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A classification scheme for fluvial-aeolian system interaction in desert-margin settings

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Abstract

This study examines 130 case examples from 60 desert regions to propose a generalised framework to account for the diverse types of interaction known to exist between active aeolian and fluvial depositional systems at modern dune-field margins. Results demonstrate the significance of aeolian and fluvial system type, orientation of aeolian versus fluvial landforms, distribution of open versus closed interdune corridors, and fluvial flow processes in controlling the distance and type of penetration of fluvial systems into aeolian dune fields.

Ten distinct types of fluvial-aeolian interaction are recognised: fluvial incursions aligned parallel to trend of linear chains of aeolian dune forms; fluvial incursions oriented perpendicular trend of aeolian dunes; bifurcation of fluvial flow between isolated aeolian dune forms; through-going fluvial channel networks that cross entire aeolian dune fields; flooding of dune fields due to regionally elevated water-table levels associated with fluvial floods; fluvial incursions emanating from a single point source into dune fields; incursions emanating from multiple sheet sources; cessation of the encroachment of entire aeolian dune fields by fluvial systems; termination of fluvial channel networks in aeolian dune fields; long-lived versus short-lived modes of fluvial incursion.

Quantitative relationships describing spatial rates of change of desert-margin landforms are presented. The physical boundaries between geomorphic systems are dynamic: assemblages of surface landforms may change gradationally or abruptly over short spatial and temporal scales. Generalised models for the classification of types of interaction have application to the interpretation of ancient preserved successions, especially those known only from the subsurface.

Keywords: aeolian system, desert geomorphology, dryland rivers, sedimentology, stratigraphy

1. Introduction

Desert dune fields are not necessarily covered with aeolian bedforms; most are also characterised by other morphological bodies of aeolian-derived or aeolian-related sediment deposits, including interdunes, sand sheets, soils, lacustrine systems, and perennial, intermittent or ephemeral fluvial systems. These geomorphic forms are commonly developed between active aeolian dunes, else they define the limits of dune fields, with sharp or gradational boundaries. Figure 1 depicts common depositional processes that operate at dune-field margins, many of which control the mechanisms by which successions accumulate to form bodies of preserved strata. Significant diversity in the arrangement and type of interaction of competing depositional sedimentary systems is recognised in modern desert dune fields and their marginal areas, and these give rise to complex yet predictable geomorphological patterns that commonly vary over space and time (e.g. Lancaster, 1989; Cooke et al., 1993; Bullard and Livingstone, 2002; Al-Masrahy and Mountney, 2013). The record of these interactions is also recognised in the ancient sedimentary record (e.g. Langford and Chan, 1989; Kocurek, 1991; Spalletti and Veiga, 2007), where spatial and temporal changes in the type of interaction between aeolian dune and associated desert sub-environments are known to have resulted in the preservation of complex arrangements of sedimentary deposits and stratigraphic architectures (Mountney, 2006a, 2012).

Permanent, intermittent and ephemeral fluvial systems occur in many dryland regions (Powell, 2009), including in parts of Australia, India, Saudi Arabia, and the Southwestern United States (e.g., Schenk and Fryberger, 1988; Tooth, 2000, Glennie, 1987, 2005; Nanson et al., 2002), and many such systems exhibit complex and long-lived interactions with aeolian dunes. Some fluvial systems serve to generate significant supplies of sediment that are subsequently available for aeolian-dune construction, as in the Kelso dune field, Mojave desert of California (Sharp, 1966; Kocurek and Lancaster, 1999). Similarly, alluvial-fan systems that form laterally extensive bajada may contribute significant sources of sediment for aeolian landform construction, as is the case for the Mojave River, southeastern California (Blair and McPherson, 2009; Belnap et al., 2011), and the alluvial-fan systems that border parts of the Rub' Al-Khali sand sea, Saudi Arabia (Figure 2). Other fluvial systems limit the spatial extent of dune fields and serve to remove significant volumes of sediment transported into river beds via aeolian processes from desert sedimentary systems (e.g. The Kuiseb River, Namibia, Goudie, 1972; Ward, 1983).

The role of fluvial systems in aeolian-dominated deserts is significant: they are important landscape-forming and developing agents in many dryland systems (Wainwright and Bracken, 2011). Although many studies have documented types of interaction between aeolian and fluvial systems in both modern systems (e.g. Langford, 1989; Trewin, 1993; Stanistreet and Stollhofen, 2002; Bullard and McTainsh, 2003) and their ancient preserved successions recognised in the geological record (e.g. Langford and Chan, 1988; 1989; Herries, 1993; Chakraborty and Chaudhuri, 1993; Mountney and Jagger, 2004; Jordan and Mountney, 2010; Spalletti et al., 2010), relatively few geomorphological studies have explicitly focused on types of interaction between contemporaneously active aeolian and fluvial systems (e.g. Frostick and Reid, 1987; Cooke et al., 1993; Tooth, 2000; Bull and Kirkby, 2002; Parsons and Abrahams, 2009; Reid and Frostick, 2011; Liu and Coulthard, 2014). Analysis of types of aeolian-fluvial system interaction has implications for gaining an improved understanding of the effects of climate change. Furthermore, such analysis aids in the reconstruction of ancient palaeoenvironments (cf. Trewin, 1993; Herries, 1993; Yang et al., 2002; Al Farraj and Harvey, 2004; Simpson et al., 2008; Jordan and Mountney, 2010).

The increasing availability and global coverage of high-resolution satellite and aerial-photograph imagery through resources such as Google Earth (Butler, 2006; Yu and Gong, 2012; Fisher et al., 2012) has enabled the study of geomorphological relationships in detail for remote dryland settings (e.g. Tooth, 2006; Bullard et al., 2011; Al-Masrahy and Mountney, 2013). Significantly, the global coverage of such data means that comprehensive analyses can now be undertaken. This study utilises the latest generation of remotely sensed imagery to investigate the nature of aeolian and fluvial system interactions in a representative set of desert systems.

The aim of this study is to propose a generalised framework with which to account for the diverse types of interaction known to exist between coeval aeolian and fluvial depositional systems, and to discuss the significance of these interactions for the geomorphological and sedimentological evolution of mixed aeolian-fluvial systems. Specific objectives of this work are: (i) to illustrate the principal types of aeolian-fluvial interactions documented from the world's major dryland systems; (ii) to propose a framework for their classification; (iii) to demonstrate how the orientation of fluvial systems relative to the trend of aeolian bedforms present at the leading edge of dune fields controls the nature of aeolian-fluvial system interaction; (iv) to document how open and closed interdune corridors act to control the type and extent of incursion of fluvial systems into aeolian dune fields; (v) to consider how different types of aeolian-fluvial interaction give rise to complex geomorphic arrangements of landforms; and (vi) to consider the implications of such arrangements for the palaeoenvironmental reconstruction of ancient preserved counterparts (Figure 1).

This research is significant because it presents a robust framework to account for all the commonly identified types of aeolian-fluvial interaction in desert systems, which can be used as a tool to predict the likely spatial extent over which such interactions occur in both modern systems and their ancient counterparts preserved in the rock record.

2. Methodology

The morphological expression and areal distribution of 130 examples of fluvial-aeolian interaction have been mapped using high-resolution satellite imagery of 60 desert dune fields around the world (Figure 3). Case study examples have been classified to propose a framework of ten distinct types of system interaction. Studied desert systems include the Namib Desert and Skeleton Coast (Namibia), Taklamakan Desert (northwest China), Rigestan Desert (southwestern Afghanistan), Sahara Desert (North Africa), Algodones (southeastern California), White Sands (New Mexico), Rub' Al-Khali and An Nafud sand seas (Saudi Arabia), and Wahiba Sands (Oman), Great Sany, Great Victoria, and Simpson deserts (Australia).

The Google Earth Pro software tool provides global coverage of remotely sensed imagery, including for desert regions that are generally not readily accessible by land. The satellite imagery used is from multiple sources and is of variable age; study sites have been selected in part on the availability of high-quality imagery with spatial resolution of resolution 15 m per pixel, derived from 15 to 30 m-resolution multispectral Landsat data that have been pan-sharpened with panchromatic Landsat image processing software. The software and its associated datasets have been used to generate a high-resolution images in the form of tiles, each up to 4800 x 2442 pixels, that have been near-seamlessly stitched together to yield detailed composite mosaic images that are well suited to detailed analysis of desert landforms.

3. Types of fluvial-aeolian interaction in aeolian dune fields

The following discussion presents a novel classification scheme for types of interaction between fluvial systems that are present both within and at the margins of aeolian dune-field systems. Ten distinct types of interaction are recorded and illustrated by 130 case-study examples from 60 deserts around the world.

3.1 Fluvial incursions oriented parallel to trend of aeolian dune forms

In cases where the configuration of aeolian dunes is such that they form elongate ridges with crestlines aligned close to parallel to the direction of fluvial flow and where neighbouring dune ridges are separated by interdune flats, fluvial systems are typically able to penetrate along the interdune corridors and into the aeolian dune field, in some cases for many tens of kilometres. One example of this type of interaction is the northern margin of the Simpson Desert, Australia (Nanson et al., 1995), where fluvial systems flow along open interdune corridors with an average width of 450 m, between linear dunes (Figure 4a). A second example is the Kharan Desert, Pakistan, where fluvial systems flow along open interdune corridors with an average width of 1250 m between barchanoid and transverse dune ridges (Figure 4b). These and other representative examples are listed in Table 1.

Where interdune corridors between dunes are open, they serve to guide flood waters and provide the required paths for water to advance significant distances into aeolian dune fields. Where interdune corridors narrow but nevertheless remain open, they may promote a localised increase in stream power as floods of a given discharge are forced through a narrow constriction, which may result in localised erosion, either laterally from the toes of adjoining aeolian dunes or via scour on the bed of the interdune corridor. Where erosion of aeolian deposits occurs, the nature of the sediment load being carried by flood waters will change, and this will influence the sedimentary character of resultant flood deposits. Where interdune corridors become closed, for example where two neighbouring dune ridges meet, flood waters will pond, giving rise to standing water bodies that gradually desiccate in the aftermath of the flood event; Sossusvlei in the Namib Desert is one such example. Where aeolian sand is blown over the course of river channels during dry episodes, the fluvial course may be progressively diverted with each successive flood event (Figure 5a) or terminated (Figure 5b).

This type of interaction results in the deposition of ribbon-like fluvial deposits in cases where the aeolian dunes that funnel the flood waters into specific interdune corridors are fixed in position. Alternatively, in cases where the dunes and their intervening interdunes gradually migrate laterally between successive flood events, fluvial deposits arising from successive floods may expand laterally to form more sheet-like depositional elements (cf. Langford and Chan, 1988). In both cases, the opportunity for aeolian reworking of flood deposits is significant, and winnowing of sand and finer fractions by the wind is likely, resulting in the generation of armoured lag deposits (Krapf et al., 2005; Simpson et al., 2008). Thus, fluvial incursion along interdune corridors can generate a local supply of sediment suitable for later aeolian construction. Conversely, the deposition of mud drapes through suspension settling in ponded flood waters may limit the availability of underlying sand substrates for later aeolian transport (Cain and Mountney, 2009, 2011).

3.2 Fluvial incursions oriented perpendicular to the trend of aeolian dune forms

In cases where the configuration of aeolian dunes is such that they form elongate ridges with crestlines aligned close to perpendicular to the direction of fluvial flow, aeolian topography will exert a significant control on fluvial flood pathways, and the nature of the flooding event. In cases where such a configuration is present at the outer margin of an aeolian dune field, flood events may be prevented from passing into the dune field and may instead become ponded or be diverted in orientations parallel to the trend of the dunes at the outer dune-field margin (Figure 6). Where flood waters pond, the water level may rise to a point where saddles (cols) between neighbouring dune crests are breached, thereby allowing fluvial incursion into the inner part of a dune field. Fluvial breaching at specific sites will rapidly lead to erosion and incision as flow is forced through a narrow gap between dunes. Three examples where this process is documented are the interaction between sand dunes of the Mu Us Desert and the Sala Us River, Inner Mongolia, China (Li et al., 2012), ephemeral rivers of the Skeleton Coast, northwestern Namibia, including the Hoanib, Uniab, and Hunkab rivers (Stanistreet and Stollhofen, 2002), and the Todd River, northwestern Simpson Desert, Australia (Hollands et al., 2012). The interaction of Wadi Batha Oman with aeolian dunes of the Wahiba Sand Sea (Warren, 1988; Figure 6a) records a 120 km-long fluvial system that flows eastwards along the northern margin of a dune field composed of north-south trending linear dunes with an average dune spacing of 1900 m. Fluvial incursion into the dune field is restricted to the outermost 1 to 2 km of open interdune corridors where localised ponding of floodwater occurs. The northern and eastern boundaries of the dune field are delineated by the Wadi Batha, which maintains a course close to perpendicular to the tip-out points of the large linear dunes. At the northern margin of the Namib Desert, Namibia (Figure 6b), the northward advance of large linear dunes of the Namib sand Sea is curtailed by the Kuiseb River, which intermittently flows westwards: aeolian sand blown into the river channel during dry episodes is periodically flushed up to 147 km downstream during major seasonal flood events. These and other representative examples are listed in Table 1.

This type of interaction is typically expressed as a sharp boundary between adjoining fluvial and aeolian environments. Where fluvial flood waters repeatedly pond against the leading edge of an aeolian dune field, fine-grained, mudstone layers will progressively accumulate (e.g. Wadi Al Ayn and Wadi Al Batha, Oman: Glennie, 2005). In cases where flood waters are saline and where ponded water evaporates or infiltrates only slowly, salts such as calcium carbonate, gypsum, halite or potash may be precipitated (Valyashko, 1972). For example, the salt flats of Umm as Samim, close to the eastern border of the Rub' Al-Khali Sand Sea, Oman, occur in a low-lying area between the alluvial fans to the north, the aeolian dunes of the Rub' Al Khali to the west and south (Figure 2, Goodall et al. 2000). If the outer edge of the aeolian dune field gradually expands over time via dune migration, aeolian deposits may become juxtaposed over flood deposits. Conversely, if the outer edge of the aeolian dune field gradually retreats (contracts), aeolian deposits may become overlain by flood deposits.

