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Interactions between fluvial and eolian geomorphic systems and processes: Examples from the Sahara and Australia

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ABSTRACT

The remains of once integrated drainage systems are still discernible in many of the hot deserts of the world. Some of these date back to the Mesozoic, as in arid Western Australia, where they now form chains of salt lakes. Others were active in Miocene times, such as the Sahabi Rivers that once flowed from Chad to the Mediterranean. A few remained active during Quaternary interglacials, as in the Sahara. All contributed sediments that were reworked by wind during drier phases to form desert dunes. The desert dunes of Australia and of the 9500 km long chain of deserts extending from the Sahara through Arabia to the Thar desert of India originated from sediments eroded from the uplands and deposited in closed interior basins formed during the course of Late Mesozoic and Cenozoic faulting, rifting and epeirogenic movements. It was the unconsolidated Neogene sediments laid down in large subsiding sedimentary basins such as the Kufra-Sirte basin in Libya and the Chad basin which provided the source material for the Late Pliocene and Quaternary desert dunes of the Sahara. One effect of the progressive build up of high latitude ice sheets during the Neogene was to steepen the temperature and pressure gradients between the equator and the poles, resulting in increased Trade Wind velocities. Stronger winds were better able to mobilize the alluvial sands of the increasingly dry Sahara and adjacent deserts and to fashion them into desert dunes.

A more subtle form of interaction between eolian and fluvial processes concerns the interplay between desert dust (loess) accumulation on hill slopes in arid regions and the onset of fine-grained valley-fill accumulation by sluggish, low energy streams in mountain valleys. Some of these Late Pleistocene wetlands served as refuge areas for plants, reptiles and invertebrates at a time when the surrounding desert plains were very cold and dry, as in the Flinders Ranges of South Australia. In the arid Flinders Ranges such valley-fills were built up between 35 kyr and 15 kyr ago, after which the return of the summer monsoon led to stream channel incision and the formation of a network of gullies, often erroneously attributed to human activities. Understanding the causes of such accelerated erosion can prevent unnecessary and expensive attempts at restoration, since the latter are based on the incorrect assumption that overgrazing and present-day land use are responsible.

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1. Introduction

Ever since William Morris Davis (1909, 1912) published his 'explanatory description of landforms', widely publicised over three decades later by the great New Zealand geomorphologist Sir Charles Cotton (1947), there has been a tendency to argue that the action of running water is to humid regions as wind action is to deserts. As far as hot deserts are concerned, this polarisation of the role of fluvial and eolian processes is in fact a false dichotomy since wind and water both play (and have played) an important role in arid and semi-arid regions. For example, Al Farraj and Harvey (2004) inferred that during the Late Pleistocene dune activity and alluvial fan formation interacted and were synchronous in the northern United Arab Emirates between the Musandam Mountains and the coast. Belnap et al. (2011) showed how fluvial and sediment transport in the Mojave Desert were coupled at different scales in time and space. Bullard and McTainsh (2003) gave a comprehensive review of the links between dust sources and fluvial sediment supply in the Lake Eyre and Murray-Darling Basins of Australia, and Bullard and Livingstone (2002) discussed the more general question of moisture availability and the transfer of sediments between eolian and fluvial systems.

De Martonne and Aufrère (1928) identified three broad classes of drainage networks. Where rivers reach the sea they are termed exoreic (external drainage); where they end in closed internal basins they are described as endoreic (internal drainage); and where they are segmented and disorganised they are called areic or 'without flow'. The genesis of many desert dunes is intimately bound up with the progressive disruption of previously integrated endoreic drainage networks as the climate became more arid. The location of major dune fields coincides with that of the closed basins formed as a result of Cenozoic and older tectonic events that created the pattern of uplands and sedimentary

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basins characteristic of many of our present-day deserts (Grove, 1980; Hesse, 2010; Mainguet et al., 1980; Williams, 2014). Some of these basins are bounded by faults and abut the adjacent ranges in a series of steep fault scarps, as in the Afar desert of Ethiopia and the Basin and Range province of North America. Others are gently subsiding depressions formed by slow epeirogenic movements, such as the Chad basin in North Africa and the Lake Eyre basin in central Australia. The drainage into these basins is presently endoreic although during times of wetter climate and overflow from the central lakes the drainage may have reverted to its former exoreic status, as with Late Pleistocene and Early Holocene Lake Chad (Drake and Bristow, 2006; Grove and Pullan, 1963; Servant and Servant-Vildary, 1980).

Once formed, the desert dune fields or ergs would have been winnowed by wind and the silt and clay particles within them were blown out as desert dust or loess (Coudé-Gaussen and Rognon, 1983; McTainsh, 1980, 1984, 1987). In addition, abrasion between sand particles also generated dust, as in the Sinai and Negev deserts during the Late Pleistocene (Crouvi et al., 2010). Deposition of the dust along the desert margins had further geomorphic consequences by altering the balance between infiltration and runoff, leading in some situations to reworking of the loess and its accumulation in the valley bottoms as fine-grained valley-fills (Williams et al., 2001; Yaïr, 1994). Once the loess mantles on the hill slopes ceased to accumulate, usually because of a reduction in dust flux, the balance between runoff and infiltration was again altered, this time in favour of runoff, leading to a cycle of valley-fill incision and gully erosion (Avni et al., 2006; Haberlah et al., 2010a,b; Williams et al., 2001). However, the processes involved are almost certainly more complex than what the previous statement suggests. Rates of dust accumulation on the hill slopes would most likely not have been constant; nor would rates of runoff. Episodic changes from phases of dust accumulation to phases of dust erosion at time scales ranging from years to decades would have resulted in equally episodic valley-fill accumulation. Thresholds, time lags and possible hysteresis effects would also have been likely to come into play, so that a simple equation between climate change and geomorphic response should not be expected.

