Fluvial-Aeolian Interactions within Arid Continental Basins: Implications for Reservoir Characterisation and Basin Modelling*

Charlotte Priddy[1], Stuart Clarke[1], Phil Richards[1], and Tom Randles[2]

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[1]Basin Dynamics Research Group, Keele University, Staffordshire, United Kingdom (c.priddy@keele.ac.uk)
[2]British Geological Survey, The Lyell Centre, Edinburgh, United Kingdom

Abstract

Arid continental basins commonly comprise sedimentary fill from fluvial and aeolian environments, and while the preserved facies associations within each environment have been studied in great depth, the relationships between coeval depositional environments have received little attention. The temporal and spatial distributions of these environments can greatly affect reservoir quality and basin-scale migration.

We present results from interactions of fluvial and aeolian deposits of the Kayenta Formation across the Colorado Plateau, USA, from proximal to distal settings, along with insights into the allocyclic controls upon them. These studies are based upon extensive regional fieldwork to examine the sedimentology, utilising 3D photogrammetry techniques to examine geometries and interactions, as well as comparing and contrasting field data to a small core study on the Leman Sandstone reservoir in the Southern North Sea, UK.

The Kayenta Formation comprises fluvial-aeolian associations of varying reservoir quality. Relationships between them are spatially predictable, governed by one system's dominance. A dominant aeolian system limits fluvial sediments to interdune corridors and controls localised sediment supply, resulting in flash flood and debris facies of moderate reservoir quality, comprising reworked sediments of aeolian calibre and texture. Dominance of the fluvial system restricts aeolian bedforms and preserves extensive ephemeral fluvial sediments of poor reservoir quality, with fluvial textures dominated by intraformational and extraformational sediment. The temporal evolution between systems preserves unique facies, but a switch in dominant system takes place quickly, severely limiting the vertical extent of interactions and potentially isolating reservoir intervals of basin fill.

Field data coupled with 3D photogrammetric models allow reconstruction of these ancient channel forms and dune fields, providing useful information for quantifiable reservoir models. This can help better characterise basin-scale migration and reservoir quality within the basin fill. We apply our model to the Lower Permian Leman Sandstone, a principal gas reservoir in the Southern North Sea Basin, adding increased complexity to further enhance recovery.

Introduction

Continental deposits of ephemeral fluvial and aeolian sandstones constitute the main reservoirs in many oil and gas fields. Understanding the interactions between these environments is vital in reservoir characterisation and determining fluid migration. This work examines the exceptional exposure of three-dimensional outcrops from the Lower Jurassic Kayenta Formation within the Colorado Plateau, western USA, to determine the proximal to distal, temporal and spatial distributions and interactions within these environments.

Models derived from these data will be used as analogues for two-dimensional core data from the Leman Sandstone, Southern North Sea. The Leman Sandstone comprises lower Permian fluvial and aeolian sediments deposited within the western margin of the Anglo-Dutch Basin. As the deposits of the Leman Sandstone are only exposed in two-dimensional core, analogue derived data from the Kayenta, such as facies, geometries and thickness to width ratios, have aided in the interpretation of the Leman.

Geological Setting

The Colorado Plateau (Figure 1) is a large, high-standing block, approximately two-thousand metres above sea level, which spans approximately one-hundred and forty-thousand square miles across southeastern Utah, northeastern Arizona, southwestern Colorado and northwestern New Mexico (Gilfillan et al., 2008). The Glen Canyon Group of the Plateau comprises four formations of late Triassic to early Jurassic age - the Moenave, Wingate, Kayenta and Navajo formations - with a range of depositional environments from aeolian to fluvial, which intertongue numerous times throughout the Group and indicate continuous deposition (Middleton and Blakey, 1983) (Figure 2). The Group is bound by the basal J-0 unconformity, and capped by either the J-1 unconformity in the west or J-2 unconformity in the east. The J-1 and J-2 unconformities truncate each other at low angles in central Utah (Pipiringos and O'Sullivan, 1978; Blakey, 2008). During the time of deposition of the Glen Canyon Group, two basins developed; the Zuni Sag and the Utah-Idaho Trough (Figure 1), which marked a transition from older tectonic trends to deposition in a foreland basin. Consequently, the rocks of the Glen Canyon Group thicken abruptly westward into the Utah-Idaho Trough, where they are truncated by sub-Cretaceous or sub-Tertiary unconformities (Blakey, 2008).

