Dune: Arenaceous Anti-Desertification Architecture

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1 Introduction

Argentinian writer Jorge Luis Borges once observed that “Nothing is built on stone; all is built on sand, but we must build as if the sand were stone” (Borges 1974).

A single grain of sand is almost nothing: a splinter of rock, a miniscule fragment of a geological formation, the residue of a microcosmic event. Myriad grains together, however, become almost everything: mesmerising landscapes, vast deserts, a fluid material capable of being transformed into solid structures, and, ultimately, flourishing cities. In aggregates of sand, interlocking angular quartz grains, we find fascinating forms and emergent patterns; possibilities, potentials, substance. In short, we find a constant unfolding of interactive opportunities (Balmond 2002).

Architects work in the mineral world, in which all design is fundamentally about aggregation and erosion. Even the most austerely minimalist structures present aggregations of elements and densifications of matter that were not there before. Through accretive processes, materials become buildings that become cities. At its most fundamental level, architecture is about the manipulation of landscape.

The project presented here, *Dune,* is an architectural speculation aimed at creating a network of solidified sand dunes in the desert—a proposition that suggests precisely such an elemental ground manipulation. It also advocates a radical shift in structural thinking, away from pre-fabricated or in situ construction, towards the localised cementation of granular materials.

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Localised cementation of the desert sand is achieved through microbially induced carbonate precipitation (MICP) using the microorganism *Bacillus pasteurii*, an aerobic bacterium pervasive in natural soil deposits (Le Metayer-Levrel et al. 1999; Nemati and Voordouw 2003; DeJong et al. 2006; Whiffin et al. 2007). In the right circumstances, the bacterium's enzymatic urease catalyst hydrolyses urea, which—when the process occurs in a calcium-rich environment—generates calcite (the most stable polymorph of calcium carbonate), which binds the individual grains of sand together. The solidification of the sand is organised into an array of specific spatial structures to create a very narrow and roughly 6,000 km long pan-African city with the capacity to mitigate against the Sahara's shifting sands. The spatial pockets would help retain scarce water and mineral resources necessary to turn *Dune* into a micro-environmental support structure capable of assisting the formation of the Great Green Wall for the Sahara and Sahel Initiative (GGWSSI). The various spatial pockets within *Dune* would also serve as habitable and programmable space for a nodal network converging with the planned Sahara Railway.

Dune is an exercise aimed at investigating a climate-conscious architecture that primarily points toward adaptive responses to the potential threats of future extreme environments. The desire is to create a framework for an innovative architecture that applies a controlled biocementation process as a strategy to mitigate the continual migration of sand dunes in the circum-Saharan drylands of Africa. The final outcome is a habitable anti-desertification structure made from the desert itself, a sand-stopping device made out of sand.

While the scale and scope of the scheme inevitably positions it within the speculative realm, and while many details are left to explore before a bacterial cementation of habitable sand dune barriers can be carried out in the real world, it is important to remember that the concept outlined here is a buildable proposition. Humankind has created larger structures in the past: a recent 2-year government mapping study of the Great Wall of China (carried out by the Chinese State Administration of Cultural Heritage and the State Bureau of Surveying and Mapping), the most comprehensive archaeological survey to date of this largest of man-made structures, stretching from Lop Nur in the west to Shanhaiguan in the east, concluded that the entire wall with all of its branches stretches for some 8,851.8 km. This example is particularly pertinent since in its western section, which is mostly located in the desert, the wall was typically built with sand and mud.

Fraught with challenges and difficulties as this stratagem might be, the *Dune* project is a beginning, a blueprint, a vision. To return to the beautiful image borrowed from Borges, it is the sand; what follows is yet another move towards turning it into stone.

2 The Threat: Deserts and Desertification

At the heart of the world's drylands are five major zones of natural desert: the Afro-Asian Desert (a great belt stretching from the Atlantic Ocean to China, including the Sahara, Arabian, Iranian, Touranian, Thar, Takla Makan, and Gobi deserts), the North American Desert (comprising the Great Basin, Mojave, Sonoran, and Chihuahuan deserts), the Atacama and Patagonian Deserts in South America, the Namib and Kalahari Deserts in south western Africa, and the Great Sandy, Great Victoria, and Simpson Deserts in Australia (Grainger 1990; Martin 2004).

Deserts emerge from the interacting processes of atmospheric circulation and oceanic circulation (Weinstock 2010). The word ‘desert’ usually connotes a landscape devoid of people, but except in the most extremely hyperarid regions, people have developed agricultures and built communities either around the desert margins or in the desert itself: today, upward of a billion people live in arid or semiarid environments, coexisting with the shifting sands, sometimes struggling to get by in the wake of increasingly harsh conditions.

The apparent spread of the desert is not a new phenomenon, but one that has occurred throughout human history: In the fourth century BC, Chinese philosopher Mencius (Mèng Zǚ) wrote about desertification and its human causes, including the cutting of trees and overgrazing. Plato, in the same century, commented upon the early deforestation of Attica the historical region of Greece that contained Athens by saying that “Our land, compared with what it was, is like a skeleton of a body wasted by disease”. Athens was forced to trade wine and olive oil for wheat and other items of food that its eroded soils could not supply (Burns 1995).

Dry areas cover more than one-third of the earth’s land surface. Some are deserts, others are being continuously degraded by the erosion brought about by grains of sand carried by aeolian forces. Though disputed by some, desertification (“the diminution or destruction of the biological potential of the land” that is “an aspect of the widespread deterioration of ecosystems under the combined pressure of adverse and fluctuating climate and excessive exploitation” according to UN-COD’s 1977 definition) is considered by many specialists in the field to be one of the most serious environmental problems facing our world (United Nations 1978). The validity of this claim is beyond the scope of this chapter: the scientific understanding of desertification is still quite limited, and the role of the climate, in particular, has until recently been thought of as mainly catalytic.

Desertification has been on the international agenda for about half a century, but we still do not know precisely how fast, or indeed whether, our deserts are growing, much less how best to address the issue should that be the case. It is estimated that firewood collection, excessive grazing, and overcultivation accounts for nearly 90% of what is perceived as desertification (Grainger 1990; Welland 2009a). *The World Atlas of Desertification* summarises the current state of scientific knowledge on the drylands of the globe, and indicates that desertification is one of the world’s most pressing environmental problems, and an accelerating global issue (Middleton and Thomas 1997). In the following, that view will be presumed to be correct.

It is safe to say that the majority of those working with desertification accept that a wide variety of pressures have led to the adoption of unsustainable land management practices in the circum-Saharan drylands, including continuous overstocking and overgrazing of rangelands; continuous cropping, with reductions in fallow and rotations, repetitive tillage and soil nutrient mining; rangeland burning; and the over-exploitation and clearance of savannas (for cultivation). The impacts of these practices include loss of natural resources, changes in natural habitats and ecosystems, loss of agrobiodiversity and wild biodiversity, degradation of ecosystem services, decreases in productivity (of both arable land and rangeland) leading to poor harvests and food shortages, which in turn result in poor living conditions and poverty. Climate change might already be exacerbating these problems, with increasing weather variability (droughts and storms), and is predicted to bring further challenges in the coming decades, with rising temperatures and changes in rainfall patterns (IPCC 2007a, b).

3 The Site and Sahelian Droughts

Desertification is a major threat on all continents, affecting more than 100 of the world's 190+ countries. Some estimates suggest that 35% of the Earth's land surface is at risk, and that the livelihoods of 850 million people are directly affected. 75% of the world's drier lands—45,000,000 km^2—are affected by desertification, and every year 6,000,000 ha of agricultural land are lost and become virtual desert (Dollo and Sen 2007). More than 80% of Africa's drylands are moderately or severely desertified, a figure that equals more than one-third of all desertified land in the world. The Sudano-Sahelian region is the most affected part of the continent, mainly due to overgrazing and overcultivation, though the other two major direct causes—poor irrigation and deforestation—also play a part (Grainger 1990).

The largest volumes of shifting sands are to be found neither in Africa nor in the Middle East, but in China. The total area of China's desert is growing at around 200 km^2 every *month,* and innovative solutions are desperately needed to combat the thousands of tons of sand and dust that are blown into Beijing every year (Welland 2009a).

That scenario might indeed form the basis for future projects. As the site for *Dune,* however, the circum-Saharan drylands were chosen because of the frequent occurrence of droughts in this region during the past century. The name Sahel itself means "edge of the desert" (Grove 1977) and this is probably the one region in the world most closely associated with desert encroachment. In the Sahel, the availability of water (or in more precise terms, the possibility of collecting and exploiting rainwater, fog, and dew) represents the fundamental limiting factor for human survival, habitation, and production. The seasonal distribution of precipitation and its annual variation is more important than the annual, global amount of rainwater (Koechlin 1997).

