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Aeolian dune field self-organization – implications for the formation of simple versus complex dune-field patterns

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Abstract

The interpretation of aeolian dune-field patterns as self-organizing complex systems is a new paradigm in which pattern evolution may be addressed. Computer simulations, supported by field and experimental data, indicate that a given wind regime produces a simple dune-field pattern. Dune type and crest orientation are determined by wind regime and pattern ordering occurs through dune–dune interactions over time. Because dunes reorient only at their crest terminations with a change in wind regime, the rate of formation of a new pattern of small dunes is typically faster than the rate of reorientation of the existing pattern, resulting in the superposition of simple patterns to give rise to complex patterns. Complex patterns are distinct from spatial changes in a simple pattern, and from the type of superposition that characterizes compound/complex dunes. Complex patterns necessarily indicate a rate of pattern formation that is rapid compared to the rate of sediment accumulation on the depositional surface.

Keywords: Aeolian; Sand-dune patterns; Complex systems; Self-organization

1. Introduction

Fields of aeolian sand dunes are among the most widely recognized examples of patterned landscapes in nature. The interpretation that dune-field patterns emerge from a nonpatterned state through self-organization within complex systems (Werner, 1995) represents a paradigm shift. The traditional approach has been through reductionism, in which dune-field evolution is considered the cumulative sum of fluid-grain-bed form interactions at an ever-increasing scale of complexity. For aeolian dune fields, as well as many other natural systems, the fundamental argument is that reductionism breaks down because these are complex systems governed by nonlinear dynamics. In such systems, emergent behavior occurs that is not predicted by the fundamental processes upon which reductionism builds (see Werner, 1999; Baas, 2002).

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In addition to the appropriateness of a complex-systems approach, an advantage it has over reductionism in understanding the evolution of aeolian systems arises from a characteristic of complex systems – a reduction of variables occurs with increasing scale as smaller-scale processes become subordinate to and decoupled from emergent, larger-scale behavior (e.g., Nicolis and Prigogine, 1977). This reduction of variables with increasing scale has allowed explanations for some key aspects of dune-field patterns, such as dune spacing (Werner and Kocurek, 1999) and dune reorientation with changes in wind regime (Werner and Kocurek, 1997).

This paper addresses the degree of complexity of dune-field patterns within the context of a review of dunes as self-organizing systems. At a basic level, dune-field patterns can be classified as *simple*, in which there is one pattern of dunes, or *complex*, in which multiple patterns are spatially superimposed. Examples of simple dune patterns include the crescentic dunes of White Sands, New Mexico (McKee, 1966) (Fig. 1), Guerro Negro, Baja California (Inman et al., 1966), and the Skeleton Coast, Namibia (Lancaster, 1982). Complex dune-field patterns show a broad range of superimposed patterns, with examples including the three trends of linear dunes of differing size in western Mauritania (Lancaster et al., 2002) (Fig. 2), and the crescentic-linear-star dune patterns of the Gran Desierto, Mexico (Lancaster, 1992), and Namibia (Lancaster, 1989). Typically, the superimposed patterns that give rise to a complex pattern can be recognized from remote images of dune fields. Pattern analysis can be applied, however, by the measurement of the two-dimensional pattern parameters of crest length, orientation, spacing, and defect density, allowing for statistical identification of individual pattern populations (Ewing, 2004; Ewing et al., in review).

The conclusion reached in this paper is that a simple pattern represents a single generation of dune-field construction, whereas a complex pattern represents multiple generations of construction. This statement represents a significant departure from some previous thinking. As discussed in detail by Lancaster (1995, 1999), complex dune-field patterns were often considered to be in equilibrium with present-day

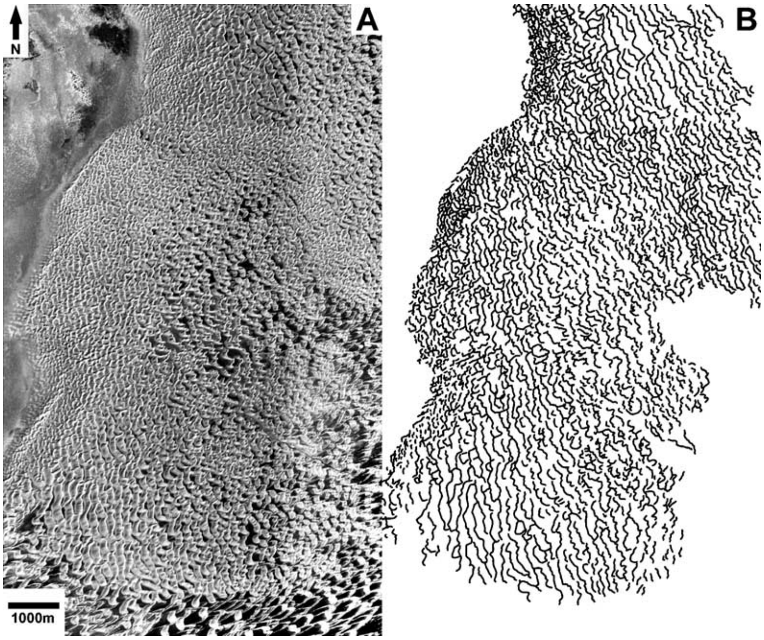

Fig. 1. (A) Simple crescentic dune-field pattern at White Sands, New Mexico. (B) Tracing of dune crests for area shown in (A). Although there is an east-to-west change in the pattern in terms of dune size and spacing and the nature of the interdune areas, these changes occur spatially and are not superimposed.

