Click to view poster presentation.

# Clastic/Evaporitic Interactions in Arid Continental Settings: Implications for Reservoir Characterization and Modelling*

**Ross Pettigrew[1], Stuart Clarke[1], Phil Richards[1], and Antoni Milodowski[2]**

Search and Discovery Article #51527 (2018)**
Posted October 15, 2018

*Adapted from extended abstract prepared for poster presentation, along with the posters, presented at 2018 AAPG Annual Convention & Exhibition, Salt Lake City, Utah, May 20-23, 2018.
 DOI:10.1306/51527Pettigrew2018

[1]Basin Dynamics Research Group, Keele University, Staffordshire, UK (r.p.pettigrew@keele.ac.uk)
[2]British Geological Survey, Keyworth, UK

## Abstract

In arid continental settings, the interactions between competing aeolian, fluvial, lacustrine, and evaporitic environments exert strong controls on the sediments deposited, their preservation, and lithofacies connectivity in the subsurface. They strongly influence basin-wide fluid migration, along with reservoir-scale character, petrophysical properties, and production behaviour. While the distribution and preservation of different facies associations within any one of these environments are reasonably well constrained, the relationships between deposits of coeval environments and their temporal evolution have received comparatively little attention despite their potential to affect both basin-scale fluid migration and reservoir quality.

We present results of sedimentary interactions between evaporitic deposits and those of other arid environments from the Paradox Basin, USA, along with the influence of physical versus chemical processes and analysis of the allocyclic-controls upon them. Studies are based upon extensive regional fieldwork examining the sedimentology, geometries, and interactions, complemented with petrographical analyses and outcrop gamma-ray logging.

The margin of the Cedar Mesa erg of the Paradox Basin preserves complex interactions of clastic and evaporitic sediments. The highly variable sedimentary fill shows large variations spatially and temporally which grade through aeolian, sabkha, and lacustrine settings with complex interactions occurring where these environments transition. Where present, the sabkha facies dominate, reworking aeolian dune sediment into poor reservoir quality evaporate-rich sands and blocking fluid pathways.

This work details the facies present in a continental sabkha allowing for identification and interpretation of these complex interbedded relationships over a regional scale. The results have been developed into idealised models and recognisable log signatures which characterise and assess their impact on reservoir quality. Wetting-or-drying-climatic cyclic trends, on various orders of magnitude, have also been identified, which govern distinct spatial facies changes. Identification of these allows for basin-wide correlation and prediction of where facies will occur in space and time.

Our results are applied to evolutionary models applicable to subsurface data from the arid Permian basins of the North Sea, in order to better characterise basin-scale migration and reservoir quality in terms of the evolving basin fill.

## Introduction

Distal arid continental deposits comprise the complex interactions of aeolian, fluvial, lacustrine, and sabkha environments. While the distribution and preservation of different facies associations within any one of these environments are reasonably well constrained, the relationships between deposits of coeval environments and their temporal evolution have received comparatively little attention. Understanding the processes behind the formation of these deposits and the controls upon them is vital in order to predict where these environments will occur preserved, their lithofacies connectivity in the subsurface, and for an understanding of the spatial and temporal interactions between them; these have a large influence on basin-scale fluid-migration and hydrocarbon potential. This work considers the distal Cedar Mesa Sandstone sediments of the Paradox Basin, western USA, as they provide unparalleled exposure of the interactions between the more proximal aeolian erg deposits that grade into continental sabkha and lacustrine deposits.

## Geological Setting

The Paradox Basin is a roughly oval shaped foreland flexural basin formed by the uplift of the Ancestral Rocky Mountains, and defined in lateral extent by the underlying evaporites of the Paradox Formation (Barbeau, 2003; Condon, 1997). The basin was initiated in the Pennsylvanian Period, and 4000 metres of basin fill were deposited between the Late Pennsylvanian and Mid-Permian periods with sediment sourced predominantly from the erosion of the Uncompahgre Plateau to the north-east (Loope, 1984).

The Lower Permian Cedar Mesa Sandstone is predominantly an aeolian succession exposed across much of the Colorado Plateau of southern Utah and northern Arizona. The aeolian deposits represent a Permian desert roughly the size of the modern day Sahara, northeast-southwest trending and bounded by a paleoshoreline to the northwest (Blakey, 1988; Blakey et al., 1988; Huntoon et al., 2000) (Figure 1). In the south-eastern corner of Utah the erg grades into continental sabkha deposits (Huntoon et al., 2000; Condon, 1997; Blakey, 1988), which are the main focus of this study

## Styles of Interaction

From detailed sedimentological studies, facies and facies associations have been derived that characterise four distinct end-member depositional environments: aeolian, fluvial, lacustrine, and sabkha (Figure 2). Within these depositional environments, interactions are seen at the bed (facies) scale and system scale.

