BOOKS & ARTS

In Retrospect: the physics of sand dunes

Ralph Bagnold's wartime posting to map the dunes of North Africa was like a desert epic — and it inspired his classic text on how wind-blown grains self-organize into regular patterns, explains **Philip Ball**.

Physics of Blown Sand and Desert Dunes
by Ralph Bagnold
Methuen: 1941. 265 pp.

Ralph Bagnold intuited that regular dune and ripple shapes embody the physics of complex systems.

"We forgave Bagnold everything for the way he wrote about dunes. 'The grooves and the corrugated sand resemble the hollow of the roof of a dog's mouth.' That was the real Bagnold, a man who would put his inquiring hand into the jaws of a dog."

This is the voice of Hungarian explorer László Almásy, as fictionalized in Michael Ondaatje's 1992 novel *The English Patient*. The remark is a piece of authorial indulgence, for Ondaatje's readers could hardly be expected to know of this Bagnold who flits across a few pages of the desert epic. Ondaatje, however, clearly knew his man, hinting at the ground-breaking way in which Ralph Alger Bagnold studied and wrote about the major obsession of his life: desert sands.

Bagnold did so with such perception and insight that his 1941 book *The Physics of Blown Sand and Desert Dunes* became the standard work on dune formation for many decades. Informed by observations in Libya and wind-tunnel experiments in the United Kingdom, Bagnold set out to explain how sand grains are organized by wind into structures ranging from ripples the width of a finger to undulations several kilometres across.

His book is more than an exploration of a hitherto-neglected aspect of geomorphology. In hindsight, Bagnold's work can be seen as a landmark in a much broader vista: the investigation of complex, self-organizing systems, in which order and regularity emerge from interactions of components that seem to prescribe nothing more than chaos and disorder. As Bagnold wrote of dunes:

"The observer never fails to be amazed at a simplicity of form, an exactitude of repetition and a geometric order unknown in nature on a scale larger than that of crystalline structure."

Thus he perceives that the problem is not simply to explain the size, shape and variety of dune-like formations, but to account for the more general phenomenon of regularity arising from a system that is initially featureless.

Sand ripples and dunes are conspiracies of grains that arise from the interplay of wind-borne transport, collision-driven piling up, and slope-shaving avalanches. They are an archetype for the self-organized patterning of systems of many interacting components. Interest in granular complexity has blossomed over the past decade, exemplified by the appearance of stationary-wave arrays in shaken, shallow layers; grain-size stratification in avalanches and rotating drums; and the use of sand piles as a model of 'scale-free' dynamics known as self-organized criticality. Such behaviour lies squarely in the domain of the physicist; Bagnold's prescience is located in his intuition that wind-formed geomorphology embodies the physics of complex systems writ large in nature.

> "The observer never fails to be amazed at a simplicity of form, an exactitude of repetition."

There is a long tradition of army and naval engineers whose scientific legacy implies that their minds were on matters other than the military. Bagnold joined the British Army's Royal Engineers in 1915 and fell in love with the deserts during postings to Egypt and India. By the 1920s he was spending his leave exploring these 'seas of sand', joining Almásy's 1929 expedition in search of the legendary city of Zerzura west of the Nile.

Before Bagnold, the transport of small particles by fluids — not just sand in wind, but sand and silt in water, wind-blown snow and industrial processing of grains such as cereal and coal dust — was afforded little more than a few empirical formulae used by engineers. But Bagnold claimed that "the subject of sand movement lies far more in the realm of physics than of geomorphology". He began from an aerodynamic perspective, conducting wind-tunnel studies in the mid-1930s to map the trajectories of individual sand grains in moving air. The key to the transport process is that the grains bounce when they hit the desert floor, and are carried along in a series of little jumps — known as saltation — that ultimately determine the length of sand ripples.

But the central issue was why wind-borne sand produces roughly regular ridges. Bagnold showed that this was caused by a self-amplifying growth instability, now recognized to drive patterning in systems such as snowflakes and dendrites, fractal aggregation and viscous fingering. He showed that a single, chance irregularity on a smooth desert floor stimulates growth and multiplication of bumps of more or less equal size and spacing.

He began fieldwork in Libya in 1938, funded by Britain's Royal Society. His book was published three years later, while he was conducting reconnaissance in the North African conflict during the Second World War. He deduced the wind conditions that produced different dune types, such as crescent-shaped barchans and undulating seif dunes — conclusions that have been recently borne out by computer modelling.