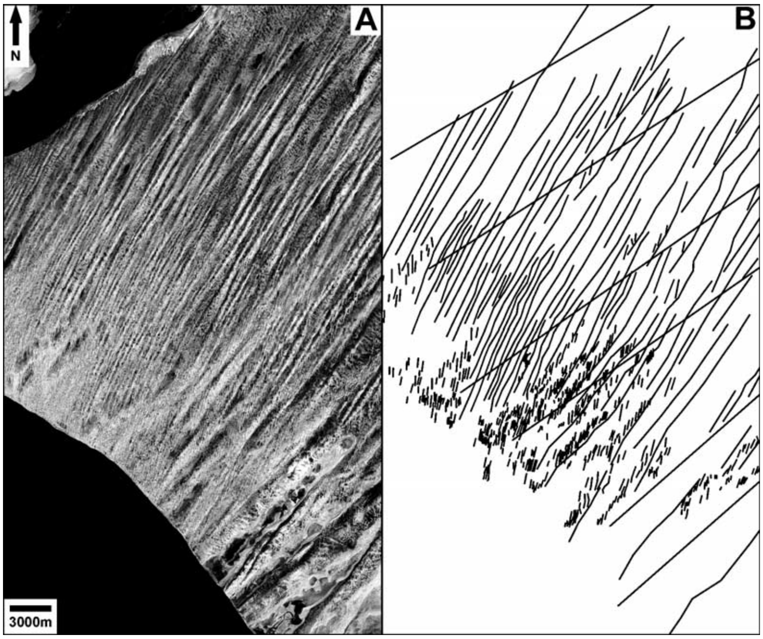

Fig. 2. (A) Complex dune-field pattern formed by the superposition of linear dunes of differing size, trends, and ages, western Mauritania. (B) Tracing of the dune crests for area shown in (A). The subdued, large NE-trending linear dunes are 15–25 ka in age and range up to 50 m in relief. The prominent, NNE-trending linear dunes are 10–13 ka in age. At the resolution of the image are N-trending linear dunes that date at <5 ka in age (see Lancaster et al., 2002).

winds in which one dune pattern modified the airflow to give rise to yet additional dune patterns (i.e., field-scale secondary flow).

2. Dunes and dune fields as complex systems

2.1. Dune models

In the computer models (cellular automaton) of Werner (1995), an algorithm was used in which slabs of "sand" were picked up and transported at random, but in a specified direction. The probability of deposition increased when a slab landed on an area already marked by deposited sand (owing to the loss of momentum in dislodging numerous grains (Bagnold, 1941)) or within the low energy lee of a bed form. No other fluid dynamics of the system were considered. Transport resulted in the collection of sandy patches of varying sizes and migration rates that were inversely proportional to patch size. Because migration rates differed, merging of patches occurred as smaller, faster bed forms overtook larger, slower bed forms. Bed form growth also occurred because adjacent dunes linked laterally and coalesced. The process of merging with migration resulted in an increase in bed form size, crest length, and spacing. Increased crest length resulted in a decrease in the number of defects (crest terminations), as reflected in the defect density (the number of defect pairs per unit crest length). The trends evident in these computer simulations strongly resembled the actual development of a dune field, as recorded on Padre Island, Texas, by Kocurek et al. (1992).

By varying the direction(s) and duration of transport, shapes emerged that resembled the basic dune types (barchan, crescentic, linear, and star dunes) (Fig. 3). Barchans and crescentic ridges formed with simulated unidirectional transport, whereas linear dune shapes emerged to bisect obtuse bidirectional transport directions of equal magnitudes. Star dune shapes emerged with a complex wind regime, in Werner's model four perpendicular directions, with the arms of the star dunes oriented at 45° to any transport direction. The only departure from wind regime as the sole discriminator of the basic dune types was that an