Bed-scale interactions include dune interacting with damp or wet interdunes in the more proximal erg regions, and dune interacting with gypsum precipitation and with fluvial, lacustrine, and sabkha sediments towards the distal end of the basin (Figure 3).

System-scale interactions are governed primarily by the influence of water and evolve temporally due to either wetting or drying of the overall climate. A dominant aeolian succession shows predictable changes in response to wetting or drying, grading from wet interdunes surrounded by small isolated dunes during periods of humidity, into larger and more connected dunes, with smaller and dryer interdunes as the climate dries. The opposite trend is observed in a response to climatic wetting. When aeolian sediments interact with sabkha facies; this standard model becomes less applicable and deposits show much more variability.

Within the system-scale interactions the observed sedimentary successions show marked temporal changes. Deposits show a cyclic variation between water-derived or non-water-derived sediments that define wetting-upwards or drying-upwards trends; these cycles can be summarised into two distinct end-member trends with marked differences in the interactions present and sediments preserved.

### Aeolian Hosted Sabkha

The Aeolian Hosted Sabkha model is characterised initially by erosive channelised fluvial systems which interact with distal lacustrine deposits and a more proximal wet aeolian erg. This is followed by large-scale dry aeolian deposits, which increase in magnitude spreading from the erg centre. Water-driven deposits are supressed and hosted by interdune areas whilst dune (Figure 4a) displays a dry interdune deposit, which grades into a palaeosol, which is followed by a wave-rippled and gypsum-rich interdune overlain by a gypsum-rich dune.

These deposits suggest a climatic cycle from drying-wetting-drying shown through the change from dry interdune deposits into rippled and gypsum-rich interdunes followed by aeolian dunes. Although water played a primary role in the formation of these deposits, the dominant sediment transport processes are still largely wind-driven, with increases and decreases in water likely from the result of water table variation, rather than the presence of long-lived bodies of water. Most evaporite deposits within this trend follow an aeolian-hosted interdunal model (Handford, 1981) and are thin and isolated. This shows a low preservation potential from the high mobility and erosional potential of migrating dunes. However, many dunes show dune/gypsum interactions and gypsum-saturated bounding surfaces.

### Lacustrine Hosted Sabkha

By contrast the Lacustrine Hosted Sabkha trend is characterised by initial fluvial sheetflood deposits intercalated with thick lacustrine suspension deposits. The aeolian erg is generally suppressed and shows a prevalence of wet interdune deposits. Following this, the fluvial and lacustrine deposits are interbedded with carbonates, eventually grading into thick-bedded gypsum deposits with only minor proportions of isolated gypsum-rich aeolian dunes.

A representative succession for this trend is shown in Figure 4c. Bedded gypsum deposits with multiple tepee structures grade upwards with increasing frequency and thickness into saline pan and fine-grained siliciclastic sediments with multiple enterolithic structures. Subaqueous crossbedded sands follow and are overlain by ripple and parallel-laminated sands, with the top of the succession displaying gypsum-rich aeolian dunes.

The Lacustrine Hosted Sabkha trend shows a similar climatic cycle of drying-wetting-drying as in the Aeolian Hosted Sabkha; however, the nature of the deposits and interactions depicted are different. These deposits are interpreted to represent a contracting saline lake subject to periodic subaerial exposure of gypsum deposits and displacive growth of gypsum around saline saturated sediment within the capillary zone. Subaqueous crossbedded sands indicate unconfined fluvial influxes propagated over this sabkha with periodic fluvially driven recharge of the previously contracting lacustrine systems. After this influx, the system continued drying and contracting, before being replaced by migrating aeolian dunes. There is an indication of a partially water-saturated system, even during aeolian dominance, as gypsum was precipitated along dune foresets. The thicker bedded gypsum deposits suggest larger and more established lakes than the previous wetting/drying trends seen within the Aeolian Hosted Sabkha model. Deposition in this instance follows a continental playa lake environment rather than restricted aeolian interdunal hosted sabkha (Handford, 1981).