The general problem that Bagnold faced — to account for spontaneous pattern formation — was addressed more famously in D'Arcy Wentworth Thompson's seminal 1917 book

© 2009 Macmillan Publishers Limited. All rights reserved

On Growth and Form. But Bagnold seemed unaware of that. Thompson's epic revised edition, published in 1942, surprisingly neglects not only Bagnold's efforts but the entire issue of ripple and dune formation. A connection to more general patterning processes ultimately emerged from Alan Turing's work on biochemical morphogenesis, described in a 1952 paper. When, in the 1970s, mathematical biologists Hans Meinhardt and Alfred Gierer identified the fundamental ingredients of Turing's stationary chemical patterns — the presence of a locally acting autocatalytic 'activator' and an inhibitor that suppresses pattern elements over longer ranges — it became apparent why sand ripples resembling in plan form the striped markings of zebras probably result from a Turing-like mechanism. The formation of a ripple is self-enhancing because it captures more sand the bigger it gets. Meanwhile, this process depletes the air of sand grains, suppressing another ripple for some distance downwind.

The fact that granular flow might serve as a universal analogy for other physical phenomena had been suspected in the late nineteenth century by Osborne Reynolds, a pioneer of fluid dynamics. In order to flow, a collection of grains must expand a little, and Reynolds decided that this 'dilatancy' of powders could explain all the mechanical behaviours in nature if space were filled with submicroscopic grains. A portrait from 1904 shows Reynolds holding a basin of ball bearings, and two years earlier he revealed what he had in mind: "I have in my hand the first experimental model Universe, a soft India rubber bag filled with small shot." William Blake's world in a grain of sand is invoked to the point of cliché in granular research, but here it was claimed as a reality. ■

Philip Ball is a consultant editor for *Nature*. His forthcoming book series is *Nature's Patterns: A Tapestry in Three Parts*.

Inside the map-maker's mind

The Natures of Maps: Cartographic Constructions of the Natural World
by Denis Wood and John Fels
University of Chicago Press: 2008. 231 pp. $49

I trace with my finger the ridgeline to the summit of Mount Everest. The beautiful, icy, white-, blue- and granite-coloured map on the cover of *The Natures of Maps* brings the peak easily within reach. Yet if I were to try to scale this mountain, it is likely I could die trying. In this sense, argue geographers Denis Wood and John Fels, this map puts nature in its place: under my thumb.

Although I know it is a representation of nature, and not the real thing, such representations are powerful. They affect how we think about the subjects they portray. And therein lies the utility of this terrific book. It uses the tools of cognitive linguistics to conduct a step-by-step analysis of how maps construct — in our minds — the versions of nature that dominate public discourse about the environment, ecology, conservation and the proper place of humans on our planet.

The authors identify eight versions of nature that are constructed by the arguments commonly embodied in maps. Nature may be awesome, a threat or a victim. It embodies a cornucopia, is collectable and an object of scientific study, yet it remains a mystery. Or it may be differentiated as a park, legally protected and codified, "a nature, ultimately, quietly put in its place".

The book is a beautiful tour de force. Laid out like an art book with stunning reproductions of maps, it also contains a trenchant, practical analysis that is useful for anyone wanting to read maps more critically and construct better maps of nature.

Wood and Fels borrow their conceptual scaffold from cognitive scientists Gilles Fauconnier and Mark Turner, who argue that language opens 'mental spaces' that can blend with other conceptual spaces in our minds to create new combinations. For example, the term computer virus is a powerful mix of two disparate ideas: one technological, the other biological. Wood and Fels analyse how a map similarly provides "a system of propositions" about nature that "get tied together into arguments about the world".

These spatial arguments are constructed 'on the fly' in our minds, say Wood and Fels, presumably using the same kind of activated neuronal assemblies that are proposed to enable the conceptual blending of their linguistic counterparts. But this neuroscience black box distracts from their analysis of how "maps hoist themselves off the page into our brains, spawning world views" as we read the complex propositions posted on their flat surfaces.

The analyses of the eight natures commonly constructed by maps provide the book's greatest value. 'Threatened nature' is the most compelling, and Wood and Fels bring all their tools to bear in an incisive deconstruction of a map from *National Geographic* entitled 'Australia under siege'. They trace the argument being made in geographic terms as this standard, seemingly objective base map is blended — in the reader's mind — with colourful maps of Australia's land cover 200 years ago and today, showing the threats posed by fire, feral species, forestry, grazing and mining. Ultimately, they say, the map argues that the past equals nature, and no map of the future is needed: "the meaning (and the fear and anxiety) emergent in the blend is perfectly clear".

The eight natures arguably encompass the most important currents in contemporary thought, save for one: nature is change. That is not just the nature that has been changed, as in Australia, but nature that is always dynamic. The omission of this dynamism is a weakness of this book, and in fairness, of most maps. It is a pity that the authors limit their analysis to static maps of nature when we are witnessing the proliferation of 'mash-ups' that link data sources to web-based applications, such as Google Earth, to create dynamic, interactive maps. Fortunately, the analytical tools that Wood and Fels demonstrate can help us understand how interactive maps work too.

Dynamic maps open up new mental spaces more quickly and readily than static

NG MAPS/NATIONAL GEOGRAPHIC IMAGE COLLECTION

The peak of Mount Everest, within touching distance.

© 2009 Macmillan Publishers Limited. All rights reserved