

Review

# Role of Aeolian Dust in Shaping Landscapes and Soils of Arid and Semi-Arid South Africa

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Received: 1 April 2018; Accepted: 7 May 2018; Published: 10 May 2018



**Abstract:** The deposition of fine aeolian sediment profoundly influences the morphology of several different landscapes of the arid and semi-arid western portion of South Africa. Such landscapes and features include: (1) regularly-spaced mounds known as *heuweltjies* of the succulent Karoo region, (2) barren stone pavements in the more arid regions, and (3) hillslopes with smooth, curvilinear slope profiles that are mantled with coarse, stony colluvium. Investigations of each of these are presented, together with comparisons of similar features found within arid and semi-arid portions of Western North America. Recent findings suggest that the formation of the distinct, regularly-spaced *heuweltjies* involves a linked set of biological and physical processes. These include nutrient accumulation by termites and the production of dense vegetation patches, which, in turn, serve as a trap for aeolian sediments. Dust deposition is also responsible for the formation of stone pavements as demonstrated by research conducted principally in the Mojave Desert region of the United States. Mineralogical and geochronological studies have demonstrated that the stone clasts remain on the surface as fine aeolian sediments are translocated downward beneath the clasts resulting in a silt-rich soil horizon directly beneath the clasts. Pavements examined in South Africa have the same morphological features that can only be explained by the same process. The formation of soils on hillslopes mantled with stony colluvium are commonly viewed as having formed through the in-situ weathering of the stony colluvium. However, like pavements, mantles of coarse, stony colluvium are effective dust traps that provide the long-term stability required for advanced development of thick, fine-grained soils. This process contributes to the evolution of smooth, vegetated, curvilinear slope profiles. In each of these examples, the accumulation of dust has a profound influence, not only in soil formation, but also on the development of dominant landform characteristics. A greater awareness of these processes will contribute considerably to the growth of knowledge about soils and landscape development in the drylands of South Africa.

**Keywords:** colluvium; cumulic soil; desert pavement; heuweltjie; hillslope; Karoo; loess; Mima mound; termite mound; vesicular horizon

## 1. Introduction

*Aeolian processes* and *Aeolian geomorphology* are terms that typically evoke mental images of extensive landforms created by the movement and deposition of large amounts wind-blown sediments. Indeed, expansive dune fields and thick periglacial loess deposits create distinct, extensive landforms that have long been recognized and much studied. However, even in areas lacking those kinds of well-defined aeolian landforms, vast quantities of wind-transported sediments in the form of

fine-grained dust are deposited worldwide [1]. However, in many cases the contributions of such sediments to soils and landforms are subtle or masked, difficult to discern and, consequently, often overlooked or misunderstood.

Although the quantity of aeolian sediments delivered over a short duration may be small, over centuries to millennia, the accumulation and subsequent modification of those sediments profoundly influence soils and landforms of arid and semi-arid environments. The purpose of this paper is to describe how aeolian sediment deposition has shaped some prominent landscape features and soils of the dryland regions of western South Africa, particularly in the *Succulent Karoo* of the Western and Northern Cape Provinces (Figure 1). Three examples are given: (1) the widespread microtopographic mound features called *heuweltjies* (Afrikaans for “little hills”) that densely cover much of the region, (2) stone pavements and the soils beneath them, and (3) soils on hillslopes that develop beneath protective mantles of coarse, stony colluvium. Biological processes contribute to the development of some of these features. Some potentially complex relationships between biotic and physical landscape components are explored in order to demonstrate the importance of broadly multidisciplinary approaches in understanding many Earth surface processes. Finally, comparisons are made with similar landscape features found in other arid and semi-arid regions, particularly Western North America, with the intent of highlighting similarities or differences that may exist in processes of development.



**Figure 1.** Location of the succulent Karoo (shaded) and place names used in text. Shapefiles for the succulent Karoo boundary from South African National Biodiversity Institute: <http://bgis.sanbi.org/SpatialDataset/Detail/18>.

## 2. The Unusual Mound-Studded Topography of the Succulent Karoo

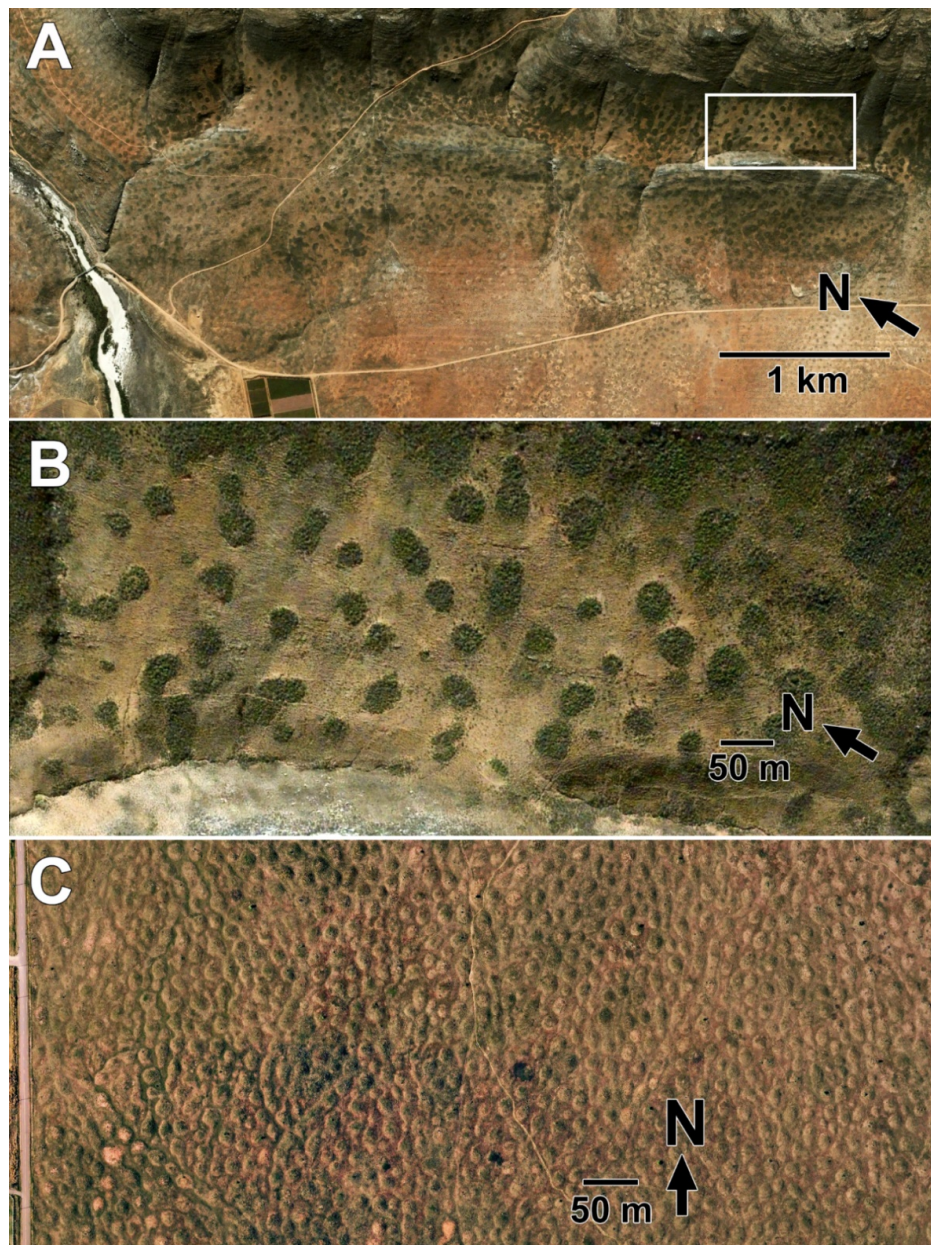
One of the more unusual and enigmatic characteristics of the succulent Karoo is the widespread dotting of the landscape with regularly spaced, earthen mounds called *heuweltjies* (pronounced “hue-vil-kees”). These mounds occur over an area of approximately 67,000 km<sup>2</sup> in Western South Africa (the distribution of *heuweltjies* is mapped in [2]) and occupy a quarter of the land surface in some

places (Figure 2A,B). The mounds typically range in height from a few decimeters to slightly more than 2 m and in diameter from less than 10 m to somewhat more than 30 m (Figure 3A). They occur on many kinds of geological substrates, including various sedimentary, metamorphic, and igneous rocks, as well as older (Pleistocene) aeolian dune and alluvial deposits. They also occupy a range of topographic settings, including nearly level valley floors and gentle to moderately steep hillslopes, but are absent from the steepest mountain slopes. Although superficially similar to the much-studied Mima mounds of the Western United States, heuweltjes are typically spaced much further apart from one another (centre-to-centre nearest neighbour distances of 40–50 m) than the considerably lesser typical distance between adjacent Mima mounds (e.g., 10–20 m at the classic Mima Prairie site, Thurston County, Washington, USA; Figure 2B,C).

Like Mima mounds, there has been considerable scientific debate regarding the origin of heuweltjes. Since 1940, many explanations involving geological and/or biological factors have been proposed. Lovegrove [3] divided various hypotheses into two separate categories: those that propose mound formation through the action of physical forces (including erosion, faulting, and wind deposition) and those that propose formation through the burrowing and earth-moving activities of subterranean animals. Colonies of the southern harvester termite (*Microhodotermes viator*) typically inhabit heuweltjes, fostering a widespread conclusion that interactions between neighbouring termite colonies are responsible for the regular spacing of mounds [4] and that earth-moving activities of termites create the mounds [5–7]. However, unlike the cemented, chimney-like or conical epigeal mounds created by some termite species (e.g., *Macrotermes* spp.), the domed surfaces of heuweltjes consist of non-cemented, fine earthen materials. In addition to the hypothesized direct role of the southern harvester termite, multiple investigators have concluded that earth-moving activities of burrowing mammals further contribute to heuweltje formation and maintenance [2,3,8–10]. Some heuweltjes contain layers of cemented pedogenic carbonate (calcrete) that are completely absent from surrounding soils (Figure 3C). Radiocarbon dating of those materials has yielded dates exceeding 35,000 years [11,12], indicating those mounds may have formed during the late Pleistocene. Given such antiquity, Midgley et al. [11] suggested that heuweltjes may be relict features, formed under different climate conditions by a termite species that no longer inhabits those landscapes.

In contrast to the majority of explanations that in some way involve the action of termites, Cramer et al. [13] suggested that termites play no role in mound formation or their regular spacing. Instead, those authors speculated that an interplay of competitive and facilitative interactions among plants generated regularly spaced aggregations of plants or “bush clumps” that occupied a geologically older surface. Over time, more sparsely vegetated areas between the clumps were subject to greater erosion by water, but soils beneath the bush clumps were protected and retained, yielding a landscape covered with regularly spaced, elevated mounds beneath the bush clumps. This conclusion that the mounds are remnants of an ancient surface was partially based on previous investigations that obtained late Pleistocene radiocarbon dates from pedogenic calcrete from heuweltjes at another site [11,12]. More than six decades before the Cramer et al. paper [13], Slabber [14] similarly proposed that heuweltjes and the calcrete layers they contained represented remnants of an ancient landscape surface protected from erosion by vegetation patches. In the view of Cramer et al. [13], the occurrence of colonies of the southern harvester termite in heuweltjes is a consequence, rather than a cause, of the mounds: the termites are merely beneficiaries of soil conditions conducive to colony success. Without question, during the last three-quarters of a century, the many explanations proposed for formation of heuweltjes have generated a mountain of controversy!





**Figure 2.** (A) Google Earth™ view of an area 14 km south-southeast of Klawer, Western Cape. The wide bright white linear feature on the left is the Doring River. The bridge crossing on the river is located at  $-31.86948^{\circ}$  S,  $18.68291^{\circ}$  E. The lower half of the view consists of agricultural lands that have been moderately to highly disturbed by livestock pasture modifications and cultivation. The upper half consists of gentle to moderately steep hillslopes that have been little impacted. The white rectangle in the upper right is the area enlarged in (B) (below). (B) A close-up of the area enclosed in the white rectangle in the upper right-hand corner of (A). Coordinates of the centre of the view are  $-31.89739^{\circ}$  S,  $18.71243^{\circ}$  E. The view consists of slopes ranging from less than 10% inclination (lowermost areas) to moderately steep (40% inclination) in upper half. Heuweltjes on the slopes are densely covered with vegetation compared to surrounding areas, whereas those of the valley floor are highly disturbed with minimal plant cover (J. McAuliffe, personal observations, October 2016). (C) Google Earth™ view of Mima mounds, Mima Mounds Natural Area Preserve, Washington State, USA. Coordinates of centre of view:  $46.89392^{\circ}$  N,  $-123.05550^{\circ}$  W. Note identical 50 m scale bars in this view and that of heuweltjes in Figure 2B.

### 2.1. Role of Aeolian Sediment Deposition

Van der Merwe [15] was the first to speculate that heuweltjes may form through the accumulation of wind-blown material beneath plant canopies and, subsequently, two unpublished master's theses [16,17] suggested the same, but with limited observations and supporting evidence. Within a dichotomous scheme of “physical” vs. “biological” mechanisms, Lovegrove [3] categorized the deposition of wind-blown sediments as a physical process that cannot account for the striking, regular spacing of heuweltjes, favouring instead an explanation invoking earth-moving activities of territorial termites and fossorial mammals. Following Lovegrove's paper [3] and two earlier ones with similar themes [2,8], further consideration of aeolian sediment deposition as a possible mechanism of heuweltjie formation disappeared entirely from discussions in the research literature for more than two decades.