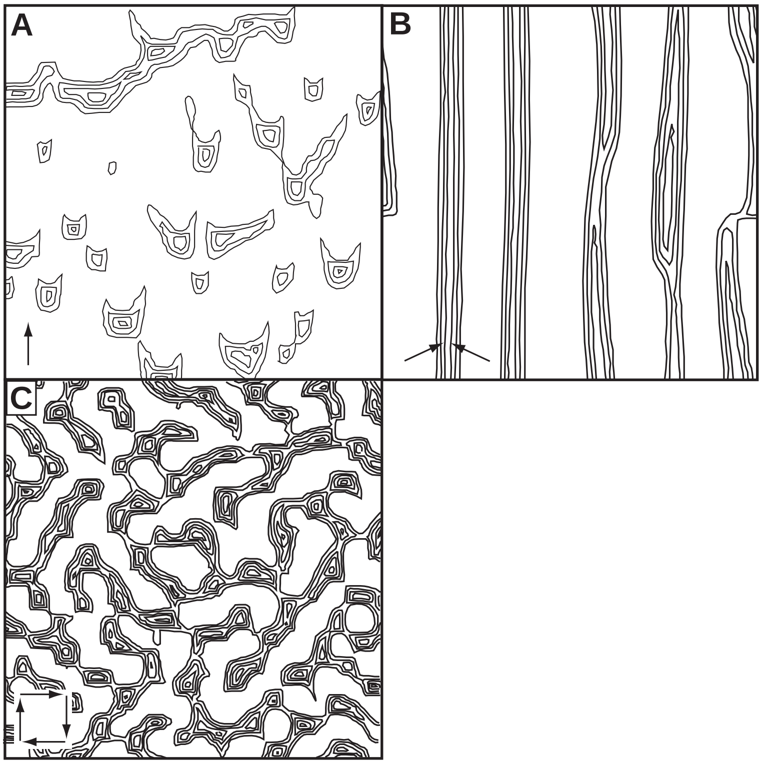

Fig. 3. Computer-modeled dunes, redrawn from Werner (1995). (A) Barchan and crescentic dunes. (B) Linear dunes. (C) Star dunes. Note wind regimes depicted by arrows.

increase in sand supply with barchan dunes caused these to link laterally to form crescentic dunes. Because there was no inherent template in the fundamental transport process that would predict dunes, Werner interpreted dune fields as complex systems in which the types of dunes are attractors of aeolian sand transport. The evolution of dunes can be described as emergent behavior.

Testing of the attractor hypothesis by Werner (1995) included an initial configuration of dunes with a wide range of orientations and number of terminations, which was then allowed to evolve under the transport conditions that had resulted in linear dunes. Regardless of the initial conditions the dunes evolved to a configuration of well-formed linear dunes in terms of orientation and number of terminations. This result is consistent with the attractor model in which the system contracts through phase space (i.e., its overall basin of attraction defined by variables describing the state of the system) to the phase subset of the attractor.

There has been significant work on dune modeling since Werner (1995), but the overall model remains robust. Momiji et al. (2000) and Bishop et al. (2002) introduced a wind speedup factor on the stoss slope, which resulted in more realistic dune shapes than in the original Werner model. Nishimori et al. (1998) used a different mathematical formulation than Werner (1995), but a similar “slab” approach in their models, and also produced shapes resembling the different dune types. The relationship between bed form size and migration rate has been shown to be more complicated than envisioned in the Werner model (Momiji and Warren, 2000; Momiji et al., 2002). The mechanics by which dunes merge with migration have also been investigated in more detail by Werner and Kocurek (1999), as discussed below.

Support for the Werner model is from both natural dune fields and experimental results. Although natural wind regimes are commonly more complex than the simple scheme used by Werner (1995), there is broad agreement between dune type and wind regime (e.g., Lancaster, 1995). The turntable experimental results of Rubin and Hunter (1987) with wind ripples and of Rubin and Ikeda (1990) with subaqueous dunes support the crest orientations achieved in the Werner models.

In the turntable experiments, combinations of two transport directions (defining the divergence angle) and transport ratio (predominate/subordinate sand transport) were considered for the class of bed forms appropriate for most aeolian dunes, in which the length of each transport direction cycle is short relative to the bed form reconstitution time. Crest orientation was found to be as transverse as possible to the differing transport directions (i.e., bed form orientation has the maximum gross bed form-normal transport). Crest orientation with respect to the resultant transport direction is the same as in the Werner (1995) model, with the exception of near a divergence angle of 90° with transport ratios greater than 1:1. In this zone the Werner model shows a smooth transition between transverse and oblique bed forms whereas a "jump" occurs with the Rubin and Hunter (1987) approach (Fig. 4). It should be noted that at a 90° divergence angle with a transport ratio of 1:1, the results from Rubin and Hunter (1987) and Rubin and Ikeda (1990) show the existence of two crestlines, one transverse and one longitudinal to the resultant. This configuration is the same as that simulated for star dunes by Werner (1995), in which the two crestlines define the arms of the star dunes.

2.2. Emergence of dune-field patterns

It is the similarity of dunes to each other in a field in terms of dune type and size, crest parameters of spacing, orientation and length, and field-scale defect density that gives dune fields their striking patterns. The emergence of these patterns can be viewed by three aspects of the system: (i) determination of dune type and orientation as a function of wind regime, (ii) dune–dune interactions in which the pattern becomes progressively more ordered, and (iii) the evolution of the dune-field pattern as a function of constructional time (all else being equal).

Both the computer simulations of Werner (1995) and the experimental results of Rubin and Hunter (1987) and of Rubin and Ikeda (1990) show the formation of one dune type of a specific crest orientation for a given wind regime. Although natural wind regimes may be more complex than in these simulations and experiments, the rule of gross bed form-normal transport states that the crests will be as perpendicular as possible to all constructive winds that comprise the overall regime. The dunes may show changes in asymmetry and other seasonal changes, but the crest orientation should be sustained. Defects, however, may shift with a given wind if they are sufficiently small.