By contrast to the Aeolian Hosted Sabkha model, the drying trend within the Lacustrine Hosted Sabkha model supresses aeolian dune development, resulting in smaller and more isolated dunes. The gypsum and surrounding saline pan deposits are much thicker than those identified in the Aeolian Hosted Sabkha model and readily aggrade, probably as the result of a reduction in aeolian sediment supply as sand adheres to saline-rich saturated mudflats and pans around the contracting lake.

Overall, these system-scale interactions are interpreted as the gradation of desert lacustrine systems into sabkhas with increasing climatic aridity. These larger-scale interactions display two distinct end members; 1) Aeolian derived water-table-controlled sabkha, and 2) Lacustrine-derived, fluvial-influx-controlled sabkha.

## Cyclicity

The two marked trends (Aeolian Hosted Sabkha and Lacustrine Hosted Sabkha) show cyclic temporal and spatial changes. Spatial changes relate to the grading of a desert environment into a marginal sabkha environment with interactions commonly seen in present-day settings; e.g., Death Valley, Lake Eyre, (Warren, 2016); however, temporal changes are governed by much larger scale allocyclic and autocyclic controls.

Cyclicity of this nature is commonly attributed to either the effects of tectonics and accommodation space (e.g., Blair, 1987), climatic variations (e.g., Cecil, 1990), or more localised autocyclic process (e.g., Cecil, 2003). Tectonically the Paradox Basin was relatively stable and in an overfilled state during the Permian deposition of the Cedar Mesa Sandstone (Condon, 1997; Barbeau, 2003), indicating a climatic control to the cyclic deposits.

A change in climatic regime within an arid and semi-arid environment, even only minor, can have a large effect on the systems present (Mountney et al., 1999), as well as effecting discharge and sediment supply to the basin (e.g., Sadler and Kelly, 1993; Hinds et al.,2004). The effects of climatic influence on the evolution of the deposits of the Cedar Mesa Sandstone and Cutler Group have been well documented (e.g., Mountney and Jagger, 2004; Mountney, 2006; Jordan and Mountney, 2010) with at least twelve recognised aeolian accumulations related to periods of climatic aridity identified from the erg centre of the Cedar Mesa Sandstone (Mountney, 2006). These periods of aridity are bounded by periods of humidity, though not preserved within the erg centre (Mountney, 2006). This lack of preservation occurs due to the deflationary nature of aeolian deposits. These humid periods can be interpreted as the lower halves of both the trends, which show predominantly lacustrine and water-born sediments derived from an increased discharge, as a result of a more humid climate increasing fluvial discharge sediment supply.

The differences between the two depositional trends can again be explained by a changing climatic regime. With trend the Aeolian Hosted Sabkha representing a much more arid period allowing for full desertification and large-scale dune development, compared to trend the Lacustrine Hosted Sabkha which shows a more humid stage and less arid stage, resulting in the large-scale lacustrine deposits. This, in turn, is overprinted by higher frequency autocyclic controls which limit dune development due to sediment trapping within enterolithic structures, formed from the concentrating and contracting of the saline lake; these, in turn, only occur due to the allocyclic controls being wetter than previous trend. The lack of large dune development in the uppermost drying stage could be due to lack of sediment supply rather than due to sediment becoming trapped within the enterolithic salt structures. However, when compared regionally, large dunes still develop close to the erg centre, and preserved dunes are seen within the sabkha succession, invalidating arguments for lack of sediment supply, as climbing dunes would not be preserved under conditions of deflation.

Initial work has shown at least four distinct climatic cycles (Figure 5) when using a qualitative wetting-and-drying-cycles approach; this is achieved by identifying the sediments deposited during more humid or arid depositional settings and creating wetting-or-drying curves independent of sediment thickness. This method has also proved useful in basin-wide correlation, because the high spatial variability of the deposits correlation can be tricky; however, when correlated on the basis of these climatic wetting-and-drying cycles, clearer trends can be determined. Additionally, spectral gamma-ray measurements have been conducted; these can aid correlation and also in the interpretation of climatic cyclicity. When matched with the sedimentary log, the gamma-ray values show distinct cleaning-up trends linked to climatic humidity and coarsening-upwards trends related to aridity.

## Conclusions and Further Work

The Cedar Mesa Sandstone shows distinct spatial and temporal changes through the logged sabkha successions. These have been divided into two distinct trends: one an aeolian hosted sabkha; the other a lacustrine hosted sabkha. Through this detailed sedimentary logging, coupled with gamma-ray measurements, climatic cyclicity has been interpreted. Further work will apply gamma-ray results to provide quantitative values which can be used for Fourier transform analysis techniques to determine the source of cyclicity, especially if it is related to orbital forcing, and can help link the cyclicity to either Milankovitch, eccentricity, obliquity, or precession orbital forces. The application of this work will allow for regional correlation, as well as the application of these techniques to subsurface data to better predict where environments are present based on the climatic regime at the time of deposition.