In such a situation, a particularly dry year can easily spark conflict in the Sahel. Climate change, drought, increased desertification, crashing food supplies, water scarcity, famine, forced migration, political instability, warfare, crisis—that's a potential (albeit admittedly worst-case) scenario if we fail to take this seriously.

African countries share an important condition with other developing countries in that they are “especially vulnerable to climate change because of their geographic exposure, low incomes, and greater reliance on climate sensitive sectors such as agriculture” (Stern 2007). The historical climate record for Africa shows warming of approximately 0.7°C over most of the continent during the twentieth century, a decrease in precipitation over large portions of the Sahel, and an increase in precipitation in east central Africa (Desanker 2002). Droughts and floods have increased in frequency and severity across Africa over the past 30 years. Throughout the twenty-first century, the warming trend and changes in precipitation patterns of the twentieth century are expected to continue, increase in rapidity, and be accompanied by an increase in the frequency of extreme weather events—droughts, floods and storms (Stern 2007). Predictions of the magnitude of changes in temperature and precipitation are subject to considerable uncertainties, but climate change scenarios for Africa indicate future warming across the continent ranging from 0.2°C per decade (low scenario) to more than 0.5°C per decade (high scenario) (Hulme 2001; Desanker and Magadza 2001).

When drought exhausted the small harvest of 1970, an estimated three million people in the Sahel needed emergency food aid, with between 100,000 and 250,000 people dying as a result of the drought, according to a UNCOD report. The FAO estimated that 3.5 million head of cattle, 25% of the region’s total, died in the Sahel in 1972–1973 alone. The drought eventually prompted the United Nations 1977 Conference on Desertification, and had a massive impact on the African drylands and the people who live there (Grainger 1990). It was a catastrophe arising from a phenomenon that gets very little attention: in our accelerated media culture, desertification is too slow to make the headlines—there are simply too few crying children and smashed-up houses to hold the attention of the general public; nothing like a tsunami or a Katrina. Despite that, this is a tragedy waiting to happen again.

Six years after the UN conference, Kenneth Hare prepared an assessment for UNEP in which he reported that “there is yet no way in which climatologists can decide whether this desiccation will continue” but that “(t)he possibility of a permanent desiccation of the drybelt climates of Africa cannot … be ruled out” (Hare 1983, 1984). If such a development were to take place during a period of unprecedented population growth and increased food demands, the situation could once again become disastrous. The population of Africa is increasing, and is set to double every 23 years (according to the UN, the fastest growing nation on the planet is Liberia, with a doubling time of about 15.5 years), while the amount of food being produced to feed each person is decreasing. Estimates show that if current trends of soil degradation and population growth continue, the continent might be able to feed just 25% of its population by 2025 (United Nations 2007). In 2007, another UN study showed that desertification currently affects 100–200 million people, and that it has become a threat to global stability, putting about 50 million people at risk of being driven away from their homes in the next decade (Adeel et al. 2007).

Such a course of events is perhaps more threatening in Nigeria than anywhere else. With a constantly growing population of more than 140 million people, it is

Fig. 1 Helicopter perspective would become a new, narrow, pan-African, urban development built straight into the dunescape

the most populous country in Africa, experiencing serious desert encroachment issues throughout its northern states. While the largest city, Lagos, is expanding northward at an unprecedented rate, the Sahara desert is pushing the border of the fertile Sahel land southward at an alarming pace. At some point in (the distant) future, these two movements of sand and people in opposite directions may meet, creating a serious desertification refugee crisis. Every year, Nigeria loses about 600 m of its arable land mass to desert encroachment (Ezigbo 2009). During a study trip undertaken by the author in 2008, several foresters in the villages outside of Sokoto confirmed this rapid migration.

Allowing *Dune,* the 6,000 km long habitable wall proposed here (the Sahara is roughly 5,150 km across at its widest point) to pass through this part of the world could be one way of creating a unified front against the encroaching desert: a new kind of city, a narrow, pan-African, urban development built straight into the dunescape, supporting a vast shelterbelt of trees, and effectuating a permacultural evolution while connecting countries and people (Fig. 1).

4 Traditional Anti-Desertification Methods

Such a support structure for a shelterbelt of trees would constitute a continuation of traditional anti-desertification methods. These include the planting of trees and other plants (cactii are popular, as are different types of acacia, eucalyptus, and bushes), the cultivation of grasses and shrubs, and the construction of sand-catching fences and walls. More ambitious projects have ventured into the development of agriculture and livestock, water conservation, soil management, forestry, sustainable energy, improved land use, wildlife protection, and poverty alleviation.

Grains of sand move in three different ways in the desert: through suspension, creep, and saltation (Bagnold 1941). The way to stop a desert in its tracks is to come to terms with saltation, the mini avalanches that break the continuity of the dune surface at the top of the shear plane, which creates the slope at the leeward side of the dune. Shelterbelt plantations are usually made up of one or more rows of trees or shrubs planted so as to provide shelter from the wind while protecting the soil from erosion. The *Dune* scheme seeks to support such a shelterbelt.

Anti-desertification and afforestation projects involving large-scale planting of shelterbelts have historically been proposed by different governments to reduce soil erosion and improve the microclimate in otherwise treeless agricultural areas. These include US president Franklin Roosevelt's Great Plains Shelterbelt project, ambitiously launched in 1934 as a way of modifying the weather and preventing the Great Plains states from eroding (by 1942, this scheme had resulted in the planting of 30,233 shelterbelts containing 220 million trees that stretched for 30,000 km). In the USSR, one section of General Secretary Joseph Stalin's Great Plan for Transformation of Nature, launched in October 1948, provided planting of a gigantic network of shelterbelts across the southern steppes of the country, while the Green Wall of China is a project intended to provide 4,800 km of shelterbelts across the northern parts of that nation by 2074. Other schemes worth mentioning include Wendy Campbell-Prudie's Tree of Life trust in the 1960's, and Richard St. Barbe Baker's Men of Trees group in the 1920's (Hurt 1995; Krech et al. 2004; Campbell-Purdie 1967; St. Barbe Baker 1944).

All of the above procedures were attempts to mitigate the advancement of the desert. They were mitigatory measures. The International Panel on Climate Change (IPCC) defines mitigation as "An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases." The ability of a system to adjust to climate change with moderate potential damage is referred to as that system's climate adaptation. These two terms—mitigation and adaptation—are fundamental in the climate change debate. The IPCC has defined adaptation as adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, with the aim to either moderate harm or exploit beneficial opportunities. Historically, mitigation has been viewed as the primary way to proactively curb human causes of climate change—in the present case desertification—whereas adaptation has been seen as a secondary measure to cope successfully with changing conditions after the fact. However, in the case of desertification, the changing nature of the sand dunes constitute the challenge (we are not so much concerned with the theory that the Earth's deserts might be expanding as with the fact that the sand within them is moving), which turns adaptation into less of a passive measure and more of an active adjustment in response to new stimuli. Simplified, we could talk about three conditions: (1) cause mitigation (such as carbon mitigation), (2) system mitigation (for instance shelterbelts), and (3) adaptation (in this case a habitable, permacultural structure).

While the IPCC generally defines the term mitigation as cause mitigation, we are here concerned primarily with the second and third conditions.

While *Dune's* sandstone barrier mitigates against the encroaching desert through its supporting the shelterbelt, it also seeks to adapt to its environment through the creation of habitable spaces inside of this barrier. Inside the dunes, we can take care of our plants and animals, find water and shade, help the soil remain fertile, care for the shelterbelt trees, and so begin to green the desert from within (Fig. 2).

The exact strategies for this sustainable land use design lie outside the scope of the present text. A brief clarification, however, might be in order. Once the sand has been solidified into solid sandstone structures, permacultural tactics would be used to sustain their inhabitants. *Permaculture* is a portmanteau of *permanent agriculture* and *permanent culture*—a school of thought based on ecological and biological principles that often translate natural patterns into a man-made environment in order to maximise effect and minimise the amount of work needed to reach that effect. The general idea, from the writings of American agricultural scientist Franklin Hiram King and onwards (King 1911) is to educate a range of individuals in a core set of design principles with which they can then design their own environments and self-sufficient settlements, creating stable, productive systems that provide for human needs. While any local settlement along the proposed 6,000-km habitable wall would have to be meticulously analysed before any proper conclusions could be drawn, some of those permacultural design principles are likely to be fog harvesting, condensation strategies, swales (a form of rain-harvesting trenches), natural ventilation principles, edible landscaping, and waste management tactics. Some prominent permaculturalists include David Holmgren, Bill Mollison, Geoff Lawton, Patrick Whitefield, and Toby Hemenway.