3.3 Bifurcation of fluvial flow between isolated aeolian dune forms

In cases where fluvial flood waters pass into the outer parts of aeolian dune fields that are characterised by isolated bedforms or small clusters of bedforms of variable size, orientation and spacing, the physical organisation of the dunes (or dune clusters) may encourage flood waters to bifurcate around the topographic obstacles on both sides. This process is common in the southeastern part of the Rub' Al-Khali Desert, Oman (Figure 2), which is dominated by fields of simple and compound star dunes that are bordered by the mountains of Oman from which flood events emanate. The distance of penetration of these fluvial systems is 20 to 40 km (Figure 7a), and this is governed by the flow frequency and magnitude, surface topography, substrate type (which governs infiltration rate and capacity) and aeolian bedform morphology. In some examples, such as the Keriya River in the Taklamakan Desert, China, intricate threading of fluvial channels between migrating but spatially isolated aeolian dunes is widespread (Figure 7b): in this example aeolian bedforms or clusters of bedforms that comprise small dune fields are fixed in position by well-established fluvial courses. Similar types of interaction are also common in non-desert aeolian settings, including on Skeiðarársandur, southern Iceland (Mountney and Russell, 2009). These and other representative examples are listed in Table 1.

The presence of flowing water in such settings may affect sand dunes either directly through erosion or indirectly by generating a local supply of sediment suitable for later aeolian construction. In cases where episodic flooding results in a water-table level that remains permanently close to the aeolian accumulation surface, such that the dune-field margin may be classed as a wet aeolian system (*sensu* Kocurek and Havholm, 1993), the long-term preservation potential of migrating but spatially isolated aeolian bedforms may be enhanced (cf. Mountney and Russell, 2009).

3.4 Through-going fluvial channel networks that cross entire aeolian dune fields

In cases where fluvial systems pass through entire aeolian dune fields, the presence of a fluvial course may act to effectively partition the dune field by disrupting or limiting aeolian sediment transport pathways (Figure 8a; cf. Ward, 1987; Krapf et al., 2003). Such fluvial channel networks (or non-channelised fluvial pathways) may be either permanent (e.g. Nile River, Sudan), intermittent (e.g. Saoura River, Algeria) or ephemeral (e.g. Uniab River, Skeleton Coast, Namibia and Wadi Juweiza, United Arab Emirates). Such fluvial systems may operate as an agent of aeolian erosion; seasonally active fluvial courses may be filled with aeolian-derived sediment during dry episodes, and this sediment will be flushed downstream out of the dune field during each flood event. In some cases, this acts to transport sediment suitable for aeolian construction to parts of the dune field further downstream. In cases where fluvial flooding along the fluvial flow pathway is frequent and regular, repeated flushing of sediment may severely limit the availability of sediment for aeolian construction to the part of the dune field lying downwind of the river course (Figure 4). Alternatively, through-going fluvial systems may act to generate a localised supply of sediment for further aeolian construction, especially if they undergo a downstream reduction in flow competency. Where aeolian dunes are prevented from migrating across fluvial courses, the aeolian bedform character (size, morphological type, sediment composition) will be markedly different on the downwind side of fluvial course. The world’s largest example is the 2000 km-long course of the Nile River through the eastern Sahara Desert (Figure 8a), which separates dune fields of the Nubian Desert from those in the main Saharan sand seas. A second example is Warburton River which separates the Simpson Desert from the Tirari Desert, Australia: average channel width is 182 m (Figure 8b). These and other representative examples are listed in Table 1.

The sedimentary record of these types of interactions is predictable. Aeolian sand transported into river courses will provide a source detritus that will typically be composed of well-sorted, fine sand suitable for fluvial transportation; fluvial deposits lying downstream from the dune field will reflect this character. By contrast, aeolian deposits in areas downwind from the fluvial course may have a sediment composition that reflects the fluvial source.

3.5 Fluvial flooding of aeolian dune fields associated with elevated water-table level

In aeolian dune fields where floods of relatively high magnitude and frequency occur, or where charge to subsurface aquifers is high due to either direct or indirect precipitation, interdune areas may be inundated by water not only during flood events. The local water table may remain permanently at or close to the accumulation surface such that low-lying interdune flats remain wet or damp between successive flood events (Nash, 2011). Thus, aeolian dunes may be surrounded for protracted episodes by wet (i.e. flooded) or damp interdunes (Figure 9). Such wet aeolian systems (*sensu* Kocurek and Havholm, 1993) undergo aeolian construction and accumulation in a manner that differs from dry aeolian systems. Aeolian sediment transport across wet and damp sediment surfaces is severely restricted (Hotta et al., 1984; Good and Bryant, 1985; Crabaugh and Kocurek,1993; McKenna and Scott, 1998; Mountney and Russell, 2009), which limits the volume of sediment available for aeolian dune construction. Airflows in wet aeolian systems are therefore commonly under-saturated with respect to their potential sand transport capacity, rendering dry sand on existing aeolian dunes susceptible to erosion as the wind attempts to entrain more sediment. If direct precipitation in the dune field acts to render dune surfaces damp for protracted periods, the effects of aeolian deflation may be limited. Rates of aeolian dune migration may be low or zero where flooded interdunes prevent bedform advancement. Fluctuations between relatively higher and lower water-table levels can allow interdunes to change from a dry, to damp, to wet state on a seasonal basis and associated aeolian activity will reflect these changes. For example, the Lençóis Maranhenses dune field, Brazil, is characterised by the presence of chains of barchanoid and transverse dunes separated by interdune lakes and lagoons that flood during the wet season (Parteli et al., 2006; Luna et al., 2012). Sauda Nethil Sabkha, Qatar (Ashour, 2013) and Chott Rharsa playa lake basin (Blum, et al., 1998) are other similar examples. Other examples of wet aeolian systems in which interdune depressions are flooded in response to a high water-table level include parts of the Gobi Desert of northern China (Figure 9a) and part of the Al Jafurah Desert, eastern Saudi Arabia (Figure 9b). In this latter example a progressive rise in relative water table is enabling preservation of the toesets of aeolian dunes that pass over the damp surface. These and other representative examples are listed in Table 1.

Damp and wet interdune deposits typical of this type of interaction include adhesion structures (adhesion ripples, adhesion warts and adhesion plane beds), aqueous-ripple structures, wavy laminations, contorted structures and brecciated laminae (Kocurek, 1981;

Kocurek and Fielder, 1982). Elevated water-table levels promote aeolian accumulation and long-term preservation, especially in systems where aeolian dune fields are constructed in subsiding sedimentary basins: slow but progressive basin subsidence will gradually cause the aeolian dune deposits to sink beneath a static but relatively high water table via a so-called relative water-table rise (*sensu* Kocurek and Havholm, 1993), as is the case for the Skeiðarársandur dune fields in southern Iceland (Mountney and Russell, 2009) and part of the Al Jafurah Desert, eastern Saudi Arabia (Figure 9b). An elevated water table also limits the effects of aeolian deflation (Fryberger et al., 1988).

3.6 Fluvial incursions into aeolian dune fields associated with a single point source

The arrangement of landforms at the margins of desert sedimentary basins can act as a fundamental control on the nature of fluvial-aeolian interaction (Mountney, 2005). In many desert settings fluvial systems emanate from basin-bounding highland areas to pass as single-thread systems into the receiving desert basin in which aeolian dune fields are developed, as is the case for wadis at the southern edge of the Rub' Al-Khali (Glennie, 1970). Thus, fluvial systems commonly intersect aeolian dune fields at specific points along their margins. One common scenario is where an aeolian dune field lies in front of a valley where a mountain stream emerges from its catchment. The confinement of the stream within a valley system, the short distance from the catchment to the aeolian dune field, and the generally high gradient of the fluvial profile each act to reduce the opportunity for fluvial avulsion, thereby confining the river to a single point for a protracted period. Thus, the site of fluvial incursion of such single-thread fluvial systems into an aeolian dune field remains fixed. Where such fluvial systems intersect the leading outer edge of an aeolian dune field, their ability to penetrate the dune system will be dictated by factors such as the magnitude and frequency of the flood events, together with the orientation and continuity of dune ridges present at the dune-field margins. The areal extent over which dune-field flooding associated with single-thread fluvial channels operates tends to be limited, as is the case in examples from the White Sand Desert, New Mexico (Figure 10a). In cases where several single-thread channels enter into an aeolian dune field, the lateral spacing of such fluvial courses dictates the types of fluvial-aeolian interaction, as is the case in the Grand Erg Occidental Desert, North Sahara Desert, Algeria (Figure 10b). These and other representative examples are listed in Table 1.

The sedimentary expression of single-thread fluvial channels will be limited to the zone of penetration of the fluvial system into an aeolian dune field, and this will tend to be present over a limited area in cases where the fluvial systems are fixed in position for protracted episodes. Consequently, the preserved sedimentary record may reveal limited lateral variations.

3.7 Fluvial incursions into aeolian dune fields associated with a multiple sheet source

Alluvial fans commonly form extensive bajada where multiple catchments are present in close proximity along mountain fronts in arid settings (e.g., Padul Depression bajada, Spain, Calvache et al., 1997; bajada of northern Oman, Rodgers and Gunatilaka, 2002; Death Valley, Nevada, USA, Harvey, 2011). Similarly, distributive fluvial systems form networks of channels where they pass out onto low relief desert plains (cf. Hartley et al., 2010; Weissmann et al., 2011). Fluvial networks in such systems are commonly arranged into broad areas occupied by poorly-defined channels and are in some cases subject to non-confined flow over low-gradient surfaces (Hampton and Horton, 2007). Where such systems meet aeolian dune-field margins, they typically do so as sheet-like sources that may be active across distances of many tens of kilometres. Examples include part of the Sonoran Desert, northwestern Mexico (Figure 11a), and part of the Gobi Desert, northern China (Figure 11b). Aeolian-fluvial system interactions of this type occur over wide areas and multiple fluvial incursions may occur at many places along the dune-field margin. Non-confined sheet-like flood flows are typical, especially in the immediate aftermath of rainstorms. High-magnitude rainfall events, catchment area and relief, the low infiltration capacity of the substrate, the short run-off length from catchment to receiving basin the lack of appreciable relief on the basin plain, and the general absence of dense vegetation cover that might otherwise act to subdue run off, are all factors that contribute to sheet-like floods over large areas (Blair and McPherson, 1994; Blair, 1999; Arzani, 2005; Goudie, 2013). Such non-confined flows typically pass into dune fields penecontemporaneously along multiple open interdune corridors with access gained from multiple points along the dune-field margin. Representative examples are listed in Table 1.

This type of aeolian-fluvial system interaction results in the widespread distribution of fluvial-derived sediment within dune fields. Flooding over a wide spatial area means that the energy of the flow at any one location will be reduced. As such, the capacity of such flood events to erode aeolian bedforms will tend to be limited, except where non-confined flows locally coalesce into channels, for example where they are funnelled into narrow interdune corridors. Such flood deposits may serve to generate a localised supply of sediment for later aeolian dune construction.

3.8 Cessation of encroachment of aeolian dune fields by fluvial systems

The downwind margins of several very large aeolian dune fields are defined as spatially abrupt boundaries due to the presence of ephemeral or perennial fluvial systems that are effective in limiting the downwind encroachment of the dune field. One large-scale example is the eastern boundary of the Sahara Desert, which terminates at the Nile River (Figure 8a). Even relatively small ephemeral fluvial systems may be effective in halting dune-field encroachment, as is the case for the Kuiseb River at the northern (downwind) margin of the Namib Sand Sea (Figure 6b). Other examples include the northern limit of the Skeleton Coast Dune Field, Namibia, which terminates at the Kunene River (Figure 12a), and the Mu Us Desert, northern China, which terminates at the Yellow River (Figure 12b). Flash floods passing down channel networks are commonly of sufficient magnitude to flush aeolian sand downstream, in some cases to a long-term sediment sink – the Atlantic Ocean in the case of the Kuiseb River that defines the northern margin of the Namib Sand Sea and the Kunene River that defines the limit of the Skeleton Coast Dune Field (both Namibia). These and other representative examples are listed in Table 1.

3.9 Termination of fluvial channel networks in aeolian dune fields

Where fluvial systems terminate within the inner parts of aeolian dune fields they do so in a variety of ways (e.g., Al Farraj and Harvey, 2004). A common type of fluvial termination is associated with a transformation from channelized to non-channelized flow, which tends to reduce flow competence, thereby expediting flow termination. Such conditions are common in ephemeral systems and may occur in any part of the aeolian dune field depending on the energy of the flow. At the point of fluvial termination, suspended sediment comprising clay and fine silt sediment fractions are deposited (Reid and Frostick, 1987; Reid, 2002) to form mud layers in interdunes and playas. During dry seasons, aeolian sediment may to migrate over fluvial channels, thereby blocking the fluvial channel course and reducing the opportunity for future flood events to breach into the central parts of aeolian dune fields during subsequent wet seasons (e.g., Mountney, 2006b). Examples include the Skeleton Coast Dune Field, Namibia (Figure 13a), the Simpson Desert, Australia (Figure 13b), and the Trarza Desert, Mauritania (Figure 13c). These and other representative examples are listed in Table 1.

3.10 Examples of short-term versus long-term fluvial-aeolian interaction

In modern dryland systems, there exist many examples of short-term aeolian-fluvial interaction (see Lancaster, 1995) whereby fluvial channels that are subject to ephemeral or intermittent flow that have been blocked by encroaching aeolian dunes or sand-sheet deposits. Damming of fluvial courses typically occurs during the dry seasons or during drought episodes that are sufficiently long-lived to allow aeolian deposits to accumulate in fluvial channels (e.g., Glennie, 1970; Figure 5). One such example is where aeolian dunes have partially migrated across a playa lake basin at the terminus of an ephemeral river in part of the eastern Sahara Desert, Egypt (Figure 14a). Another example is in the Hamada Du Draa Desert, Algeria (Figure 14b). Episodic floods commonly act to flush out the system. Such fluvial flood deposits typically have a sedimentary character similar to that of the surrounding aeolian deposits, though grains are usually more tightly packed, producing lower primary porosities and permeabilities sandstones.

Over longer time scales, the impact of climate variation on depositional environments tends to be pronounced and significant, since it influences sediment yield, aeolian transport capacity of the wind, and the availability of sediment for aeolian transport. Together these factors govern the aeolian sediment state of the system (e.g., McKee et al., 1967; Herries, 1993; Kocuerk, 1999; Kocurek and Lancaster, 1999; Robinson et al., 2007). Short-term or long-term shifts in the positions and form of the boundaries between aeolian and fluvial systems are controlled by the competition between fluvial flood events and sites of aeolian dune construction, which are subject to the external (allogenic) control of climate change (cf. Porter, 1986). During relatively more arid episodes, for example, accumulated sedimentary successions tend to be characterised by dry aeolian deposits such as dunes and sand sheets (Kocurek and Nielson, 1986; Basilici et al., 2009). During relatively more humid episodes, fluvial process tend to dominate, generating more heterogeneous successions (e.g., Stanistreet and Stollhofen, 2002). Representative examples are listed in Table 1.