## References Cited


Barbeau, D., 2003, A flexural model for the Paradox Basin: implications for the tectonics of the Ancestral Rocky Mountains: Basin Research, v.15/1, p. 97-115.

Blair, T.C., 1987, Tectonic and hydrologic controls on cyclic alluvial fan, fluvial, and lacustrine rift-basin sedimentation, Jurassic-Lowermost Cretaceous Todos Santos Formation, Chiapas, Mexico: Journal of Sedimentary Petrology, v.57/5, 845-862.

Blakey, R.C., 1988. Basin tectonics and erg response: Sedimentary Geology, v. 56/1-4, p. 127-151.

Blakey, R.C., F. Peterson, G. Kocurek, 1988, Synthesis of late Paleozoic and Mesozoic eolian deposits of the Western Interior of the United States: Sedimentary Geology, v.56/1-4, p. 3-125.

Cecil, C.B., 1990, Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks: Geology, v. 18/6, p.533-536.

Cecil, C.B., 2003. The concept of autocyclic and allocyclic controls on sedimentation and stratigraphy, emphasizing the climatic variable: SEPM Special Publication no. 77, p. 13-20.

Condon, S.M., 1997, Geology of the Pennsylvanian and Permian Cutler Group and Permian Kaibab Limestone in the Paradox Basin, southeastern Utah and southwestern Colorado: U.S. Geological Survey Bulletin 90-P, 59p.

Handford, C.R., 1981, Coastal sabkha and salt pan deposition of the lower Clear Fork Formation (Permian), Texas: Journal of Sedimentary Petrology, v. 51, p. 761-778.

Hinds, D.J., E. Aliyeva, M.B. Allen, C.E. Davies, S.B. Kroonenberg, M.D. Simmons, and S.J. Vincent, 2004, Sedimentation in a discharge dominated fluvial-lacustrine system: the Neogene Productive Series of the South Caspian Basin, Azerbaijan: Marine and Petroleum Geology, v.21/5, p.613-638.

Huntoon, J., J. Stanesco, R. Dubiel, and J. Dougan, 2000, Geology of Natural Bridges National Monument, Utah: Geology of Utah's Parks and Monuments: Utah Geological Association Publication, 28, p. 233-249.

Jordan, O.D., and N.P. Mountney, 2010, Styles of interaction between aeolian, fluvial and shallow marine environments in the Pennsylvanian to Permian lower Cutler beds, south-east Utah, USA.: Sedimentology, v.57/5, p.1357-1385.

Kelley, V.C., 1958, Tectonics of the Black Mesa Basin region of Arizona: New Mexico Geological Society Ninth Field Conference, p. 136-145. Website accessed September 26, 2018, https://nmgs.nmt.edu/publications/guidebooks/downloads/9/9_p0136_p0145.pdf.

Lawton, T.F, and B.J. Buck, 2006, Implications of diapir-derived detritus and gypsic paleosols in Lower Triassic strata near the Castle Valley salt wall, Paradox Basin, Utah: Geology, v.34/10, p. 885-888.

Loope, D.B., 1984, Eolian origin of upper Paleozoic sandstones, southeastern Utah: Journal of Sedimentary Research, v.54/2, p. 563-580.

Mountney, N., J. Howell, S. Flint, and D. Jerram, 1999. Climate, sediment supply and tectonics as controls on the deposition and preservation of the aeolian-fluvial Etjo Sandstone Formation, Namibia.Journal of the Geological Society, London, v.156/4, p.771-777.

Mountney, N.P., and A. Jagger, 2004, Stratigraphic evolution of an aeolian erg margin system: the Permian Cedar Mesa Sandstone, SE Utah, USA. Sedimentology, v.51/4, p. 713-743.

Mountney, N.P., 2006. Periodic accumulation and destruction of aeolian erg sequences in the Permian Cedar Mesa Sandstone, White Canyon, southern Utah, USA: Sedimentology, v.53/4, p. 789-823.

Sadler, S.P., and S.B. Kelly, 1993, Fluvial processes and cyclicity in terminal fan deposits: an example from the Late Devonian of southwest Ireland: Sedimentary Geology, v.85/1-4, p.375-386.