However, the segregation of a “physical” process like wind deposition and “biological” processes as mutually exclusive categories of explanations represents a conceptually restrictive dichotomy that hinders an understanding of ways these two realms might interact to create the observed phenomenon. In separating the biological processes into “faunal and floral hypotheses” such as that done by Cramer and Midgley [18], the potential interaction between those different components is similarly overlooked. McAuliffe et al. [19] presented soil developmental and soil stratigraphic evidence that heuweltjes were indeed formed through aeolian deposition, but proposed a developmental pathway that involves a linked set of biological (including both plants and animals) and physical processes. Due to territorial interactions, termite colonies tend to be regularly spaced (*a biological process*). Colonies create localized fertile islands, enriched with plant nutrients (*biological*), which in turn promote development of denser vegetation patches (*biological*) (see Figure 2B). The patches trap and retain aeolian sediments (*physical*), thereby creating the mound. In the scenario of McAuliffe et al. [19], heuweltjes are much like *coppice dunes* or *nabkhas*, formed by the accumulation of wind-transported sediments beneath dense plant canopies, but are inherently linked to soil changes mainly generated by termite occupation. Although Van der Merwe [15], as well as several soil science students working in the 1960s, suggested similarities between coppice dunes and heuweltjes, a fuller integration of knowledge of diverse biological and physical processes as presented in McAuliffe et al. [19] provides a more comprehensive and compelling explanation.

Based on soil stratigraphic relationships and substantial contrasts in soil development, McAuliffe et al. [19] concluded that both old and young mounds occurred together at a site. Older mounds possessed the same kinds of strongly cemented calcic (petrocalcic) horizons or calcrete that have yielded late Pleistocene  $^{14}\text{C}$  dates (Figure 3B) [11,12], as well as other features of advanced pedogenic change, including development of reddened, clay- and carbonate-enriched argillic (Btk) horizons. In contrast, younger mounds consisted of deep accumulations of fine to very fine sandy loam sediments exhibiting minimal pedogenic alteration, and only a fraction of the  $\text{CaCO}_3$  accumulation, including a lack altogether of any cemented calcic horizon (Figure 3C). Soils exhibiting such minimal pedogenic change indicated more recent accretion of aeolian sediments during the Holocene. In contrast, the soils of the landscape surrounding mounds exhibited considerably advanced pedogenic characteristics, including a strongly reddened argillic horizon with sandy clay texture, beneath which was a silica-cemented duric horizon. This indicates that a considerable amount of time is required to generate those soil characteristics compared to the relatively unaltered sediments of the younger mound.



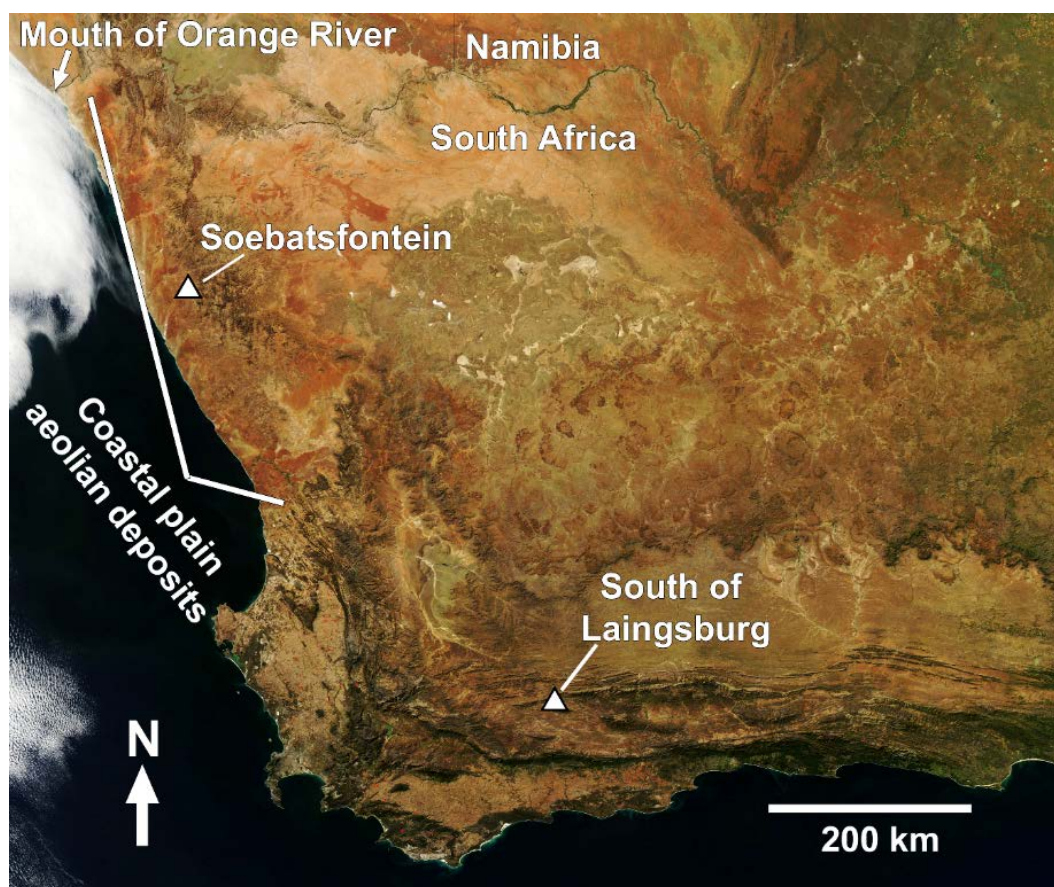


**Figure 3.** (A) A large heuweltjie and co-author M.T. Hoffman 7 km southwest of Soebatsfontein, Northern Cape bisected by road excavation work ( $-30.17718^{\circ}$  S,  $17.55423^{\circ}$  E). This is the “Soebatsfontein 2” mound described in McAuliffe et al. [19]. This entire area has been heavily used by livestock for decades and the relatively barren surface of the mound can be attributed to such use; (B) Cemented pedogenic carbonate layer approximately 50 cm below the surface of another heuweltjie near Soebatsfontein. The red pocket knife handle, positioned vertically in the centre foreground, is 9 cm long; (C) Heuweltjie researcher Natalie Kunz and co-author M.T. Hoffman at an excavation in the Soebatsfontein 2 heuweltjie (Figure 3A), showing the deep, relatively non-cohesive, fine sandy loam with little pedogenic modification. The depth of this more recently accumulated sediment was 138 cm.

The occurrence of mounds exhibiting starkly different, largely time-dependent soil developmental features in the same area and the superposition of young sediments on top of older surfaces provides evidence that (1) not all mounds are old features whose formation dates to the late Pleistocene, as suggested by Midgley et al. [11], and (2) differential accretion of fine aeolian sediments, not differential erosion as proposed by Cramer et al. [13], generates the vertical relief of the mounds.

McAuliffe et al. [19] further explained the considerable geographic variation in heuweltjie size (mound diameter, height, and volume) and the proportion of the landscape covered by the mounds as a function of substantial differences in aeolian sediment supply in different regions. At sites within the western coastal plain, a low-relief plain covered by Tertiary and Quaternary aeolian sand deposits that extend 50 km or more inland in some places (Figure 4) [20], heuweltjies achieved average diameters and heights of 30 m and 1–1.5 m, respectively, average individual volumes of 400 m<sup>3</sup> or more, and covered approximately a quarter of the land surface (Figure 5A). The large size of mounds was attributed to the abundance of readily mobilized aeolian sediments in this region. In contrast, at sites in small interior, inter-montane basins lacking such voluminous supplies of potential aeolian sediments, diameters and heights of individual mounds were approximately half that of coastal plain sites. Although mounds

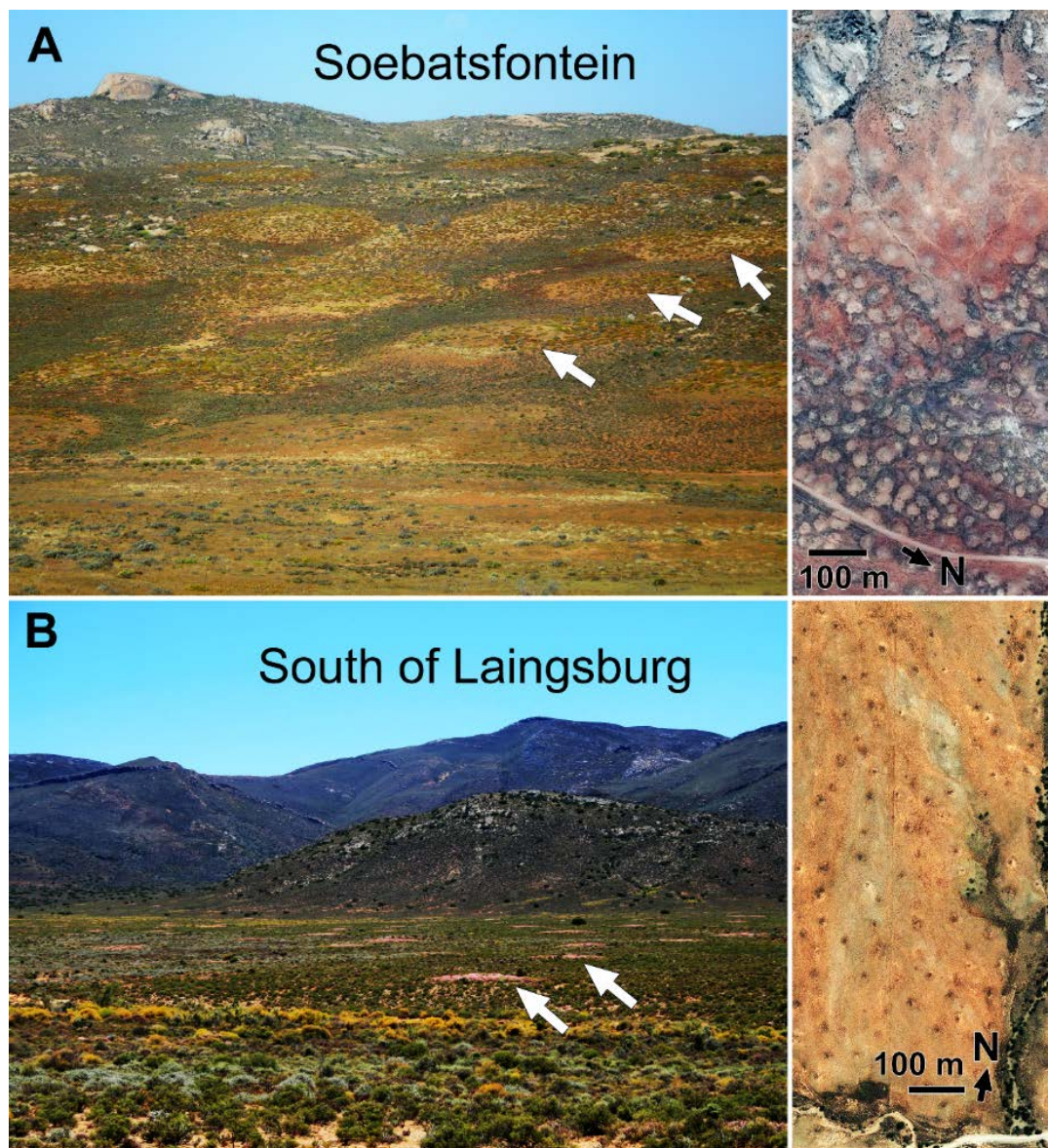
occurred at similar densities in the landscape, average mound volumes in inland sites were on the order of 5% to 16% of that of coastal sites, collectively covering only 10% or less of the land surface (Figure 5B).



**Figure 4.** Satellite view of western portion of South Africa (same area as map in Figure 1). The red-hued areas along the coastal plain are old (mainly Pleistocene) dune deposits reddened by pedogenic alteration over time. The *Soebatsfontein* site is within the area covered to variable extent by those aeolian sand deposits. The *South of Laingsburg* site, in contrast, is located in an inland, narrow intermontane basin lacking such regionally extensive, fine-grained sediments that can be mobilized by the wind. Sizes of heuweltjies at these two sites and several others were compared in McAuliffe et al. [19].

Following the work of McAuliffe et al. [19], additional publications provided further support for the conclusion that heuweltjies form through the accretion of aeolian sediments. Cramer and Midgley [18] used aerial imagery to quantify the sizes of heuweltjies and the fraction of the land occupied by the mounds throughout the entire range of their occurrence. This effort corroborated the earlier conclusions of McAuliffe et al. [19] and showed that heuweltjies achieved the largest sizes and occupied the largest portion of the landscape in the western coastal region where sparsely-vegetated areas with sandy soils, relatively strong winds, and summer droughts provided an ample supply of aeolian sediments. Cramer and Midgley [18] concluded that this relationship supported the formation of the mounds through vegetation-induced aeolian sediment deposition, reversing the earlier conclusion of Cramer et al. [13] that the mounds were produced by differential erosion of the landscape. In another paper, Cramer et al. [21] directly examined soil stratigraphic relationships of mounds and surrounding off-mound areas. As found in several other studies, the silt-rich soil profiles of mounds they examined were nearly devoid of gravel particles, but layers of quartz gravels deep within the mound profiles, at the same elevation of quartz-gravel rich surfaces of the surrounding landscape, indicated accumulation of the fine materials on top of the landscape through aeolian deposition.