4. Discussion

4.1 Geomorphic and sedimentary impact of fluvial-aeolian system interactions

Where externally sourced fluvial systems cannot reach the interior parts of dry aeolian systems because of the great density of aeolian dunes present and the closed nature of associated interdune depressions, the opportunity for aeolian sediment reworking via fluvial processes is limited. Minor fluvial streams may, however, develop in such settings in response to localised surface run-off associated with rainfall events that occur within the dune field itself. Streams associated with intra dune-field flooding are highly ephemeral; reworking of aeolian sediment by such flows will be limited in extent and resultant deposits will be composed solely of fluvially reworked aeolian sand (Svendsen et al., 2003; Stromback et al., 2005).

Where externally sourced fluvial systems are able to penetrate into the interior of aeolian dune systems (Figures 15 and 16), the principal morphological controls on the distance and type of fluvial incursion are as follows: (i) morphological dune type, which defines the length and continuity of individual dune segments; (ii) the orientation of dunes relative to the direction of fluvial flooding; (iii) the form of interdune corridors that are present between dune segments, which are defined in terms of their width and length, and spatial changes in these parameters that dictate whether such features are classed as open or closed morphological elements (Table 1); (iv) the type and rate of aeolian dune and interdune migration relative to the frequency of fluvial flood events.

Accumulation and preservation of the sedimentary record of aeolian-fluvial interactions requires an appropriate mechanism to enable accumulation of both aeolian and fluvial deposits. One such mechanism is the gradual and progressive subsidence of the system within an evolving sedimentary basin (Blakey, 1988; Mountney et al., 1999). The nature of preserved types of interaction will be dictated in part by both the *spatial* arrangement of interdune corridors along which fluvial systems penetrate into aeolian dune fields and the *temporal* change in the morphology of these interdune corridors (Mountney, 2012). Additionally, the nature of preserved types of interaction will also be dictated by the frequency and intensity of the flood events. The spatial extent of fluvial incursions may vary over time between successive floods as aeolian dunes and their intervening interdunes migrate, or as the intensity of successive flood events wax or wane in response to external controls such as climate change.

4.2 The role of fluvial flooding in controlling aeolian dune-field expansion and contraction

Although climatic aridity is a dominant factor that controls the distribution and extent of many sandy deserts, aeolian dune fields are present not just in arid and semi-arid settings but also in a range of humid, non-climatic desert settings where sediment supply, sediment availability for transport, and the potential sediment transport capacity of the wind are sufficient to enable aeolian bedform construction. Climate exerts a fundamental control on the relative dominance of fluvial versus aeolian processes and plays a primary role in governing how aeolian dune-field margins expand or contract over time (e.g., Herries-1993; Clarke and Rendell, 1998; Yang and Li Ding, 2013).

Increases in either the frequency or magnitude of fluvial flood events in dune-field margin areas in response to climate change will impact continued aeolian dune-field construction in a number of ways. Increased fluvial discharge and stream power will promote erosion of older aeolian deposits. Fluvial reworking of aeolian sediment, its transport downstream and its ultimate re-deposition in areas where floods terminate will influence the supply and availability of sediment of a calibre suitable for later aeolian construction (Figure 15). Increased fluvial flood activity will limit the potential for aeolian dune migration (e.g., Pickup, et al., 2002; Bullard and McTainsh, 2003). The availability of water provides conditions suitable for vegetation colonisation, thereby promoting stabilisation of interdune flats and limiting the capability of the wind to erode such substrates (e.g., Levin et al., 2009). Similarly, the deposition of mud drapes via settling from suspension over wide areas in the aftermath of repeated flood events will also limit the availability of underlying sediment for aeolian transport. Frequent floods will act to charge the ground-water table beneath the aeolian dune field, thereby raising the water table, possibly to the level whereby formerly dry interdunes become damp or wet (Figures 13, 15 and 16). An elevated water table tends to limit the availability of sediment for aeolian transport. However, it also increases the preservation potential of the aeolian bedforms that gradually subside beneath it (e.g., Mountney and Russell, 2009).

4.3 Controls on the form and spatial extent of fluvial incursion into aeolian dune fields

The distance that fluvial systems are able to penetrate into dune fields is partly dependent on bedform morphological type and spacing, which itself controls interdune width and shape (Figure 16). Further, the orientation of open interdune corridors relative to the angle of incidence of fluvial floods also plays a significant role, as does the rate of lateral migration of the dunes and their adjacent interdunes. The distance of penetration of fluvial incursion into the margins of aeolian dune fields is greatest for regularly-spaced trains of relatively straight-crested aeolian dunes for which bedforms are separated by broad interdune flats and where fluvial systems impact the dune-field margin at an angle whereby flood waters associated with high-magnitude events can pass relatively unhindered along open interdune corridors.

Open interdune corridors play an important role where they occur adjacent to the path of fluvial systems passing into aeolian dune fields (e.g., Hoanib River in Skeleton Coast, northwestern Namibia; Stanistreet and Stollhofen, 2002): they act as a catchment for excess water during flood events, thereby acting to buffer flood discharge (Figure 15b,c). In cases where interdune corridors terminate in closed depressions, they typically host ponded flood waters, the suspended-load deposits of which commonly form mudstone or salt layers that are relatively resistant to erosion due to their cohesive nature (Loope et al., 1995; Bloomfield et al., 2006 McKie et al., 2010; Höyng et al., 2014; Figure 15b). This has an important impact on sediment preservation potential. From an applied perspective, understanding the distribution of such layers in ancient preserved successions is important because they act as stratigraphic heterogeneities that restrict flow in water aquifers and hydrocarbon reservoirs, thereby compartmentalising subsurface bodies (e.g., Fryberger et al., 1990; Mountney 2006a).

4.4 Controls on the accumulation and preservation of mixed aeolian and fluvial deposits

In modern desert dune-field settings, the relative dominance of aeolian versus fluvial activity is highly variable over a range of spatial and temporal scales, and this gives rise to complex arrangements of aeolian and fluvial morphological landforms and their deposits. In systems subject to infrequent or low-magnitude flood events, aeolian processes tend to dominate; conversely in systems subject to high-frequency, high- magnitude floods, fluvial processes dominate.

The frequency and persistence of fluvial flooding controls the period of occupancy of interdune corridors by active fluvial systems; in cases where aeolian dunes continue to migrate whilst flooding is on-going, the preserved architectural elements of fluvially-flooded interdunes tend to expand laterally as successive flood deposits develop in-front of advancing aeolian dunes. In non-climbing (i.e., non-accumulating) aeolian systems, such behaviour favours the development of sheet-like bypass supersurfaces (e.g. flood surfaces of Langford and Chan, 1988); in aeolian systems that climb at low angles (i.e., where a modest component of vertical accumulation is coincident with on-going aeolian dune and interdune migration), thin intercalations of vertically stacked, sheet-like fluvial and aeolian elements tend to accumulate (Mountney, 2012). The scale and connectivity of fluvial flood deposits tends to diminish with increasing distance toward the aeolian dune-field centre (Figures 1 and 16), though exceptions occur where aeolian dunes act as natural dams, thereby encouraging floodwaters to pond creating temporarily lakes over large areas within more central parts of dune fields. This type of interaction tends to be characterised by the accumulation of clay and silt deposits, and potentially of salt if the water salinity is high. The accumulation of such fine-grained or crystalline deposits is important from an applied perspective because elements composed of such material have the potential to form laterally extensive and continuous low-permeability baffles or barriers to flow in subsurface water aquifers and hydrocarbon reservoirs (e.g., Fryberger et al., 1990; Bloomfield et al., 2006; Bongiolo and Scherer, 2010; McKie et al., 2010; Höyng et al., 2014; Romain and Mountney, 2014).

5. Conclusions

Fluvial and aeolian processes in desert-margin settings rarely operate independently: they are usually dynamically linked and exhibit a range of sedimentary interactions between fluvial and aeolian systems that are important and widespread in modern deserts. The diverse range of system interactions gives rise to considerable complexity in terms of geomorphology, sedimentology and preserved stratigraphy. Ten distinct types of fluvial-aeolian interaction are recognised (Figure 16, Table 1): fluvial incursions aligned parallel to trend of linear chains of aeolian dune forms; fluvial incursions oriented perpendicular to trend of aeolian dunes; bifurcation of fluvial systems around the noses of aeolian dunes; through-going fluvial channel networks that cross entire aeolian dune fields; flooding of dune fields due to regionally elevated water-table levels associated with fluvial floods; fluvial incursions emanating from a single point source into dune fields; incursions emanating from multiple sheet sources; cessation of the encroachment of entire aeolian dune fields by fluvial systems; termination of fluvial channel networks in aeolian dune fields; and long-lived versus short-lived types of fluvial incursion. These interaction types form the basis for a classification scheme that can be applied to desert dune-field systems generally.

The varied range of temporal and spatial scales over which aeolian-fluvial processes interact means that simple generalised models for the classification of types of interaction must be applied with caution when interpreting ancient preserved successions, especially those known only from the subsurface. By understanding the nature and surface expression of various types of aeolian and fluvial interaction, and by considering their resultant sedimentological expression, predictions can be made about how the preserved deposits of such interactions might be recognised in the ancient stratigraphic record and assessment can be made of the spatial scale over which such interactions are likely to occur.

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Figure captions

Figure 1: Schematic model illustrating common depositional processes that operate at dune-field margins, and resultant stratigraphic relationships. No particular scale implied.

Figure 2: Google Earth image from southern Arabian Peninsula showing the location of the Rub' Al-Khali sand sea and surrounding mountains. Note the presence of alluvial systems with catchments in the mountainous regions that surround the dune fields and the fluvial drainage networks that enter the dune fields.

Figure 3: Geographic locations of the sixty studied desert systems: 1 – Rub' Al-Khali Desert, 2 – An Nafud Desert, 3 – Ad Dahna Desert, 4 – Al Jafurah Desert, and 5 – Tihama Dune Fields Saudi Arabia; 6 – Wahiba Sands, Oman; 7 – Coastal Dune Field southern Yemen; 8 – Syrian Desert, Syria; 9 – Eastern Desert, 10 – Western Desert, and 11 – Sinai Desert, Egypt; 12 – Nubian Desert, northern Sudan; 13 – Libyan Desert, eastern Sahara Desert; 14 – Idhan Murzuq Desert, Sahara Desert, Libya; 15 – Grand Erg Occidental Desert, 16 – Grand Erg Oriental Desert, 17 – Tassili-N-Ajjer Desert, 18 – Erg lguidi Desert, and 19 – Hamada Du Draa Desert, Sahara Desert, Algeria; 20 – Tassili-Oua-Ahaggar Desert, Sahara Desert, Niger; 21 – Tenere Desert, Southern Sahara Desert, Chad; 22 – El Djouf Desert, 23 – Akchar Desert, and 24 – Trarza Desert, Sahara Desert, Mauritania; 25 – Western Sahara 26 – Chalbi Desert, Kenya; 27 – Namib Desert, 28 – Skeleton Coast, and 29 – Giribes Plain, Namibia; 30 – Kalahari Desert, South Africa; 31 – Rigestan Desert, Afghanistan; 32 – Thar Desert, 33 – Kharan Desert, Baluchistan, Pakistan; 34 – Garagum Desert, Turkmenistan; 35 – Qizilqum Desert, Uzbekistan; 36 – Betpaqdala Desert, Southern Kazakhstan; 37 – Kavir Desert , and 38 – Lut Desert, Iran; 39 – Taklamakan Desert, 40 – Mu Us Desert, 41 – Gobi Desert, 42 – Turpan Desert, 43 – Gurbantünggüt Desert, 44 – Junggar Basin, and 45 – Horqin Desert, Inner Mongolia, China; 46 – Dune Fields northern Tibetan Plateau, China; 47 – Simpson Desert, 48 – Tirari Desert, 49 – Strzelecki Desert, 50 – Great Sandy Desert, 51 – Great Victoria Desert, and 52 – Tanami Desert, Australia; 53 – White Sand Desert, New Mexico, 54 – Algodones Dune Field southeastern California, and 55 – Mojave Desert, California, United States; 56 – Sonoran Desert, Northeastern Mexico; 57 – Marayes Dune Field, and 58 – Vallecito Dune Field, Monte Desert, Argentina 59 – Salinas Grandes Desert, Argentina; 60 – Lençóis Maranhenses, or Brazilian Sahara, Brazil.

Figure 4: Examples of fluvial incursions oriented parallel to trend of the crestlines of aeolian dune forms. (a) Northern Simpson Desert, Australia (24 23 07 S 135 28 24 E); (b) Kharan Desert, Baluchistan Province, Pakistan (28 16 54 N 65 29 20 E). See text for discussion.

Figure 5: Examples of mobile dunes occupying fluvial channel courses. (a) Sahara Desert, Northern Chad (19 59 03 N 19 31 19 E); (b) Gurbantünggüt Desert, northwestern China (44 24 03 N 91 05 17 E). See text for discussion. (Image source: Google Earth Pro).

Figure 6: Examples of fluvial incursions oriented perpendicular to trend of the crestlines of aeolian dune forms. (a) Wahiba Sand Sea, Oman (22 25 19 N 58 49 11 E); (b) Namib Desert, Namibia (23 40 59 S 15 14 16 E). See text for discussion. (Image source: Google Earth Pro).

Figure 7: (a) Example of ephemeral fluvial channel network between star draa, southeastern Rub' Al-Khali Desert, Oman (18 31 24 N 53 22 06 E). (b) Example of intricate threading of fluvial channels between migrating aeolian dunes and small disconnected dune fields in the Taklamakan Desert, China (38 22 42 N 81 53 46 E). (Image source: Google Earth Pro).

Figure 8: Examples of through-going fluvial channel networks that cross entire aeolian dune fields. (a) Eastern Sahara Desert (18 55 06 N 30 33 47 E); (b) Tirari Desert, Australia (27 49 13 S 137 37 34 E). (Image source: Google Earth Pro).

Figure 9: Examples of fluvial flooding of aeolian dune fields associated with elevated water-table level. (a) Gobi Desert, northern China (39 46 11 N 102 09 00 E); average interdune width is 1.13 km. (b) Al Jafurah Desert, eastern Saudi Arabia (25 47 17 N 49 48 28 E); progressive migration of barchan dunes across a damp, water table-controlled surface. Note how lee-slope strata of the lowermost flanks for the migrating barchans have been left as a record of the passage of the dunes. (Image source: Google Earth Pro).

Figure 10: Examples of fluvial incursions into aeolian dune fields associated with a single point source. (a) White Sands, New Mexico, USA (32 51 54 N 106 12 11 W); (b) Grand Erg Occidental Desert, northern Sahara Desert, Algeria (32 30 19 N 00 08 39 W). The maximum extent of fluvial channel penetration into the dune field is 5 km. (Image source: Google Earth Pro).