The late Sinemurian to early Toarcian Kayenta Formation comprises a continental redbed assemblage of fine- to coarse-grained sandstone, siltstone and occasional intraformational conglomerates (Harshbarger et al., 1957; Peterson and Pipiringos, 1979; Luttrell, 1993), deposited in a dominantly ephemeral fluvial system, with minor perennial influxes and aeolian interactions. Deposition occurred on a broad alluvial plain, by southwestward to westward flowing rivers, sourced from the Uncompahgre Uplift in the Ancestral Rocky Mountains (North and Taylor, 1996), and northwestward flowing rivers sourced from the Mogollon Highlands in the Cordilleran Magmatic Arc (Luttrell, 1993) (Figure 1).

Two distinct lithofacies can be recognised within the Kayenta Formation, the ‘sandy’ and ‘silty’ facies, each resulting from the lateral variation of the fluvial system across the Colorado Plateau (Harshbarger et al., 1957) (Figure 1). In southeastern Utah and western Colorado, the Kayenta is characterised by grey to reddish orange, fine- to coarse-grained, well-sorted, well- to sub-rounded sandstone, with minor reddish purple siltstones and matrix-supported conglomerates (Wilson, 1958). In northwestern Arizona, the Kayenta is characterised by reddish purple siltstone, mudstone and minor sandstones. The transition from predominately sandy sediments in southeastern Utah to predominately silty sediments in northwestern Arizona is a gradual progressive change across several miles in the Vermilion Cliffs (Wilson, 1958).

Sedimentology of the Kayenta Formation

The Kayenta Formation is well exposed across southeastern and southern Utah, northern Arizona and southwestern Colorado. Data have been collected from eighteen localities in the proximal and medial settings of the basin (‘sandy’ facies), and one locality with the distal setting (‘silty facies’) (Figure 1). Nine elements have been identified (Figure 3): aeolian dune (AD), sandsheet (SS), interdune (AI), fluvial channel (FC), sheetflood (SF), lateral accretion (LA), downstream accretion (DA), bank collapse (BC) and overbank (OB).

Sheetflood elements dominate the formation especially in the upper and lower thirds, whereas fluvial channels are more dominant in the middle third, often incising into elements of the same type or sheetflood deposits, showing an increase in vertical and lateral channel amalgamation. Lateral and downstream accretion elements form minor parts of the fluvial system, but are also more abundant within the middle third. Aeolian elements (AD, SS, AI) are more prevalent within the upper third of the Kayenta where the formation starts to intertongue with the overlying Navajo. The rarest features within the Kayenta are the bank collapse and overbank elements. The bank collapse element has only been identified in two localities in the proximal setting, in and around Moab, Utah and preserves some unique sedimentology. Deposition of this element could be related possibly to salt movement within the Paradox Basin. Overbank elements constitute a minor part of the Kayenta, however this is due to abundant reworking and poor preservation of a probably extensive floodplain, rather than evidence of small or limited floodplain development (North and Taylor, 1996), as siltstone rip up clasts are abundant throughout the formation.

Interactions

This work has identified complex interactions between ephemeral fluvial and aeolian environments throughout the whole expanse of the Kayenta Formation and at a variety of scales, from small-scale reworking of aeolian sediment into the fluvial system, to large-scale intertonguing of the aeolian Navajo Sandstone within the top third of the Kayenta. These interactions can greatly influence reservoir characterisation at bed scale, element scale and system scale.

Bed-scale interactions include the reworking of aeolian sediment into the fluvial system. The majority of the ‘sandy’ fluvial facies are composed of aeolian calibre sediment, which has been blown off deflating dune fields, and transported by the fluvial system, therefore improving the reservoir quality potential. The fluvial sediment can also be seen being reworked into the aeolian system as the rivers dry out during more arid times. Evidence of this recycling and reworking can be seen in thin sections of sandy channels of the Kayenta.