**Figure 5.** (A) Ground photo (left side) paired with a Google Earth™ view of the Soebatsfontein site (right side). Heuweltjies are the large, lighter-colored patches (several indicted with white arrows). Heuweltjies at this site are approximately 30 m wide, from 1–2 m in height, and collectively cover approximately a quarter of the land surface. (B) Ground photo (left side) paired with a Google Earth™ aerial view of the South of Laingsburg site (right side). The light-colored (pinkish) vegetation of heuweltjies at this site (white arrows) consists of flowering *Mesembryanthemum junceum*, the dominant perennial plant on mounds, but not in intervening areas. Heuweltjies at this inland site range from 8–15 m diameter with maximum heights of approximately 0.5 m and cover only an estimated 3% of the land surface, despite similar densities of heuweltjies (4.5/ha and 3.8/ha) at Soebatsfontein and South of Laingsburg, respectively.

Some investigators have explained the superposition of fine, well-sorted sediments on top of coarser materials like that reported by Cramer et al. [21] as the consequence of particle size sorting by termites, where termites are capable of transporting only fine-grained materials upwards, leaving coarser clasts beneath [22]. However, both Cramer et al. [13] and McAuliffe et al. [19] argued that the earthen volume of the largest heuweltjies is an order of magnitude greater than volumes of the largest cemented, conical termite mounds in other parts of Africa (e.g., those constructed by *Macrotermes*) and



it is difficult to attribute such great volumes simply to local redistribution of soil materials by termites. Furthermore, the only soil materials transported and redistributed by the southern harvester termite are those removed in tunnel construction (M. Picker, personal communication).

A further test of these competing hypotheses (aeolian accretion of fines vs. size-selective redistribution of materials by termites) was provided by geochemistry data reported by Midgley et al. [23], collected at the same site examined by Cramer et al. [13]. Midgley et al. [23] compared bulk chemistry and trace elemental signatures of soils of heuweltjies, off-mound soils, and the underlying bedrock. The hard, silica-cemented sandstone bedrock (Nardouw Formation quartz arenite) contains 93.6% SiO<sub>2</sub>. The thin soils that mantle the bedrock are similarly dominated by SiO<sub>2</sub> (91.4%), reflecting a dominant volumetric contribution of sandy residuum derived from sandstone bedrock (Table 1). In contrast, soil from heuweltjies had twice the silt content of off-mound soils, and an average of 71.3% SiO<sub>2</sub>, but approximately double the Al<sub>2</sub>O<sub>3</sub> content of bedrock and off-mound soils (Table 1). The substantially higher Al<sub>2</sub>O<sub>3</sub> content of the silt-rich soils from heuweltjies reflects materials derived from aluminosilicate and phyllosilicate minerals (feldspars, micas, and clays) that are dominant components of many kinds of rocks, but are present in only miniscule amounts in the quartz arenite bedrock of the site. In addition, concentrations of a variety of terrigenous, chemically-conservative trace elements, including rubidium, zirconium, and hafnium, all derived from the weathering of a variety of rock types were from 2.5 to four times greater in soil samples from heuweltjies than in the quartz arenite bedrock (Table 1). Soils of the mounds with these chemical and elemental signatures could not have been derived from weathering of the quartz arenite bedrock. Delivery and accumulation of silt-rich sediments derived from other locales is the only possible source for these materials within heuweltjies. The site is located on a hillslope, positioned topographically well above (~20 m elevation) the floodplain of the Olifants River and its tributaries and there are no fluvial terrace remnants present in this landscape. Consequently, the sediments cannot reflect an alluvial origin. In this setting, aeolian deposition is the only possible means by which the silt-rich, allochthonous materials with these distinct geochemical signatures could have been delivered to generate the observed soil volumes within the mounds. Furthermore, size-selective redistribution of earthen materials by termites cannot account for the different geochemical signatures.

**Table 1.** Soil texture and geochemistry data from soils of heuweltjies, off-mound areas, and bedrock at the *Clanwilliam* site.

<b>A. Soil Particle Size Distributions (%) <sup>1</sup> (Underlined Values Statistically Different, <i>p</i> &lt; 0.05)</b>			
	<u>Heuweltjies</u>	<u>Off-mound</u>	
Sand	72	77	
Silt	<u>11</u>	5	
Clay	17	18	
<b>B. Bulk Chemistry (% by Weight) <sup>2</sup></b>			
	<u>Heuweltjies</u>	<u>Off-mound</u>	<u>Bedrock</u>
SiO <sub>2</sub>	71.27	91.9	93.57
Al <sub>2</sub> O <sub>3</sub>	6.08	3.1	2.51
<b>C. Terrigenous Trace Elements (ppm) (Off-Mound Soils Not Measured) <sup>2</sup></b>			
	<u>Heuweltjies</u>		<u>Bedrock</u>
Zirconium	65.3		16.4
Rubidium	41.9		16.2
Hafnium	1.96		0.54

<sup>1</sup> From Cramer et al. [13], Table 2. <sup>2</sup> From Midgley et al. [23], Tables 1 and 2.

## 2.2. Other Influences of Aeolian Deposition

In addition to the role played by aeolian sediment deposition in mound development, aeolian inputs also contribute to the peculiar soil characteristics of heuweltjies, particularly enrichment with calcium carbonate ( $\text{CaCO}_3$ ). Throughout the succulent Karoo where annual precipitation ranges from 100–300 mm, soils of the surrounding off-mound landscape “matrix” typically have low pH (3.0–5.0), compared to the neutral to slightly alkaline soils of heuweltjies (for a summary of multiple studies, see [3]). Calcic horizons occur only within heuweltjies, where they sometimes are manifested as relatively thick (25–75 cm), strongly-cemented petrocalcic horizons discussed previously, with  $\text{CaCO}_3$  content exceeding 45% (Figure 3B) [5,7,12,19,24]. Radiocarbon dating of strongly-cemented pedogenic carbonates from heuweltjies has yielded dates as old as 36,700 years [12], indicating mounds containing such materials were apparently developing during the late Pleistocene. However, even in younger mounds (Figure 3C),  $\text{CaCO}_3$  content may range from a few percent to as much as 10%, which nevertheless represents a substantially greater content than that of surrounding, off-mound areas, where the neutral to acid soils are essentially free of carbonates [19].

Like the origin of the mounds themselves, varied explanations have been proposed for the  $\text{CaCO}_3$  enrichment of heuweltjies, including in situ weathering of the bedrock in some locales [15], differential erosion of landscapes that originally contained calcareous strata near the surface that were retained only beneath dense vegetation patches [14], and deposition of solutes by groundwater [5]. However, none of these account for the occurrence of  $\text{CaCO}_3$ -enriched soils of heuweltjies in landscapes of different types of bedrock (plutonic, sedimentary, and metamorphic rocks) and arid, upland terrains where groundwater deposition within soils near the surface can be discounted due to the great depth (>30 m) to the water table [25].

Mounds of many species of termites, for example those of the genus *Macrotermes* found throughout savanna regions of Africa, are similarly highly enriched with  $\text{CaCO}_3$ , even in humid and sub-humid regions where surrounding soils lack  $\text{CaCO}_3$  and underlying parent materials are entirely non-calcareous [26–30]. Collection and transport of plant materials by colonies of central-place foraging termites generate a net flow of materials from the overall foraging area to the colony focus, leading inexorably to the accumulation and concentration of many materials over time [27]. Milne [26] and Trapnell et al. [31] both suggested that such a process was involved in the enrichment of *Macrotermes* mounds with  $\text{CaCO}_3$ . The same was proposed for the elevated  $\text{CaCO}_3$  contents of heuweltjies in South Africa [3,7,19,24]. Mujinya et al. [28] furthered the understanding of the general process by demonstrating the  $\text{CaCO}_3$  accumulations in *Macrotermes* mounds at a site in the D.R. Congo are pedogenic, rather than derived from the underlying bedrock, with  $\text{Ca}^{2+}$  principally derived from calcium oxalates in plant materials collected by the termites. Both Francis et al. [7] and McAuliffe et al. [19] pointed out the common occurrence of plants of the succulent Karoo with high calcium oxalate contents and suggested the same process involving transport of these materials by termites as the source of calcium for eventual formation of  $\text{CaCO}_3$ . Recent advances in other systems have shown that soil fungi and bacteria are instrumental in weathering calcium oxalates to calcium carbonate via a process called the *oxalate-carbonate pathway* (OCP) [32,33].

Although there is growing support that the plant materials collected by termites are the proximate source of calcium for  $\text{CaCO}_3$  enrichment of termite mounds, what is the ultimate source of calcium extracted from the soil by plants in these environments? This is where deposition of aeolian sediments once again comes into play as a process that affects the nature of heuweltjies. In upland settings where deposition of alluvial sediments does not occur, soil calcium is potentially replenished through the weathering of underlying bedrock and through atmospheric inputs (aeolian dust, precipitation, marine aerosols). Most of the succulent Karoo where heuweltjies are found is underlain by non-calcareous bedrock from which scant amounts of calcium can be derived by weathering. For example, granitoid rocks (granites and gneisses) of the Namaqualand complex outcrop over a large portion of the geographic range of heuweltjies [34]. Bulk chemistry analyses of these kinds of rocks from this region reveal CaO contents generally less than 1% [35]. At the *Clanwilliam* site studied by Midgley et al. [23], the weathering-resistant



quartz arenites contain even far less calcium (CaO content of 0.04%). However, atmospheric deposition delivers appreciable amounts of calcium to these landscapes. Soderberg and Compton [36] measured atmospheric inputs in the vicinity of Citrusdal, located 47 km south of Clanwilliam, and determined that these inputs, consisting in large part of the washout of aeolian materials by precipitation, is the ultimate source of most of the soil calcium and many other plant nutrients in that area. Plants effectively extract and sequester that calcium. Soderberg and Compton [36] estimated that above-ground vegetation at the site contained the equivalent of the amount of Ca delivered by rainout over a 25-year period and the two pools of Ca contained in the soil and above-ground plant tissues were equivalent.

As emphasized earlier regarding the importance of a multidisciplinary perspective in investigating processes responsible for heuweltjie formation through aeolian sediment accretion, a similarly broad view is also key to a fuller understanding of the soil conditions within heuweltjies. Atmospheric deposition replenishes the pool of soil calcium across the landscape (*physical process*). Plants extract calcium from the soil and store this in tissues (*biological*); colonies of termites (regularly spaced due to territorial interactions) collect and transport plant materials to their colony foci (*biological*), where yet little-studied potential paths of weathering, possibly involving bacteria and fungi (e.g., via the OCP) convert materials such as calcium oxalate to  $\text{CaCO}_3$  (*likely a complex combination of physical and biological phases*). Subsequent dissolution, leaching, and re-deposition of this primary  $\text{CaCO}_3$  ultimately yields soil horizons highly enriched with this material, including the massive petrocalcic horizons within heuweltjies. Even this last stage involves a combination of physical and biological influences because  $\text{CO}_2$  released into the soil environment by plant respiration (via roots) and termite respiration (*biological inputs*) influences solubility of carbonate, the depth of leaching, and ultimately provides the carbon source for the formation of  $\text{CaCO}_3$ , as demonstrated in stable isotope studies [37].

### 2.3. Comparison of Heuweltjies with other Mounds

Dome-like earthen mounds occur throughout the western United States and south-central Canada [38]. Different names have been given to these mounds, including Mima mounds (after the type locality, *Mima Prairie*, in Washington State, USA), Mima-type mounds, prairie mounds, and pimple mounds. Explanations for their origins date to the early 1800s and, since that time, hundreds of publications have included descriptions of them and a multitude of explanations for their formation (see Appendix D in [38]).

Some investigators have sought to identify similarities of processes that could be responsible for producing mounds in different parts of the globe, including heuweltjies [39–41]. Although the heuweltjies and Mima-type mounds share some features, including evidence from a site in the south-central USA for an aeolian sediment component [42], substantial contrasts exist that suggest differing developmental pathways and origins. Johnson and Johnson [43] provide evidence for the operation of a complex set of mechanisms including bioturbation, seasonal frost heaving, erosional processes, and occasional aeolian inputs in forming mounds in cooler, high-elevation sites with thin, clay-rich soils above basalt flows. Although the Mima-type mounds at sites in North America commonly tend to be regularly spaced (e.g., Figure 2C; [44,45]), they are typically smaller in diameter and much more closely spaced than are heuweltjies (Figure 2B,C). Nevertheless, the strong tendency for regular spacing in both Mima-type mounds and heuweltjies could similarly be influenced by interactions among animals occupying and contributing in some way to the formation of those mounds.

The termite fauna of North America is meagre, with less than a tenth of the number of species in Africa [46], and no association between termites and Mima-type mounds has ever been presented. In Africa, as well as Australia, the substantial enrichment of soils around termite mounds with  $\text{CaCO}_3$  is nearly universal [27], a similarity shared by heuweltjies, but not the Mima mounds of North America. However, a biotic common denominator of most Mima-like mounds in North America is their occupation by small burrowing mammals, most notably pocket gophers (genus *Thomomys*). These mammals have been implicated in mound development through their process of *centripedal* soil movement, which occurs as animals burrow outward from a focal activity area, displacing soil to the rear of the animal; i.e., towards

the focus [47]. This is especially the case in environments in which relatively thin soils cover any materials that restrict the depth of burrowing, including bedrock, dense layers of coarse gravel, cemented hardpans, and silicic horizons, or a seasonally-fluctuating, shallow water table [38]. Over time, such centripetal soil displacement can form a mound, within which the mammals continue to inhabit.