Given a specific dune type and crest orientation, pattern ordering is thought to occur though dune–dune interactions that have been simulated in models (Werner, 1995; Werner and Kocurek, 1997, 1999), observed in nature (Kocurek et al., 1992), and which share similarity with ordering in fields of wind ripples (Werner and Gillespie, 1993; Landry and Werner, 1994; Valentine, 2004). These interactions provide insights, albeit simplified, to dune-pattern ordering in natural systems (Fig. 5).

The simplest interaction is merging, which appears to be dominant when bed forms are small, diverse in size and closely spaced (Fig. 5A). Smaller, faster bedforms overtake larger, slower bedforms, resulting in increased size and spacing. Lateral coalescing of terminations is a type of merging, which results in increased crest length (Fig. 5B). Both aspects of merging result in a decrease in defect density. Merging can be viewed as a selection process toward bed forms of similar size, and hence, migration rate. This selection process toward larger bed forms would cease if dunes achieved the same size, migration rate, and lacked terminations.

The smaller, faster-migrating terminations provide the dynamics for continued evolution of the dune-field pattern (Werner and Kocurek, 1999). In this dune model and as observed with natural wind ripples (Anderson and McDonald, 1990) and simulated by Landry and Werner (1994), a migrating termination attaches and merges with the immediate downwind crest, forming a *Y*-junction (Fig. 5C). Merging is followed by detaching of the downwind fork of the *Y*-junction, thus creating a continuous crestline from the upwind fork and a new defect that continues to propagate downwind. In simulations the downwind fork detaches as the merging termination shadows the downwind crest, capturing a portion of its sand and growing larger, while the downwind fork shrinks in