Element-scale interactions include the rapid switch in dominant environment producing very limited vertical (temporal) extents of interactions. During more arid times, aeolian environments dominate, restricting the fluvial systems to interdunal corridors, controlling localised sediment supply, resulting in flash-flood and debris facies, comprising sediments of aeolian calibre and texture. The aeolian system shuts down rapidly during slightly more humid times allowing the fluvial system to dominate and preserve extensive ephemeral fluvial sediments, with fluvial textures dominated by intraformational and extraformational sediment.
System-scale interactions include the large-scale intertonguing with the Navajo Sandstone, especially prominent in the ‘silty facies’ of the Kayenta in the southwestern region of Utah from St George to Kanab, where these tongues reach up to one-hundred metres thick and can be

individually mapped (Middleton and Blakey, 1983). Smaller scale intertonguing of the magnitude of tens of metres can also be identified across most of the formation, even within the more ‘sandy facies’.

Depositional Model and Discussion

Geobody identification from detailed photogrammetric models of the proximal setting within the Kayenta Formation has been used to investigate the interactions and geometries of architectural elements within the system. Thickness to width ratios were collected and used to create a semi-quantifiable facies model (Figure 4). The model is dominated by sheetflood and channel elements, with thickness to width ratios of 1:100 and 1:50 respectively. Sheetflood deposits and smaller channels are more abundant in the lower half of the Kayenta, often eroding into the underlying Wingate, whereas in the upper half the Kayenta, larger stacked channels are more abundant as well lateral and downstream accretion elements. Isolated tongues of aeolian facies also become more prevalent in the upper half of the Kayenta suggesting there was a gradual transition into the overlying aeolian Navajo, as fluvial deposits become restricted to interdune corridors, as the more arid climate dominates.

Understanding the interactions between fluvial and aeolian environments, at multiple scales, are vital in reservoir characterisation and determining fluid migration. On a bed scale, reworking of aeolian calibre sediment into the fluvial system will increase the reservoir quality as the grains are well sorted and well rounded, increasing the porosity and permeability. Understanding the element scale interactions can help identify the three-dimensional geometry of baffles and barriers to flow as well as the internal heterogeneity of the reservoir. System scale interactions such as large-scale intertonguing can add increased complexity to production, as the aeolian tongues can often act as thief zones within mixed continental reservoirs.

Conclusions and Future Work

The relationships between the fluvial-aeolian sediments of the Kayenta Formation are spatially predictable, and are governed by one system's dominance. A dominant aeolian system limits fluvial sediments to interdune corridors whereas a dominance of the fluvial system restricts aeolian bedforms and preserves extensive ephemeral fluvial sediments. A switch in the dominant system takes place quickly and severely limits the vertical extent of interactions.

Future work includes a further field season to study the distal interactions within the Kayenta Formation, to establish their extent and relationships with the medial and proximal facies, along with recognition of climatic cycles. Further quantifiable reservoir models will be produced from the reconstruction of bedforms using measurements off photogrammetric models.

A provenance study of the fluvial units will be conducted to identify the source(s) of the Kayenta streams, which is currently a source of contention in the literature, with palaeocurrent analysis suggesting a multiple sourced system from the Ancestral Rocky Mountains and Cordilleran Magmatic arc (Harshbarger et al., 1957; Middleton and Blakey, 1983), and zircon dating suggesting a single source from the East Mexico arc (Dickinson and Gehrels, 2009). Identification of the provenance along with palaeocurrent may help characterise the sediment supply and help with understanding some of the high sediment load features seen within the formation.

Following the extensive outcrop analogue study of the Kayenta Formation, a detailed sedimentological study of the Leman Sandstone of the Southern North Sea will be conducted. Facies, facies associations and interactions will be identified from several cores containing fluvial-aeolian interactions. The photogrammetry and statistical analysis of the geobodies from the outcrop study will aid in the three-dimensional reconstruction of a two-dimensional data set, providing valuable information for subsurface application for enhanced reservoir characterisation in complex mixed aeolian-fluvial systems.