Burrowing mammals capable of displacing soil also occupy heuweltjies, ranging from small rodents to considerably larger armadillos, and evidence of mammalian bioturbation on heuweltjies is ubiquitous [5,10,48]. Although mammals can move a considerable amount of soil materials, this kind of displacement cannot be responsible for the substantial differences in the geochemical fingerprints of heuweltjie soils versus those of the surrounding, off-mound area and underlying bedrock, which had to have originated through the accretion of allochthonous aeolian sediments as discussed previously (Table 1).

Perhaps the most important commonality between heuweltjies and Mima-type mounds is that there is increasing evidence that both kinds of mounds are long-lasting, relatively fixed landscape features that are persistently occupied by the animals that are, in some way, involved in their creation. This persistence can be linked to the survival advantage gained by such occupancy [38]. Such is likely the case for pocket gophers inhabiting landscapes with shallow soils underlain by materials that prevent deep excavation. The thickness of the earthen mound environment provides multiple benefits (greater protection and varied escape routes from burrowing predators, like badgers; greater access to plant food materials) that are rare or altogether absent in the surrounding terrain. Colonies of the southern harvester termite may reap comparable survival benefits within the deeper soil environment of heuweltjies. Existing colonies are undoubtedly better protected from predators by the greater soil depth. However, even if the resident colony of a heuweltjie were completely destroyed by an excavating predator, such as an armadillo, the likelihood of subsequent recolonization of that vacant mound by flying reproductive termites (alates) is probably considerably higher than in off-mound areas with thin soils. Such benefits would promote long-term continuity in site occupancy and maintenance of the soil conditions required for the formation and retention of the mound. With this comparison, both pocket gophers in North America and the southern harvester termite in Western South Africa function as primary *ecosystem engineers*—organisms that create or modify environments to their benefit by causing physical state changes in biotic and abiotic materials, which, in turn, influence many other ecological processes [49]. Clearly, the role of biota must be well understood in order to interpret these unusual landforms in different parts of the world.

#### 2.4. Unanswered Questions

The recent recognition that aeolian sediment accretion plays an important role in the formation of heuweltjies provides a foundation for many new lines of both basic and applied scientific inquiry. Relatively little is yet known about many basic elements of the biology of the southern harvester termite, including factors influencing success in new colony establishment, and the average longevity and turnover of colonies, and the nature of between-colony interactions. Further investigation is also required to determine the nature of territorial interactions that apparently underlie the relatively uniform spacing of heuweltjies.

Although there have been many investigations of soil characteristics of heuweltjies, the processes that are responsible for the concentration of  $\text{CaCO}_3$  in heuweltjies are only poorly understood. Recent advances in the role of soil microbes in the chemical transformation of calcium oxalates to  $\text{CaCO}_3$  [32,33] provide a foundation for further investigation. The biogeochemistry of calcium in these systems is poorly understood. The complete restriction of calcic soils to heuweltjies in the arid and semi-arid environments where calcic horizons would be expected to occur throughout the landscape is an enigma that might be better understood through detailed studies of calcium inputs and the role of the termites in the spatial redistribution and concentration of calcium.

In addition, the recognition of the importance of aeolian sediment accretion is important to conservation of the succulent Karoo's environments. Heuweltjies typically possess unique vegetation



compared to the surrounding matrix and, in many cases, the more lush vegetation of the mounds has been selectively used by livestock, causing marked vegetation changes, reduction of cover, or even denudation [50–52]. Any type of landscape use that diminishes the vegetation cover on *heuweltjies* potentially hinders the very processes by which new aeolian sediments are added and existing ones are retained. Study of the linked relationships among termites, soil, vegetation, and aeolian deposition could ultimately provide valuable guidance regarding which kinds of landscape uses are sustainable and which are not.

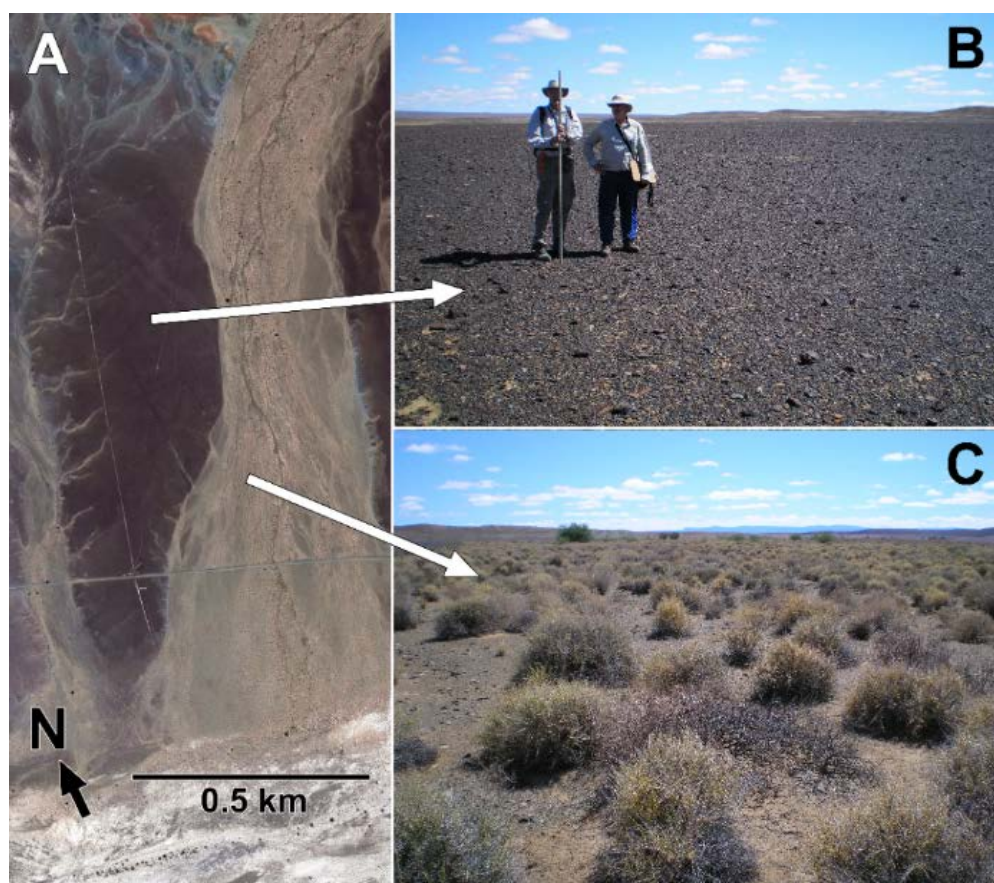
### 3. Stone Pavements

In stark contrast to hummocky landscapes dotted with regularly spaced *heuweltjies*, some of the more arid portions of western South Africa contain barren, low-relief landscapes covered by stone pavements (Figure 6). Pavements like these consist of a mono-layer of closely tessellated, coarse gravel to small cobble-sized clasts, beneath which are fine-grained soil horizons that are relatively free of clasts. Coatings of rock varnish typically cover the upper surfaces of pavement clasts, imparting a characteristic dark appearance. The many names given to these kinds of terrains, including *reg* and *serir* (both Arabic, applied in different parts of the Saharan region and Middle East), *gibber plains* of Australia, and *desert pavement* in the southwestern United States, attest to their global occurrence in deserts.

Like the controversy over the origin of *heuweltjies*, processes responsible for formation of stone pavements have been long debated. Some early prevailing views suggested that clasts, which were originally distributed throughout a fine-grained soil matrix, became concentrated on the surface, forming the pavement. Proposed processes included exposure of clasts by deflation, fluvial erosion and horizontal redistribution of clasts on the surface, or the upward displacement of clasts by alternating shrinkage and swelling of clay-rich soils [53].

Research conducted in the 1980s in the Mojave Desert, USA generated a radical new view of how pavements form. Wells et al. [54] and McFadden et al. [55,56] studied pavements in the Cima volcanic field, California that formed atop Quaternary basalt flows ranging in age from approximately 16 ka to >500 ka. Their investigations demonstrated that the thick (exceeding 100 cm in some cases), relatively clast-free, silt- and clay-enriched soil horizons beneath stone pavements were accretionary aeolian mantles. These mantles grow upwards over time as new sediments accumulate, lifting and maintaining the clasts on the surface in the process. Mineralogical and geochemical evidence demonstrated the aeolian origin of the fine-grained soils underlying the pavements. For example, the soil horizons are quartz-rich (in the form of very fine sand and smaller particles), but quartz is not present in the mafic basalts of the flows, nor could quartz have been derived from the weathering of basalt. Development of new geochronological dating tools facilitated further testing of the accretion model and assessment of the timing of aeolian sediment additions. Wells et al. [57] used cosmogenic  $^3\text{H}$  exposure dating [58] to compare the duration of exposure of basalt pavement clasts positioned on top of the soil with that of emergent basalt bedrock on the same flows that had been continuously exposed since the origin of those flows. Within each flow examined, surface exposure dates for pavement clasts were indistinguishable from those of basalt outcrops. This demonstrated that pavement clasts positioned on top of the deep, fine-grained soils had been exposed to bombardment by cosmic rays for the same duration as the emergent outcrops (ranging from 30 ka–80 ka for the different surfaces). The accordant exposure durations indicated that pavements are born and maintained on the surface of an upward-building, aeolian accretionary soil mantle. Spalling and physical weathering of basalt on the original flow surfaces generate the small clasts beneath which dust accumulates, raising the clasts, and ultimately forming the pavement. As aeolian materials accumulate beneath those materials, the irregular surface of the original flow becomes increasingly smoothed and levelled as the accretionary mantle thickens [54–56]. Optical-thermal luminescence (OTL) dating of aeolian materials from the vesicular A horizon demonstrated the considerably younger age of those materials (as young as 5 ka to less than 1 ka) compared to the basalt bedrock [59]. In a functional sense, the actual parent material for the developing soil is not the basalt bedrock of the flow, but rather, the aeolian sediments added to the surface and incorporated into the vesicular A horizon directly beneath

the stone pavement. A considerable amount of additional evidence supporting the accretionary model of pavement development based on investigations of other types of geological surfaces (e.g., cobbly to bouldery alluvial fan deposits) has appeared over the last two decades; Laity [60] and McFadden [61] provide comprehensive summaries of this body of work. Although there are geological settings where selective erosion (aeolian or fluvial) of fine materials may first be required to generate a lag of coarser clasts on the surface (e.g., see later section on *Quartz pavements of the Knersvlakte*), even in those situations, once such a surface lag is created, the dust-trapping effect of the surface clasts contributes to the accumulation of aeolian sediments and development of an underlying accretionary mantle beneath a stone pavement.



**Figure 6.** (A) Google Earth™ view of the Tankwa Karoo pediment site. The dark, elongated feature occupying most of the left half of the view is a pediment remnant covered with a dark stone pavement. The wide, light-coloured swath to the right of the pediment remnant is an ephemeral drainage (direction of flow to the south) and associated alluvial deposits inset below the pediment remnant. The white margin at the lower end of the image are deposits within the floodplain of the Tankwa River. Coordinates of the centre of the view:  $-32.318^{\circ}$  S,  $19.671^{\circ}$  E; (B) Co-authors McFadden (with pole) and Hoffman on the Tankwa Karoo pavement; (C) Vegetation on Holocene alluvial deposits east of the pavement surface is dominated by dense, hemispherical canopies of the coarse perennial grass, *Cladoraphis spinosa* (spiny love grass), with fibrous roots largely within the upper 20 cm of the soil. Less common woody plants with deeper taproots include the low shrub *Tetraena* (formerly *Zygophyllum*) *microcarpa* (partly behind *Cladoraphis* canopy in centre foreground) and the small tree *Acacia karroo* (background).

The accumulation of aeolian sediments beneath stone pavements is linked to two features. First, the layer of surface clasts is a highly effective dust trap [62]. Second, characteristics of the underlying A horizon facilitate the downward translocation and incorporation of those fine aeolian materials into the thickening soil profile. The A horizon is typically silt-rich, generally free of coarse particles,



and is densely filled with prominent, relatively large (to a few mm) vesicular pores that apparently originate after wetting and expansion of soil air following summer precipitation [63,64]. This vesicular A horizon has frequently been referred to as an Av horizon in the American literature, but has no universally-accepted designation. However, use of the “v” subordinate departure in the label “Av” as a reference to “vesicular” conflicts with the accepted use of that subordinate for the presence of plinthite in the U.S. soil taxonomy [65]. Consequently, we use the label “vesicular A” horizon rather than “Av.” The term “yermic” horizon has also been used to describe fine-grained vesicular horizons (after the Spanish *yermo*, for wilderness or barren) [66]. However, under the FAO designation, yermic horizons include fine-grained, vesicular soil horizons whether or not stone pavements are present on the surface. These represent two very different modes of formation (aeolian accretion beneath stone pavements vs. ponding or other processes that yield platy structure at the surface). Consequently, we believe that the name “yermic horizon” represents an imprecise lumping of soils formed under very different processes, and we do not use that designation.