Warren, J.K., 2016. *Evaporites:* A geological compendium: Springer, 490p.

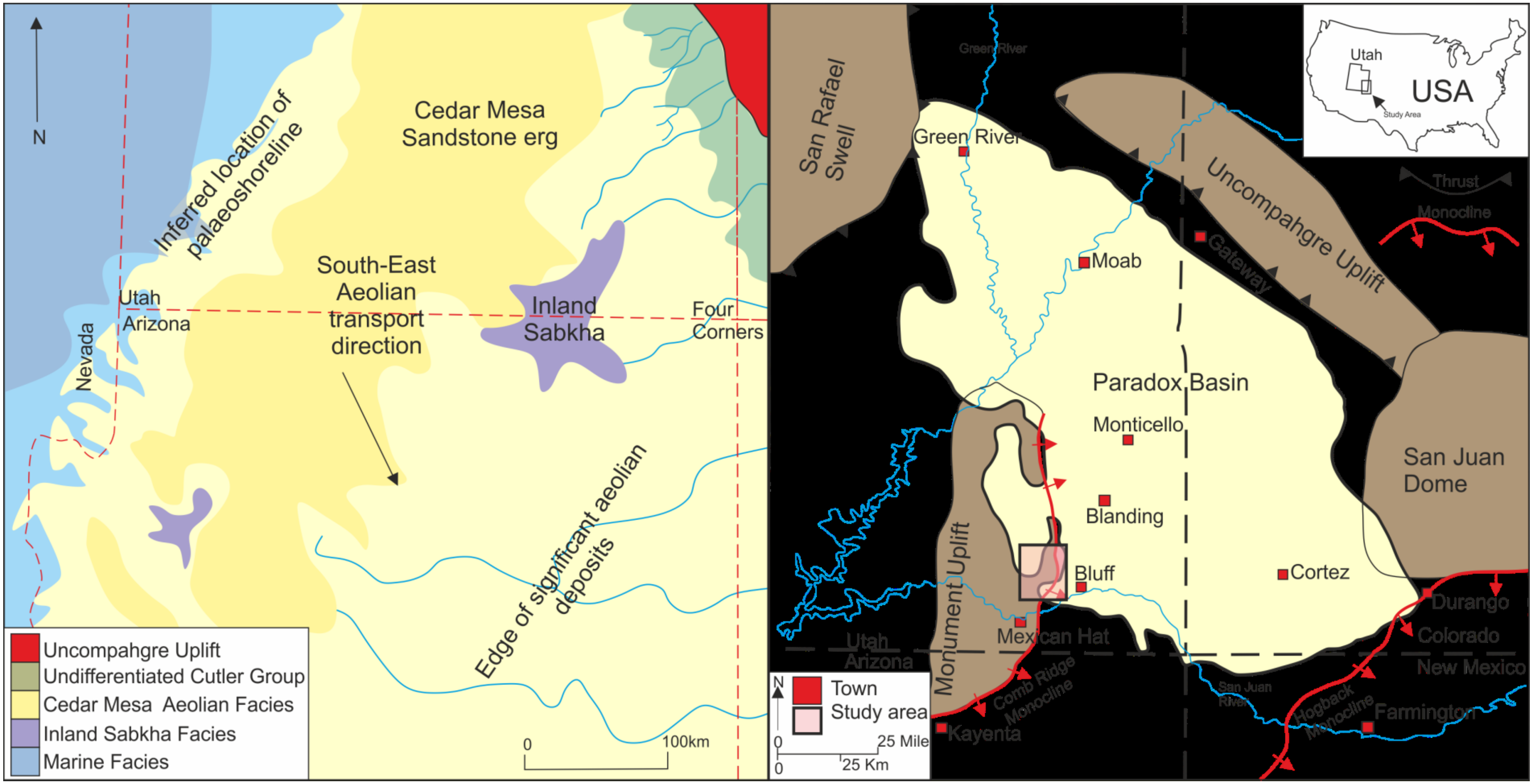


Figure 1. Paleogeography of the Cedar Mesa Sandstone (after Blakey et al., 1988) and the location of the Paradox Basin within the Four Corners region of the western USA (after Lawton and Buck, 2006: Kelley, 1958).