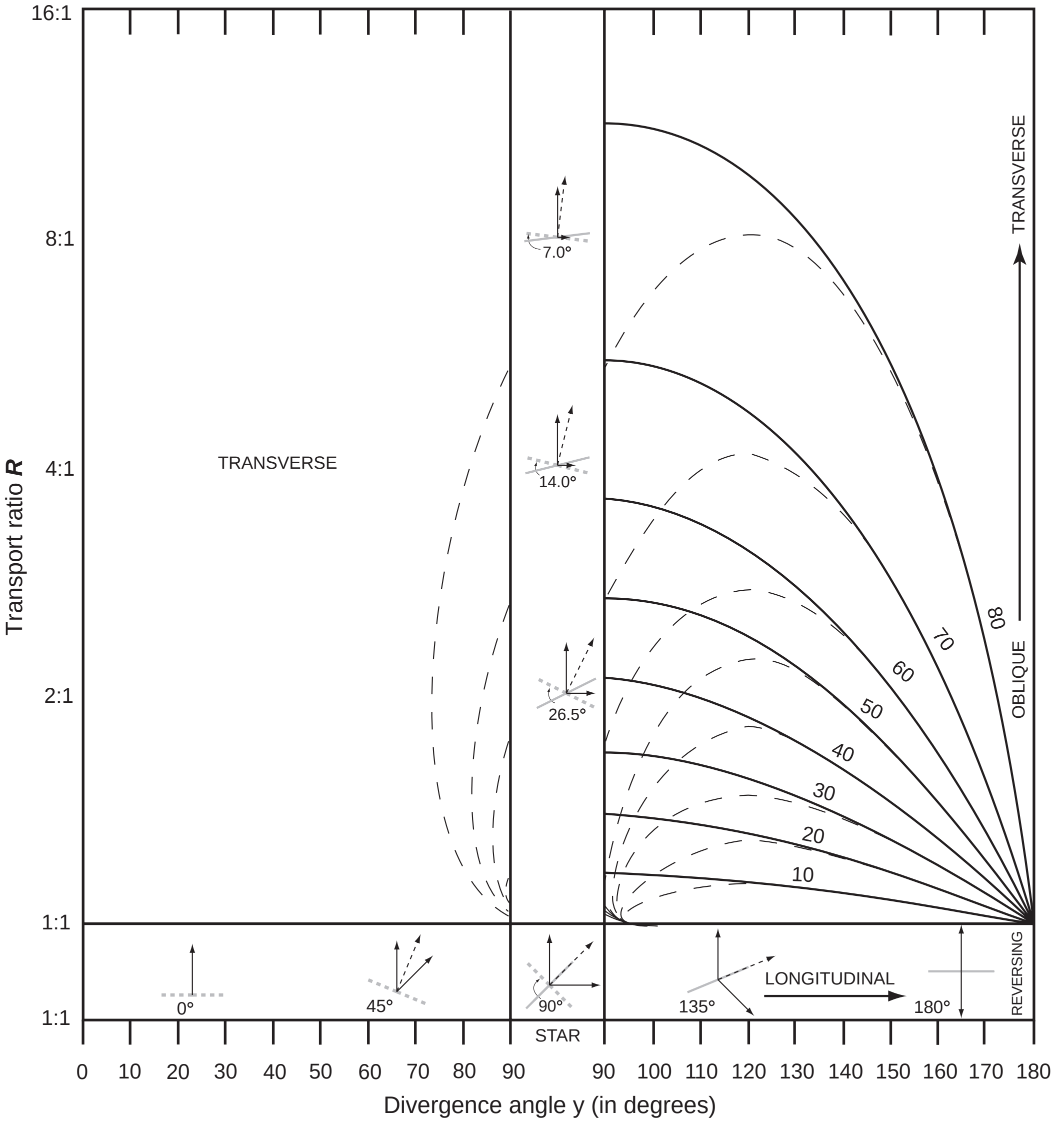

Fig. 4. Plot showing crestline orientation (obliquity) with respect to the resultant vector of transport as a function of the divergence angle between two transport directions, and the transport ratio between the dominant and the subordinate transport directions. Bold lines showing angle of obliquity are from Rubin and Hunter (1987), whereas lines diverging as a divergence angle of 90° is approached are calculated from Werner and Kocurek (1997). Note fields of transverse, oblique and longitudinal dunes. Star dunes occurred in the Werner (1995) simulations where $R=1:1$ and $\gamma=90°$. As shown in Rubin and Ikeda (1990), at progressively higher transport ratios the originally longitudinal crest becomes increasingly oblique until it merges with the transverse arm. Calculations from Werner and Kocurek (1997) show both crests becoming oblique until merging as a single transverse crest.

size, increases its migration speed and detaches as a free termination (i.e., "repulsion" of Landry and Werner, 1994). A loss of crest length corresponding to the length of the merged termination must also occur, representing a decrease in cumulative crest length (L) within the entire dune field of area (A). There is a corresponding increase in spacing (λ) because $\lambda = A/L$ (Werner and Kocurek, 1999).

Repulsion may work independent of defect dynamics where a dune approaches a downwind larger dune (Fig.

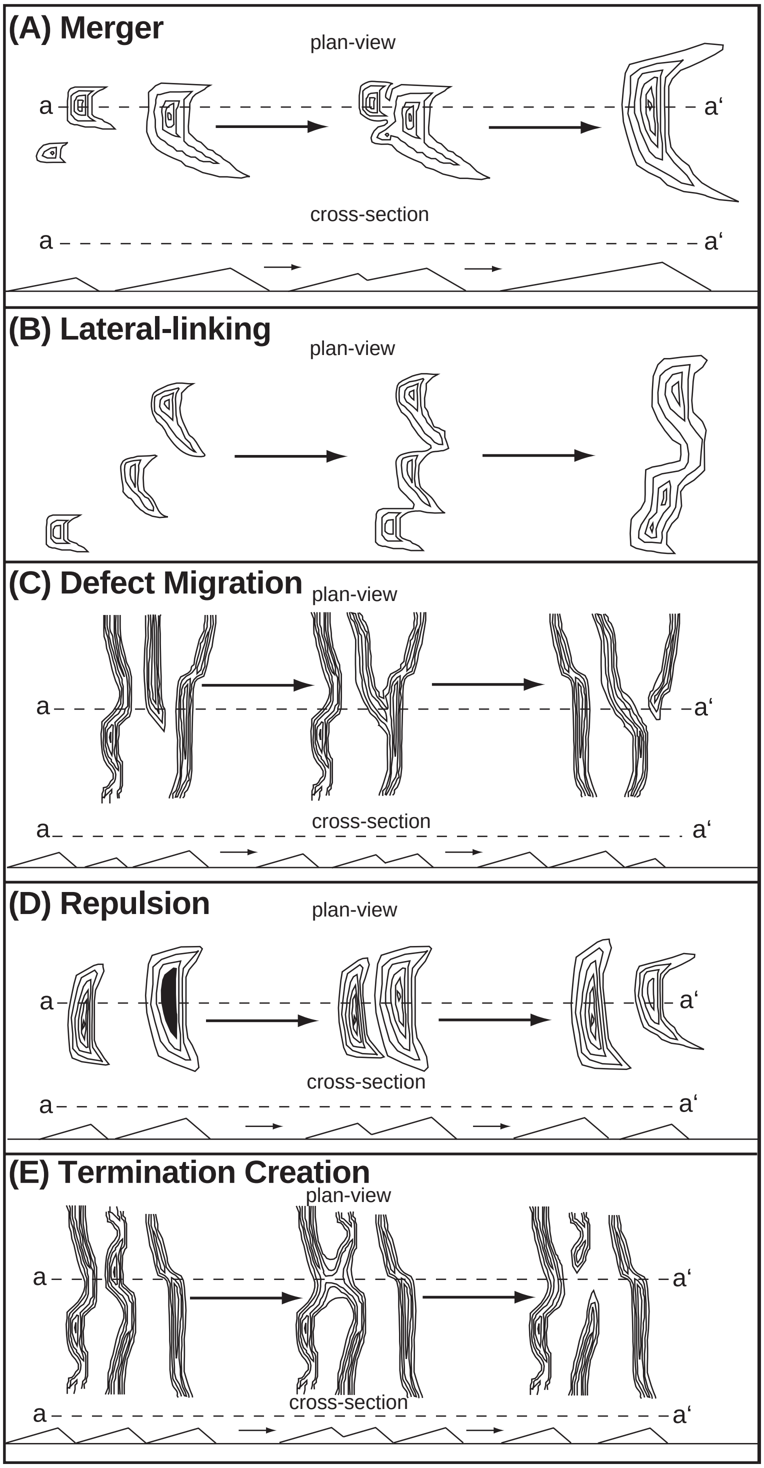

Fig. 5. Dune–dune interactions that contribute to pattern ordering of a dune field. (A) Merging. (B) Lateral linking of opposing crest terminations. (C) Defect migration through a field. (D) Repulsion. (E) Termination creation. See text for discussion.