The elegant flume experiment of Schumm and Parker (1973) provides an excellent example of a complex response, with incision of a small channel being followed by the formation of a multiple set of alluvial terraces. To quote the authors: 'initial channel incision and terrace formation were followed by the deposition of an alluvial fill, braiding and lateral erosion, and then, as the drainage system achieved stability, renewed incision followed by a low alluvial terrace' (Schumm and Parker, 1973, p. 99).

Drawing upon the examples from the Sahara and Australia, this paper argues that continuing and close interactions between fluvial and eolian processes are in fact characteristic of hot deserts and their margins, and have been so since the deserts first began to form.

2. Desert inception, drainage disruption and dune genesis

Before the present-day deserts came into being in response to tectonic and climatic changes, integrated drainage networks traversed the lands they now occupy. For example, a well-integrated drainage network occupied the western third of Australia between Early Cretaceous and Late Eocene times (130–40 Ma). Once Australia had separated from Antarctica some 45 Ma ago it drifted north at a rate of 6 cm/year into latitudes characterised by anticyclonic conditions and dry, subsiding air (Fujioka and Chappell, 2010; Williams, 1984). As a consequence, the once integrated drainage networks became progressively disrupted, and by middle Miocene times these rivers had ceased to flow and are evident today as a linear series of saltpans (Bunting et al., 1974; van de Graaff et al., 1977; Salama, 1997; Zheng et al., 1998).

From the moment aridity set in and the various hot deserts began to develop there has been a constant interplay between eolian and fluvial processes. Consider, for example, the Sahara, which is the largest hot desert in the world. It extends over 4800 km from the Atlantic coast of Mauritania in the west to the arid Red Sea Hills in the east, and is continued eastwards across the deserts of Arabia, Iran, Afghanistan and Pakistan to the Thar Desert in India, a total distance at the Tropic of Cancer of about 9500 km. The Cenozoic desiccation of the Sahara was diachronous, but was well under way by the Late Neogene (Maley, 1980, 1981; Schuster et al., 2006; Sepulchre et al., 2006) by which time the major Saharan uplands such as Tibesti, the Hoggar, the Aïr Mountains and Jebel Marra were already in existence. Some of the sandy alluvium eroded from the Saharan uplands was carried to the Atlantic and Mediterranean by the Late Cenozoic rivers, but a substantial amount of sediment was deposited in closed interior basins created during Late Mesozoic and Cenozoic faulting, rifting and subsidence (Grove, 1980), resulting also in disruption of the previously integrated Neogene Saharan drainage network such as the Sahabi rivers that flowed north from Chad (Griffin, 2006, 2011). These unconsolidated Neogene sandy sediments laid down in large subsiding sedimentary basins such as the Chad basin and the Kufra-Sirte basin in Libya provided the source material for the Late Pliocene and Quaternary desert dunes. Servant (1973) identified wind-blown sands in late Tertiary stratigraphic sections in the Chad basin, and concluded that the onset of aridity and the first appearance of desert dunes in this part of the southern Sahara was a late Tertiary (i.e., pre-Quaternary) phenomenon. Furthermore, the Late Cenozoic expansion of high latitude ice sheets led to steeper temperature and pressure gradients between the equator and the poles, resulting in intensified Hadley circulation and increased Trade Wind velocities (Parkin, 1974; Parkin and Shackleton, 1973). Stronger winds were better able to mobilize the alluvial sands of an increasingly dry Sahara and to fashion them into desert dunes. This scenario applies equally to the deserts of Australia as well as to those east of the Sahara, although the timing differed from region to region. Evidence for the earliest phases of dune activity is hard to find since many of the older dunes were continually reworked by wind and water, but in the Sahara and Afar deserts they certainly date back to at least the time when *Homo erectus* roamed the Sahara and left behind a legacy of Lower Palaeolithic Acheulian stone tools, with a minimum age of ~0.5 Ma and a maximum age of ~1.5 Ma (Alimen, 1955; Asfaw et al., 2002; Clark, 1980; Potts et al., 2004).

Around the margins of many hot deserts there are extensive areas of vegetated and now stable dunes (Grove, 1958; Grove and Warren, 1968; Mainguet et al., 1980; Talbot, 1980). A number of these fixed dunes have soils developed upon them and some have polygenic profiles, with buried horizons of calcium carbonate and/or clay-rich textural B-horizons (Singhvi et al., 2010; Williams, 1968). In the Sahel region south of the Sahara, extending from Mauritania to Chad, many of the now fixed dunes show signs of gully erosion (Daveau, 1965; Talbot and Williams, 1978, 1979). During the course of a camel survey of the Wadi Azouak basin in central Niger in late 1974, near the end of a long interval of drought, Talbot and Williams (1978, 1979) observed a series of sandy alluvial fans located on the lower slopes of fixed dunes near Janjari village situated roughly midway between Niamey and Agadès. The most recent fans had formed during an intense downpour in the previous wet season. The distribution of these fans indicated that the impact of this extreme rainfall event was confined to an area no more than about 10–15 km in radius. The downpour caused channel entrenchment above the fan apices and fan sedimentation below. Weakly developed buried soils exposed in the banks of the most recent gully showed repeated episodes of dune dissection, fan deposition, and soil development. The soils would have formed when the fan surface was vegetated and stable. The youngest soil probably formed during a regionally wetter interval in the Sahel dated to about 150–350 years ago, coeval with the later stages of the Little Ice Age in Europe. Continuation of these processes of episodic dune erosion, alluvial fan formation, plant cover establishment, and soil formation would eventually lead to a landscape of very gently sloping degraded dunes with the intervening swales occupied by vegetated sandy alluvial fans. During prolonged

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