Figure 11: Examples of fluvial incursions into aeolian dune fields associated with a sheet source. (a) Sonoran Desert, northwestern Mexico (31 28 13 N 112 55 36 W); (b) Gobi Desert, north China (41 36 31 N 101 58 43E). Note the area of fluvial encroachment into the aeolian system. (Image source: Google Earth Pro).

Figure 12: Examples of the cessation of encroachment of aeolian dune fields by fluvial systems. (a) Namib Desert, Namibia (17 15 29 S 11 49 17 E); (b) Mu Us Desert, northern China (40 04 26 N 106 44 06 E). Note the direction of the resultant aeolian sand drift direction. (Image source: Google Earth Pro).

Figure 13: Examples of termination of fluvial channel networks in aeolian dune fields. (a) Skeleton Coast, Namibia (20 01 46 S 13 16 17 E); (b) Simpson Desert, Australia (24 10 29 S 135 15 53 E); (c) Trarza Desert, Mauritania (19 33 58 N 13 19 54 W) showing the recent flooding. (Image source: Google Earth Pro).

Figure 14: Examples of long-term versus short-term fluvial-aeolian interaction. In modern dryland systems many examples demonstrate how fluvial channels subject to ephemeral flow have been blocked by encroaching aeolian sediment. This usually occurs during the dry season or during drought episodes that are sufficiently long-lived to allow aeolian deposits to accumulate in fluvial channels. Episodic floods act to flush out the system and promote the development of vegetation at later stage. (a) Eastern Sahara Desert, Egypt (23 09 39 N 30 42 44 E); (b) Hamada Du Draa Desert, Algeria (28 58 03 N 4 02 14 W). (Image source: Google Earth Pro).

Figure 15: Examples of aeolian system expansion and contraction. (a) Taklamakan Desert, China. (37 46 00 N 81 27 30 E). (b) Namib Desert, Namibia (24 43 41 S 15 20 40 E); depicts various types of fluvial-aeolian system interaction and their geomorphic and sedimentary impact. Note the fluvial terminations within the dune fields, where large-scale dune bedforms have acted to pond flood waters and limit the extent of fluvial incursion. Playa deposits result in the generation of a significant surface crust of calcrete or gypcrete (white colour on the image) where flood waters have repeatedly ponded. (c) Southeastern Sahara, Sudan (15 39 11 N 26 25 44 E); shows vegetation development within a repeatedly flooded interdune and on the lower flanks of adjacent aeolian dunes; the presence of vegetation may act to partially stabilize the aeolian system. (d) Rigestan Desert, Afghanistan (31 22 26 N 65 53 19 E); demonstrates the role of fluvial flooding in controlling aeolian dune-field expansion and contraction. (Image source: Google Earth Pro).

Figure 16: Schematic model summarising the classification of types of aeolian-fluvial system interaction. Numbers in black boxes relate to the ten types of fluvial-aeolian system

interaction discussed in the text and listed in Table 1. The frequency of types of interaction for the 130 case studies listed in Table 1 is indicated.

Table caption

Table 1: Scheme for the classification of types of aeolian-fluvial system interaction, with 130 notable case-study examples documented from 60 modern desert systems. Column labelled "Fig. 3" provides a cross-reference to the desert locations shown in Figure 3. Abbreviations for aeolian bedform types: S – star; Cs – complex star; Br – barchan; Bi – barchanoid ridges; SB – superimposed barchanoid ridges; T – transverse; L – linear; P – parabolic; Cb – compound barchan; R – reverse; D – dome; SS – Sand sheets.

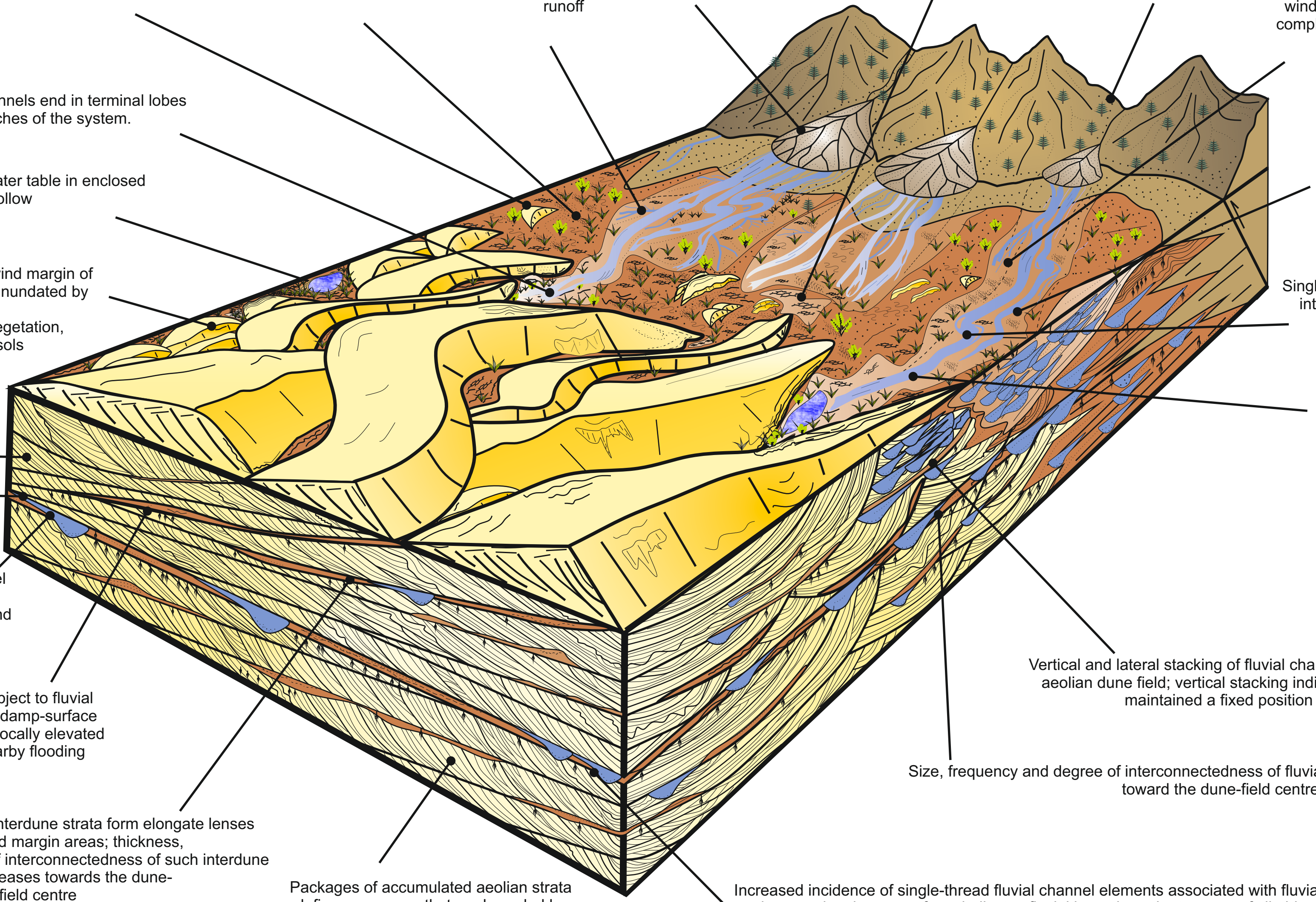
Table 1: Scheme for the classification of types of aeolian-fluvial system interaction.

Interaction type	Case Study No.	Example Desert	Desert No. (see Fig. 3)	Case Study Location	Dune spacing at outer dune-field margin (km)	Dune spacing at inner dune-field margin (km)	Interdune width at outer dune-field margin (km)	Interdune width at inner dune-field margin (km)	Mean fluvial channel width (m)	Fluvial channel extent within dune-field (km)	Dominant aeolian bedform type
1: Fluvial incursions oriented parallel to trend of aeolian dune forms	1	Southern El Djouf Desert, Mauritania	22	18 04 17 N 11 11 09 W	2.26	1.51	2.21	1.40	244	114	L/T
	2	Western Idhan Murzuq Desert, Libya	14	24 34 52 N 11 43 59 E	3.38	1.64	3.31	1.35	21	13	Bi
	3	Southwestern Rub' Al-Khali Desert	1	16 46 26 N 45 25 39 E	4.32	1.42	4.10	1.52	68	58	L
	4			17 01 50 N 45 16 23 E	4.65	1.17	4.20	0.35	80	34	L
	5	Grand Erg Oriental Desert, Algeria	16	29 00 56 N 04 36 20 E	2.40	1.30	2.10	1.62	31	15	L
	6	Northern Simpson Desert , Australia	47	24 23 07 S 135 28 24 E	0.51	0.19	0.45	0.45	67	29	L
	7			24 03 46 S 135 55 26 E	1.91	0.18	1.82	0.42	62	33	L
	8	Kharan Desert, Baluchistan, Pakistan	33	28 16 54 N 65 29 20 E	1.40	0.45	1.25	1.01	57	27	T/Bi
2: Fluvial incursions oriented perpendicular to the trend of aeolian dune forms	9	Mu Us Desert, China	40	40 22 29 N 109 18 00 E	1.6	0.49	1.40	0.18	50	07	Bi
	10	Wahiba Sand Sea, Oman	6	22 25 19 N 58 49 11 E	1.90	1.60	1.60	1.07	327	120	L
	11	Eastern Rub' Al-Khali Desert, Saudi Arabia	1	19 10 06 N 44 24 58 E	0.18	0.13	0.15	0.10	36	06	Bi/T
	12	Namib Desert, Namibia	27	23 40 59 S 15 14 16 E	2.21	1.60	1.90	1.45	205	147	L
	13	Southern Simpson Desert, Australia	47	27 13 18 S 137 56 43 E	0.81	0.17	0.75	0.45	124	89	L
	14	Northern Simpson Desert, Australia	47	24 15 14 S 135 35 09 E	0.83	0.18	0.72	0.42	148	16	L
	15	Strzelecki Desert, Australia	49	28 25 11 S 138 56 35 E	1.35	0.78	1.12	0.40	133	198	L
	16	Kharan Desert, Baluchistan, Pakistan	33	27 46 16 N 63 48 19 E	2.31	0.24	2.11	0.04	165	86	Bi/L
	17	Tassili-N-Ajjer Desert, Sahara, Algeria	17	26 32 28 N 07 53 49 E	3.39	2.80	2.90	1.21	460	53	CS/L
	18	West Salinas Grandes Desert, Argentina	59	31 45 04 S 67 04 05 W	0.15	0.13	0.10	0.07	260	20	L
3: Bifurcation of fluvial flow between isolated aeolian dune forms	19	Rub' Al-Khali Desert, Oman	1	18 31 24 N 53 22 06 E	1.30	1.27	0.90	1.67	18	32	S
	20			18 27 00 N 53 12 06 E	1.40	1.10	1.00	1.19	82	20	S
	21			18 35 23 N 53 25 35 E	1.85	1.38	1.50	1.47	73	39	S/Cs
	22	Rub' Al-Khali Desert, Northeastern Yemen	1	18 37 12 N 51 24 40 E	3.03	1.57	2.60	2.43	120	7.61	S/CS/D
	23	Tenere Desert, Southern Sahara Desert, Chad	21	13 40 22 N 16 16 34 E	2.70	1.87	2.10	2.20	188	135	T/Br
	24	Taklamakan Desert, China	39	38 22 42 N 81 53 46 E	1.46	1.58	1.20	1.67	74	161	Cb/SB
	25	Horqin Desert, Inner Mongolia, China	45	43 12 45 N 118 48 25E	0.69	0.48	0.53	0.22	134	06	T
	26	Dune Field southern Tibetan Plateau, China	46	29 55 57 N 83 31 48 E	0.66	0.34	0.73	0.14	63	60	Br
4: Through-going	27	Mu Us Desert, China	40	40 15 15 N 109 46 35E	0.16	0.15	0.11	0.04	74	17	Bi
	28	Eastern Grate Victoria Desert, Australia	51	28 57 46 S 135 56 51 E	0.98	0.62	0.85	0.35	138	98	L
	29	Tirari Desert, Australia	48	27 49 13 S 137 37 34 E	1.17	0.48	1.12	0.26	182	162	L
	30	Southern Libyan Desert, Sudan	13	15 42 49 N 26 27 06 E	0.49	0.31	0.35	0.08	116	97	Bi/SS
	31	Nile River, eastern Sahara Desert/Sudan	12-13	18 55 06 N 30 33 47 E	0.49	0.31	0.41	1.23	620	800	Br
	32	Tihama Dune Fields, Saudi Arabia	5	19 26 36 N 41 06 29 E	0.35	0.11	0.31	0.24	142	34	Br/SS