5D). Sand capture can result in the downwind dune becoming a similar size (rare) or smaller than the upwind dune. Merging of crests at a point can foster the creation of a pair of terminations (Landry and Werner, 1994), and represents one way in which defects are created in the dune pattern (Fig. 5E).

Because the process of dune-field pattern ordering occurs by dune–dune interactions pattern development is a function of time. Werner and Kocurek (1999) modeled rates of increasing spacing and decreasing defect density as a function of time. Ewing et al. (in review) measured dune-field parameters in four fields in which the constructional time could be reasonably estimated. Their curves show increasing dune spacing and crest length, decreasing defect density, tighter clustering of crest orientations, and an overall reduction in the statistical variance of all parameters with constructional time.

Estimation, however, of constructional time is not straight-forward because what is actually being evaluated is the volume of sand moved in pattern development. Complications include (i) estimating the time when the field may have been stabilized, (ii) whether or not a specific dune pattern was exposed on the surface and not buried beneath younger generations of dunes, (iii) the degree to which a dune pattern continues to evolve versus being reworked because of changes in the wind regime, and (iv) the differences in the magnitude of the winds during specific constructional events.

3. Implications for simple and complex dune-field patterns

Dune-field pattern evolution as detailed above describes a simple pattern that progressively becomes better ordered with time. This trend continues so long as the wind regime does not change. In the computer simulations of Werner and Kocurek (1997) the response of an existing dune pattern to a change in wind regime is a reorientation of the crestlines to match the new regime. However, crestline reorientation occurs only at crest terminations. Reorientation of the termination is then translated progressively through the length of the dune body such that (if all else is equal) the rate of dune reorientation is proportional to the defect density. In itself, this observation explains the geomorphic stability of linear dunes, which have the lowest value of defect density of all common dunes (Werner and Kocurek, 1997). Defects may be created along existing crestlines, thereby facilitating reorientation. In any case, however, pattern redevelopment with change in the wind regime is a function of the rate of reorientation of existing dunes versus the rate of formation of new dunes. Because both rates are generally dependent upon the volume of sand transported, the formation of new, small dunes and development of a new pattern typically exceed the rate of reorientation of the existing dunes, and the new pattern becomes superimposed upon the older pattern. This is especially true where the existing pattern consists of linear dunes.

Because a given wind regime forms a simple pattern and the rate of formation of a new pattern typically exceeds the rate of reorientation of the old pattern, a reasonable interpretation of complex patterns is that they represent the superposition of multiple generations of construction, each pattern recording a distinct wind regime. Lancaster (1999) reached a similar conclusion based upon a growing body of data for dune fields in which the specific elements of complex patterns have been shown to represent distinctly different constructional events based upon luminescence dating (Stokes et al., 1997). Well documented examples include the three trends of linear dunes in Mauritania (Lancaster et al., 2002) (Fig. 2), the multiple superimposed patterns of the Gran Desierto, Mexico (Beveridge, 2004), and the Simpson–Strzelecki Deserts (Nanson et al., 1995).

Creation of a complex pattern, however, implies sand from which the new pattern develops. Creation of a new superimposed pattern is best accomplished where the change in wind regime is accompanied by an influx of sand. In many natural examples, however, sand to construct the new superimposed dune pattern is derived from a combination of sources including (i) new or continuing sand flux to the field, (ii) sand blown from existing dunes, and (iii) partial reworking of existing dunes into new patterns.

Partial reworking of existing dunes into new patterns should be especially prevalent where the existing dunes are large linear features, owing to their resistance to reorientation. As seen in the Gran Desierto, for example, star dunes occur on elevated lineations that have been interpreted as large, relict linear dunes

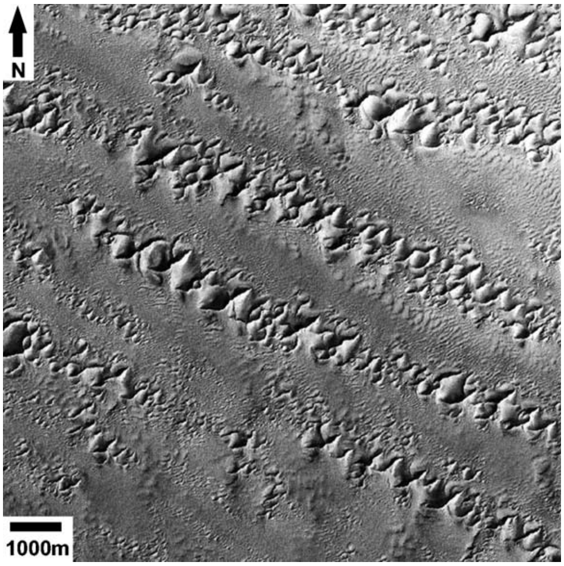

Fig. 6. Star dunes superimposed upon relict linear dunes, forming "chains of stars", Gran Desierto, Mexico. Superposition and OSL dating brackets the linear dunes as forming between 26–12 ka, whereas the star dunes formed after 7 ka. The relict linear dunes are interpreted to represent both very stable features and a source of sand for the emergence of the star dunes with a change in wind regime.