Fig. 2 Interior perspectives: Inside the solidified dunes, we can find water and shade, care for the shelterbelt trees, and begin to green the desert from within

5 The Great Green Wall for the Sahara and Sahel Initiative

Sand dunes cover only about one-fifth of our deserts (Welland 2009a), but those extreme areas are good places to introduce a barrier of greenery to check desert encroachment and counter soil degradation, halt the shifting sands and stop the dunes from migrating.

Dune's focus on adaptation seems to be in line with Jauffret and Woodfine's 2009 feasibility study for the Great Green Wall for the Sahara and Sahel Initiative (GGWSSI). As of late December 2009, 525 km out of the 7,000-km-long shelterbelt have been planted, all within Senegal (Dell'Amore 2009).

The idea of a 'Green Wall for the Sahara' was first proposed by former Nigerian president Olusegun Obasanjo in 2005, and presented first to the Community of Sahel-Saharan States (CEN-SAD) and then to the African Union (AU) that same year. The idea was further discussed in Lisbon in December 2007, and in Brussels in January 2008, after which it was agreed that a feasibility study would be carried out.

The initiative originally called for 23 African countries to come together in order to plant trees across a 7,000-by-15-km stretch south of the Sahara—a total area of 105,000 km^2, or 10.5 million hectares—so as to cover parts of the land that lie within the 100–400 mm annual rainfall band. The aim was to catalyse "sustainable development and poverty reduction in the desert margins north and south of the Sahara" and "to strengthen the implementation of existing continental frameworks and plans addressing the menaces of land degradation and desertification in the margin of the Sahara desert" (AU/CEN-SAD 2009).

An early press release from the African Union proposed that under the programme "300 million trees, covering three million hectares of land will be planted" and that "the goals and objectives of the green wall … are to slow the advance of the Sahara desert, enhance environmental sustainability, control land degradation, promote integrated natural resources management, conserve biological diversity, contribute to poverty reduction, and create jobs" (African Union 2006).

Planting a shelterbelt, as we have seen, is a traditional method on a grand scale, using the trees to stop the grains from avalanching over the dunes' crests. The vegetation belt was planned to run across the entire African continent, offering mitigation against desertification and some adaptive effects through the harvesting of fruit from the trees. However, assuming 460 trees/ha and 100% survival, this plan would equal at least 4,838 million tree seedlings; unquestionably an unrealistic figure.

At the onset of the project, the solidified dunes of the *Dune* scheme were intended to support the existing GGWSSI. Following the feasibility study, a much wider range of sustainable land management practices have been proposed as "a more ecologically appropriate and holistic approach to directly benefit local land users (farmers, agro-pastoralists, and mobile pastoralists)" (Jauffret and Woodfine 2009). This move away from the original shelterbelt idea could mean that the sandstone structure no longer has any real-life trees to support. However, over and above how the structure performs in terms of tree support/desertification mitigation, its adaptive qualities—the creation of oases for people in the desert—still makes, at the very least, the nodes of this structure justifiable.

One aspect of climate change pointed out by the feasibility study is of particular concern: not so much the shift in long-term average climate, but rather the increased frequency and magnitude of climatic extremes. Climate change is eroding the social network mechanisms that have been used in the past to cope with drought, by causing climatic extremes that leave the affected people without enough time to recover. Recurrent droughts have led to the degradation of the resource base and forced millions of farmers to sell their assets, in some countries forcing them into absolute destitution. Using the *Dune* structure to physically bring people together could be one way of restoring these mechanisms and start building up the adaptive capacity of the local communities. Staying put and finding ways of adapting to the situation would be an alternative to trying to run away from the encroaching dunes. The *Dune* scheme is designed as a network around a set of nodal points at which conditions are optimal for living in these harsh environments (sheltered points with good access to water, a topography that lends itself to the sculpting of shaded areas, proximity to existing infrastructures, and so on). Just as a node in physics is a point along a standing wave where the wave has minimal amplitude, so the nodes in *Dune* would be points where the encroaching desert has a minimal impact on the way of life, and thus would be ideal places for human habitation.

6 Arenaceous Architecture

Designing with aggregates may commence either from the design of the elements that will make up the aggregate itself, or from the utilisation of natural grains used together with designed and/or natural constraints to guide the design and/or construction process. This project is entirely positioned within the latter realm. The systems underlying naturally occurring sand formations are interesting, as dune and ripple formations suggest a mutual modulation—airflow and water modulate dunes that in turn modulate those initial forces, which brings about formations that follow clearly discernible rules (Takahashi 2006).

When those rules and modulations are first observed and analysed, and then strategically controlled through the local solidification of sand into sandstone, turning the natural phenomena into architectural structures, we move towards a novel technology with staggering potentials. As mentioned above, the *Dune* scheme advocates a radical shift in structural thinking, away from pre-fabricated or in situ construction, towards the localised cementation of granular materials: if we can control the solidification of sand into sandstone, then we can begin to investigate a completely monolithic architecture based not on components that are attached to each other in order to create a structural system, but on the binary densification of aggregate matter: the sand is either turned into stone, or it's not. Introducing this notion of an architecture of solidification calls for a brief discussion on the nature of technology itself.

Alan Kay is a brilliant polymath with a CV that reads like a *Who's Who* of creative technology companies: Apple, Atari, Disney, Xerox. Kay's definition of technology is "anything that was invented after you were born". While neither transistors nor steam cars nor nylon carry technological connotations to me, at the time of writing this, the iPad does. If we were to ask a kindergarten teacher, however, we would probably learn that today's children feel the same way about the iPad that I do about nylon. The things that were there when we were born are simply part of the fabric of everyday life (or museum pieces). Technology is what happens next.

The US inventor, entrepreneur, and author Danny Hillis used to be Alan Kay's colleague. Hillis refined Kay's definition by concluding that technology is "everything that doesn't work yet". This points to the fact that successful inventions disappear from our awareness. We do not really consider the toothbrush a technology, not only because it was already invented when we were born, but also because it has proved so successful as to render itself essential. Essential things are not technologies. They are just indispensable parts of our existence (Kelly 2007).

The processes described here possibly constitute a technology following Kay's definition, and definitely fall within Hillis's interpretation of the term: whereas microbially induced carbonate precipitation (MICP) of grains of sand is a naturally occurring phenomenon, the exploitation of these procedures as a design and construction method is, to the best of my knowledge, an architectural speculation that has never before been proposed, and thus has yet to be implemented into a functioning system. However, just because the idea has yet to be tested does not mean that such a system could not be established—most of our tools and building materials have been subjected to hundreds if not thousands of years of research and development, but they all started out as speculations—and the success of some recently developed architectural materials (from Corian to LiTraCon) adds weight to this argument.

The dream scenario for the current proposal, then, would be to first turn this process from observable phenomenon to a technology (the controlled 'growing' of sandstone structures) that then becomes so ubiquitous as to disappear from our awareness. A common and ancient occurrence in nature becomes a technology when carried out and controlled by humans.

The word 'arenaceous' is a geological term meaning "consisting of sand or sandlike particles". Used from the mid-seventeenth century, its roots lie in the Latin *arenaceus,* from *arena* (*harena*): 'sand'. In biology, it is also used to describe animals or plants that live or grow in sand. Since the present scheme resembles, is derived from, and contains sand, while (literally) growing in highly sand-filled areas and utilising organisms that live and grow in sand, it seems natural to call it arenaceous. This novel arenaceous architecture is characterised by new material methods, new construction methods, new methods to mitigate against desertification, and new spatial, programmatic, environmental, performative, and affectual concerns.

7 Aggrerosion: Sand and Sandstone

I love sand. From the famous black lava grain beaches of Hawaii to the stunning stretch of white sand in Turkey known as Cleopatra's beach, from the star sands in Japan to the active dune ridges in Egypt's Great Sand Sea, this naturally occurring granular matter composed of finely divided rock and mineral particles—one of the most ubiquitous materials on the planet—is a beautifully paradoxical, seemingly magical building element.