fluvial channel networks that cross entire aeolian dune fields	33	Sinai Desert, Egypt	11	30 56 43 N 33 57 26 E	0.49	0.32	0.42	0.17	57	56	Cb/L
	34	Southern El Djouf Desert, Mali	22	16 57 07 N 01 52 06 W	2.04	0.96	1.90	1.80	561	500	L
	35	Holtan River, Taklamakan Desert, China	39	39 15 31 N 80 52 22 E	2.28	0.12	2.10	0.10	157	396	Bi/SB/Cb
	36	Garagum Desert, Turkmenistan	34	40 17 42 N 61 50 23 E	2.45	0.16	2.20	0.18	475	275	SB/Br
	37	Kalahari Desert, South Africa	30	25 06 26 S 20 20 37 E	0.75	0.26	0.68	0.21	90	602	L
	38	Horqin Desert, Inner Mongolia, China	45	43 07 51 N 119 17 45E	0.28	0.22	0.14	0.07	48	42	T/Br
	39	Grand Erg Occidental Desert, Algeria	15	29 07 22 N 01 01 50 W	6.90	0.11	5.09	0.03	115	289	Cs/T/SB
5: Fluvial flooding of aeolian dune fields associated with elevated water-table level	40	Gobi Desert, northern China	41	39 46 11 N 102 09 00 E	4.23	2.99	1.13	2.59	NA	NA	SB
	41			38 40 42 N 104 54 15 E	2.70	3.22	1.90	0.86	NA	NA	T/Br
	42	Taklamakan Desert, China	39	40 54 43 N 85 30 27 E	1.42	1.24	0.95	0.51	NA	NA	Cb
	43	Al Jafurah Desert, Eastern Saudi Arabia	4	25 47 17 N 49 48 28 E	0.62	0.51	0.38	0.15	NA	NA	T/Br
	44	North-eastern Rub Al-Khali, Saudi Arabia	1	24 26 14 N 51 09 37 E	0.83	0.91	0.67	0.45	NA	NA	Br/T
	45	Western Desert, Egypt	10	29 08 13 N 25 26 33 E	2.64	0.69	1.30	0.51	NA	NA	L/SB
	46	Northern Grand Erg Oriental Desert ,Tunisia	16	33 37 35 N 07 56 32 E	2.30	0.38	0.97	0.15	NA	NA	L
	47	Libyan Desert, Northeastern Chad	13	18 56 52 N 20 51 36 E	NA	0.57	NA	0.21	NA	NA	Br/Bi
	48	Tenere Desert, Southern Sahara Desert, Chad	21	14 35 38 N 14 42 29 E	3.85	2.65	2.40	0.63	NA	NA	T
	49	Betpaqdala Desert, Southern Kazakhstan	36	43 32 33 N 72 18 11 E	1.65	2.80	0.97	1.65	NA	NA	Br/Bi
	50	Thar Desert, Pakistan	32	26 23 01 N 69 45 01 E	4.11	0.67	2.10	0.22	NA	NA	SB/Bi
	51	Lençóis Maranhenses Desert, Brazil	60	02 34 31 S 42 57 03 W	0.43	0.54	0.27	0.27	NA	NA	Br/Bi/T
	52	Great Victoria Desert, Australia	51	28 39 16 S 128 20 58 E	1.31	1.42	0.65	0.63	NA	NA	L
	53	Dune Field northern Tibetan Plateau, China	46	37 04 20 N 90 33 05 E	1.14	0.70	0.53	0.22	NA	NA	Cs/Bi
	54	Mu Su Desert, China	40	39 14 43 N 108 50 36 E	0.52	0.34	0.37	0.18	NA	NA	T/Br/Bi
	55	Horqin Desert, Inner Mongolia, China	45	42 57 47 N 119 33 38E	0.71	0.61	0.42	0.23	NA	NA	T/Br/Bi
6: Fluvial incursions into aeolian dune fields associated with a single point source	56	Giribes Plain, Namibia	29	19 01 34 S 13 21 34 E	NA	NA	NA	NA	32	2.91	SS
	57	Southern Kavir Desert ,Iran	37	33 36 37 N 53 45 55 E	2.14	1.26	1.42	0.25	26	17	L/Bi
	58	Simpson Desert, Australia	47	24 08 55 S 135 13 56 E	1.74	1.68	1.33	1.24	15	05	L/SS
	59	Sonoran Desert, Northwestern Mexico	56	32 03 08 N 113 37 37 W	0.38	0.56	0.28	0.09	13	04	L
	60			34 12 03 N 115 16 50 W	0.31	0.38	0.12	0.04	04	06	D/SS
	61	White Sand Desert, USA	53	32 51 54 N 106 12 11W	0.21	0.16	0.10	0.06	07	05	T/Br/P
	62	Grand Erg Occidental Desert, Algeria	15	32 26 55 N 00 10 53 E	3.35	3.16	2.20	0.67	262	135	T/L/Br
	63			32 30 19 N 00 08 39 W	0.19	0.80	0.12	0.04	63	03	L
	64	Libyan Desert, central Sahara Desert, Libya	13	23 55 43 N 19 46 42 E	3.57	3.07	2.73	0.49	105	09	L
	65	Tenere Desert, central Sahara Desert, Chad	21	19 23 40 N 16 37 02 E	1.00	0.88	0.57	0.36	187	93	T/Bi/SB
	66	Akchar Desert, Mauritania	23	20 42 53 N 11 59 50 W	0.32	0.12	0.27	0.03	127	10	Br/Bi/L
	67	Erg lguidi Desert, Algeria	18	27 31 26 N 03 45 48 W	2.30	3.60	1.20	2.30	112	22	S/L
	68	Sonoran Desert, Northwestern Mexico	56	31 28 13 N 112 55 36 W	0.56	0.26	0.46	0.19	228	08	L/Bi
	69			31 45 29 N 113 08 19 W	0.37	0.17	0.27	0.07	397	07	L/Bi
	70	Algodones Dune Field, south California, USA	54	33 06 00 N 115 14 44 W	1.48	0.43	0.75	0.15	244	02	T/Bi
	71	Tassili-N-Ajjer Desert, Algeria	16	26 43 05 N 06 54 04 E	6.08	2.96	3.94	0.96	240	02	Cs/SB/L

7: Fluvial incursions into aeolian dune fields associated with a multiple sheet source	72	Hamada Du Draa Desert, Algeria	19	29 54 39 N 03 08 59 W	0.71	1.14	0.48	0.34	385	1.6	Cs
	73	Akchar Desert, Mauritania	23	21 26 46 N 11 42 37 W	0.53	0.32	0.35	0.07	387	1.74	Bi/SB/L
	74	Southern Kavir Desert ,Iran	37	33 32 33 N 53 56 43 E	1.74	1.25	1.09	0.41	580	06	Br/Bi
	75	Lut Desert, Iran	38	30 03 51 N 59 37 57 E	0.43	2.41	0.12	0.51	1200	07	T/S/L
	76	Kharan Desert, Baluchistan, Pakistan	33	28 47 10 N 64 23 01 E	0.31	0.11	0.09	0.05	289	2.4	T/Bi/SB
	77	Betpaqdala Desert, Southern Kazakhstan	36	44 17 57 N 68 43 37 E	0.82	1.12	0.53	0.49	269	540	Bi/T
	78	Gobi Desert, northern China	41	41 36 31 N 101 58 43 E	0.83	1.44	0.38	0.24	197	0.86	S/Bi
	79	Mojave Desert, California	55	34 56 27 N 115 39 10 W	0.35	0.18	0.17	0.05	377	0.91	Bi/SB
8: Cessation of encroachment of aeolian dune fields by fluvial systems	80	Qizilqum Desert, Uzbekistan	35	44 12 28 N 66 08 20 E	1.30	0.27	0.64	0.09	326	589	T/Bi
	81	Kuiseb River, Namib Desert	27	23 30 21 S 14 59 00 E	2.28	2.25	0.97	0.77	307	150	L/Bi
	82	Swakop River, Namib Desert	27	22 41 14 S 14 32 36 E	0.12	0.21	0.13	0.08	185	04	L/Bi
	83	Kunene River, Namib Desert	27	17 15 29 S 11 49 17 E	0.42	0.49	0.17	0.03	180	63	Bi/SB/Br
	84	Hoarusib River, Skeleton Coast, Namibia	28	19 01 15 S 12 39 07 E	0.61	0.41	0.37	0.17	274	26	Bi/SB/Cb
	85	North Namib Desert, Angola	27	16 17 40 S 12 16 23 E	0.17	0.28	0.04	0.18	119	08	Bi/SB
	86			15 46 50 S 11 59 01 E	0.18	0.27	0.04	0.06	462	86	Bi
	87	Yellow River, Mu Us Desert , China	40	40 04 26 N 106 44 06 E	0.28	0.27	0.19	0.04	687	147	Bi/SB/T
	88			40 06 38 N 110 40 57 E	0.33	0.11	0.19	0.03	53	10	Bi/T
	89	Irtysh River, Junggar Basin, Northwestern China	44	47 57 22 N 85 42 40 E	0.22	0.40	0.33	0.08	342	100	Bi/T
	90	Tuolahai River, Northern Tibetan Plateau, China	46	36 42 06 N 94 30 03 E	0.33	0.17	0.41	0.09	232	24	Br/T
	91	Vallecito Dune Field, Monte Desert, Argentina	58	31 52 15 S 67 49 43 W	1.98	2.34	1.04	0.35	116	50	L/Bi/SB
	92	Marayes Dune Field ,Monte Desert, Argentina	57	31 22 32 S 67 29 52 W	1.07	1.47	0.41	0.17	258	27	L/Bi
	93	Helmand River, Rigestan Desert, Afghanistan	31	31 22 34 N 65 53 27 E	0.22	0.18	0.09	0.04	218	176	Bi/SB
	94	Euphrates River, Northern Syrian Desert, Syria	8	34 50 25 N 40 24 35 E	NA	NA	NA	NA	391	65	SS
	95	Chalbi Desert, Kenya	26	02 51 35 N 37 45 13 E	0.26	0.13	0.16	0.02	75	16	L/SS
	96	Nile River, Western Desert, Egypt	10	28 12 00 N 30 31 26 E	0.59	0.23	0.31	0.04	643	364	Bi/SB/SS
	97	Northern Hamada Du Draa Desert, Morocco	19	31 33 00 N 04 31 21 W	0.07	0.04	0.05	0.02	55	13	T/Br
9: Termination of fluvial channel networks in aeolian dune fields	98	Coastal Dune Field southern Yemen	7	14 17 22 N 47 54 39 E	3.42	1.34	1.83	0.15	189	11	Bi/SB
	99	An Nafud Desert, Saudi Arabia	2	24 22 58 N 46 14 14 E	2.07	1.08	0.72	0.29	53	04	Bi/SB/D
	100	Tassili-Oua-Ahaggar Desert, Sahara , Niger	20	20 06 00N 08 37 51 E	1.73	0.43	0.74	0.05	40	03	S/R/Bi
	101	Tenere Desert, Sahara, Niger	21	19 20 29 N 16 34 23 E	0.58	0.27	0.38	0.12	165	101	T/Bi
	102	Ad Dahna Desert, Saudi Arabia	3	25 17 40 N 47 24 12 E	5.42	7.38	2.46	2.69	68	03	Bi/SB
	103			25 20 58 N 47 17 31 E	5.63	8.56	3.34	2.28	67	01	Bi/SB
	104	Taklamakan Desert, China	39	37 41 22 N 82 41 28 E	3.53	3.07	1.24	1.35	199	95	L/Br
	105	Turpan Desert, China	42	42 31 06 N 90 21 53 E	1.12	1.99	0.65	0.37	95	04	Cs/T/R
	106	White Sand Desert, USA	53	32 57 57 N 106 14 03 W	0.59	0.10	0.59	0.03	46	12	T/Br/P
	107	Sonoran Desert, Northwestern Mexico	56	31 50 15 N 113 11 39 W	0.42	0.24	0.33	0.18	78	06	Bi/L/SS
	108	Gurbantünggüt Desert, Northwestern China	43	44 26 50 N 89 20 33 E	0.36	0.24	0.18	0.06	102	53	L/Bi
	109	Lut Desert, Iran	38	29 37 35 N 58 50 09 E	2.60	2.05	1.78	0.21	108	04	Bi/L
	110	Great Sandy Desert, Australia	50	22 09 41 S 122 55 00 E	1.50	0.33	1.02	0.26	188	68	L

	111	Simpson Desert, Australia	47	24 10 29 S 135 15 53 E	0.63	0.35	0.55	0.25	115	11	L
	112	Vallecito Dune Field, Monte Desert, Argentina	58	31 49 59 S 67 53 02 W	1.23	1.47	0.63	0.19	41	08	L/Bi/SB
	113	Tsondabvlei, Namib Desert, Namibia	27	23 55 37 S 15 22 36 E	2.67	2.08	1.89	0.98	40	60	L/S/Bi
	114	Namib Desert, Angola	27	16 22 05 S 12 09 36 E	0.15	0.22	0.09	0.03	135	1.5	SB/T
	115	Trarza Desert, Mauritania	24	19 33 58 N 13 19 54 W	7.22	3.45	3.69	1.32	61	05	Bi/SB/Br
	116	Skeleton Coast, Namibia	28	19 57 15 S 13 12 24 E	0.88	0.27	0.64	0.12	99	1.4	SB/Bi/L
	117			20 01 46 S 13 16 17 E	0.38	0.26	0.29	0.06	145	03	SB/Bi/L
	118	Western Sahara	25	27 09 45 N 13 15 10 W	0.84	0.14	0.73	0.08	40	58	Bi/Br/Cb
10: Examples of short-term versus long-term fluvial-aeolian interaction	119	Southeastern Libyan Desert, Sudan	13	15 39 11 N 26 25 44 E	0.48	0.42	0.28	0.20	84	09	T/SS
	120	Western Libyan Desert, North Chad	13	19 59 03 N 19 31 19 E	0.14	0.35	0.05	0.11	374	30	Br/Cb/L
	121	Hamada Du Draa Desert, Algeria	19	28 58 03 N 04 02 14 W	6.56	4.81	3.84	3.86	217	23	Bi/S/L
	122			28 52 38 N 04 02 13 W	5.35	2.46	2.89	1.12	410	NA	Bi/S/L
	123	Eastern Sahara Desert, Egypt	9	23 09 39 N 30 42 44 E	0.57	0.28	0.34	0.04	NA	NA	Bi/Cb/D
	124	Great Sandy Desert, Australia	50	22 38 00 S 123 18 36 E	1.23	0.76	0.97	0.40	NA	NA	L
	125			22 18 10 S 128 56 12 E	2.87	0.26	5.56	0.18	NA	NA	L
	126	Tanami Desert, Australia	52	19 23 02 S 131 35 10 E	2.04	1.05	1.67	0.75	NA	NA	L
	127	Gurbantünggüt Desert, Northwestern China	43	44 24 03 N 91 05 17 E	0.22	0.23	0.13	0.09	NA	NA	T/Bi
	128	Betpaqdala Desert, , Southern Kazakhstan	36	43 34 11 N 72 12 56 E	8.71	4.01	5.28	1.21	NA	NA	Bi
	129	Taklamakan Desert, China	39	37 55 41 N 81 28 49 E	1.48	2.18	0.98	0.61	NA	NA	Cb/SB
	130			37 56 35 N 81 32 18 E	1.48	2.18	0.98	0.61	NA	NA	Cb/SB



Smaller, non-climbing barchan dunes at lateral aeolian dune-field margin

Extensive areas of palaeosol development

Fluvial splays and floodouts during periods of increased runoff

Large alluvial fans at mountain front

Playa deposits

Highlands; major sediment source

Inter-channel-belt regions dominated by non-confined fluvial sheet-like bodies, wind-blown (loessite) sheets, isolated dune complexes; colonisation by sparse vegetation and development of calcisols

Terminal fluvial system; channels end in terminal lobes within the distal reaches of the system.