The vesicular A horizon is typically a few centimetres thick, with pronounced gaps between columnar to prismatic ped faces when dry (Figure 7). These gaps facilitate the downward movement and accumulation of new aeolian sediments between and on ped faces. The secondary platy structure of peds facilitates the lateral movement of materials into peds [67]. Interiors of and lower portions of peds typically exhibit stronger reddening and higher clay content than the silt-rich exteriors [67]. Continued additions and incorporation of aeolian materials coupled with time-dependent pedogenic changes (clay eluviation, reddening) in lower portions of surface peds contributes materials to the underlying, clay-enriched Bt horizon and thickening of the entire accretionary soil mantle [55,56,61].



**Figure 7.** Upper portion of soil profile beneath a pavement of basalt clasts, Cima Volcanic Area, California, USA. Only the top 20 cm of the profile is pictured; soil depth exceeded 72 cm in the original description of this site (MP-27 in McFadden et al. [55]). The age of the basalt flow on which the soil and pavement formed is 260 ka (K-Ar dating of basalt). The 7 cm thick, light-coloured horizon directly above the pocket knife is the vesicular A horizon. Note the vertical faces of prismatic peds. Original colour recorded for this horizon is 10 YR 7/3. Behind the knife is the uppermost portion of a sequence of reddened Bt horizons; the colour is 7.5 YR 6/4.

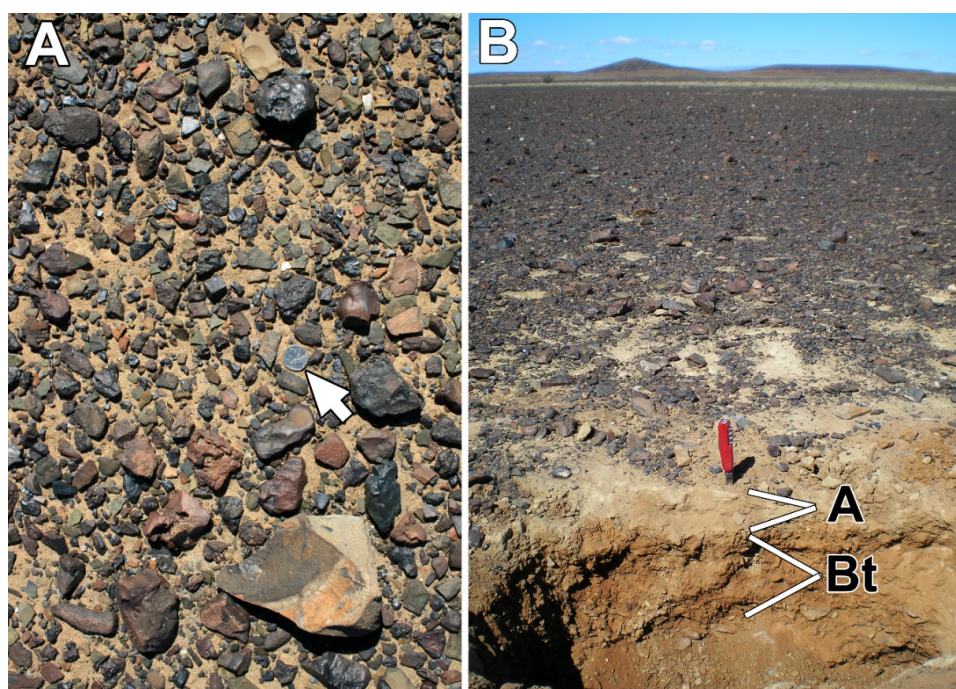
Stone pavements and their associated, underlying clast-free vesicular A horizons derived largely from the accretion of aeolian sediments occur on diverse substrates, including fan deposits and terraces of coarse gravelly to stony alluvium and pediments in arid regions throughout the world [60,68–72]. Soils with the same kinds of clast-free vesicular A horizons beneath pavements have been described for arid regions of South Africa [15,73], and Ellis [74] mapped their overall geographic distribution in western South Africa. However, little to no research in has been focused on the role of aeolian sediment deposition in the formation of these pavements. The soil beneath the varnished pavement surfaces in the Tankwa Karoo pictured in Figure 6 displays the same key features possessed by the soils and associated pavements studied by McFadden et al. [56] and others (Figure 8, Table 2). The pavement is located on a remnant surface of an ancient pediment cut into hard, slate-like mudrocks (Palaeozoic Dwyka Series). This geological unit has yielded durable pavement clasts that are highly resistant to weathering. Between the surface clasts, non-cohesive fine sands lie directly above the A horizon peds and represent some of the more recent aeolian additions. The 1–2 km wide, sparsely-vegetated floodplain of the Tankwa River located nearby (Figure 6A) provides an ample source for large amounts of readily-mobilized aeolian sediments, including fine sands like those occupying gaps between pavement clasts. The largely gravel-free, silt- and clay-rich vesicular A horizon exhibits considerably less reddening than the underlying Bt horizons and exteriors of A horizon peds are less reddened (10 YR hue) than interiors (7.5 YR hue). Fey [73] referred to lighter-coloured vesicular A horizons beneath stone pavements as “bleached” horizons, and suggested that the removal of coatings (e.g., iron oxides) from quartz sand particles through clay dispersion and eluviation is responsible for that condition. However, the absence of reddening of this uppermost horizon is not due to the removal of materials by leaching, but rather is due to relatively unaltered nature (and lighter colours) of the most recently accumulated, young aeolian sediments comprising that horizon, particularly on the exterior surfaces of peds [55,59,67]. Furthermore, the exceptionally high salinity of the vesicular A horizon, as well as the underlying horizons (Table 3), demonstrates that leaching of the most soluble materials has not occurred; therefore, leaching or translocation of even less soluble materials does not plausibly explain the lighter colours of the vesicular A horizon. The horizons exhibiting the greatest degree of pedogenic alteration are the underlying Bt horizons, as evidenced by the presence of illuvial clay and considerably stronger reddening (Figure 8B).

**Table 2.** Profile description of soil beneath a desert pavement in the Tankwa Karoo, Northern Cape Province, South Africa. (described by L.D. McFadden, 22 October 2012).

Horizon	Depth (cm)	Color	Structure	Pores	Granules	Wet Consistence	Plasticity	Textural Class
A	0–5	10YR 7/4 (ped exterior) 7.5 YR 5.4 (ped interior)	Very coarse platy to weakly prismatic	Many fine vesicular pores	Few (contained within vertical gaps between peds)	Very sticky	Very plastic	Non-gravelly silty clay
Bt	5–21	2.5–5 YR 5/6	Single-grain, to weak fine and medium, subangular blocky		Few	Sticky	Plastic	Silty clay
Btz1	21–32	5–7.5 YR 5/6	Single grain		Few	Sticky	Slightly plastic	Coarse sandy clay loam
Btz2	32–42	5YR 5/6	Single grain		Very gravelly (angular slate fragments)	Sticky	Plastic	Sandy clay loam
R	42 +							

Latitude and longitude:  $-32.3169^{\circ}$  S,  $19.6702^{\circ}$  E, Elevation: 300 m; Landscape position—remnant of ancient pediment surface formed on Dwyka series shales; Surface—stone pavement covering 75% of surface; 5–10% of clasts 8–12 cm diameter; >90% less than 5 cm diameter. Clasts have strongly- to moderately-varnished upper surfaces. Loose, fine sand partly infills spaces between surface clasts.





**Figure 8.** (A) Surface of the Tankwa Karoo stone pavement, approximately three-quarters of which is covered by coarse gravels and pebbles. The white arrow points to a 20 mm diameter coin. (B) View of exposed soil profile showing light-coloured, essentially clast-free vesicular A horizon (5 cm thick) and underlying, strongly-reddened Bt horizon. The red handle of the pocket knife is 9 cm long. Profile description in Table 2.

### 3.1. Ecohydrology Interrelationships

Pavements occur only at the drier end of the semi-arid to arid gradient. For example, in the Sonoran Desert of Arizona, USA, pavements and their associated vesicular A horizons become a recognizable landscape feature in areas receiving less than 200 mm average annual precipitation, but only become regionally extensive in areas receiving less than 100 mm [75]. Pavement formation requires landscape stability that is possible only at the more arid end of the gradient. In less arid settings, denser occupation of the surface by plants combined with associated bioturbation by animals ranging from termites to an array of burrowing mammals interferes with the stability required for pavement formation. However, below some threshold of precipitation input and associated levels of biotic activity, the entrapment and accumulation of aeolian dust below surfaces of coarse gravels and cobbles apparently outpaces the capacity for continual mixing by bioturbation. This, in turn, generates self-enhancing feedback where a thickening, fine-textured A horizon increasingly restricts infiltration, deeper soil moisture recharge and, ultimately, the capacity of the surface to support vegetation and associated faunal activity [76–81].

At the Tankwa Karoo site (Figure 6), infiltration rates measured on the pavement and adjacent Holocene alluvial surfaces differed by an order of magnitude. Average infiltration on the pavement (two measurements at different locations) was only 0.07 mm/s; but was 0.83 mm/s on the Holocene surfaces (six measurements at different locations) (surface infiltration measured by recording the time required for infiltration of the equivalent of 20 mm depth of water applied within a 190 mm diameter ring pressed into the soil surface). Due to the high moisture-holding capacity of the vesicular A horizon and associated extremely low infiltration capacity on the pavement, deep percolation and leaching is impeded, thereby leading to accumulation of salts, delivered to the surface through various forms of atmospheric deposition e.g., [36]. Within the pavement soil, total soluble salt contents of the vesicular A horizon and underlying B horizons were approximately 20 times and 70 times that



of the average salinity of all soil horizons sampled on adjacent Holocene alluvial surfaces (Table 3). Similar, highly-saline soil environments beneath barren stone pavements have been reported for other desert regions [68,75,80,82–84]. Although the fine-textured vesicular A horizon by itself directly affects vegetation due to its inhibiting effect on infiltration and percolation of precipitation [77,79], the accumulation of such high salt contents ultimately contributes to an extremely hostile physiological environment for most plants. In highly-permeable soils with loamy sand textures that lack high salt concentrations, such as the Holocene alluvial surfaces next to the Tankwa Karoo pavement, relatively dense perennial vegetation can be supported by the meagre average precipitation of this arid region (Figure 6C). *Cladoraphis spinosa*, the dominant perennial plant on those surfaces, has a dense fibrous root system largely restricted to the upper 20–30 cm of the soil (personal observations of excavated plants). This indicates that the low precipitation of this area (~100 mm/year or less), can support vegetation in soils with a high infiltration capacity and corresponding non-saline conditions.

**Table 3.** Total salt contents of soil horizons sampled on a desert pavement and adjacent Holocene alluvial surfaces at the Tankwa Karoo site.

Surface	Horizon	Depth (cm)	Total Salts (ppm) <sup>1</sup>
Pavement	A	0–5	5300
	Bt	5–21	14,700
	Btz1	21–31	16,800
	Btz2	31–42	16,800
Holocene alluvial surfaces			
Pit B	A	0–2	280
	Bw	2–10	553
	C	10–19	217
Pit C	A	0–5	105
	Bw	5–15	98
	C	15–28	336
Pit D	A	0–6	308
	C	6–42	140
	Bwb	42–53	84

<sup>1</sup> From conductivity measurements taken from a 1:2 (volumetric) soil:deionized water mixture; electrical conductivity measured with a LaMotte multi-range conductivity meter (Model DA-1); total dissolved salts calculated following procedural directions for agricultural soil testing accompanying the instrument (ppm dissolved salts = microsiemens/cm  $\times$  0.7).

### 3.2. Quartz Pavements of the Knersvlakte

Stone pavements of white quartz gravels and pebbles create gleaming white landscapes within portions of the succulent Karoo in Namaqualand, north of Vanrhynsdorp (Figure 9A). European colonizers named this region the *Knersvlakte* (pronounced ka-NES-flak-te), literally translated as “grinding plains”, due to the sound produced by wagon wheels travelling on these unusual pavement surfaces.