Grains of sand are at the same time granular and massive, simple and complex, peaceful and violent, static and dynamic, too heavy to be held in suspension in the air yet light enough to be moved by the wind, individually evanescent to the point of invisibility yet capable of aggregating into highly pronounced (and huge) forms. Sand is the quintessential granular material.

It is also ever-present in architecture: its history is part of the material history of the discipline. Without sand no brick, no concrete, no glass—even wooden structures are sanded down to smoothen out their edges. How many cathedrals and mosques, how many temples and churches are made of sand? How many of our greatest cities rest on sand?

It is thrilling, in an age in which silica-based technologies control an ever-increasing part of our social, economical, and political interactions, to reassess the possibilities inherent in sand as a highly underused, exceptionally renewable building material.

One billion grains of sand come into existence around the world every *second*. It's a cyclic process: as rocks and mountains die, grains of sand are born. These grains may then become naturally glued together, or lithified (from *lithos*, greek for 'stone' or 'rock'), into a *clastic* sedimentary rock, a sandstone. When that sandstone is weathered, new grains break free. In a way, the static stone mountain becomes a moving mountain of sand. The majority of quartz sand grains are derived from the disintegration of older sandstones; perhaps half of all grains of sand have been through six cycles. Typically, the landscape of a mountain range will be lowered by a few millimetres every year (Welland 2009a).

The rule in nature, then, is that erosion follows aggregation follows erosion. Hacking into this perpetual cycle is a novel way of making exceptionally sensitive physical interventions in the landscape: exploring the poetic qualities of infinitesimal building blocks, and how they can be utilised in innovative ways to establish an understanding of (near-)microscopic stacking, packing, heaping, massing, mounding, piling, sheafing, and so on, could lead to a new building typology, one that utilises aeolian forces to define its exterior while harnessing the power of biocementation processes to sculpt its interiors. The morphological variations of dune types lie beyond the scope of the present study, but it's worth mentioning that their peculiar physics—examined first by Ralph Bagnold (1941) and later by Per Bak (1996)—yield volumes that could easily fit any existing architectural typology, from skyscrapers to railway tracks: dust sediment deposits can be more than 300 m deep; linear dunes that form parallel to the direction of

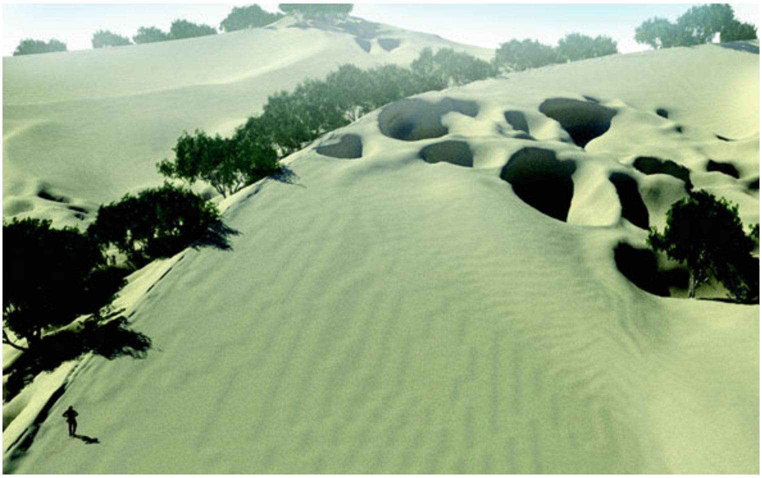

Fig. 3 Exterior perspective: The peculiar physics of dune type variations yield volumes that could easily fit any existing architectural typology, from skyscrapers to railway tracks

strong and persistent winds may be 100 or more kilometres long; the centre of a radially symmetrical star dune can be positioned several hundred metres above ground (Weinstock 2010) (Fig. 3).

Putting aggregation and erosion together was the starting point for *Dune's* use of *aggrerosion,* a design strategy based on the accumulation and reduction of granular materials. As a building material, grains of sand can be employed across a gradient of conditions: granular mass, solid stone, dynamic medium carried by aeolian forces, compressive membrane, and so on. One of the more fascinating facts about sand dunes is that they are both stable and fluid at the same time. Individual dunes have ripples on their surface, and these are fluidly active, as is the dune itself. Their geometry is consistent over time, but since they move—travelling across a vast sand sheet that perhaps covers thousands of square kilometres while largely maintaining their form—they are also fluid (Weinstock 2010).

Thus the granularity allows for both structural and constructional inventions: the sand can for instance be used both as primary ingredient of the finished structure and as its formwork during construction. If we solidify parts of a dune to hold it in place, the non-solid parts will continue moving, making it possible to plan for the aeolian forces to excavate the structure for us.

Bagnold defined this as the power of self-accumulation, a dune's skill in using the energy of the wind to collect all its scattered grains and build them into heaps, separated by areas free of sand. "In many areas of the desert," expands Michael Welland (2009a), "the sand is piled into dunes with bare rock in between, as if some giant combination of a vacuum cleaner and a bulldozer is constantly at work". It's a construction site waiting to be deployed: aeolian forces become our extended, invisible hand in the design process—the wind carries the material to the site, and then carries the excess material away from it again.

As soon as we begin to view them in this way, the sand dunes turn into readymade buildings. All we need to do is solidify the sand wherever we need solid surfaces, and then excavate the sand we do not need—or have the wind excavate it for us. Using the existing sand as our base material, we can sculpt arches, gaps, caves, and other patterns straight into the dune. As long as we take care to design *with* the aggregation rather than *against* it, we can simply allow saltation to propel the grains in place, and then, once the sand has aggregated into a beneficial form, use an intelligent strategy for how to solidify it, petrify it, freeze it into a solid state that speaks of that one moment in time. This is the novel idea at the heart of *Dune—Arenaceous Anti-Desertification Architecture.*

The solidification process turns the sand into sandstone, a sedimentary rock composed mainly of rock grains and sand-sized minerals—usually feldspar and/or quartz, as these are the most common minerals in the Earth's crust. Resistant to weathering, yet easy to work, some sandstones have become common building and paving materials. Over and above the obvious advantages arising from the abundance of sand in the Sahel, another fact that speaks in favour of creating sandstone structures in this part of the world is that such edifices usually allow percolation of water while being porous enough to store large quantities, turning a sizeable part of the final building into a potential aquifer. Sandstone aquifers are also fine grained, and therefore better at filtering out pollutants from the surface than are, for instance, limestones (Pettijohn et al. 1987).

8 Thinking Big: Radical Optimism and Anti-Walls

All acts of design are inevitably and inherently radically optimistic, and architecture is all about opportunities. Old buildings give way to new, structures are razed and new ones take their place, one city turns into the foundations of the next. The moment we stop believing in the possibility of making the world a better place is the moment we give up on architecture.

So what is an architect to do when moving mountains of sand threaten to push people away from their homes and induce catastrophic scenarios? Why, adopt the position of the radical optimist. Come up with an architectural response to the predicament. Find a way of using sand dunes to stop the desert from moving. It's true that architects are trained to solve problems, but I do not believe in architectural problems. I believe in opportunities. To borrow a line from a description of the late Tibor Kalman, I hold that we need to become perversely optimistic about the opportunities around us (Hall et al. 1998).

The opportunity at the outset was the challenge of turning *Dune* into a scheme that would support the pan-African green wall, but other paths soon opened up. It became clear that an existing technology for microbially induced carbonate precipitation (MICP) could be used to suggest, in effect, an addition to our existing architectural material palette. This technology is based on the bacterium *B. pasteurii*, which has a urease enzyme that enables it to hydrolyse urea, which in a calcium-rich environment generates calcite, which in turn acts as a binding agent to cement the individual grains together. This insight opened up discussions about the first two tiers of the issue at hand: how to make it possible for people at risk of becoming desertification refugees to keep on living in their existing home area, and how to take advantage of the underused local materials in order to offer better spaces for social interaction while providing sound housing and thermal comfort in these extreme environments.

But there was a third tier: how to tackle the challenge that comes with the history of the region, a challenge that truly has to do with matters of life and death. The Sahel Belt is not very well defined, but at least covers parts of the countries of Mauritania, Senegal, Mali, Burkina Faso, Niger, Nigeria, Chad, Sudan, Somalia, Ethiopia, and Eritrea. The region includes more than 100 million of the poorest people on Earth, and is one of the most violence-prone areas on the planet. The entire Sahel is already racked by political instability and warfare—climate change and increased desertification can only make matters worse. The capriciousness of weather patterns could easily mean the collapse into violence, as in this region fluctuations in rainfall have critical implications. Without water, crops can not be grown nor animals raised. As people become increasingly desperate, many try to move to neighbouring states, and a few repatriations and droughts later, it becomes easier to understand the rationale for an armed rebellion (Fisman and Miguel 2008).

