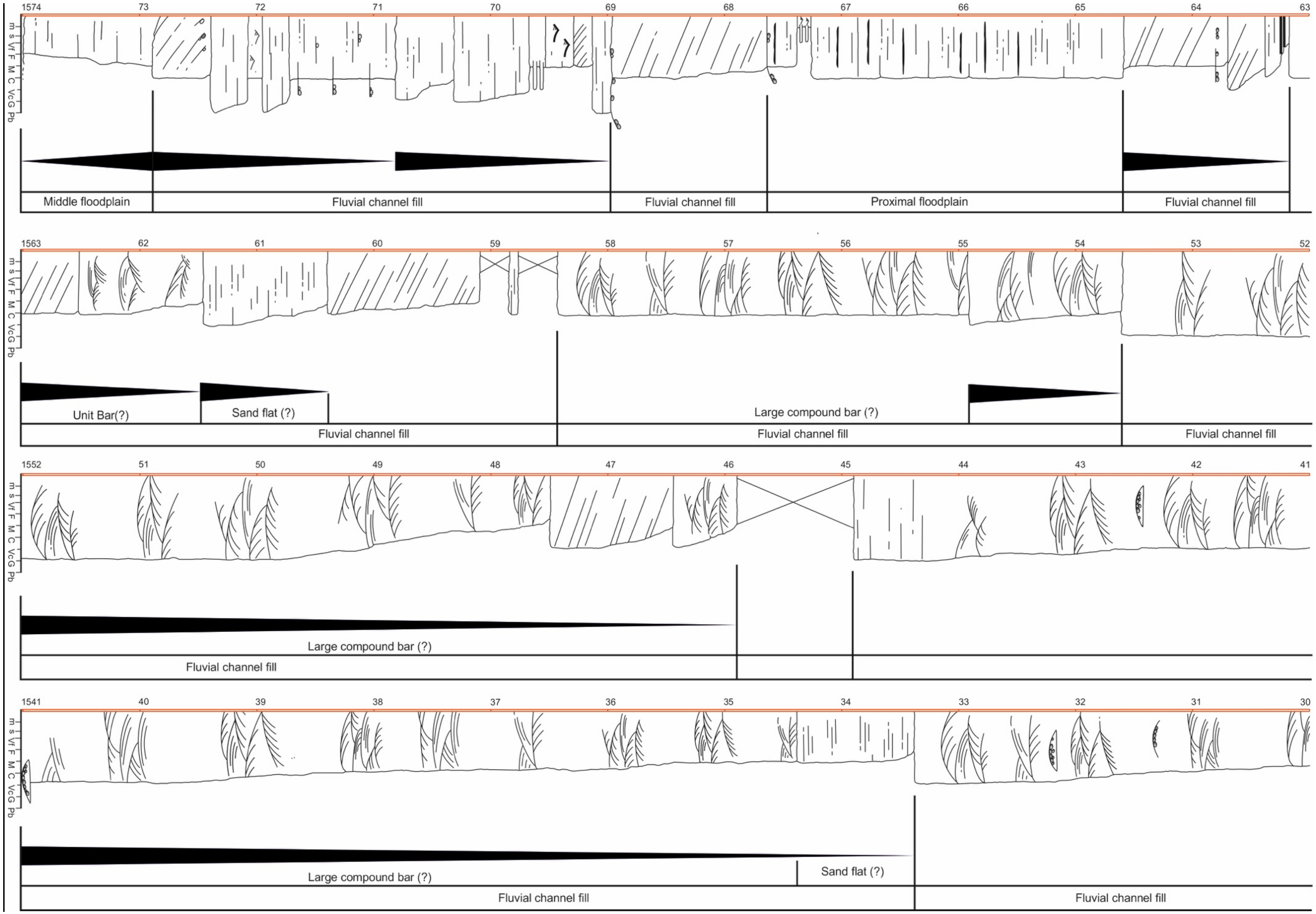
Legend
Asymmetric Ripples
Symmetric Ripples
Upper flow regime plane beds
Planar cross stratification
Lobe 3
Lobe 2
Int. bay
Lobe 1
0 mt.
1
2
3
4
5
6
7
Mud
Silt
F M C
Sand
Log. 4
Log. 5