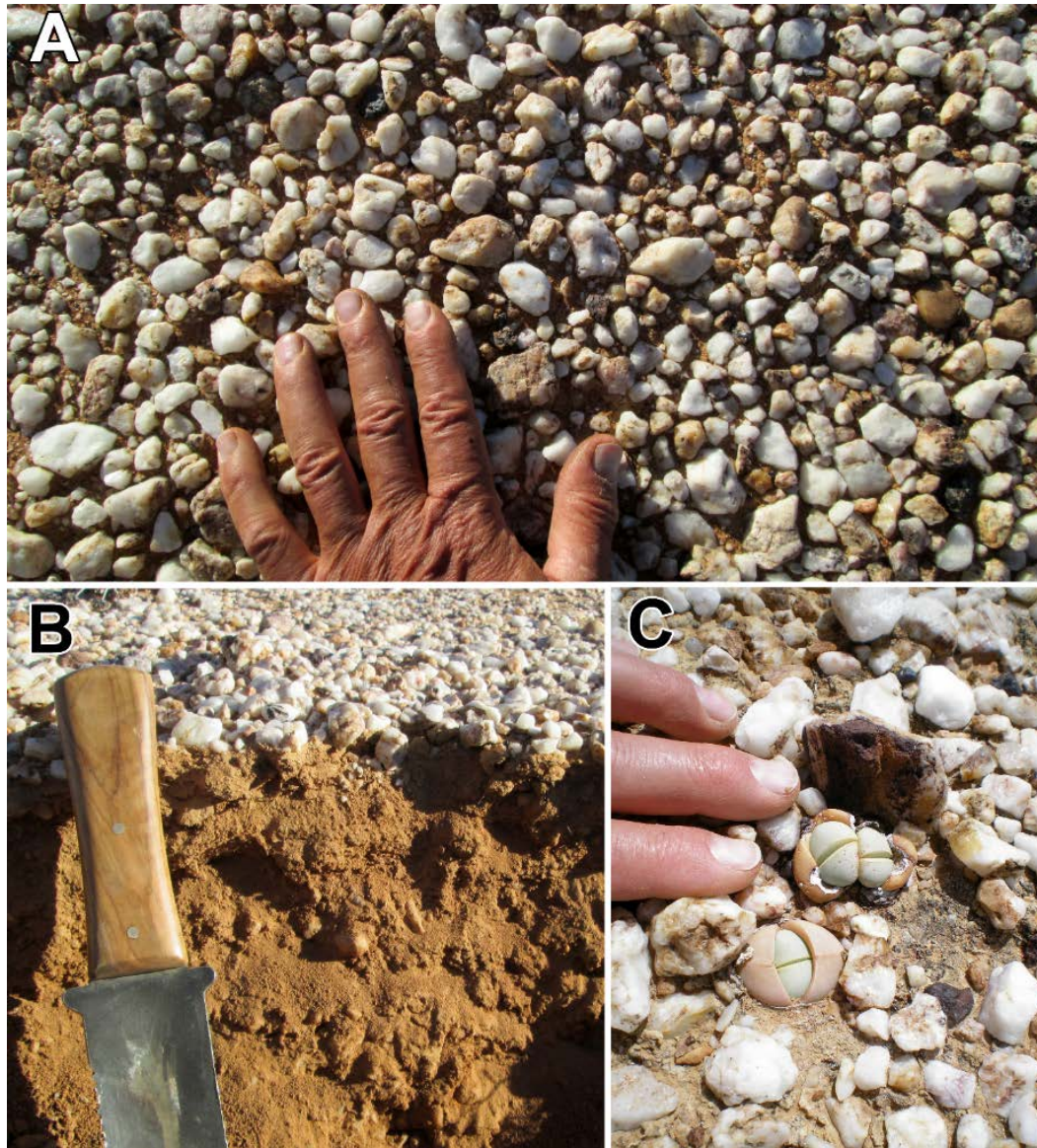
**Figure 9.** (A) Co-author M.T. Hoffman (left) and research assistant M.P. King in a Knersvlakte quartz pavement landscape, 42 km north-northwest of Vanrhynsdorp, Western Cape Province, located 0.5 km west of Highway N7. Note the white pavements on gentle footslopes of the distant hillslope. Coordinate of site:  $-31.2669^{\circ}$  S,  $18.5477^{\circ}$  E, 257 m elev. (B) M.P. King points out a quartz vein (between arrows) in highly-folded, readily-weathered shale. Excavated exposure 25 km north-northwest of Vanrhynsdorp to the west of Highway N7. Coordinates:  $-31.3993^{\circ}$  S,  $18.6580^{\circ}$  E, 124 m elev.

Although there is considerable interest in the ecology and evolution of the unusual plant life of these environments, little research has been devoted to the geomorphic evolution of the quartz pavements. Veins of quartz within highly-folded and deformed soft shales and phyllites of the late Proterozoic Malmesbury Group are the source of the pavement clasts (Figure 9B). Erosion of the more weatherable matrix generates the surface lag of highly weathering resistant, angular to subangular quartz clasts [85] (Figure 10A). Diffusive movement of clasts over the surface is likely involved in the horizontal redistribution of clasts, particularly to areas not directly underlain by quartz veins; fluvial transport and redistribution is probably also involved in certain topographic settings. Schmiedel and Mucina [86] briefly stated that the fine-grained soil beneath the quartz pavement is mainly derived from the weathering of the soft shale or phyllite, but there have been no detailed studies of soil forming processes in this environment. However, the surface lag of quartz clasts creates the same kind of effective dust trap as do other kinds of pavements, and the accretion of aeolian sediments probably contributes to much of the fine-grained soil beneath the quartz pavements.

Schmiedel and Jürgens [87] and Schmiedel et al. [88] identified two general categories of soil/topographic habitats of these quartz pavement habitats from a plant ecological perspective (1) *saline quartz fields* with high soil salinity at the surface, slightly acidic to neutral soil pH, low skeletal (i.e., gravel + rock) content in the soil, and found on homogeneous plains, and (2) *acidic quartz fields* with comparatively low salt content, low soil pH (3.9–5.0), high skeletal content (40–70%), and typically found on gentle slopes or hilltops. Both of these are pictured in Figure 9A. Soil characteristics, particularly of saline quartz fields in more level settings, strongly indicate a major aeolian sediment component. The non-skeletal nature (low rock + gravel content) of the fine-grained soil beneath the pavements in those settings is comparable to other types of pavements (Figure 10B). Laboratory soil analyses from 168 localities by Schmiedel et al. [88] strongly point to a dominant aeolian sediment component (Table 4). The soils average more than 50% silt, but have exceptionally low clay content (averaging  $\sim 1\%$ ). Clays are typically the dominant component of shales and, likewise, the dominant minerals in phyllite weather directly to various clays. Consequently, if the soil beneath these pavements was derived from the direct, in situ weathering of either shale or phyllite bedrock, considerably higher



clay contents would be expected. The predominance of silt-sized particles, together with the high content of fine sand (>20%) of these soils, is best explained as the accumulation of wind-blown sediments. Although highly variable, salinities of these soils are comparable to other pavements where the bulk of salts represent the accumulation of atmospherically-deposited salts, as described previously. In some topographic settings, runoff received in lower-lying, level areas (e.g., the “salt pan” quartz fields [88]) may further contribute to these salt accumulations. Nevertheless, the atmospheric input of salts throughout the entire landscape is probably the dominant source of salts in these soils, rather than the weathering of the underlying bedrock.



**Figure 10.** (A) Vertical view of quartz pavement; (B) Vertical profile through upper portion of the same pavement. The fine-grained, silt-rich soil contains very little gravel; (C) Fully-developed specimens of a microsucculent plant species (*Argyrodema delaetii*, family Aizoaceae) growing amidst clasts on a quartz pavement. This species has an amusing common name in Afrikaans—*bababoudtjies*—“baby bums”.



**Table 4.** Soil characteristics of soils associated with quartz pavements identified as “saline quartz fields.” Data from Schmiedel et al. (2015) and habitat types “S” and “FS” are the designations used in that paper, partly based on associated plant species. Bold-faced values are means; the range of values are italicized in parentheses.

	Habitat Types	
	S (n = 87 plots)	FS (n = 81 plots)
Quartz cover (%)	<b>87</b> (13.7–95.0)	<b>81</b> (16.6–95.0)
Mean soil depth (cm)	<b>18.5</b> (8.7–45.3)	<b>20.0</b> (5.3–49.7)
E.C. (mS/cm)	<b>5194</b> (538–12,660)	<b>3378</b> (288–12,660)
Sand (%)		
Coarse	<b>3.17</b> (0–14.27)	<b>4.33</b> (0–17.66)
Medium	<b>14.71</b> (1.87–46.61)	<b>19.58</b> (2.55–47.26)
Fine	<b>20.62</b> (6.63–31.28)	<b>23.07</b> (10.37–34.45)
Silt %		
Coarse	<b>20.18</b> (8.25–33.53)	<b>20.27</b> (8.24–31.84)
Medium	<b>29.30</b> (6.99–51.43)	<b>22.97</b> (6.86–51.1)
Fine	<b>11.00</b> (3.22–19.13)	<b>8.77</b> (3.2–20.23)
<b>Total Silt %</b>	<b>60.48</b>	<b>52.01</b>
Clay %		
Coarse	<b>1.03</b> (0–2.78)	<b>1.01</b> (0–3.57)
Medium	<b>0.003</b> (0–0.354)	<b>0.005</b> (0–0.681)
Fine	<b>0</b>	<b>0</b>
<b>Total clay %</b>	<b>1.033</b>	<b>1.015</b>

Unlike many kinds of rocks, dark rock varnish does not develop on surfaces of quartz clasts. Consequently, the much higher albedo of white quartz pavements contributes to a far less hostile thermal environment than that on darkly varnished pavement surfaces [89]. Unlike the dark, varnished pavements, such as those of the Tankwa Karoo that lack perennial plants, a diverse array of perennial plant species occupy the quartz pavements of the *Knersvlakte*, and many are endemic to those environments [85,87]. The more moderate thermal regime of quartz pavements is probably a major factor that enables that occupation. However, those plants are typically diminutive succulents in the family Aizoaceae with very shallow root systems, capable of extracting and storing water that does not infiltrate deeply into the soil. (Figure 10C). The predominance of this kind of plant lifeform likely reflects the restrictions imposed by textural and chemical characteristics of the soil (high moisture-holding capacity, slow infiltration and shallow percolation, high salt contents) where shallow root systems coupled with moisture storage are essential adaptations.

### 3.3. Future Investigation

As discussed in the section on *heuweltjies*, recognition of the importance of aeolian sediment deposition to the formation of stone pavements provides a foundation for new lines of inquiry on these landscapes in South Africa. Although pavements of the arid portions of South Africa share similarities with those in other parts of the world, examination of differences that may exist can further an understanding of developmental processes. Formation of pavements, coupled with the underlying vesicular A horizon profoundly affects surface hydrology (infiltration vs. runoff), thereby fundamentally influencing landscape evolution over long periods of time [54]. The geologically old landscapes of South Africa contrast sharply with the young ones of the southwestern United States and comparisons of pavements in these old terrains can contribute to an understanding of both the development and longevity of pavements and landscape evolution. Investigation of pavements located at varying distances from major dust sources (e.g., extensive dry lake beds or “pans” like those in a wide area approximately 200 km south-southwest of Upington) can contribute

to knowledge about relationships between the proximity of major dust sources, accretion of aeolian sediments, and pavement formation. Use of geochronological tools, like optical thermoluminescence dating of aeolian sediments within soils beneath pavements, can help identify past periods of heightened aeolian flux and deposition [59,67]. Coupled with paleoclimatological records, these kinds of investigations could contribute significantly to knowledge about how future climate changes may influence landscapes and human livelihoods in these arid regions.

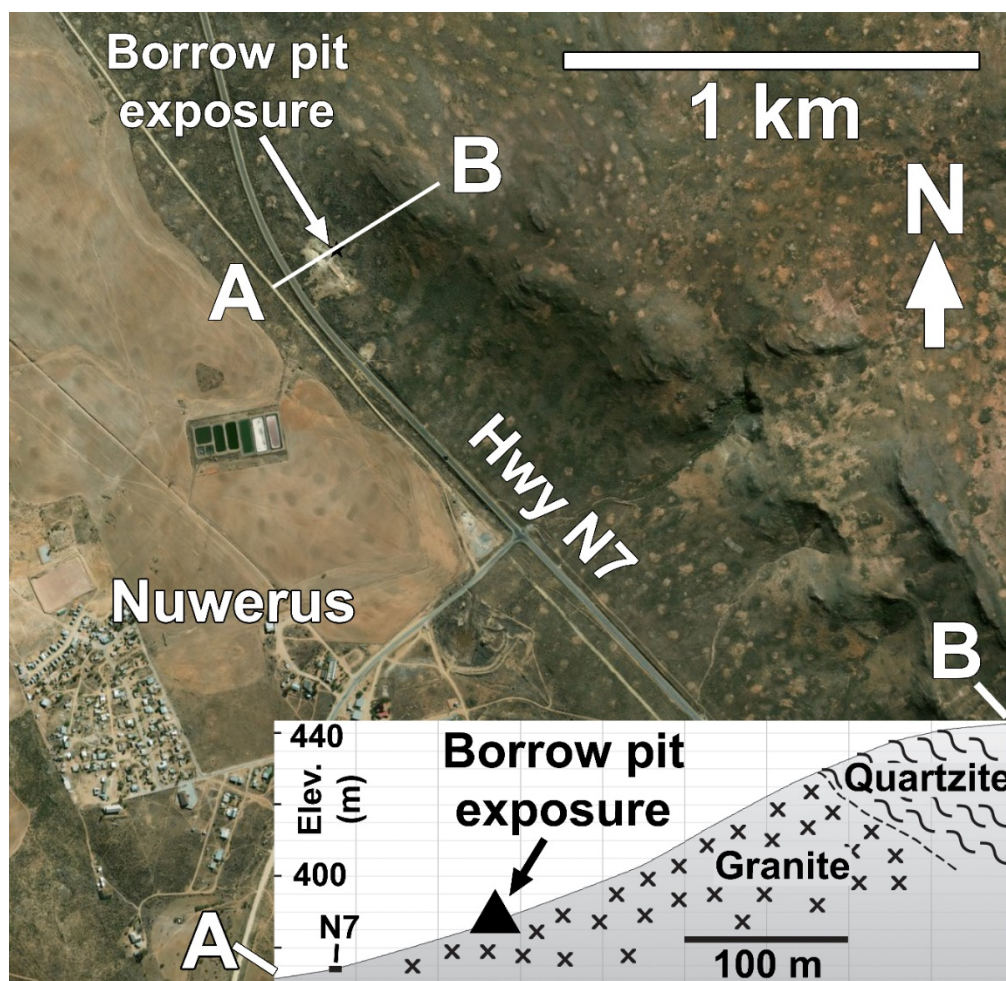
#### 4. Hillslope Environments

Processes that shape hillslopes in arid and semi-arid environments, particularly those involving weathering processes and soil formation, are poorly understood. Much geomorphic research on slopes in drylands has been devoted to factors influencing erosion and transport via fluvial processes, but not nearly as much work has been devoted to processes involved in generating soil mantles [90]. On hillslopes mantled by rocky debris (colluvium) derived from the underlying bedrock, soil development has generally been viewed as a process where in situ weathering of those colluvial mantles generates the fine-grained materials responsible for profile development [90,91]. However, given the ubiquitous delivery of dust to terrestrial environments [1], under what conditions do inputs of aeolian sediments to hillslope environments influence soil profile formation, the kind of vegetation that can exist, and ultimately, landform development? The following is an example from western South Africa of a hillslope environment with characteristics that have apparently fostered the accumulation of aeolian sediments, leading to the development of thick, fine-textured soil horizons. That example is compared with recent research conducted in western North America where multiple lines of evidence demonstrate the profound influence of aeolian dust accumulation on soil- and hillslope-forming processes in drylands.