Another recent study found strong historical linkages between civil war and temperature in Africa. Warmer years lead to significant increases in the likelihood of war. When the researchers combined this fact with climate model projections of future temperature trends, the results suggests an increase in armed conflict incidence by 54% by 2030. That would mean an additional 393,000 battle deaths if future wars remain as deadly as recent wars (Burke et al. 2009).

It may be asking too much of architecture to try and come up with responses to armed conflicts, but learning more about the situation gave birth to the idea of turning *Dune* into an inverse separation barrier—a sheltered safe haven, a bridge between areas or even countries sharing the desert condition and the threat of desertification. Not so much a habitable wall as a habitable anti-wall; the wall as a cross-border connection rather than a means of national exclusion.

The Great Wall of China, the Berlin Wall, the Israeli West Bank barrier: history has taught us to think about monumental walls as physical structures that limit the movement of people across invented lines in space. *Dune* fundamentally opposes this view through the creation of a wall that never existed before, the opposite of a wall. The word ‘wall’ usually connotes a membrane that demarcates space, that divides one space in two. We think of a surface that prevents us from entering the next space. But dare to think big, allow the wall to straddle an entire continent, place the habitable spaces *inside* of it, and we get a stretch of architecture that could bind places, villages, people, even countries together. As with Rem Koolhaas’s 1972 project *Exodus, or the Voluntary Prisoners of Architecture* (Koolhaas 1995), the built structure becomes an architectural refuge, an enclosure that keeps both environmental ferocity and human violence out while bringing people together on the inside.

9 Material Process, Construction, Structure

In his 1996 novel *Idoru,* science fiction writer William Gibson offered a premonition of a twenty-first century Tokyo in which nanomachines would weave buildings from near nothingness:

> …you could see those towers growing at night. Rooms up top like a honeycomb, and walls just sealing themselves over, one after another (…) Like watching a candle melt, but in reverse. That's too scary. Does not make a sound. Machines too small to see (Gibson 1996).

Following a cataclysmic quake, walls are spun and joints sealed by devices that operate on an atomic or molecular scale. Gibson's dream of a built environment in which a combination of genetically engineered materials and nanotechnological processes opens up new possibilities for radically innovative architectures may seem embryonic and premature to some, but this unfledged sketch of a future society in which very small things accumulate to build and/or become very large things may not be too distant.

The use of (micro)organisms to improve the properties of ground materials in the subsurface and of construction materials is an emerging technology. To borrow yet another sentence from Gibson, "the future is already here, it's just unevenly distributed" (Gibson 1999, Johnston 1999). At Deltares, the Dutch institute for delta technology, a long-term research program called SmartSoils has been initiated, and literature searches reveal that various research groups at different institutions, such as the Delft University of Technology, are active within this rather new field. Remarkably few researchers, however, focus on architectural applications.

It has been speculated that the biblical demise of Sodom and Gomorrah (assuming the twin cities existed in the first place) was due to earthquakes and liquefaction, the ground effectively swallowing buildings and people. As a result of liquefaction, waterlogged sand can lose all of its strength, with disastrous results. As the grains move apart causing the friction and adhesion between them to disappear, the stability of the material is lost, which causes it to flow and compact, expelling the water. This is what happened when an earthquake devastated the region around Bhuj in northwestern India in 2001, killing around 20,000 people. Liquefaction often causes more damage than the tremors of an earthquake—this was the case in San Francisco (1906), Anchorage (1964), and Loma Prieta (1989). In order to counteract (or at least mitigate) this process, scientists have proposed novel engineering solutions. One way would be to inject chemicals such as epoxies into sandy soil in an attempt to improve the ground by binding the grains together to make them withstand liquefaction. These chemicals, however, may be toxic (Welland 2009a, b).

A more sustainable alternative was suggested by Professor Jason DeJong at the University of California at Davis in 2007: use *B. pasteurii*, a natural bacterium that lives between sand grains and in soils, and that causes calcite (the most stable polymorph of calcium carbonate, $CaCO_3$) to precipitate, which glues the grains together and turns loose sand into solid rock. “Starting from a sand pile, you turn it back into sandstone,” DeJong explained, before making clear that there are no toxicity problems, that the treatment could be applied after the construction of a building, and that the structure of the soil does not change as the void spaces between the grains are filled in (The Engineer 2007). DeJong’s method had one writer at Time magazine (which included DeJong’s findings on its “Best Inventions of 2007” list) to exclaim: “Mix urea, soil and calcium, inject a little bit o’ bug and voilà! The cementer bug feeds on urea and deposits calcite, which cements the soil together and turns shifting sand into sandstone” (Time 2007).

That’s not an altogether bad explanation of the process. Inject sand with cultures of *B. pasteurii*, also known as *Sporosarcina pasteurii*, feed them well and provide them with oxygen, and they will solidify loose sand into sandstone. DeJong and his colleagues experimented with sterilised sand and bacteria, and were able to control and monitor nutrients, oxygen levels, and other variables to determine exactly how the bacteria hardened their sand specimens.

Basing their experiments on the notion that current methods to improve engineering properties of sand all have benefits and drawbacks, and that the need to explore new possibilities of soil improvement is particularly strong as suitable land for development becomes more scarce, the team studied how natural microbial biological processes can be used to engineer a cemented soil matrix within initially lose and collapsible sand. Microbially induced calcite precipitation (MICP) was tested through the introduction of *B. pasteurii* to sand specimens. The microbes were added in a liquid growth medium amended with urea and a dissolved calcium source (nutrients are required by microorganisms for cellular material—carbon and minerals—as well as for an energy source). Subsequent cementation treatments were passed through the specimen to test the increase in cementation level of the sand particle matrix. The results for the MICP-cemented specimens were compared with those of gypsum-cemented equivalents, and were assessed by measuring the shear wave velocity with bender elements.

The experiments indicated that the MICP-treated specimens exhibit a noncollapse strain softening shear behaviour, with a higher initial shear stiffness and ultimate shear capacity than untreated loose specimens—a behaviour similar to that of the gypsum-cemented specimens, which represent typical cemented sand behavior. SEM microscopy formation of a cemented sand matrix with a concentration of precipitated calcite forming bonds at particle–particle contacts, while X-ray compositional mapping confirmed that the observed cement bonds were comprised of calcite.

The reason why DeJong’s team selected this particular species of bacterium to create their microbially cemented sand, out of the huge number that occur naturally in soils, is both that *B. pasteurii* is a common bacterium naturally occurring in the subsurface, and that it is a highly aerobic microorganism particularly good at making the waters in soils more alkaline. For MICP to be effective, a microbe must be selected that is capable of CO_2 production paralleled by a pH rise in the surrounding environment to an alkaline level that induces precipitation of calcium carbonate. This forces calcium and carbonate dissolved in the water to combine and form crystals of calcium carbonate—calcite—the same natural cement that binds together sandstone, as well as manmade concrete. Aerobic microorganisms capable of consuming urea as an energy source (such as *B. pasteurii*) are particularly good candidates because they provide two sources of CO_2: respiration by the cell and decomposition of urea. Furthermore, cells of *B. pasteurii* do not aggregate, which ensures a high cell-surface-to-volume ratio—an essential condition for efficient cementation initiation (DeJong et al. 2006).

This is a rapidly evolving research area. Another team, led by Leon A. van Paassen at the Delft University of Technology, concluded that a range of new ground reinforcement techniques are currently being developed that are based on MICP. Going beyond urea hydrolysis strategies (in which bridges are formed between the grains of sand following precipitation of calcium carbonate crystals in the presence of dissolved calcium; the process proposed by DeJong's team), this research seeked to evaluate the feasibility of other microbial processes that can lead to the precipitation of calcium carbonate (and thus to ground reinforcement). Studying evaluation factors were substrate solubility, $CaCO_3$ yield, reaction rate, as well as the type and amount of side-product. Microbial denitrification of calcium nitrate, using calcium salts of fatty acids as electron donor and carbon source, was singled out as the most promising alternative. This process leads to calcium carbonate precipitation, bacterial growth, production of nitrogen gas and some excess carbon dioxide—and could be another way forward for microbially constructed architectures (van Paassen et al. 2010).