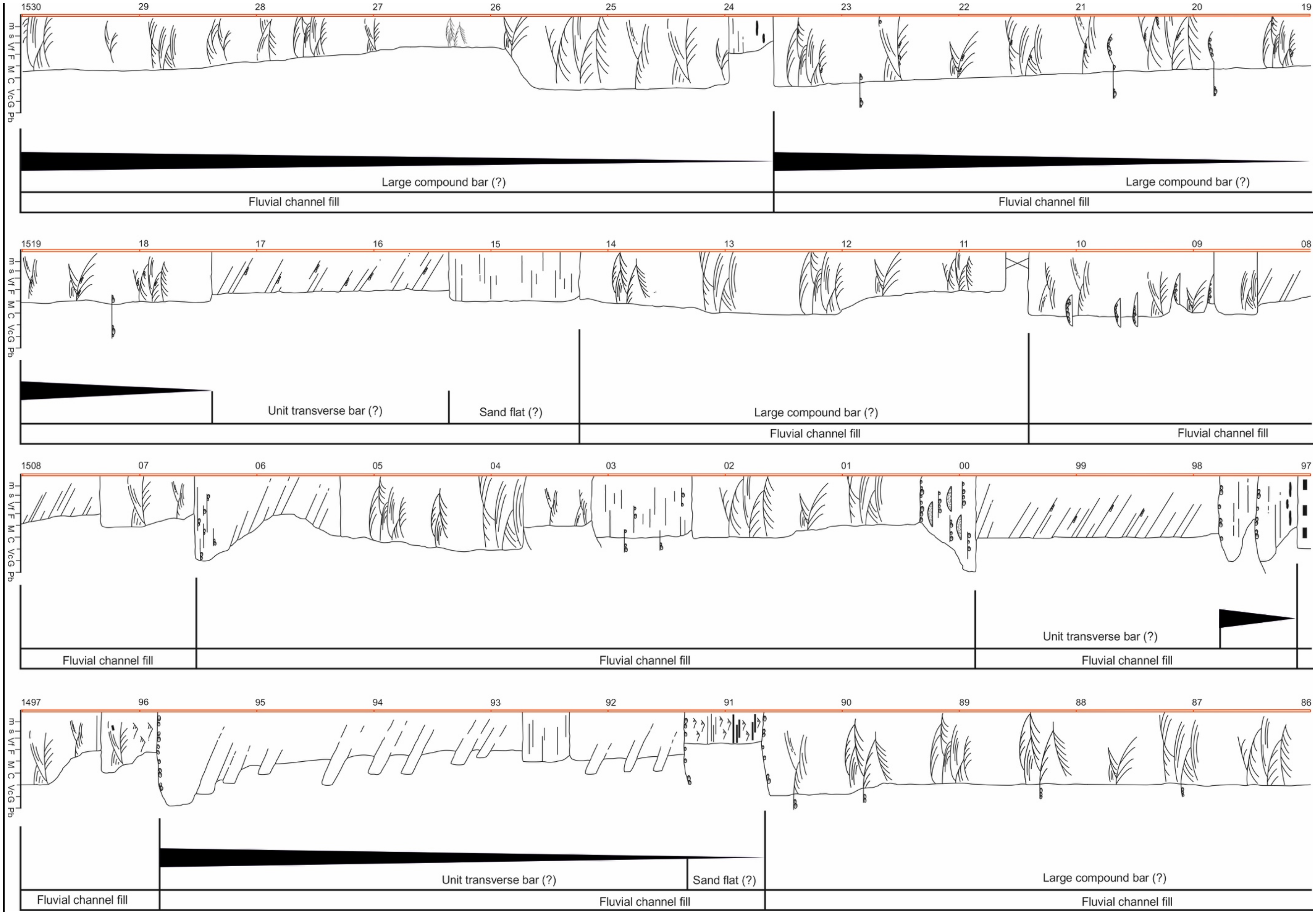
Legend
Asymmetric Ripples
Symmetric Ripples
Climbing Ripples
Upper flow regime plane beds
Plant fragments
Plant debris
Lobe 3
Lobe 2
0 mt.
Mud
Silt
F M C
Sand
Log. 6
Log. 7
Log. 8