Interdune pond; elevated water table in enclosed interdune hollow

Damp interdune flats at upwind margin of aeolian dune field; may be inundated by sheet-like non-confined fluvial flows; vegetation, bioturbation, calcisols

Predominately aeolian dunes with limited evidence for fluvial incursion

Supersurface

Only small, single-thread fluvial channel elements tend to reach dune-field centre settings and these tend to be relatively uncommon

Interdunes that are not subject to fluvial incursion may accumulate damp-surface adhesion structures due to locally elevated water table related to nearby flooding

Climbing damp and wet interdune strata form elongate lenses within dune-field margin areas; thickness, lateral extent and degree of interconnectedness of such interdune deposits decreases towards the dune-field centre

Packages of accumulated aeolian strata define sequences that are bounded by supersurfaces

Laterally extensive ephemeral, medial channel belts flowing across a low-gradient fluvial plain

Single- or multi-thread fluvial channels pass into the dune field along poorly defined channel networks

Distance of fluvial incursion along interdune corridors is controlled by the magnitude of the flood and the length of the open corridor; in this example the corridors are closed off by merging dune bedforms and the distance of fluvial penetration is therefore limited

Vertical and lateral stacking of fluvial channel elements at the outer margin of aeolian dune field; vertical stacking indicates a dune-field margin that has maintained a fixed position for a protracted period

Size, frequency and degree of interconnectedness of fluvial channel elements decreases toward the dune-field centre

Increased incidence of single-thread fluvial channel elements associated with fluvial incursions across desert plain directly above regional supersurface; indicates fluvial incursion prior to onset of climbing associated with next major phase of aeolian system accumulation

Figure 1

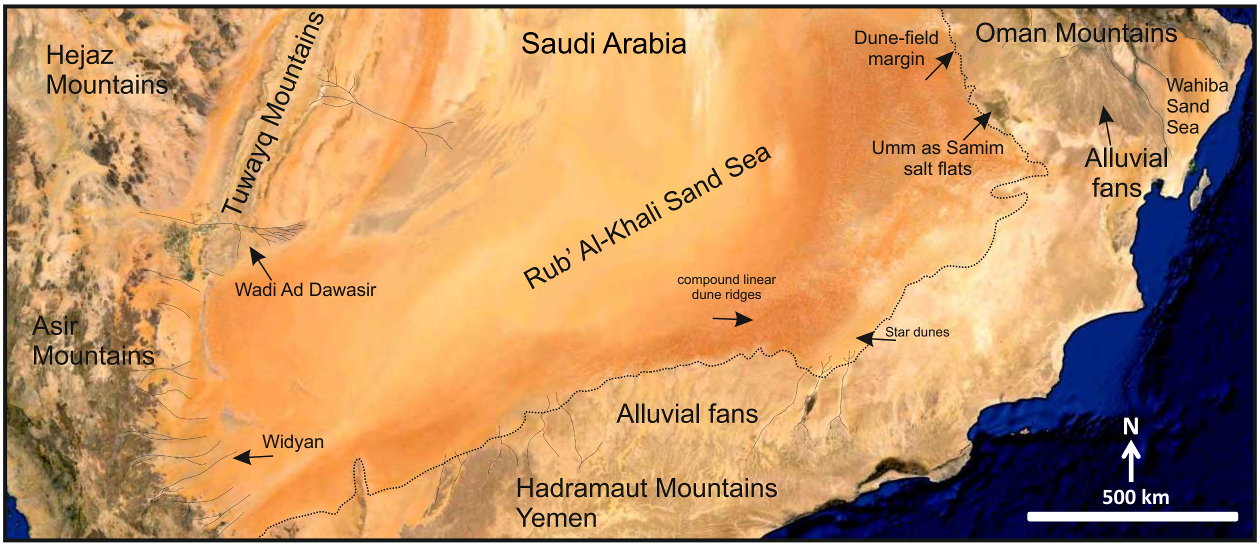
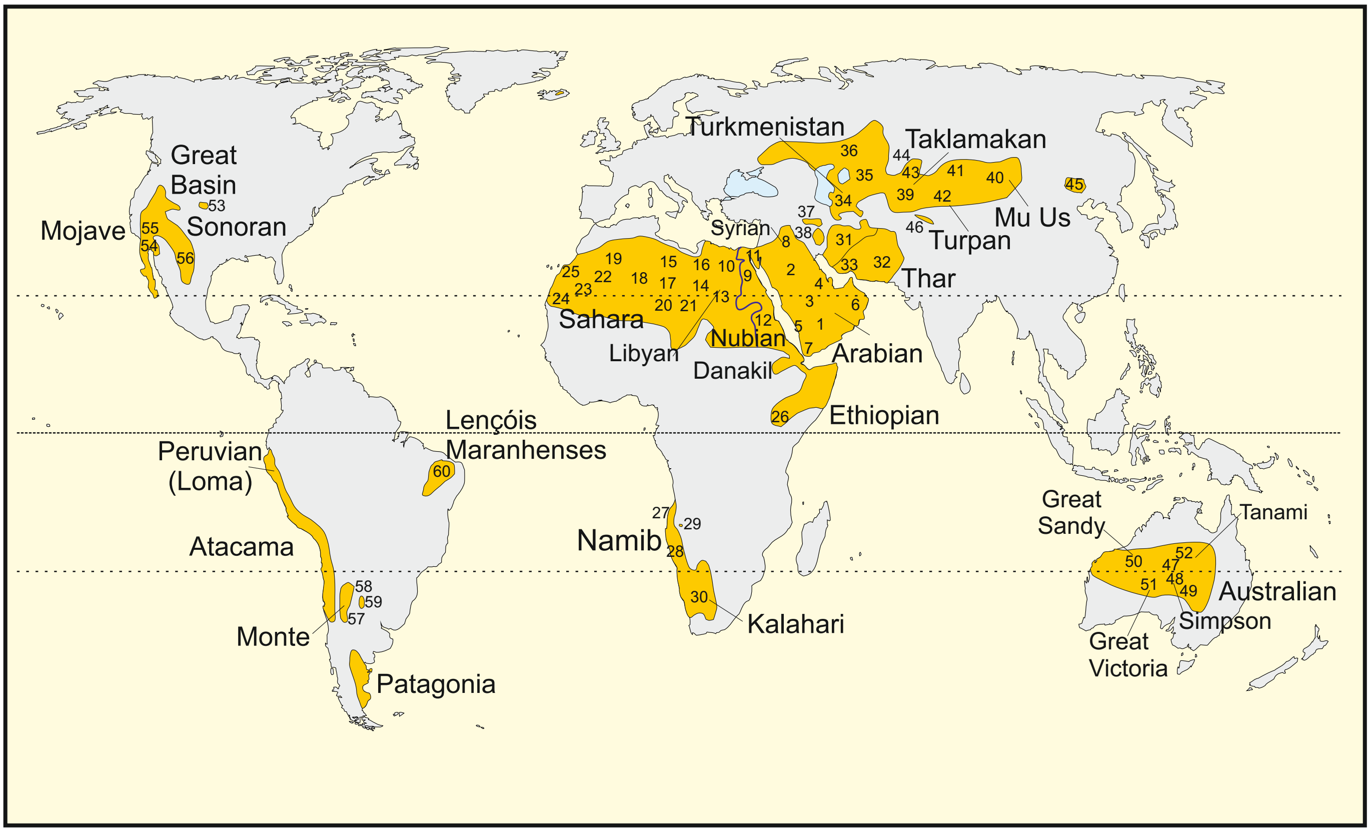

Hejaz Mountains
Tuwayq Mountains
Saudi Arabia
Dune-field margin
Oman Mountains
Wahiba Sand Sea
Umm as Samim salt flats
Alluvial fans
Rub' Al-Khali Sand Sea
Wadi Ad Dawasir
compound linear dune ridges
Star dunes
Asir Mountains
Alluvial fans
Widyan
Hadramaut Mountains
Yemen
N
500 km

Figure 2


Turkmenistan
Taklamakan
Great Basin
Mojave
Sonoran
Mu Us
Turpan
Syrian
Thar
Sahara
Libyan
Nubian
Danakil
Arabian
Ethiopian
Lençóis Maranhenses
Peruvian (Loma)
Atacama
Monte
Patagonia
Namib
Kalahari
Great Sandy
Tanami
Australian
Simpson
Great Victoria
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
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37
38
39
40
41
42
43
44
45
46
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48
49
50
51
52
53
54
55
56
57
58
59
60

Figure 3

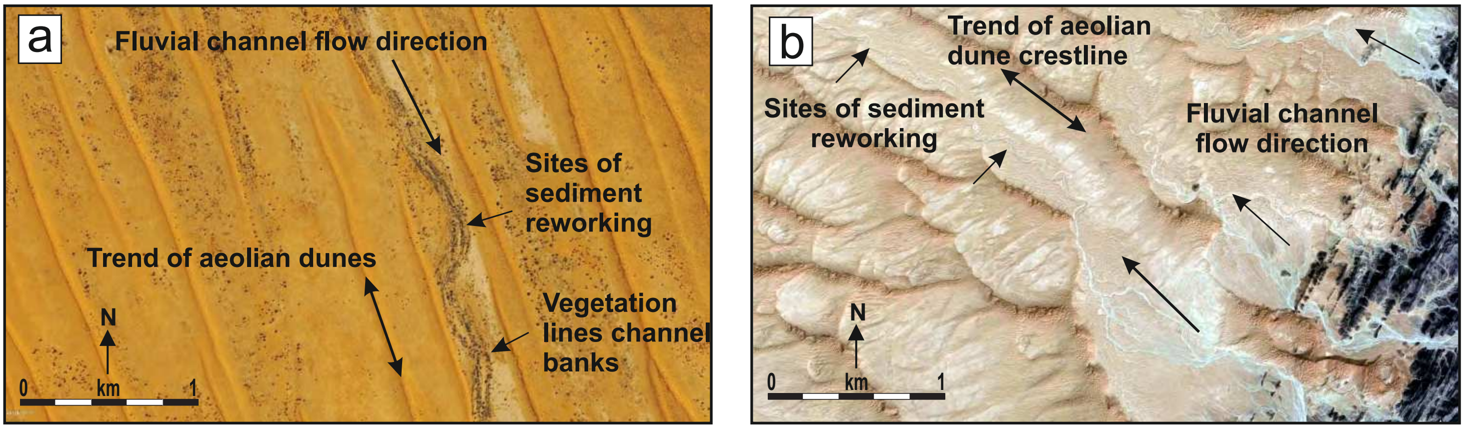
a
Fluvial channel flow direction
Sites of sediment reworking
Trend of aeolian dunes
Vegetation lines channel banks
N
0
km
1
b
Trend of aeolian dune crestline
Sites of sediment reworking
Fluvial channel flow direction
N
0
km
1

Figure 4

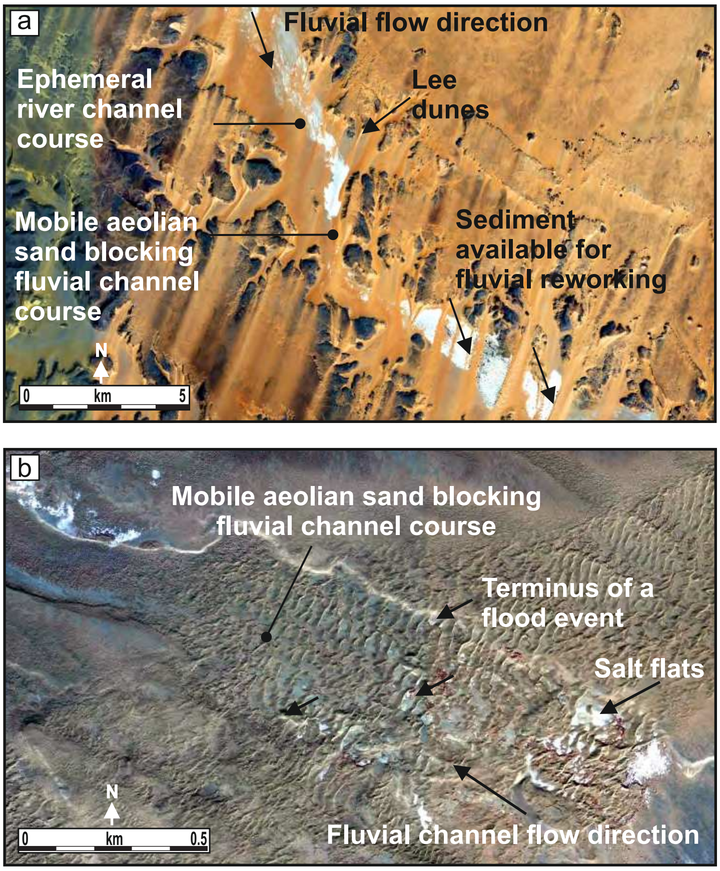
a
Fluvial flow direction
Ephemeral river channel course
Lee dunes
Mobile aeolian sand blocking fluvial channel course
Sediment available for fluvial reworking
N
0 km 5
b
Mobile aeolian sand blocking fluvial channel course
Terminus of a flood event
Salt flats
N
0 km 0.5
Fluvial channel flow direction

Figure 5

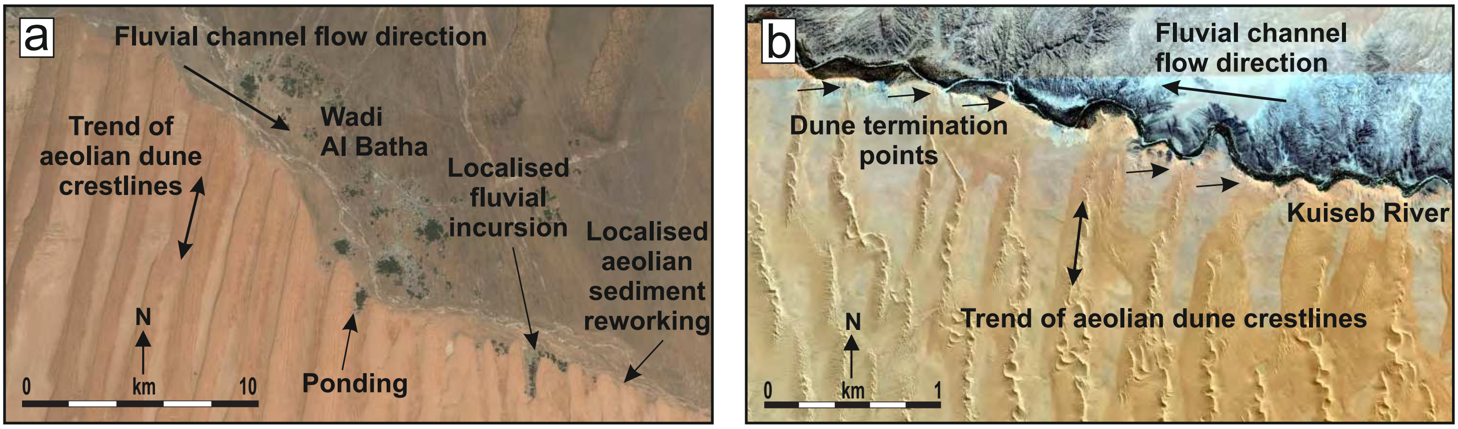
a
Fluvial channel flow direction
Trend of aeolian dune crestlines
Wadi Al Batha
Localised fluvial incursion
Localised aeolian sediment reworking
N
0
km
10
Ponding
b
Fluvial channel flow direction
Dune termination points
Kuiseb River
Trend of aeolian dune crestlines
N
0
km
1