That word—'architectures'—is of course the difference between this underlying research and the deliberate misuse of it that eventually became *Dune*. Once it had been established that this new way of creating sandstone could be used to create new architectures at a human scale, the next step in the development of *Dune* was to define potential strategies and methods for how to actually construct the microbial sandstone structures in situ. The aggregational qualities of sand were explored through the appropriation and redefinition of existing sand dunes. Instead of viewing the dunes as hills of sand built by aeolian processes, they were read as readymade building volumes. This conceptual shift opens for the process of densification, adhesion and petrification described above, binding the grains together into solid sandstone surfaces: a floor datum; a wall membrane; a spatial divider. Once excavated, the biocemented sandstone surfaces demarcate habitable spaces, turning the interior and exterior of the dune into a perfectly seamless, seemingly 'weightless' architecture of solidified sand caves inside of the initial volume. Over time, more and more loose sand is eroded away from the structure. New strands of the dune can then be precipitated with the microorganism, producing an infinitely variable structural system.

Two construction options were further developed: pneumatic balloon precipitation and injection pile precipitation.

The former involves creating a pneumatic, balloon-like structure, filling it with a mixture of *B. pasteurii* and the necessary nutrient medium, and then allowing a sand dune to migrate and wash over the vessel. Once the wind has sculpted the sand dune into an optimal shape for the solidification process to take place, the microbial solution is distributed through specifically designed apertures in the skin of the structure, solidifying the sand surrounding it into structural compressive surfaces. Some time after the solidification, once the interior of the resulting sandstone structure has reached optimal strength, the balloon structure is recycled for the construction of the next stretch of the scheme. This method could be viewed as similar to that of the application of spraycrete, the high-strength polymer coating designed predominately for the re-surfacing of old concrete and tarmac. Using air compressors and various levels of air pressure, the spraycrete can be sprayed straight onto the surface to be treated (Fig. 4).

The second alternative is to use injection piles. These piles—normally used for grouting processes—would be pushed through the dune, after which a first layer of bacteria would be distributed through the piles to solidify an initial surface within the dune. They are then pulled up, creating almost any conceivable (structurally sound) shape along the way, with the loose sand acting as a jig or mould before being excavated either by hand or by the wind to create our spaces. The procedure would be analogous to using an oversized 3D printer, solidifying parts of the dune as needed (Manaugh 2009) (Fig. 5).

Furthermore, this method would be in line with one particular system that has been developed specifically for the purpose of using calcium carbonate as a laboratory cementation agent: the Calcite In Situ Precipitation System, or CIPS. This involves injecting a proprietary chemical solution that causes the precipitation of calcite crystals within the pore fluid and on the surfaces of constituent sand grains (Ismail et al. 1999a). Studies using CIPS have shown that the solidification level and cementation rate can be altered by using different chemical formulations or multiple solution flushes (Ismail et al. 1999b).

The mechanical properties of the soil itself (cohesion, friction, stiffness, and permeability) are important parameters for engineering constructions and ecosystems in sedimentary environments. In order to control the injection through the piles, it is necessary to find ways of distributing bacterial activity homogenously in the sand bed in order to prevent clogging during injection, as well as to provide homogeneous reinforcement results. A recent study describes a methodology for distributing and fixing bacteria (with their enzyme activity) relatively homogenously in for instance a sand dune, before supplying cementation reagents. The method involves a multi-step injection procedure: a bacterial suspension is injected into the fine-grained sand body, immediately followed by a fixation fluid (a solution with high salt content). The bacteria are retarded by adsorption and filtration processes, and are permanently adsorbed to the sand grains when overtaken by the fixation fluid. Finally, the cementation fluid is introduced. One advantage of this method is that the composition of the bacterial suspension and fixation fluid can be varied to either stimulate adsorption and flocculation with high salinity, or to stimulate transport and remobilization of reversibly adsorbed bacterial cells to improve bacterial distribution with low salinity (Harkes et al. 2010).

Yet another construction method could involve solidifying just the surface of the dune rather than creating solidified subsurface spaces, using much simpler distribution methods that might perhaps include the use of machines similar to

Fig. 4 Pneumatic balloon precipitation: The microbial solution is distributed through specifically designed apertures in the skin of the structure, solidifying the sand surrounding it into structural compressive surfaces

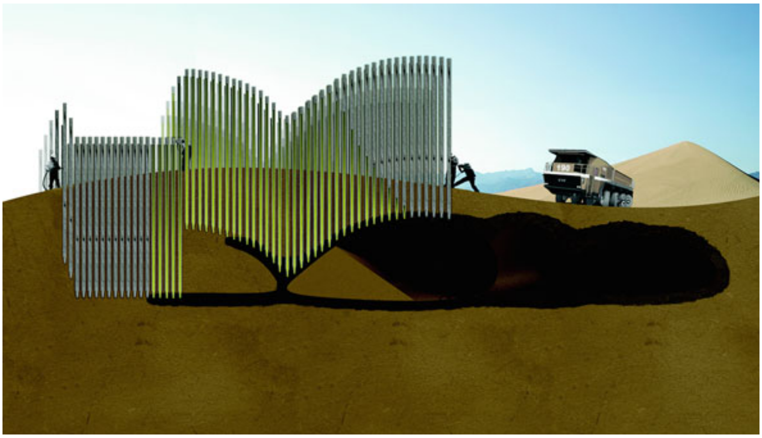

Fig. 5 Injection pile precipitation: This construction method would be analogous to using an oversized 3D printer, solidifying parts of the dune as needed

today's fertiliser spreaders—or even agricultural robots capable of driving themselves using GPS maps and electronic sensors—and to then connect these surfaces to the loadbearing sandstone structure. When deployed as shading devices rather than structural elements, these shell surfaces could become rather thin. Following in the footsteps of engineers such as Félix Candela, Eduardo Torroja, Pierre Lardy, Hans Hauri, Jörg Schlaich, and, in particular, Heinz Isler (Chilton 2000), these delicate shells could be designed so as to pronounce the slender character of the layers within the striated sandstone. Different methods for flushing the bacteria through the sand, as well as different sand qualities, could be investigated in order to find ways of articulating the material properties and characteristics further. The possibilities for research within this area are vast.

The five-minute theorem for masonry could be used as a basic statement to quickly assess the structural capability of such a shell in situ. This rule of thumb states that if the structure stands for five minutes once its supports have been removed, the boundaries of the masonry contain its thrust line, and will remain standing for 500 years. Admittedly, this flamboyant statement does assume static loads arising from self-weight, and dead thrust rather than resistance against live loads such as wind forces and migrating sand, while also ignoring any interaction with the foundations, but as an indicative test, it could still provide a historically proven demonstration of structural soundness (Heyman 1995).

The cementation of a previously uncemented sand dune lowers the effective void ratio of its sand mass, which in turn induces minor decreases in the porosity and increases in the density. As we solidify the dune, we also densify it. These changes occur through cementation, adding substance to the particulate mass forming around individual particles and at particle–particle contacts.

So how long would the microbial part of the construction process take? According to DeJong's study, factors critical to the success of the microbial treatment include pH, oxygen supply, metabolic status, concentrations of microbes, ionic calcium in the biological and nutrient treatment flushes, and the timed sequence of injections. While the treatment time is dependent on numerous factors such as microbial concentration, reaction kinetics, and soil characteristics, DeJong found the maximum shear wave velocity versus time value to be 1,700 min, and the relative amount of cementation resulting from each treatment to reach its peak towards the fifth or sixth injection. This would indicate that an initial sandstone surface could be created within the dune in approximately 28 h, and that the structure could reach its optimal structural strength in a single week (1,700 × 6 = 10,200 min) (DeJong et al. 2006). In private conversation with the author, however, DeJong has indicated that variations are likely to occur, and that "the more patient you can be, the better" (DeJong 2008).

Soils are ecosystems, geoenvironments in which microorganisms are ubiquitous due to their great diversity and fast reproduction rate. For microbial activity to occur, a source of carbon for cell mass is required, as is a source of energy to sustain life activity, water, and a favourable environment. All of these requirements could be artificially controlled during the construction process, negating arguments about these strategies being recipes for disasters due to uncontrolled solidification.

However, many aspects still remain to be researched before a final construction method can be developed. Cost is one, though initial calculations seem to indicate that microbial construction could be cheaper than concrete construction, once the necessary machinery has been developed and accounted for. The best way of assessing the economic performance may be to meditate on the alternative: losing land to the desert, watching people die in the wake of desertification. Viewed in that light, the cost of prevention is far less than that of the cure.