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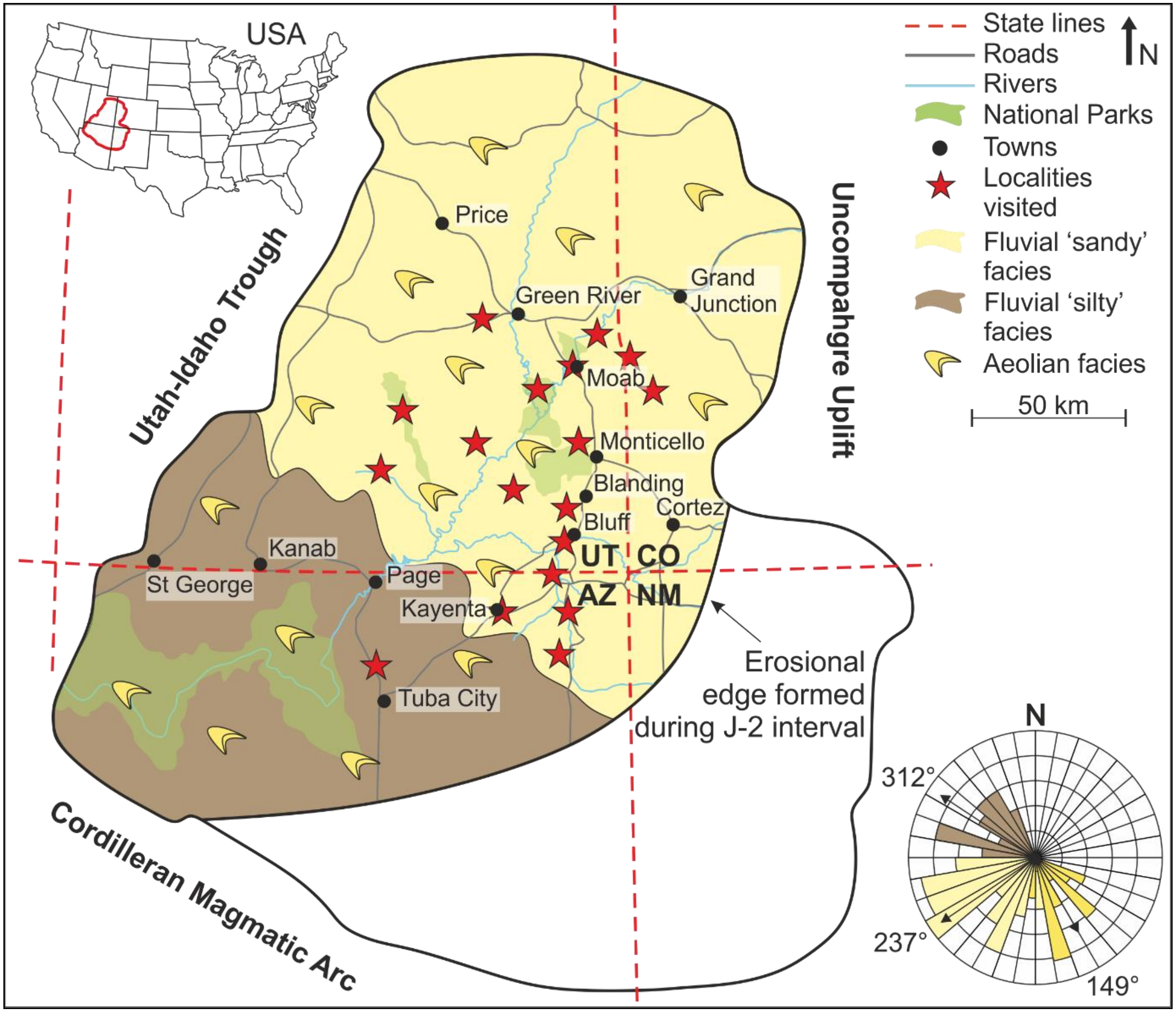

Figure 1. The Colorado Plateau located across the Four Corners states, showing the modern day San Juan, Green and Colorado Rivers and palaeogeography of the Lower Jurassic fluvial-aeolian deposits. The Kayenta fluvial systems deposited sediment across the Colorado Plateau sourced from the Ancestral Rocky Mountains (Uncompahgre Uplift) to the Northeast and the Cordilleran Magmatic Arc to the southwest. The rose diagram depicts palaeocurrent measurements from the 'silty' (brown) and 'sandy' (light yellow) fluvial system and the aeolian system (yellow), as well as their arithmetic averages (modified after Harshbarger et al., 1957; Middleton and Blakey, 1983; Blakey 1994).