##### 4.1. A South African Example

A site examined one kilometre north of Nuwerus, Western Cape Province contains a hillslope with a curvilinear profile (Figure 11). Two different kinds of bedrock underlie this hillslope. The footslope and backslope are underlain by late Proterozoic, medium-coarse grained leucocratic granite of the Namaqualand granite-gneiss complex [34,92]. Weathering-resistant quartzite of the late Proterozoic Nama Sequence [34,93] unconformably overlies the granite [94]. The quartzite prominently outcrops on the shoulder and summit of the slope (Figures 11 and 12A). Angular, cobbly quartzite colluvium derived from those outcrops continuously mantles slopes below the outcrops all the way to the footslope.

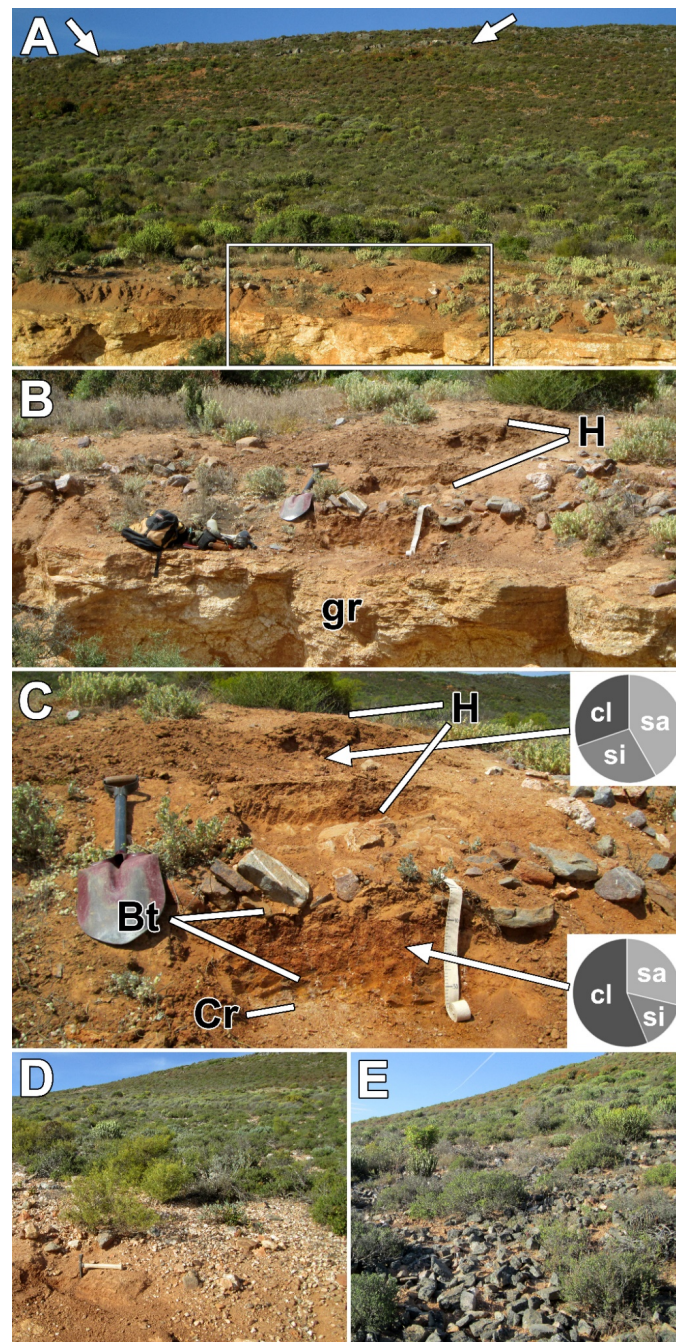
A well-developed soil has developed beneath the mantle of quartzite colluvium and above the weathered granite surface. Exposures of this soil are visible in a borrow pit in the lower portion of the slope (Figure 12A–C). Several features indicate that the soil was not principally derived from the weathering of either the quartzite colluvium or granitic bedrock. A prominent, strongly-reddened (2.5 YR 5/6 to 5 YR 5/6), clay-enriched argillic (Bt) horizon is positioned directly beneath the layer of little-weathered, angular quartzite cobbles (Figure 12B,C). The layer of cobbles is laterally continuous across the exposure. *Heuweltjies* are distributed over the hillslope (Figure 11) and the exposure cuts through the lowermost portion of one of the mounds. The less reddened (7.5 YR hue) soil with higher fine sand and silt content of the *heuweltjie* and its stratigraphic position on top of the layer of quartzite cobbles indicate that development of the mound post-dates formation of the underlying Bt horizon. The contrasts in both colour and texture (Figure 12C) of the soil materials from the mound and the underlying Bt provide further evidence of the mound's aeolian origin, rather than due to the upward redistribution of materials from the underlying Bt by termites (see earlier section on *heuweltjies*). Excavation of a portion of the *heuweltjie* indicated the layer of quartzite cobbles was continuous beneath the mound (Figure 12C). To either side of the *heuweltjie*, quartzite cobbles and coarse gravel are exposed directly on the surface with the same reddened, Bt horizon beneath it (Figure 12D).



**Figure 11.** Location of the hillslope study site north of Nuwerus. Coordinates of the borrow pit exposure are  $-31.13939^{\circ}$  S,  $18.35702^{\circ}$  E. The light-coloured spots on the dark hillslopes are *heuweltjies*. The inset in the lower right shows the cross-sectional profile A–B; the profile was generated in Google Earth Pro™ along the designated path.

The reddened Bt horizon is non-gritty and virtually clast-free (3.7% by weight 2–5 mm gravels) and contains 56% clay (clay textural class, Figure 12C). The lower boundary of the Bt horizon is clear and smooth and the light-coloured, highly grussified granite (Cr) directly below the Bt horizon shows no evidence of clay accumulation. It is hard to explain the highly clay-enriched, relatively sand- and gravel-free Bt horizon as a product of either the in situ weathering of the quartzite colluvium or granite. The angular quartzite clasts on top of the Bt horizon are minimally weathered (Figure 12C); consequently, the quartzite colluvium could not have contributed significantly to the mass of fine-textured materials in the underlying Bt. Alternatively, if the Bt horizon was principally derived from the weathering of granite, a considerably higher content of residual quartz gravels and sands would be expected, giving the Bt horizon a considerably coarser texture (e.g., sandy clay or sandy clay loam). Recent work in a nearly-identical geological and topographical setting in the southwestern United States demonstrates that this kind of soil is largely a product of the accumulation and alteration of aeolian dust beneath a protective mantle of coarse, weathering- and transport-resistant stony colluvium.





**Figure 12.** (A) Upslope view across the borrow pit location north of Nuwerus. The white arrows at the top of the view indicate outcroppings of quartzite. The white rectangle in the lower centre is shown in enlarged view below in (B); (B) View of the borrow pit exposure showing the continuous line of quartzite cobbles, beneath which is the reddened Bt soil horizon (centre of view) and weathered granite (gr). The downslope edge of a *heuweltjie* (H) is exposed in the section and contains lighter-coloured, silt- and fine sand-rich soil materials; (C) Close-up view of the well-developed, reddened Btk horizon beneath the quartzite cobbles. The Cr horizon consists of weathered granite with little clay accumulation. Light-coloured soil materials of the *heuweltjie* are emplaced on the top of the layer of quartzite cobbles. Note the continuity of the layer in the exposed section of the *heuweltjie* in the centre. Pie diagrams show the percentages of sand (sa), silt (si), and clay (cl) as measured with the hydrometer method; (D) The margin of borrow pit exposure to the immediate north of the view in (C) showing the surface layer of quartzite colluvium, with the reddened Bt horizon beneath it (lower left corner beneath hammer); (E) Backslope location showing the surface clad in a continuous mantle of angular colluvial cobbles, derived from outcrops further upslope.

#### 4.2. A North American Comparison

Persico et al. [95] compared the soils of different hillslopes that exhibit contrasting slope morphologies in foothills of the Sandia Mountains, New Mexico, USA. The high biotite content (~10%) of the porphyritic granite Proterozoic Sandia granite, the predominant rock type in this area, makes it highly susceptible to weathering and grussification. In some places, the granite contains dikes of fine-grained aplite, which is highly resistant to weathering due to its fine-grained, interlocking crystals and minimal mica content. On a hillslope with outcrops of aplite at its shoulder and summit, the granitic slopes below those outcrops are clad with a colluvial mantle of angular aplite cobbles that covers 50–75% of the surface from just below the outcrops to the footslope. The slope profile and vertical relief (50 m) of the site are nearly identical to that of the *Nuwerus* site (Figure 11, inset, compared with Figure 2 in [95]). The only difference between the sites is the type of weathering-resistant rock comprising the colluvial mantles: quartzite (*Nuwerus*) vs. aplite (Sandia Mts.). Nevertheless, both rock types are similarly highly resistant to chemical weathering, but physical weathering of both yields angular, coarse colluvium. Colluvium derived from both rock types mantles the more easily weathered granites with a protective armour of coarse, angular, weathering-resistant cobbles, that are also highly resistant to movement by fluvial transport because of their size.

The thick, clay-enriched and reddened B horizon of soils developed beneath the surface of the colluvial mantle at the Sandia Mts. site in backslope and footslope positions are similar to those at the footslope position at the *Nuwerus* site. Multiple lines of evidence from the Sandia Mts. study area indicated that the fine-grained B horizons were not generated by the weathering of either the aplite colluvium or the underlying granite. Like the quartzite-rich colluvium at the *Nuwerus* site, the angularity of aplite cobbles and lack of weathering rinds indicated that the deep, fine-grained soil horizons of the Sandia Mt. soils could not have been derived from the weathering of aplite colluvium. Additionally, like the *Nuwerus* site, the weathered granites beneath the colluvial mantles lack any evidence of in situ B horizon development. Comparisons of the optical thermoluminescence of fine-grained quartz sand within the Bt horizon with that of similar-sized quartz grains extracted from weathered granite clasts within the same horizon yielded evidence of multiple bleaching episodes for the first (i.e., multiple exposures to light during aeolian transport) compared to that of quartz from the granite. This evidence indicated that the fine sand component of the soil was delivered as aeolian sediment rather than being derived from in-situ weathering of granite below the surface. Soils were enriched in conservative elements ( $\text{Fe}_2\text{O}_3$ ,  $\text{MnO}$ ,  $\text{TiO}_2$ ) over that contained in the rocks. This enrichment could not be explained as a consequence of weathering of the rock and concentration of those conservative elements in the soil as more mobile elements were lost to leaching because the soil also had elevated levels of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , both of which are highly mobile. Addition of aeolian materials is the only way to account for the observed geochemical differences between soil and bedrock. Collectively, these lines of evidence indicate that additions of aeolian sediments were the predominant source of fine-grained materials within soil horizons below the mantle of aplite colluvium.