| Environment | Contained Facies | Contained Associations | Examples |
|---|---|---|---|
| **Aeolian** | Planar-crossbedded sandstone, Trough-crossbedded sandstone, Translatent ripple sandstone, Pinstriped sandstone, Convolute bedded sandstone, Massive sandstone. | Dune, Sandsheet, Dry Interdune, Wet Interdune, Damp Interdune. |  |
| **Fluvial** | Intraformational conglomerate,Planar-crossbedded gravel,Planar-crossbedded moderate sorted sandstone,Horizontally laminated sandstone, Climbing-ripple sandstone,Calcrete rich palaeosol, Horizontally laminated palaeosol | Channelised Fill, Unconfined Flow |  |
| **Lacustrine** | Fine-grained carbonate, Clastic-rich carbonate, Wave-rippled sandstone, Massive mottled silt, Carbonate mudstone | Ponded Deposits, Settle from Suspension, Palaeosol |  |
| **Sabkha** | Calcrete rich palaeosol, Horizontally laminated palaeosol, Crystalline gypsum, Gypsum-bound sandstone | Sabkha, Palaeosol |  |

Figure 2. Facies, facies associations, and depositional environments present within the Cedar Mesa Sandstone.

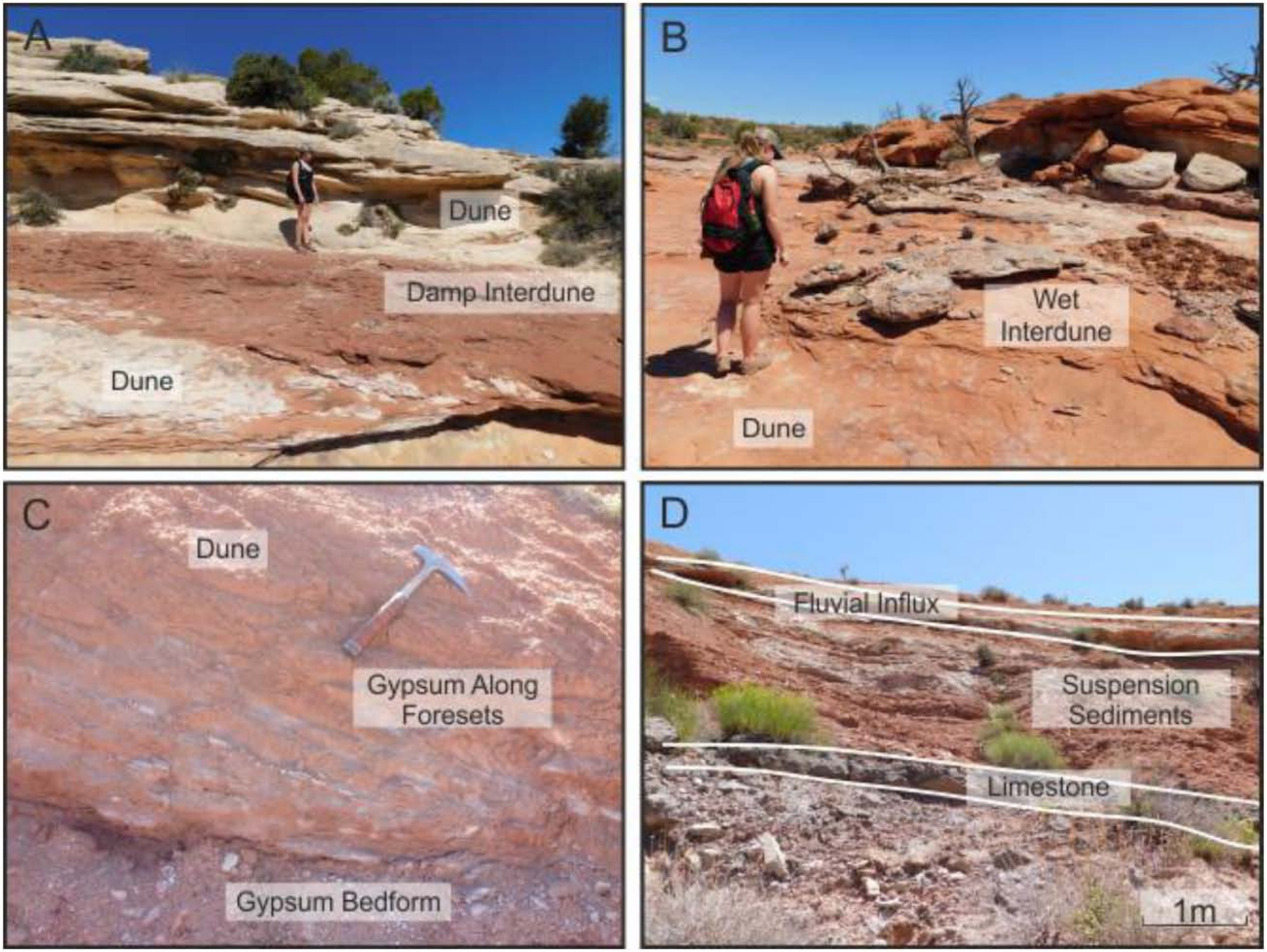


Figure 3. Bed-scale interactions. A: Dune-Damp interdune interactions, B: Dune-Wet interdune interactions: C Dune-Gypsum interactions: D Fluvial-Lacustrine interactions.