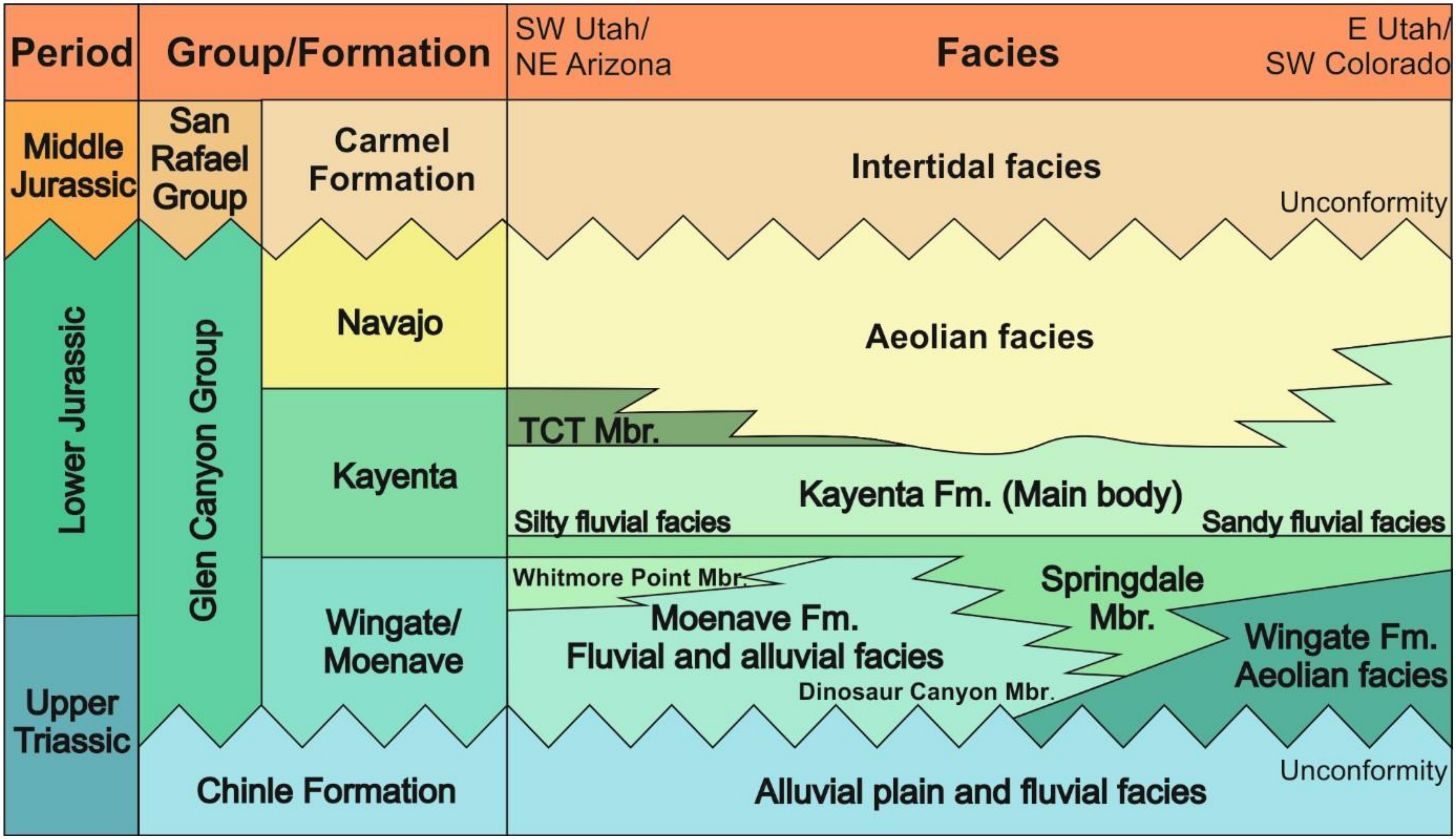

Figure 2. The lithostratigraphy of the Glen Canyon Group including members, facies and spatial distribution of sediments across the Colorado Plateau. The Kayenta Formation along with the underlying Wingate and overlying Navajo formations form the Upper Triassic to Lower Jurassic Glen Canyon Group (modified after North and Taylor 1996; Tanner and Lucas 2007).