Another aspect is the practical issue of supplying the microbes with water in a desert environment (though any physical intervention would clearly require water at some stage). While *B. pasteurii* is a very resistant strain that replicates easily, can live under extreme conditions, and is non-pathogenic, and while the bacteria are able to grow at high ammonium concentrations, tolerate alkaline environments, and can be grown on an industrial scale in non-sterile environments, how exactly to grow them in the desert remains an open question. Resources need to be allocated so as to provide for the further testing of soil qualities, there is a demand for the reconsidering of proper sampling and laboratory testing procedures or protocols to account for microbiological activity, and a call for rescrutinising some poorly explained laboratory results and field responses (Mitchell and Santamarina 2005). To do this properly, geotechnical engineers and 'dune architects' will need a better understanding and appreciation of both geochemistry and microbiology—as well as architecture.

But there is also a need for the architectural community to open up to new research topics, new materials, new paradigms. The promise of the use of biological treatments has already been demonstrated within a wide range of other fields. The study by DeJong et al. (2006) mentions microbes being used in environmental applications including the stabilisation of metals, the development of biological shields for zonal remediation, encapsulation of hazardous and other contaminants in natural soils, microbially enhanced oil recovery, bacteriogenic mineral plugging, and the remediation of cracks in concrete structures. What it does not mention are architectural, constructional applications, presumably since very few have been conceived of. Whereas future architects obviously need not become microbiologists, it is the author's hope that the present project stimulates interest in seeking further architectural implementations of the here described or similar biological processes. Multiple new opportunities for both soil-based and other innovative "green" construction technologies can be envisioned. Opening up a serious conversation between geotechnical engineers, microbiologists, other experts in the field, and architects can only advance the state of knowledge and practice in this area.

10 Formal Strategy: Tafoni

So we have a way of turning sand into sandstone in order to create spaces that people can live in, inside of the sand dunes. But how should those spaces function? How are they organised? What are the structural considerations given to configuration versus form? And what should they look like?

The architectural form of the first execution of *Dune* is inspired by tafoni, a kind of cavernous rock weathering/erosional patterns. Tafoni often include nested and cellular forms, found in granular rock such as sandstone, and hypothesised to be the results of salt weathering. It appears that this weathering might be due to water bringing dissolved minerals to the rock surface and drying, which makes the minerals form crystals that force small particles of the interior of the rock to flake off, leaving parts of the harder surface layer (had the crust not been harder, the whole rock surface would erode more or less evenly).

Tafoni, also known as honeycomb weathering patterns, are usually easily recognisable from their rounded entrances and smooth, concave walls: exquisite structures that typically develop in groups on inclined or vertical surfaces. The development and evolution of tafoni are puzzling, and continue to arouse curiosity (Hejl 2005). Since the late nineteenth century, more than 100 research articles have been published on this geomorphic topic (Boxerman 2009) (Fig. 6).

Tafoni are known to cause rapid coastal landscape retreat on geologic time scales (in desert landscapes, the retreat is slower). It has been estimated that weathering processes leading to the development of tafoni patterns cause 10% of all coastal retreat (Gill et al. 1981). On human time scales, tafoni destroy important sea walls and monuments: during a visit in 2008, this author noted tafoni patterns on the ruins of the otherwise exceptionally well-preserved Greek temple of Poseidon at Sounion (probably destroyed by the Persians in 480 BC) (Spawforth 2006).

Scaling up a tafone or a cluster of tafoni provides us with an interesting starting point for a spatial investigation: the hollow structure allows light to shine through

Fig. 6 Tafoni detail: A kind of cavernous rock weathering/erosional patterns, Tafoni such as these, from the Greek temple of Poseidon at Sounion, often include nested and cellular forms, found in granular rock such as sandstone. They are hypothesised to be the results of salt weathering. (Photo: Magnus Larsson)

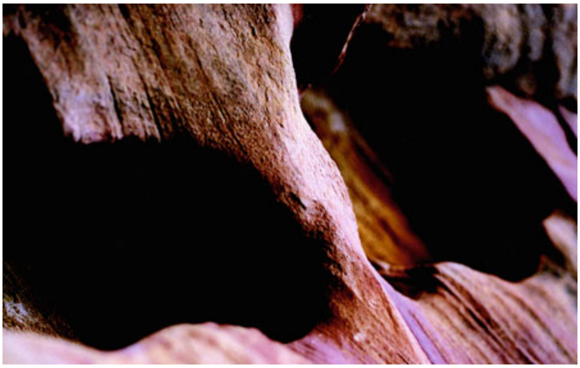

Fig. 7 A certain level of formal control would be lost to nature as the bacteria solidify the sand, giving birth to a boundless beauty, the traces of *B. pasteurii* being harnessed to sculpt the desert

yet shelters from the sun, and could provide a good formal precedent for the provision of ventilation and thermal comfort. The highly differentiated and articulated section of a typical tafoni space can be viewed as a cluster of voids regulated by a highly specific yet essentially unknown growth pattern, a typological branching or stacking model that can be controlled through their structural connection points, their ratio between void and solid, their loadbearing capacity, and so on.

Basing the aesthetic, performative, and organisational strategy on tafoni gives the project a visual impact that seems surreal and continuous—the solidified dune mitigating against the migrating dune whilst offering interesting spaces; porous sandstone surfaces providing selectively shaded areas. By sculpting those surfaces according to local parameters, the wind can be controlled so that the resulting spaces shelter from sandstorms while providing ventilation and comfort. A series of pockets of sponge-like spaces could be created, voids in which to gather for a conversation, a meal, a prayer. A certain level of formal control would be lost to nature as the bacteria solidify the sand. This could give birth to a boundless beauty, the traces of *B. pasteurii* being harnessed to sculpt the desert into these habitable environments (Fig. 7).

11 Dune Living

One of the striking but perhaps not so obvious challenges attached to the planting of a green wall in the Sahel region is that the current level of poverty brings people to chop the trees down for firewood. This has also been a historical problem with shelterbelts, for instance in Algeria's 1970s "steampunk geoengineering project," the planting of a wall of trees up to 25 km wide and 1,200 km long that was to stretch along the length of the Sahara's edge, from the Moroccan to the Tunisian border. The planned scheme ended not only with the arrival of the pine processionary moth and the shortage of funding, but also with the local population—separated from the project's planning and planting phases—viewing the trees as a good source of building materials and firewood (Twilley 2009).

However, there is an alternative to planting trees and hope that they would not get chopped down. The habitable sandstone structure proposed in these pages essentially does three things: it adds a roughness to the surface texture of the dune in order to bind the grains to the ground and thus aid the mitigation against saltation, it provides physical support for the shelterbelt trees, and it creates habitable spaces inside of this barrier. People living inside the Green Wall could protect the trees from both humans and the forces of nature. Inside the dunes, the inhabitants have a better chance of finding shade, harvesting condensation, and beginning to green the desert from within using permacultural strategies for water harvesting and desert cultivation (Fig. 8).

Crucial to this is the temperature difference between the interior of the solidified dunes and the exterior dune surface, which makes it possible to start building an oasis-like, permacultural network, the nodal points of which could support

Fig. 8 Performative section: The habitable sandstone structure adds a roughness to the surface texture of the dune (1), provides physical support for the shelterbelt trees (2), and creates habitable spaces inside of this barrier (3)

water harvesting and habitable thermal comfort zones. In some parts of the scheme, this would merely stabilise the shelterbelt and articulate the ground so as to provide for better local water management (adaptively storing what little rainwater there is, supplying shaded areas, creating connections to underground condensation spaces, and so on) as well as create a mitigatory shelter against wind, sand, and animals.

In nodal areas the intervention could become much more advanced, creating actual habitations or villages, with communal spaces, collaborative agriculture schemes, and large-scale water management systems; dune schools, dune mosques, dune plantations, dune wells, dune factories. The proposal is based on permacultural feedback loops. Water is a good example: from rainwater swales through to the creation of microbial sandstone tunnels down to aquifers. The latter could pick up on the history of the Garamantes tribe, a Saharan Berber-speaking people who used an incredibly elaborate network of tunnels known as *foggaras*—a subterranean water-extraction and irrigation system that allowed their part of the Sahara to bloom again—turning them into a local power between 500 BC and 500 AD (Keys 2004).

Water is obviously key. The poverty in the Sahel region means that drought can cause famine while good rains can cause drops in crop prices. *Dune* could hopefully form a stable base from which to fight back against both effects. Once the structure is in place and the permacultural network begins to support water harvesting and habitable thermal comfort zones, the economical sustainability of regions in dire need of such improvements could be increased. Social and economic conditions (poverty and food security) have a major impact on the progress and control of desertification. What we cannot do is stick our heads in the sand.