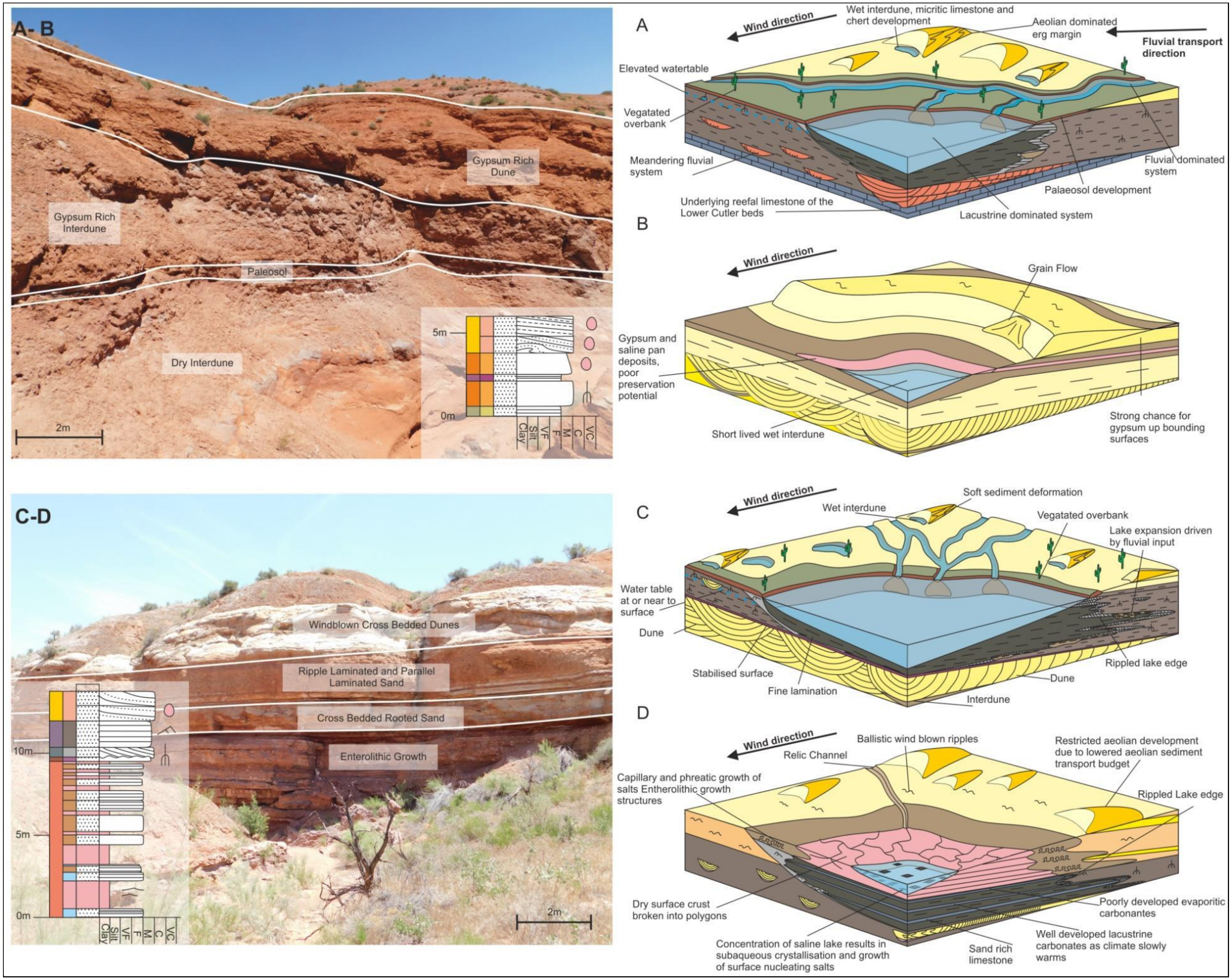


Figure 4. System- scale interactions and depositional models: A-B trend showing Aeolian-hosted sabkha models, C-D showing lacustrine-hosted sabkha models.