Figure 6

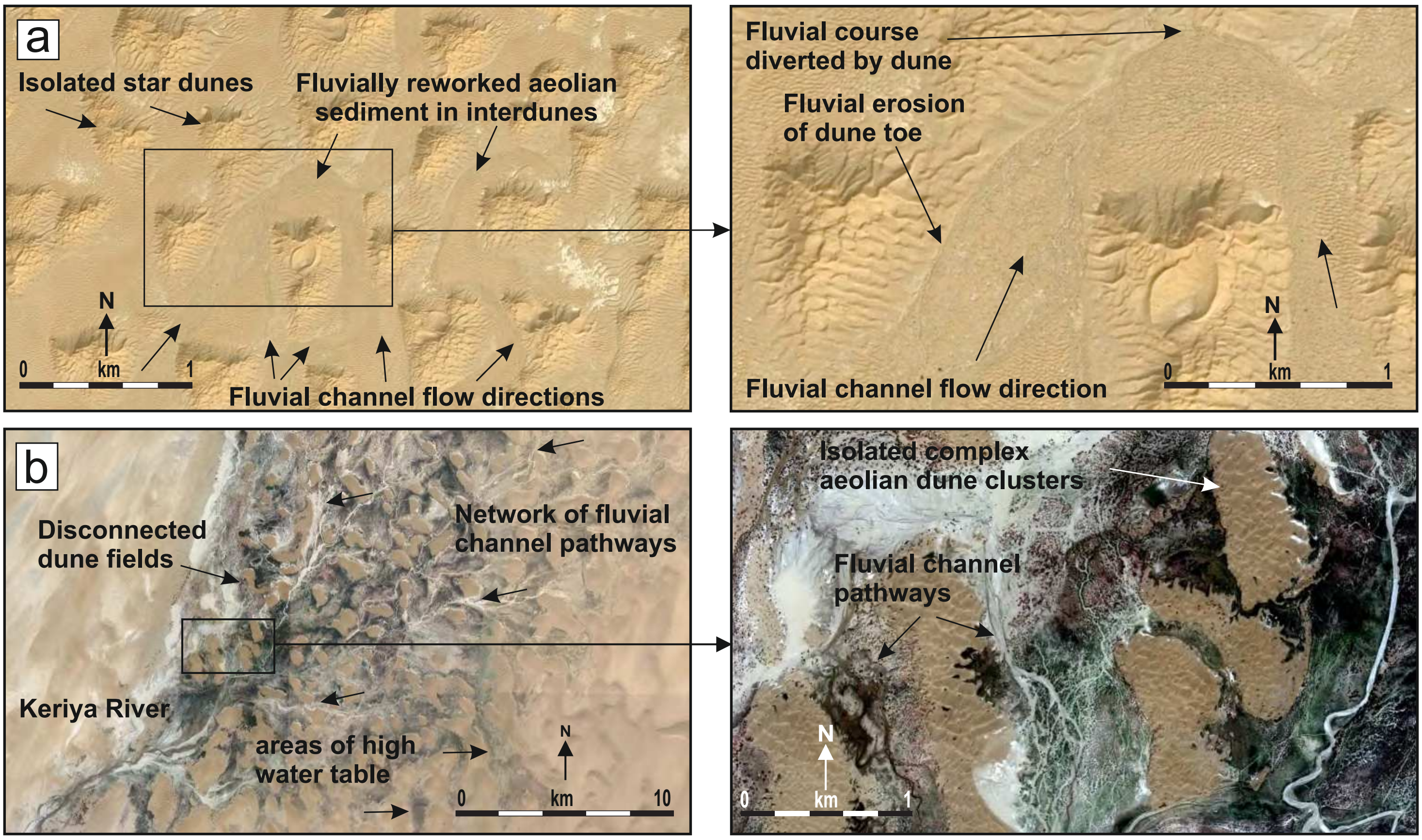
a
Isolated star dunes
Fluvially reworked aeolian sediment in interdunes
N
0
km
1
Fluvial channel flow directions
Fluvial course diverted by dune
Fluvial erosion of dune toe
N
0
km
1
Fluvial channel flow direction
b
Disconnected dune fields
Network of fluvial channel pathways
Keriya River
areas of high water table
N
0
km
10
Isolated complex aeolian dune clusters
Fluvial channel pathways
N
0
km
1

Figure 7

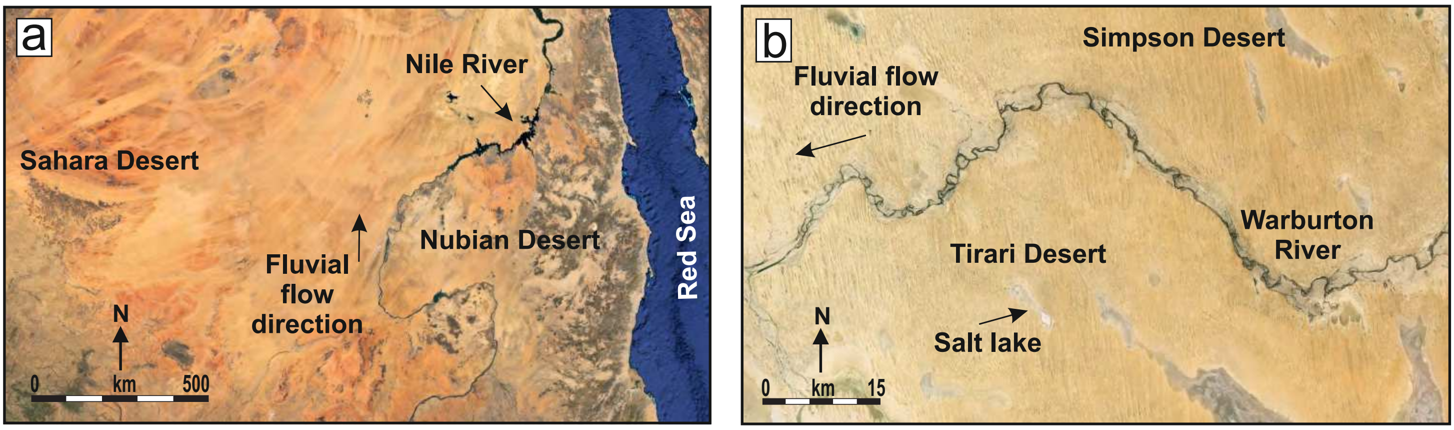
a
Nile River
Sahara Desert
Nubian Desert
Red Sea
Fluvial flow direction
N
0
km
500
b
Simpson Desert
Fluvial flow direction
Warburton River
Tirari Desert
Salt lake
N
0
km
15

Figure 8

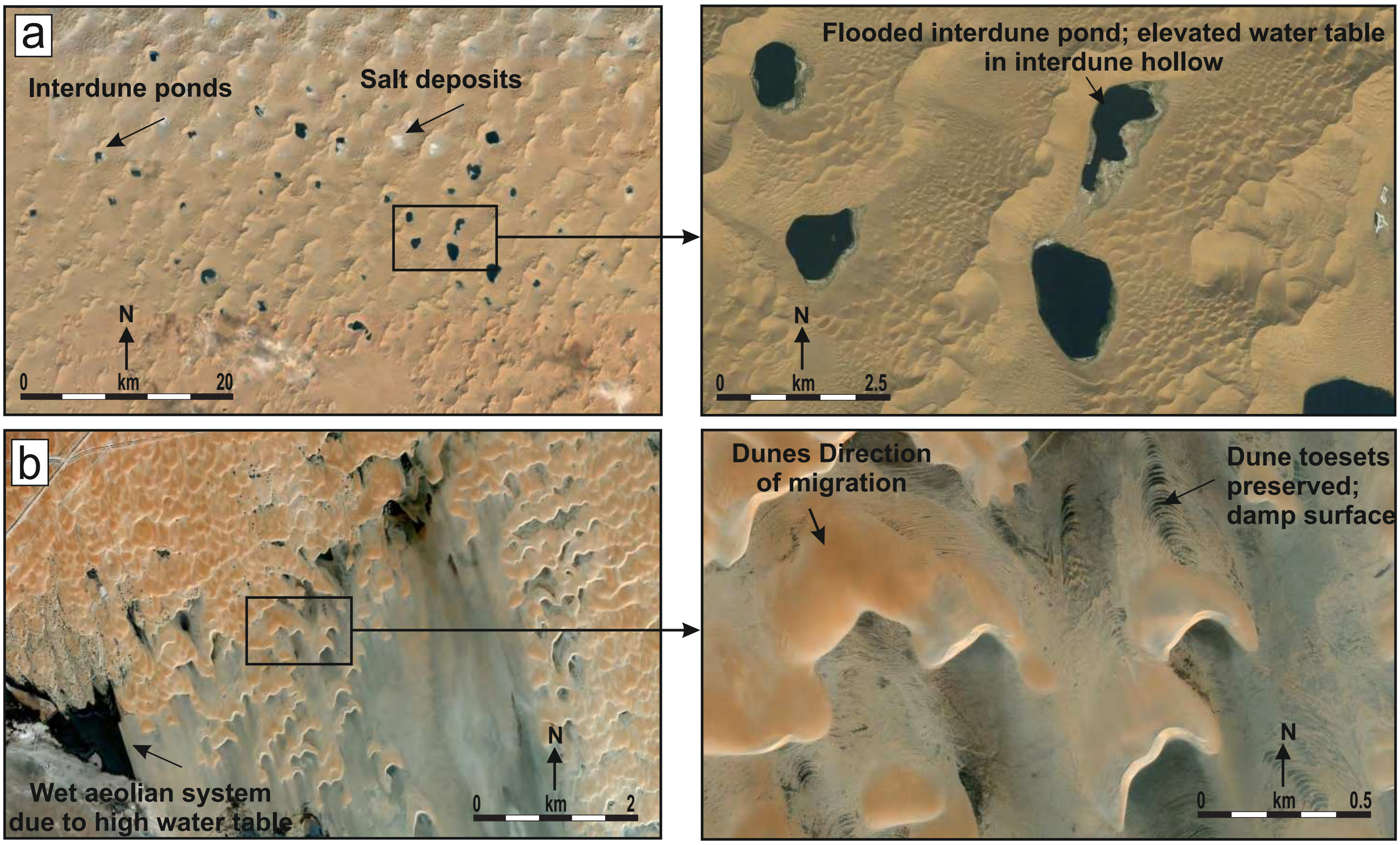
a
Interdune ponds
Salt deposits
N
0 km 20
Flooded interdune pond; elevated water table in interdune hollow
N
0 km 2.5
b
Wet aeolian system due to high water table
N
0 km 2
Dunes Direction of migration
Dune toesets preserved; damp surface
N
0 km 0.5

Figure 9

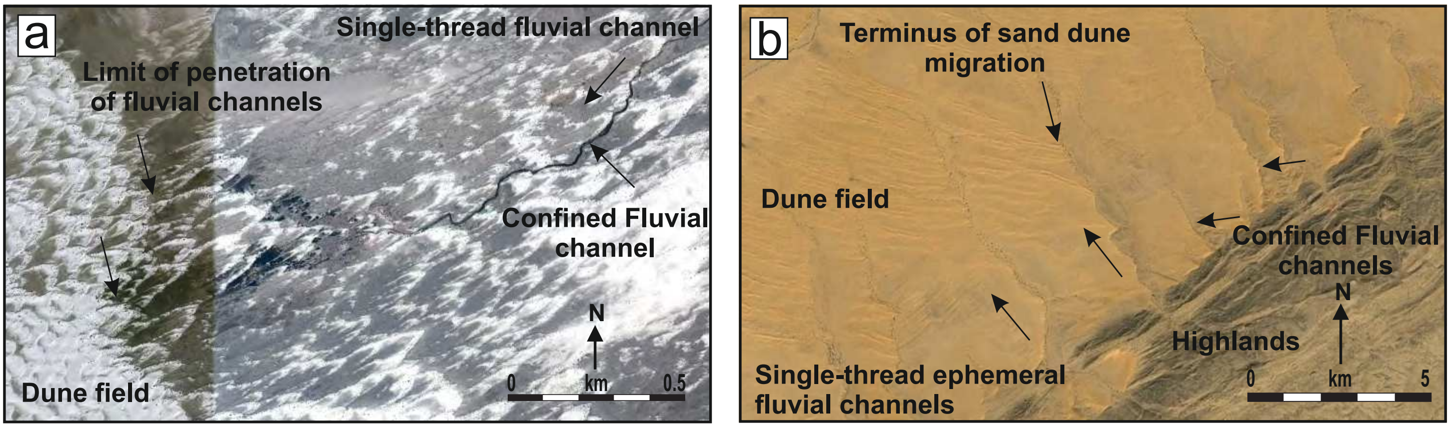
a
Single-thread fluvial channel
Limit of penetration of fluvial channels
Confined Fluvial channel
N
Dune field
0 km 0.5
b
Terminus of sand dune migration
Dune field
Confined Fluvial channels
N
Highlands
Single-thread ephemeral fluvial channels
0 km 5

Figure 10

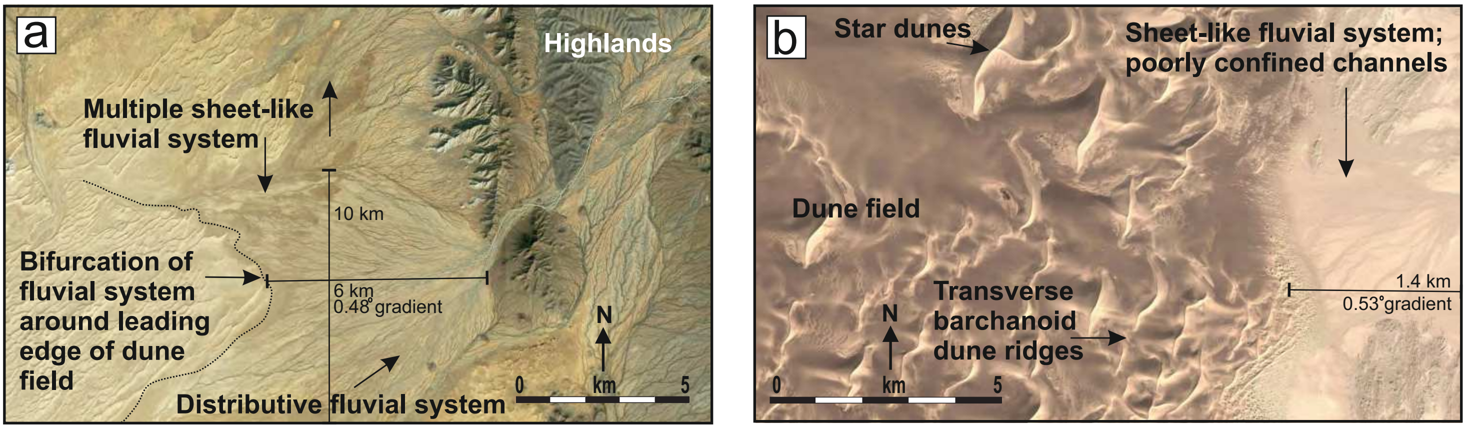
a
Highlands
Multiple sheet-like fluvial system
10 km
Bifurcation of fluvial system around leading edge of dune field
6 km
0.48° gradient
N
0
km
5
Distributive fluvial system
b
Star dunes
Sheet-like fluvial system; poorly confined channels
Dune field
Transverse barchanoid dune ridges
N
0
km
5
1.4 km
0.53°gradient