(Beveridge, 2004). These linear dunes represent both very stable features and a large source of sand (Fig. 6). As shown through OSL dating, the linear dunes formed between 26 ka and 12 ka, the star dunes after 7 ka, and these are separated by a generation of crescentic dunes dated at about 12 ka (Beveridge, 2004).

4. Variation within simple dune patterns

4.1. Multiple dune types within a dune field

Although wind regime is almost certainly the primary discriminator in determining dune type, it is not the sole one in the overall dune attractor and multiple dune types may coexist within the same field. For these cases, however, patterns are spatially distinct and do not represent an actual superposition of patterns (i.e., these are not complex patterns).

Parabolic dunes owe their existence to vegetation (e.g., Lancaster, 1995); and because of differences in the extent of vegetation spatially, parabolic dunes could coexist with crescentic dunes within the same wind regime, as apparently is the case at White Sands (Fig. 7). Similarly, at the coarse end of the dune spectrum with respect to grain size, dunes with slipfaces are replaced by rounded bed forms termed zibars; and these could coexist with dunes with slipfaces owing to spatial variation in grain size (see Nielson and Kocurek, 1986). Some linear dunes are clearly the product of the asymmetrical lengthening of one horn of barchan dunes (e.g., Bagnold, 1941). The Algodones, southeastern California, shows the coexistence of zibars, barchans, and linear dunes that clearly originate from the western horns of crescentic dunes (Fig. 8).

Although not a change in dune type, differences in a simple dune pattern may exist across a dune field in terms of the measurable parameters. Where dunes originate at the upwind margin of a field, dune size and spacing can be expected to increase in the migration direction, as at White Sands (Fig. 1). On Padre Island, Texas, the larger oblique dunes that persist throughout the year have a different orientation than the small transverse dunes that occur only during the summer constructional period (Hunter et al., 1972). Dunes commonly change orientation with the wind direction such as the linear dunes of central Australia

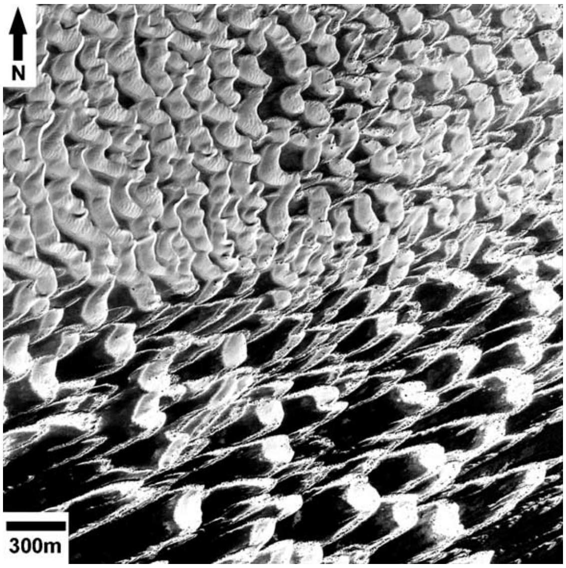

Fig. 7. Abrupt change from crescentic to parabolic dunes at White Sands, New Mexico. This spatial change in dune type is thought to reflect a change in vegetative cover of the substrate.

(Brookfield, 1970), and different dune types are expected where the wind regime changes across a large field.

4.2. Compound/complex dunes

Smaller dunes of the same type (compound) or different type (complex) superimposed upon the stoss or lee slopes of larger bed forms potentially represent the most difficult case to distinguish from superimposed multiple generations. In the simplest explanation, dunes can become superimposed upon larger dunes as soon as the main bed forms are sufficiently large to host the superimposed dunes, and many large dunes are easily as large as some dune fields. Superimposed dune type and crest orientation may differ from the main bed form as the smaller dunes conform to the secondary airflow over the main bedform or respond to only a portion of the overall wind regime.

Ideally, compound/complex dunes can be distinguished from a complex pattern because the superimposed dunes exist only upon the larger bed forms and can be understood in terms of the environment of the host bed form. Conversely, a complex pattern is suggested (i) where the superimposed dunes extend beyond the host bed forms, (ii) are in the process of reworking the larger bed forms, and (iii) the larger dunes can be traced as a relict pattern under the reworking pattern. As seen at the Algodones, for example, crescentic dunes exist as both superimposed features upon larger crescentic dunes and as the dominant pattern under which the trace of the larger dunes is evident (Fig. 9). The pattern of smaller crescentic dunes has been interpreted to represent a younger generation of dunes that are reworking the western portions of the larger dunes as the entire field migrates to the SSE (Derickson, 2005). This interpretation, however, does not preclude the existence of superimposed dunes upon the larger bed forms at some earlier period.