Element	Code	Description
Aeolian Dune	AD	Tabular bodies with lateral extents up to 300m and vertical extents up to 150m, containing facies: planar crossbedded, trough crossbedded, parallel laminated and undulose laminated sandstones
Sandsheet	SS	Tabular bodies with lateral extents over 100's m and vertical extents up to 3m, containing facies: massive, parallel laminated and undulose laminated sandstones
Interdune	AI	Lensoidal or sheet-like bodies with lateral extents up to 20m and vertical extents up to 2m, containing facies: massive, parallel laminated and ripple laminated sandstones with parallel laminated siltstones
Fluvial Channel	FC	'U' shaped elements with lateral extents up to 115m and vertical extents up to 4m, with a thickness to width ratio of 1:50, containing facies: matrix and clast supported conglomerates, planar crossbedded, trough crossbedded, parallel laminated, recumbent bedded and massive sandstones
Sheetflood	SF	Tabular bodies with lateral extents of 250-400m and vertical extents up to 5m, with a thickness to width ratio of 1:100 and containing facies: rip up clast conglomerates with planar crossbedded, trough crossbedded, planar bedded, sigmoidal bedded, parallel laminated and ripple laminated sandstones
Lateral Accretion	LA	Lensoidal elements with lateral extents of 2-15m and vertical extents up to 3m, containing facies: trough crossbedded, low-angle crossbedded, recumbent bedded and ripple laminated sandstones
Downstream Accretion	DA	Lensoidal elements with lateral extents up to 30m and vertical extents up to 4m, containing facies: matrix-supported conglomerates with planar crossbedded, low-angle crossbedded, parallel laminated and ripple laminated sandstones
Bank Collapse	BC	Tabular bodies with lateral extents up to 20m and vertical extents up to 3m, containing facies: soft sediment deformed sandstones and parallel laminated siltstones
Overbank	OB	Tabular bodies that are rarely preserved with lateral extents up to 10m and vertical extents up to 4m, containing facies: parallel laminated sandstones and siltstones

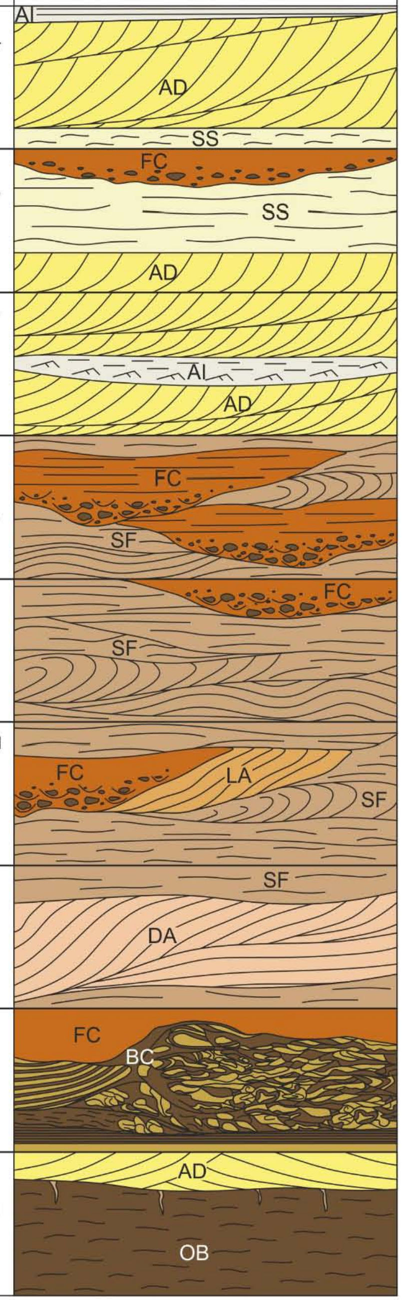

Figure 3. Architectural elements of fluvial and aeolian deposits of the Kayenta Formation with geometries, facies and interactions.