WOLEEBEE CREEK GW4 – CORE LOGGING STUDY

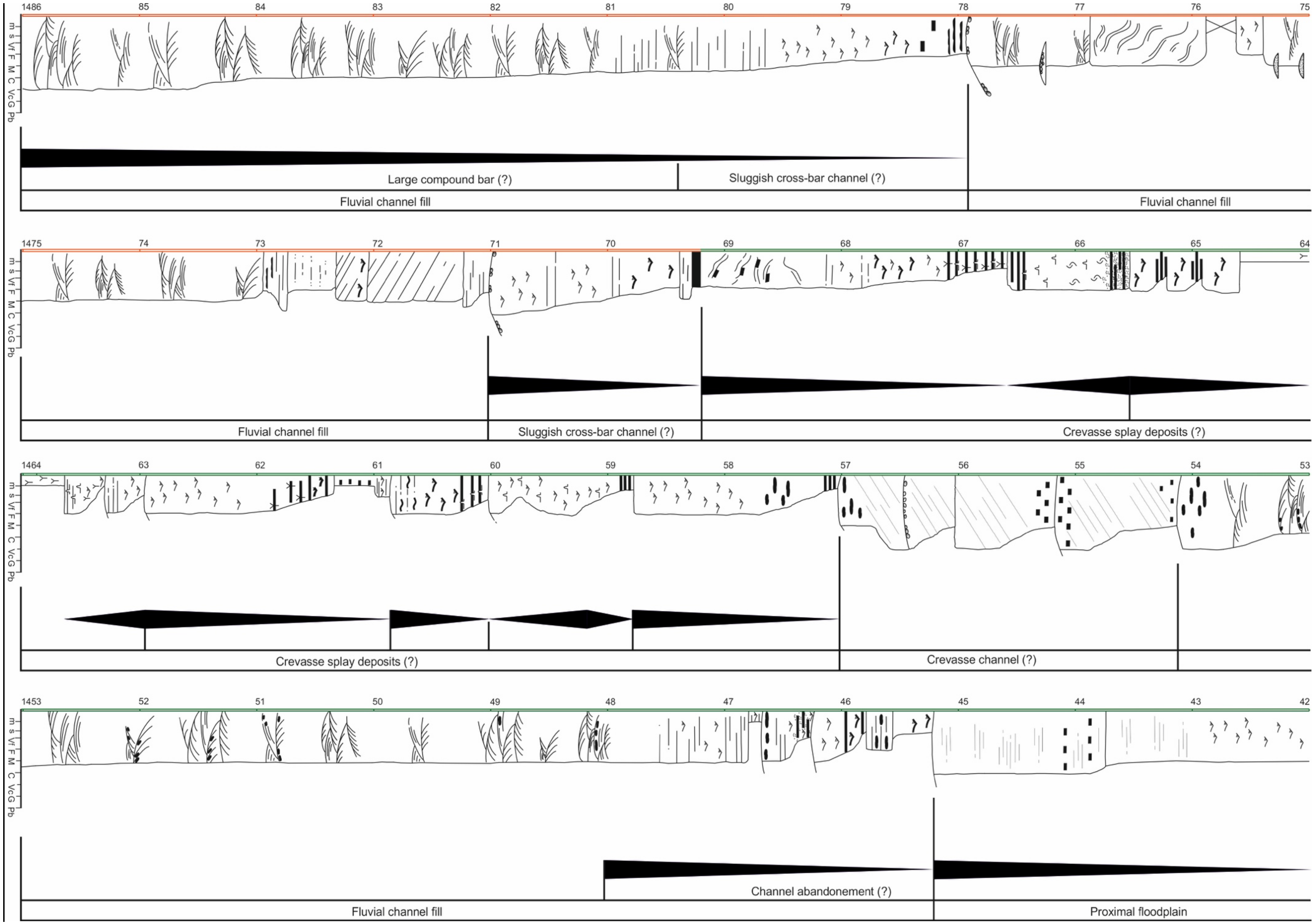


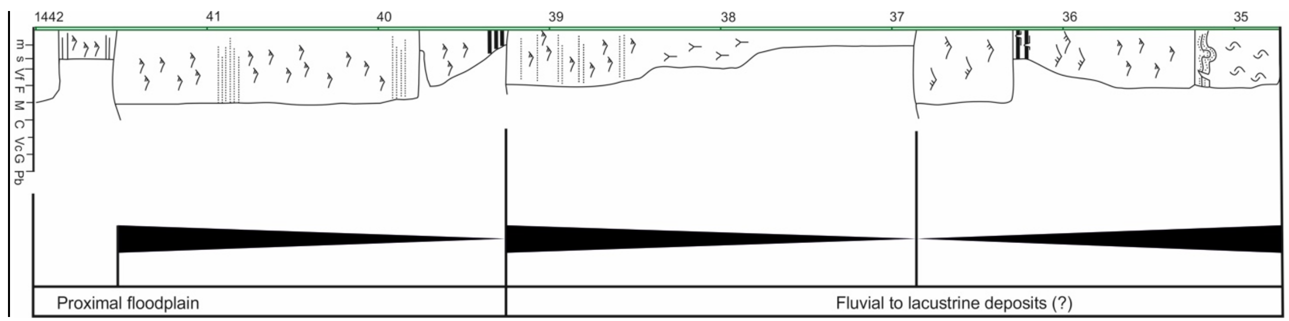


1574
73
72
71
70
69
68
67
66
65
64
63
m s Vf F M C VcG Pb
Middle floodplain
Fluvial channel fill
Fluvial channel fill
Proximal floodplain
Fluvial channel fill
1563
62
61
60
59
58
57
56
55
54
53
52
Unit Bar(?)
Sand flat (?)
Large compound bar (?)
Fluvial channel fill
Fluvial channel fill
Fluvial channel fill
1552
51
50
49
48
47
46
45
44
43
42
41
Large compound bar (?)
Fluvial channel fill
1541
40
39
38
37
36
35
34
33
32
31
30
Large compound bar (?)
Sand flat (?)
Fluvial channel fill
Fluvial channel fill



1530 29 28 27 26 25 24 23 22 21 20 19
m s Vf F M C VcG Pb
Large compound bar (?)
Fluvial channel fill
Large compound bar (?)
Fluvial channel fill
1519 18 17 16 15 14 13 12 11 10 09 08
m s Vf F M C VcG Pb
Unit transverse bar (?)
Sand flat (?)
Large compound bar (?)
Fluvial channel fill
Fluvial channel fill
1508 07 06 05 04 03 02 01 00 99 98 97
m s Vf F M C VcG Pb
Fluvial channel fill
Fluvial channel fill
Unit transverse bar (?)
Fluvial channel fill
1497 96 95 94 93 92 91 90 89 88 87 86
m s Vf F M C VcG Pb
Fluvial channel fill
Unit transverse bar (?)
Sand flat (?)
Fluvial channel fill
Large compound bar (?)
Fluvial channel fill