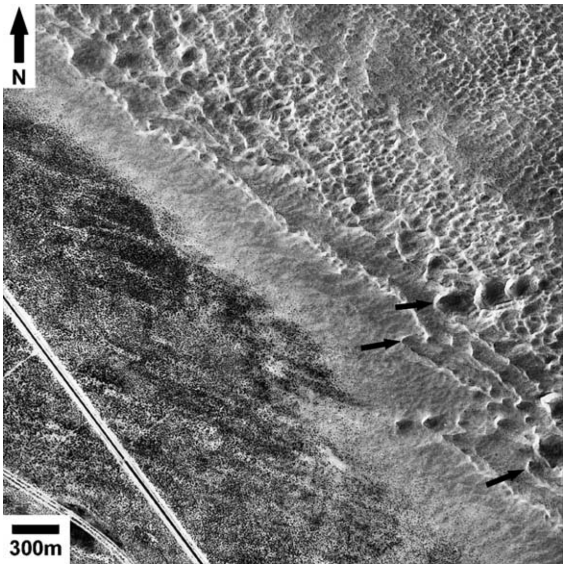

Fig. 8. Formation of linear dunes by the elongation of the western horns of crescentic dunes (some noted by arrows), Algodones, southeastern California.

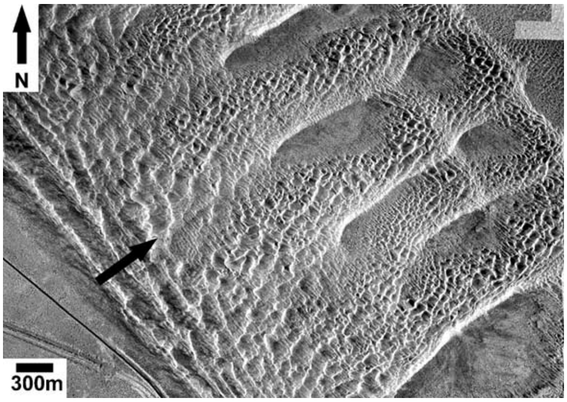

Fig. 9. Occurrence of superimposed crescentic dunes upon larger crescentic dunes, yielding westward to a pattern of simple crescentic dunes in which the trace of the larger dunes is still evident (one noted by arrow). The crescentic dune pattern is interpreted to be reworking the older pattern of larger dunes. Differences in orientation and size of the crescentic dune pattern to the west and the superimposed crescentic dunes is interpreted to represent secondary flow over the larger bed forms and less time for development of the dunes because these are lost or reformed when they migrate to the brink of the larger dunes.

5. Geomorphic surfaces and the rock record

In order for generations of dune-field patterns to become superimposed, the rate of change of the wind regime and formation of new patterns must be faster than the rate of burial of the depositional surface upon which the dune-field pattern rests. At one extreme, depositional surfaces, upon which dune fields exist but accumulation of a stratigraphic record does not occur, remain indefinitely as exposed surfaces subject to reworking and pattern superposition. Some of the sand seas of the Sahara Desert, for example, rest upon bedrock and are leaving no accumulation for the stratigraphic record (Kocurek, 1998). At the other extreme, depositional surfaces with high rates of sediment accumulation or in which the rate of change of the wind regime is slow in comparison to the rate of accumulation will reflect a vertical succession of largely simple dune field patterns.

Although cross-strata formed by complex dune patterns must exist in the rock record, much of the ancient compound cross-strata (see examples in Rubin, 1987) appear to reflect dunes superimposed upon larger bed forms, in which both scales of bed forms simultaneously migrated. By its very nature, the aeolian rock record reflects surfaces upon which accumulation occurred and in which the accumulations were preserved through a rising water table or subsidence with burial (Kocurek, 1999). The rock record is biased, therefore, toward large influxes of sand (hence large bed forms with likely superimposed dunes) that accumulated in active tectonic basins. An additional driving factor is that within Greenhouse times (e.g., Jurassic) climatic change in arid regions may have been slow and minimal. Conversely, the Quaternary Icehouse (similar to the Permian) has been a time of rapid climatic change, thus favoring the formation of complex dune patterns.

6. Conclusions

Although computer modeling of dune-field evolution is in its infancy, simulation of dune and ripple patterns, supported by experimental and field data, argues for the formation of a simple pattern for a given wind regime. The occurrence of spatial variation within simple patterns because of factors such as substrate control argues that wind regime is the primary but not sole discriminator in pattern formation. Given the input for the Werner (1995) model (i.e., higher probability of deposition on a sandy surface and the lee shadow zone), bedform growth is inevitable. The wind regime serves to define the shape and orientation the growing body of sand. Pattern evolution proceeds by dune–dune interactions at the dune field scale.

Computer models indicate that reorientation of the dune pattern occurs by reorientation of the crest terminations, which is translated through the length of the dune. Based upon a sand volume argument, the formation of a new pattern of small dunes can proceed more rapidly than reorientation of existing dunes where the existing dunes are large and the defect density is low. The resulting complex pattern is the superposition of simple patterns formed during different generations of construction. The new pattern emerges from sand that is available, including new or continued influx, sand blown from existing dunes, and sand housed in existing dunes. The commonness of complex dune-field patterns reflects both the frequency of climatic change during the Quaternary and the fact that many of these dune fields occur on surfaces with little or no sediment accumulation.

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