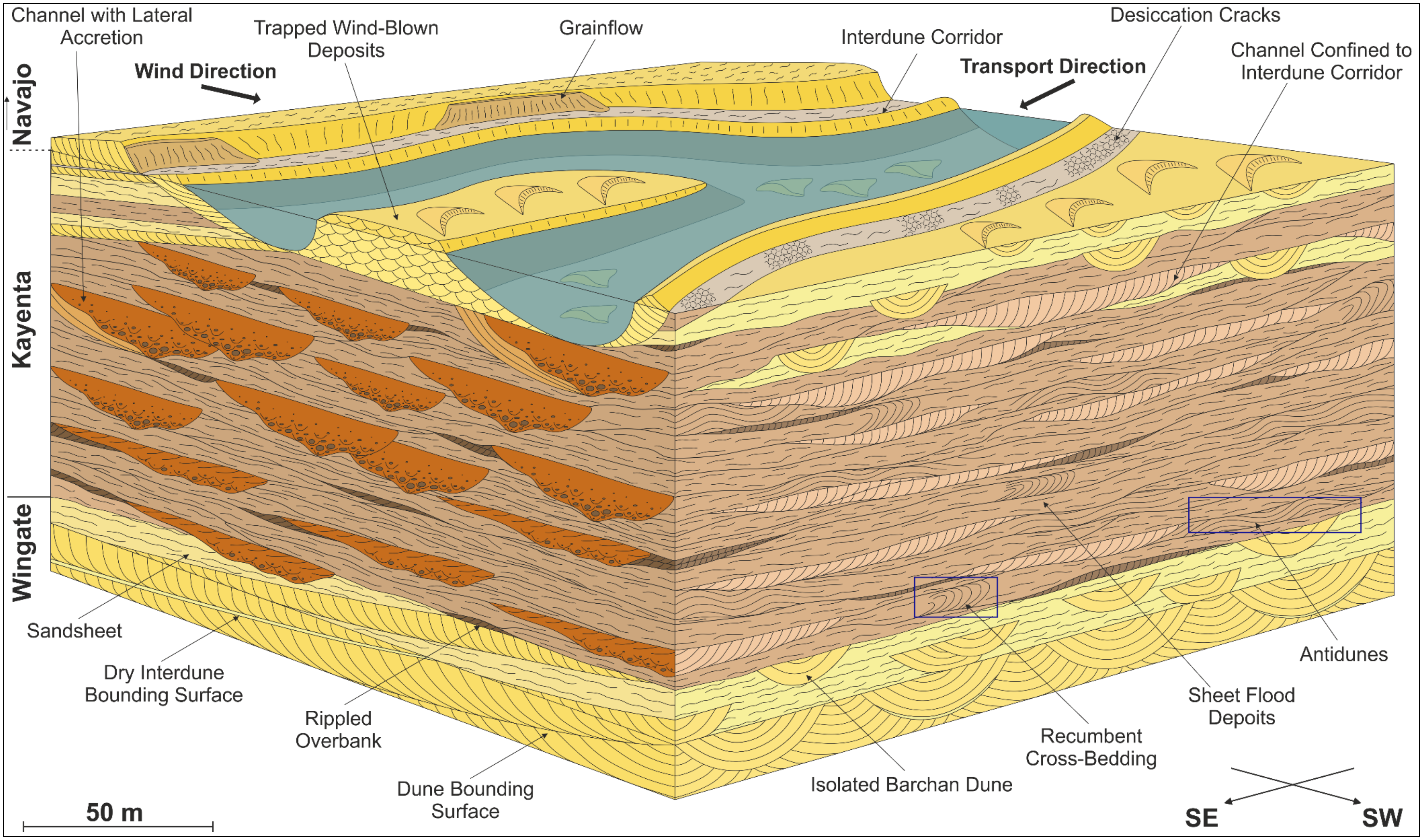

Figure 4. Semi-quantified facies model for proximal Kayenta, coloured by architectural elements, showing the erosional contact between the Wingate and Kayenta, then a dominance of the fluvial system restricting aeolian bedforms, drying upwards into a dominant aeolian system limiting the fluvial sediments to interdune corridors and controlling localised sediment supply.