Figure 11

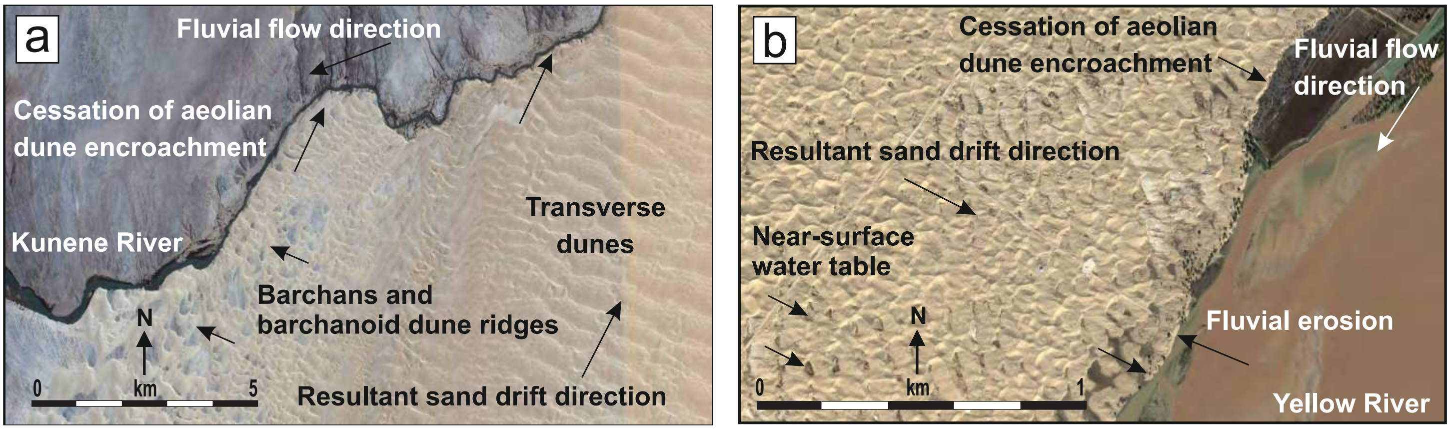
a
Fluvial flow direction
Cessation of aeolian dune encroachment
Kunene River
Transverse dunes
Barchans and barchanoid dune ridges
Resultant sand drift direction
N
0
km
5
b
Cessation of aeolian dune encroachment
Fluvial flow direction
Resultant sand drift direction
Near-surface water table
Fluvial erosion
Yellow River
N
0
km
1

Figure 12

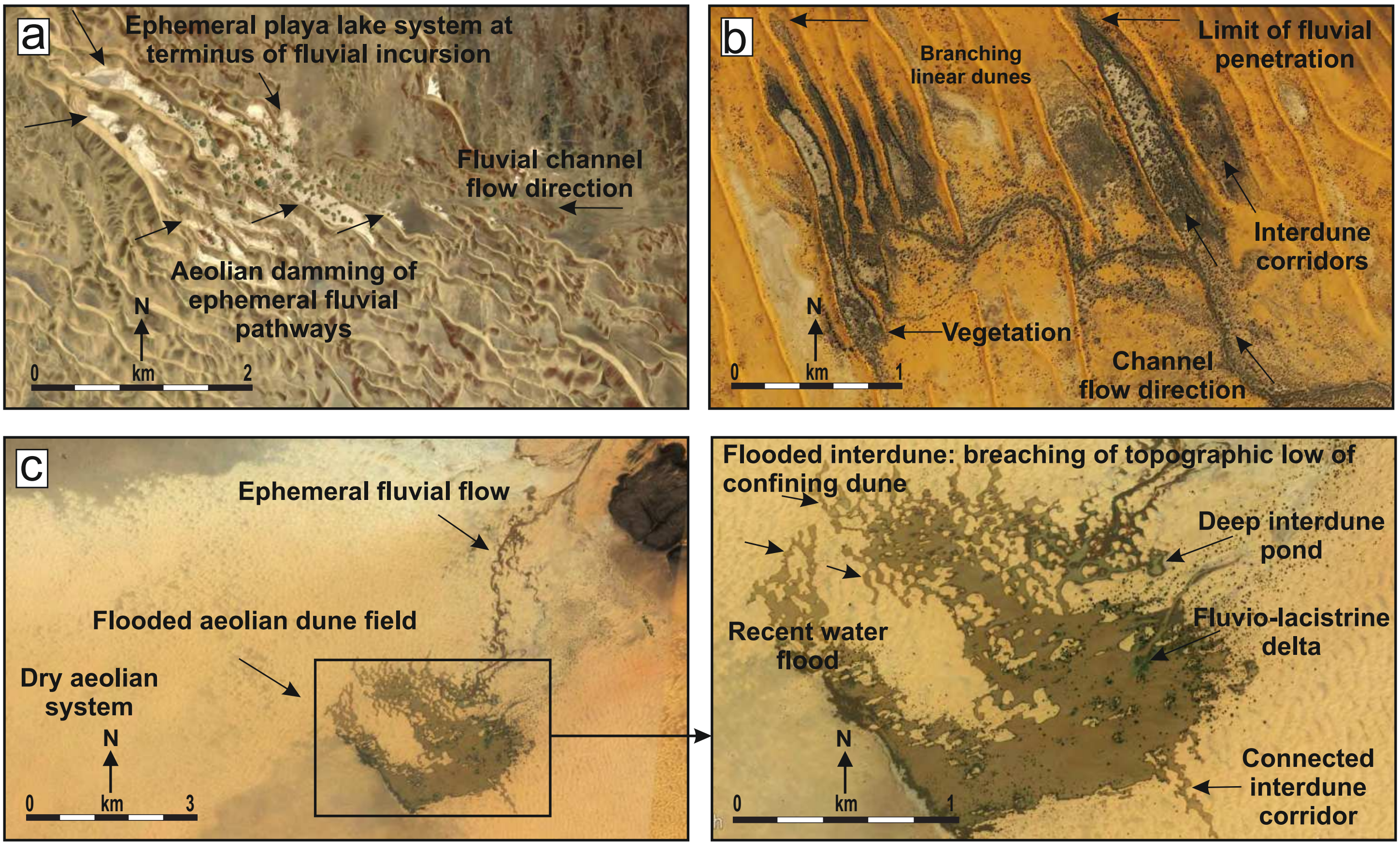
a
Ephemeral playa lake system at terminus of fluvial incursion
Fluvial channel flow direction
Aeolian damming of ephemeral fluvial pathways
N
0
km
2
b
Branching linear dunes
Limit of fluvial penetration
Interdune corridors
Vegetation
Channel flow direction
N
0
km
1
c
Ephemeral fluvial flow
Flooded aeolian dune field
Dry aeolian system
N
0
km
3
Flooded interdune: breaching of topographic low of confining dune
Deep interdune pond
Recent water flood
Fluvio-lacistrine delta
Connected interdune corridor
N
0
km
1

Figure 13

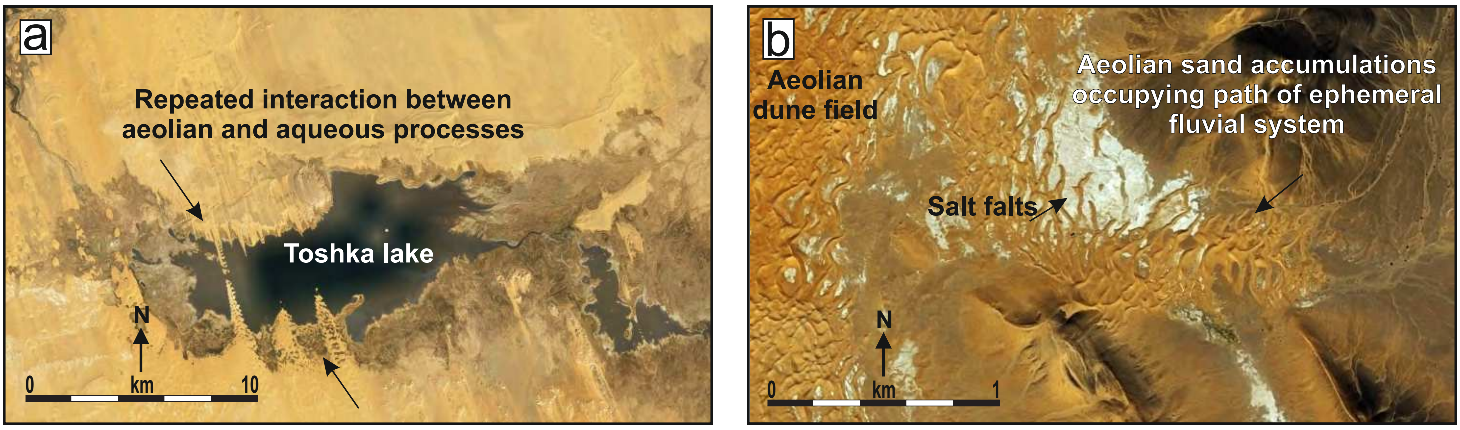
a
Repeated interaction between aeolian and aqueous processes
Toshka lake
N
0
km
10
b
Aeolian dune field
Aeolian sand accumulations occupying path of ephemeral fluvial system
Salt falts
N
0
km
1

Figure 14

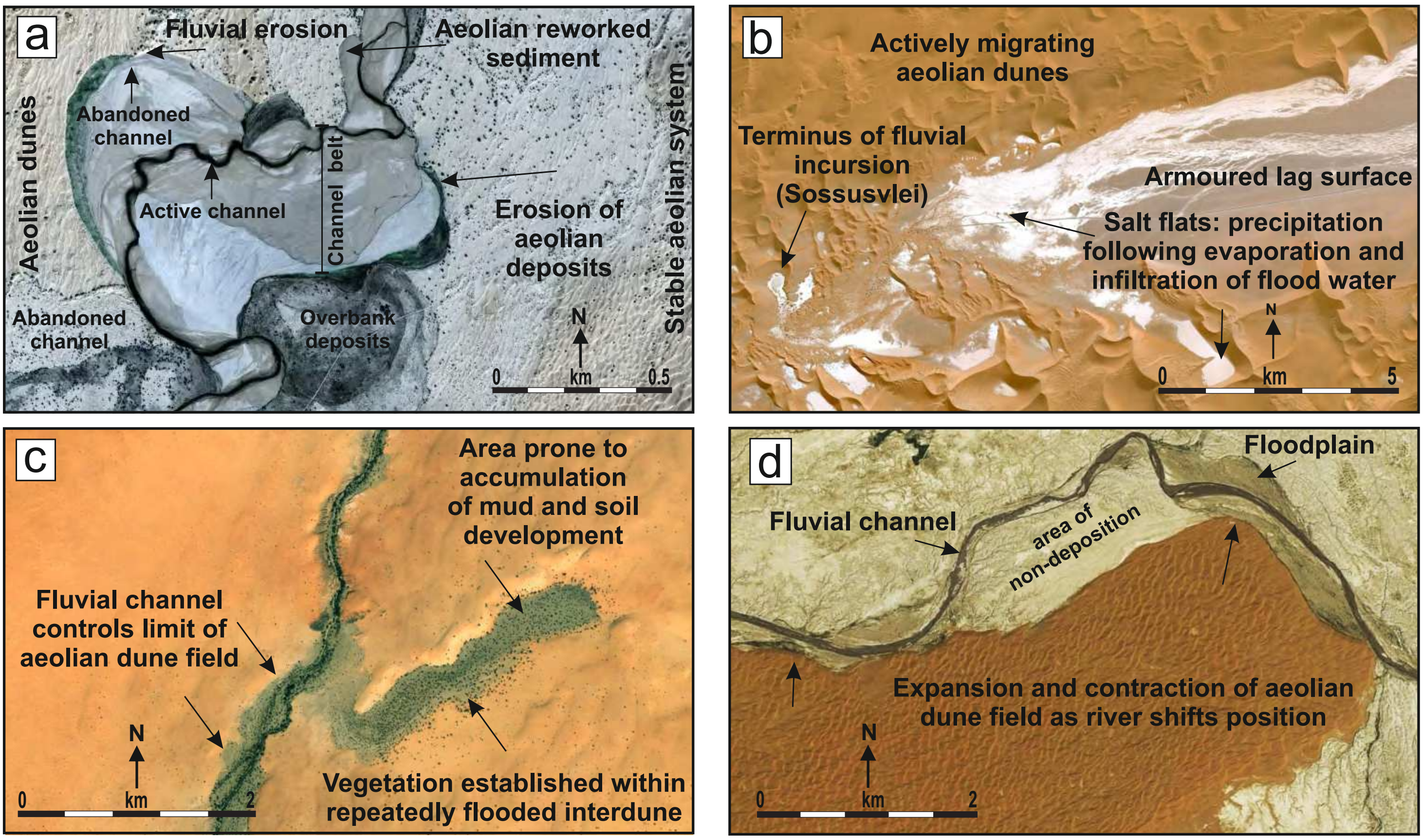
a
Fluvial erosion
Aeolian reworked sediment
Abandoned channel
Aeolian dunes
Active channel
Channel belt
Erosion of aeolian deposits
Stable aeolian system
Abandoned channel
Overbank deposits
N
0
km
0.5
b
Actively migrating aeolian dunes
Terminus of fluvial incursion (Sossusvlei)
Armoured lag surface
Salt flats: precipitation following evaporation and infiltration of flood water
N
0
km
5
c
Area prone to accumulation of mud and soil development
Fluvial channel controls limit of aeolian dune field
Vegetation established within repeatedly flooded interdune
N
0
km
2
d
Floodplain
Fluvial channel
area of non-deposition
Expansion and contraction of aeolian dune field as river shifts position
N
0
km
2

Figure 15