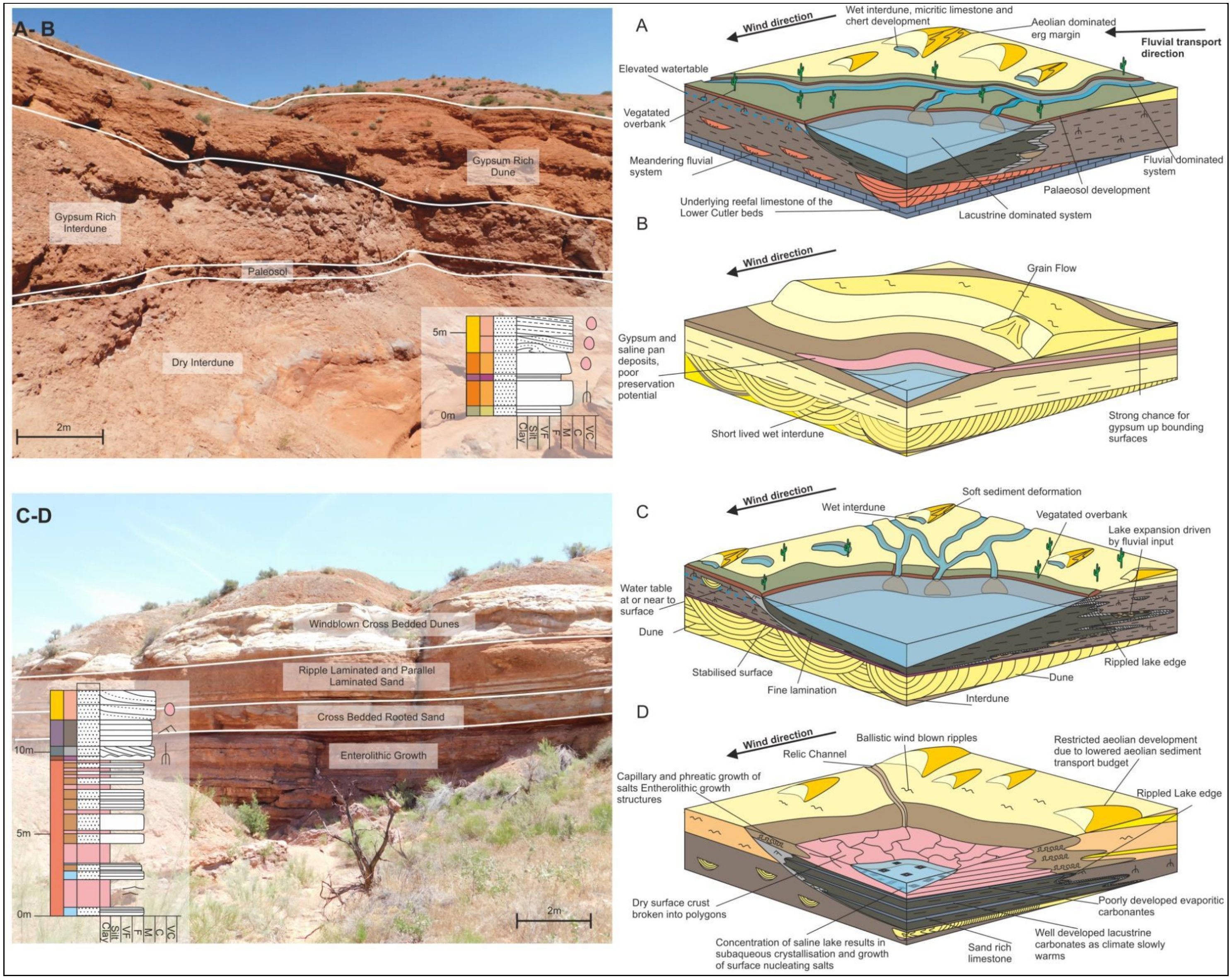


Figure 5. (A) Correlated gamma-ray and sedimentary log, with initial interpreted sedimentary climatic cycles and coarsening- and cleaning-gamma-ray trends. (B) Sedimentary logs correlated on the basis of wetting-and-drying climatic cycles, based on technique shown in (C), which plots sediments against climatic cycles independent of sediment thicknesses.

Click to return to Page 1.