What would it be like to live in one of these sandstone structures? It would be a perfectly novel experience—or a highly familiar one. The tafoni form employed for the first iteration of the scheme could make up one part of it, but in others, *Dune* could take on traditional forms, indeed any form that could be made with more common materials, from adobe to concrete. The architecture could be orthogonal rather than sinuous, vernacular rather than contemporary, or a combination of all of them. The structure would have to support local habits and building traditions, and would need to find ways of braiding one such tradition into the next, possibly across national and religious borders. The three things the different potential adaptations would hopefully share is a connectedness within the architectural refuge, a common materiality—a seamless plasticity—as the microbes close some of the gaps in between its grains and turns it into sandstone, and a shared opportunity to use the structure to improve the local economy.

In economic terms, one aspect we must not ignore is solar power. Journalist and author George Monbiot has pointed out that we are currently experiencing an inverse relationship between human habitation and the availability of solar power, which is most concentrated and most reliable in deserts. Monbiot notes that solar electricity "generated in Sahara could supply all of Europe, the Gobi could power China, and the Chihuahuan, Sonoran, Atacama and Great Victoria Deserts could electrify their entire continents." He further mentions a calculation done by the

International Energy Agency, which shows that if solar photovoltaic panels were used to cover 50% of the land surface of the Earth's major deserts, they would produce 18 times as much energy (or 216 times as much electricity—16,742 TWh out of a suggested total of 200,000 TWh for the entire planet) as the world uses today. If people used electricity only when the sun was shining, this would mean that we only need to cover 0.23% of the land to meet demand, and "When the sun in the eastern Sahara is going down, the sun in the western Sahara is at full strength" (Monbiot 2007). The bacterially solidified sand structure proposed here could provide some of the surface area and foundation structure for such a solar panel scheme, as well as house long-distance cables to aid in the intermittency of this ambient power.

12 Towards Tattoine: City of Quartz

Whereas the first iteration of *Dune* was based on a system of tafoni-like habitable spaces, and future iterations may focus on the possibility of creating a novel kind of solar power facility, the very next step in the process is to bring the scheme onto the railroading scene.

On 5 March 2010, fashion designer Ozwald Boateng announced his plans to initiate a massive development plan that involves a $200 billion bond and a high-speed rail network connecting countries in Western Africa.

The scheme is the latest initiative by Boateng's Made In Africa organisation, aimed at introducing innovative ideas and new capital to help Africa go from being a developing continent towards achieving an emerging status. To date, the organisation's projects have included a mobile banking scheme in east Africa, plans for a low-carbon city in the centre of Kampala, and the planting of highly effective bio-energy trees on a 20,000-acre site (Reuters 2010).

The new pan-African railway is intended to function as a catalyst for economic and social growth. Envisioned as a high-speed connection, the railway is currently suggested to link the port of Tripoli on Libya's northern coast to the port of Takoradi in Ghana. Land would be cultivated within a strip on either side of the rail track, and state-of-the-art sustainable cities would be built at the stops.

Whereas it is still too early to go into any further detail about the scheme, the next version of *Dune* is currently being planned as part of this ambitious undertaking. At the point where the line of the cross-Saharan shelterbelt crosses the line of the new railway, a sandstone city could be built that would both function as an urban centre in its own right, and open up for tourism to this new, sustainable, infrastructural, and cultural desert node. Like Tattoine, the fictional desert planet and setting for many scenes in the *Star Wars* saga (Lucas 1977), this new city could allow moisture farmers to live in subterranean dwellings and possibly even grow crops in subterranean, hydroponic labs—though it would also aim for a more contemporary, Masdar-like quality. An environmentally ambitious, pedestrian-friendly, self-sustaining development encouraging urban growth in what is today a landscape in which it is near-impossible to feed or house human populations. An ecological desert city made from microbial sand, future home of the Sahelian Dream, the true City of Quartz.

13 Closing Remarks: Everything and Nothing

Estimates of recent losses of productive land suggest that the world had lost close to one-third of its arable land in the 40 years leading up to 1995 (Pimentel et al. 1995). Most specialists seem to agree that we will continue along this trajectory into the future.

As always with complex situations, action against desert-related challenges must not await complete knowledge of the circumstances. Immediate efforts need to be made using our existing understanding, not only to stop the physical processes of desert encroachment, but also to create opportunities for the people of the Sahel to get educated in how to minimise the harm done to fragile ecosystems—and to provide them with better standards of living. I believe that *Dune* could be part of such a programme. And I think the first stretches of the scheme could be created following a rather brief period of research.

In the longer run, extensive research is needed to delineate the full impact of the conceptual outline sketched above. While *Dune* underlines the need for urgent short-term relief measures, it can also be viewed as a long-term programme to prevent further desertification. This should not be delayed either: again, the cost of prevention is bound to be far less than that of the cure.

Architects create spaces that accommodate human activity. As opposed to many of its contemporary counterparts, *Dune* is not so much focused on the *styling* of that activity, as on the *supporting* of it. While designed to visually seduce, *Dune* is not primarily a formal exercise, but a social, ecological, cultural one. How are we to live with the desert, in the desert, within the desert? As architects, we have the mechanisms to understand and respond to such questions, the ability to allow them to adjust the various forms and accommodations of functionalities within the systems we design. Hopefully such adjustments turn *Dune* into a conceptually striated system, built up in layers like a sedimentary stone, possible to read on several different levels.

Let's have a closer look at one of those layers by returning one final time to the notion of *aggrerosion*. The self-organising, gregarious grains of sand almost seem to enjoy taking on different shapes as time passes, patterning the ground into three-dimensional traces of the paths they have been propelled along across the desert floor in the short and shallow trajectories known as saltation: rocky surfaces, flat sand sheets, vast dune fields. Though stratigraphically positioned within a much longer geologic timescale, sand also offers us the prospect of a rapid construction (and almost instant destruction) cycle carrying inherent possibilities of constant formal and physical invention and reinvention. In between solid and liquid, sand is an endlessly fascinating material. Its defining feature is that it aggregates—indeed, this is the mysterious heap-of-sand quality of the Sorites Paradox (Fisher 2000)—and as we have seen, all design is fundamentally about aggregation and erosion: we add and we take away.

As with other natural systems, aggregations of granular materials are self-stabilising optimisation machines. Changes in the internal or external environment have direct consequences on their emergent organisations and forms, many of which are breathtakingly beautiful: solemnly sweeping ridges of sand dunes in the desert, honeycomb rock weatherings created through salt crystallisation: the intricate geometries and endless variety of the natural phenomena at the heart of *Dune's* formal precedents.

If the morphologies of granular media are inspiring, some of their properties and potentials when interacting with biological agents such as microorganisms seem to be astonishingly underdeveloped in architectural terms—and even, to an extent, in the world of material sciences. The biocementation of sand is an example of such a granular material process. In the rare instances when it has been suggested that microorganisms be employed as a construction element in our built environment, the aim has usually not been architectural—exploring formal, performative, algorithmical, material, and similar properties—but rather related to large-scale, mitigatory engineering projects.

The novel process of engineered *architectural lithification,* creating from a pile of loose sand a solid sedimentary rock structure, a sandstone *building,* effectively involves gluing one grain of sand to the next on a microscopic level, thereby having the material shift from sand to stone. The resulting architecture becomes an infinitude of binary bits, a system of either/or relationships: solidified mass or excavated void, sand that's been precipitated or left untouched, that is grounded or fluid, sand or sandstone, very light or very heavy. The building speaks of the chronology of the sand, the vast rhythms of geological history, the evolution of villages and cities built on sand, from sand, covered in shimmering grains, forgotten in a sea of sand.

Such are the radical tectonics of similarly-sized building blocks, some of which are readily available to us today, but which constitute a conceptual virgin territory for which there is still very few maps. A cartography that *Dune* seeks to expand.

A single grain of sand is almost nothing, yet at the same time almost everything. At the end of his short story *A Passion in the Desert,* Honoré de Balzac concluded: "In the desert, you see, there is everything and nothing … It is God without mankind" (Balzac 1830). He was almost right. As we have seen, despite the Biblical admonition against building a house on sand (Matthew 7:26), close to a billion people live in arid or semiarid environments, often in substandard dwellings, but in close proximity to massive volumes of sand that we now know how to turn into pioneering buildings. Mankind has already moved into the desert. To extend the Biblical analogy, the question now is how to bring God closer to them in a landscape in which sandstorms are far more common than brainstorms.

The answer, my friend, is blowing in the wind.

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