1486
85
84
83
82
81
80
79
78
77
76
75
m s Vf F M C VcG Pb
Large compound bar (?)
Sluggish cross-bar channel (?)
Fluvial channel fill
Fluvial channel fill
1475
74
73
72
71
70
69
68
67
66
65
64
m s Vf F M C VcG Pb
Fluvial channel fill
Sluggish cross-bar channel (?)
Crevasse splay deposits (?)
1464
63
62
61
60
59
58
57
56
55
54
53
m s Vf F M C VcG Pb
Crevasse splay deposits (?)
Crevasse channel (?)
1453
52
51
50
49
48
47
46
45
44
43
42
m s Vf F M C VcG Pb
Channel abandonement (?)
Fluvial channel fill
Proximal floodplain



1442
41
40
39
38
37
36
35
m s Vf F M C VcG Pb
Proximal floodplain
Fluvial to lacustrine deposits (?)

WELL COMPLETION REPORT - WEST WANDOAN 1

Geology.

REWAN FORMATION – Moolayember Unit (Triassic)

Base: uncored Top: 1237m
Thickness: 13m

1249 – 1240m
Predominantly SANDSTONE

SANDSTONE (~100%): White to pale grey , fine to medium occasional coarse, sub-angular to sub-rounded, moderate sorted, minor to common silty/carbonaceous laminae, moderate clay matrix, silica cement, friable to moderately hard, fair to good porosity.

SUMMARY INTERPRETATION: Channel fill to Proximal Floodplain deposits

1240 – 1237m
Predominantly SILSTONE with SHALE, minor SANDSTONE

SILTSTONE (~90%): Interlaminated / interbedded moderate to dark grey carbonaceous siltstone/shale and pale grey very fine silty SANDSTONE (~10%). Minor carbonaceous root casts.

PRECIPICE SANDSTONE (Jurassic)

Base: 1237 Top: 1162
Thickness: 75m

1236 – 1209m
Predominantly SANDSTONE

SANDSTONE (~100%): pale grey, predominantly coarse to very coarse, sub-angular to sub-rounded, poor to moderate sorted, cross bedded, minor lithic/quartzite grains, minor clay matrix, weak silica cement, friable, good porosity.

SUMMARY INTERPRETATION: Channel fill to Proximal Floodplain deposits

1209 – 1207M
Predominantly SILTSTONE with SANDSTONE

SILTSTONE (~60%): Interlaminated/interbedded SANDSTONE (40%), light grey, fine to medium, sub-angular to sub-rounded, moderate sorted, common carbonaceous laminae, minor clay matrix, weak silica cement, friable to moderately hard, fair to good porosity and SILTSTONE/SHALE, moderate to dark grey to black, hard, carbonaceous.
1209 – 1162m

Predominantly SANDSTONE

SANDSTONE (~100%): pale grey, fine to predominantly coarse to very coarse, granular and conglomeratic in part with minor pebbles to 6cm, sub-angular to sub-rounded, poor to moderate sorted, cross bedded, minor lithic / quartzite grains, minor clay matrix, weak silica cement, friable, good to very good porosity. Carbonaceous SHALE and SILTSTONE bands.

SUMMARY INTERPRETATION: Channel fill to Proximal Floodplain deposits

<u>EVERGREEN FORMATION </u>(Jurassic)

Base: 1162 Top: uncored
Thickness: 16m

1162 – 1146m
Predominantly SANDSTONE with SILTSTONE

SANDSTONE (~70%): white to light grey, very fine to fine, occasional medium, angular to sub-rounded, moderate sorted, feldspathic, minor lithics, occasional silty carbonaceous laminae, moderate clay matrix, moderately hard, very poor porosity.
SILTSTONE (~40%): Interlaminated/interbedded SILTSTONE/SHALE, light to dark grey, carbonaceous, moderately hard to hard, minor laminae /interbeds of white to pale grey, very fine silty SANDSTONE.

SUMMARY INTERPRETATION: Medial Floodplain – stacked splays, Proximal Floodplain – Levee, Medial Floodplain and Proximal Floodplain