We maintain that the hillslope characteristics and soils at the *Nuwerus* site (Figures 11 and 12) and others like it we have observed in western South Africa (Figure 13A,B) have formed through the operation of the same processes described by Persico et al. [95]. Much like the behaviour of clasts of desert pavements described in the previous section, coarse, stony colluvial mantles on hillslopes are effective dust traps that facilitate the accumulation of aeolian materials and accretionary soil profile development [61,96]. The resistance to chemical weathering of both quartzite (*Nuwerus*) and aplite (Sandia Mts.) inhibits the comminution of colluvial clasts, thereby imparting the lengthy duration of surface stability required for substantial pedogenic change (e.g., further weathering and alteration of aeolian materials to clays, downward translocation and accumulation of altered materials, as well as continued accrual of aeolian sediments). Aeolian sediments are typically highly enriched in silicate clays at the time of their emplacement [1,97,98], therefore, greatly accelerating the development of thick, fine-textured soils in arid or semi-arid climates over what would develop exclusively from

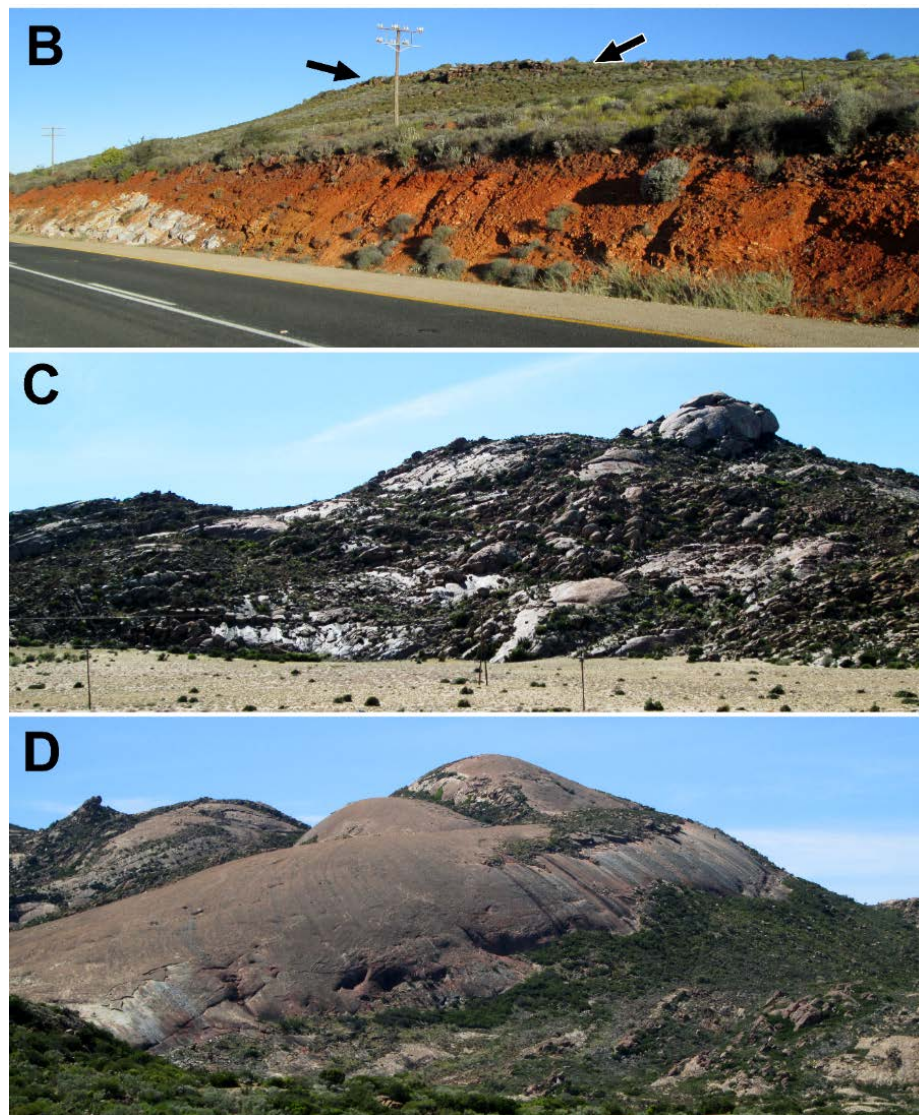
the direct weathering of rocky parent materials. In semi-arid settings, the high moisture-holding capacity of deeper, fine-textured soils fosters the development of vegetation that differs markedly from the vegetation on either shallower soils or those lacking such pedogenic development [75,99,100]. The protective canopy cover of vegetation and below-ground root systems imparts further stability to hillslope soils [101].

At the Sandia Mts. site studied by Persico et al. [95], slopes lacking aplite dikes and associated mantles of coarse colluvium mainly exhibited corestone topography dominated by exposed bedrock, with limited and patchy soil cover. Where soils are present on these hillslopes, they typically consist of thin A horizons directly over a thin C horizon and weathered bedrock (Cr). The dominant mode of weathering of granite is grussification, yielding granule-sided and smaller particles. Those materials are readily removed by surface runoff, preventing the accumulation and lengthy retention of sediments required for sustained soil profile development. As a consequence, rather than the smooth, curvilinear profiles exhibited by slopes mantled by aplite colluvium, the exposed granite slopes at the Sandia Mts. site displayed rugged, irregular corestone relief. Similar contrasts are evident in South African landscapes. For example, the Namaqualand granite-gneiss complex is exposed in an area of about 70,000 km<sup>2</sup> in the northwestern corner of South Africa. In places where relatively weathering-resistant rock types outcrop above granitic units like the *Nuwerus* site, accumulations of weathering-resistant, coarse colluvium over the more weathering-prone rocks creates conditions that enhance dust entrapment, soil formation, development of smooth, curvilinear slope profiles, and continuous vegetation cover (Figure 13A,B). Areas dominated by the same kinds of granitic rocks, but lacking units capable of generation weathering-resistant colluvial mantles exhibit profoundly different slope forms including exposed corestones and domed inselbergs (bornhardts). Such landforms are characterized by processes including exfoliation or sheeting [102], combined with grussification, which generate relatively fine materials that are efficiently removed from the slopes (Figure 13C,D).



Figure 13. Cont.





**Figure 13.** (A) View to the north from Nuwerus showing the smooth, curvilinear slope profile. The bedrock in the lower portions of the slope is medium-coarse grained leucocratic granite. Outcrops of quartzite in upper slope locations (black arrows) contribute weathering-resistant, cobbly colluvium that armours the lower surfaces, facilitating entrapment of dust, formation of thick soils, development of a smooth slope profile, and a continuous vegetation cover; (B) Exposure on the south side of Highway R382, 6 km northwest of Steinkopf, Northern Cape Province (coordinates:  $-29.22874^{\circ}$  S,  $17.69074^{\circ}$  E). Weathering-resistant quartzite strata (late Proterozoic Nama group) prominently outcrop at the top of the hill (black arrows). The exposure reveals a continuous layer of cobbly quartzite colluvium on the surface, beneath which are at least two buried soils, indicating multiple episodes of colluviation followed by dust accumulation and soil formation. The bedrock beneath the soils is shale; (C) View to the east from Highway N7 south of Springbok showing the corestone topography of a granitic terrain where a source of weathering-resistant, coarse colluvium is not present; (D) View to the east from Highway N7 south of Springbok showing a granitic dome (bornhardt), also in a terrain devoid of rock units that can contribute coarse, weathering-resistant colluvium. Notice the occurrence of sheeting in the lower left. Although portion of the dome is mantled by colluvium (lower right) and such a mantle may have at one time been more extensive, under the current climate regime, such a mantle may be undergoing progressive stripping due, in part, to the ease at which colluvium derived from granite is weathered and eroded.

## 5. Lessons Learned and Concluding Remarks

The deposition of aeolian sediments is universal [1] and contributes substantially to soil development and landscape phenomena in arid and semi-arid environments around the world. Whether aeolian sediments accumulate in discrete patches, forming the above-ground mounds called *heuweltjies*, or are more evenly distributed, but hidden from view below the land's surface as they contribute to soil development, inputs of aeolian dust play a central role in shaping landscapes, soils, and the composition of biotic communities in the drylands of western South Africa. There are recognizable similarities between the way aeolian sediment inputs shape some soils and landscapes in the arid regions of the southwestern United States and those of South Africa. Although the distinct *heuweltjies* of South Africa have no exact counterpart in North America in terms of the particular processes responsible for their formation, other phenomena, like desert pavements and the fine-grained soil horizons beneath stony colluvium on hillslopes, apparently have similar developmental pathways.

The role played by aeolian dust in shaping many soil attributes has a long history of investigation in arid and semi-arid portions of the southwestern United States. McFadden [61] provided a brief history of how the work of American soil scientists in the 1950s and 1960s, as well as the contributions of others, including Israeli soil scientists, provided an essential foundation for understanding the central importance of dust inputs to soil development. That pioneering work, led in the United States by soil scientist Leland Gile, provided an essential foundation for subsequent soil-geomorphic research in the American Southwest. Knowledge of the processes of soil development and how soils change over time provided a key to investigating the development of both stable landforms (e.g., stone pavements), as well as unstable ones (hillslopes) [65,95,103]. Without recognition of the role that aeolian dust plays in the development of certain soil characteristics, it is impossible to understand processes that shape the evolution of many kinds of landforms [61].

In contrast to the widespread recognition since the 1960s of the importance of dust inputs to development of soils in arid and semi-arid landscapes of Western North America, this topic has not received the same level of attention in South African soil research. For example, the role of dust as an important input to the development of soil features is not addressed in the recently published *Soils of South Africa* [73]. Similarly, other soils-related papers that focus directly on features of South Africa's arid lands soils e.g., [74,104] make no mention of the role of dust input and accumulation in explaining some of the soil features of the region. This apparent lack of recognition of aeolian addition to soils has contributed to misinterpretation of processes responsible for observed soil features (i.e., the light-coloured vesicular A horizons beneath stone pavements described as “bleached” horizons due to leaching processes; [73]). Although dust and other atmospheric inputs have been recognized by South African researchers as a significant source of plant nutrients [36], attention from the South African soil science community regarding the role of dust as a source of basic soil forming materials (e.g., clays and other materials contributing to soil mass) is not apparent in the published literature.

This paucity of soil science research in South Africa on aeolian dust inputs is not because the transport and delivery of aeolian dust is a rare phenomenon in dryland regions of the country. The western half of South Africa has ample sources that contribute to dust production and aeolian transport. The Northern Cape Province has over 500 pans of varying sizes with exposed, largely-unvegetated fine-grained sediments at the surface [105]. For example, approximately 200 km south of Upington, a 200 km × 200 km area contains scores of pans of various sizes, among the larger is Verneukpan, with a surface area of ~390 km<sup>2</sup> (measurements from Google Earth™ images). Thermally-induced dust devils on pans like this contribute to the mobilization of fine sediments from the barren basin floors [105]. These pans are, no doubt, major sources of fine aeolian sediments, as are the dry lake beds (*playas*) of the arid regions of Western North America. In South Africa, *berg winds* may play an important role in transporting sediments from interior regions such as this [36]. These katabatic winds blow from the direction of the interior and are most frequent in the western coastal region, which experiences them approximately 50 times per year, associated with coastal lows [106,107].

Satellite imagery has documented plumes of aeolian sediments by berg winds more than 100 km offshore of the western coast of Namibia [108].

The generation and transport of aeolian sediments is only part of the story; spatial variation in the sediment-trapping potential of landscapes can apparently generate substantial contrasts in soil and landscape features. In places where the entrapment and incorporation of dust is relatively spatially uniform (e.g., on gravelly or cobbly pavement surfaces or on coarse colluvium deposits of hillslopes), the resulting modifications of soil features would likewise be expected to be relatively uniform. However, in some landscapes, the patchy occurrence of vegetation with substantially greater capacity to entrain and retain aeolian sediments, such as that associated with fertile islands generated by termites, can lead to the superposition of pronounced, localized aeolian sediment deposits (*heuweltjies*), forming microtopographic relief superimposed on other kinds of soils features influenced by dust deposition. Such is the case at the Nuwerus site, with geologically younger *heuweltjies* superimposed on older soil horizon features (Figures 11 and 12B,C).

In many ways, the geologically old landscapes of western South Africa differ greatly from the young ones of the Basin and Range Province of the American Southwest, where Quaternary geological surfaces predominate in intermontane basins. Likewise, there are pronounced differences in many kinds of soil features, despite the universal inputs of aeolian sediments. However, it is the accumulation of dust together with the interaction of several important and regionally-specific biological, climatic, and physical processes acting over long periods of time that generate the particular features of a region. For example, the widespread occurrence of indurated, non-calcic duric (silica-cemented) horizons in western South Africa and restriction of calcic horizons to soils associated with termite activity in *heuweltjies* differ considerably from the kinds of soils found in similar climate regimes in North America. These differences apparently arise due to differences in a complex set of interacting biological and physical processes that develop over time and differ from region to region depending on the presence of termites and on climate, topography, in situ parent material, as well as the proximity and mobility of fine-grained sediments.

Two of us (J.R.M. and L.D.M.) have investigated soil-related phenomena in the arid portions of the United States for more than three decades, and are fascinated by these contrasts, but, at the same time, find some of them perplexing and challenging. South Africa possesses a wide range of Earth surface features that require much further investigation in order to better understand potentially complex developmental processes. We are convinced, though, that a wider consideration and investigation of the role of aeolian dust in shaping soils and landscapes of South Africa as outlined in this paper will contribute to a much deeper understanding of many of the causes underlying the similarities that exist, as well as the contrasts between these different parts of the world.

**Author Contributions:** Fieldwork in South Africa was carried out in collaboration by J.R.M., L.D.M., and M.T.H.; J.R.M. prepared the original manuscript draft with input and review by L.D.M. and M.T.H. All authors read and approved the final manuscript.

**Acknowledgments:** We thank all those who contributed to the success of our South African fieldwork in 2012 and 2016. Matthew King, Sam Jack, and Wesley Bell assisted in the field and with laboratory soils analyses. Des Barnes facilitated the use of soil laboratory facilities at the University of Cape Town (UCT) and Dawood Hattas and Lesego Khomo helped secure equipment and supplies. Mike Picker shared his knowledge with us about the biology and natural history of *M. viator* and examined collected specimens. Jeremy Midgley graciously invited us to visit several of his *heuweltjie* research sites and shared his perspectives with us. Anthea Stain and Samantha Venter of the UCT Plant Conservation Unit made logistical arrangements for travel and fieldwork accommodations in South Africa. Samantha Venter also translated several unpublished theses and reports from Afrikaans to English. The Mazda Wildlife Vehicle Fund provided a sturdy 4 WD vehicle used in the 2012 fieldwork. Wesley Bell of the Plant Conservation Unit, UCT and Veronica Nixon of the Desert Botanical Garden (DBG) created base maps and imagery for preparation of Figures 1 and 11, respectively. Beth Brand, Librarian of the DBG Schilling Library obtained interlibrary loan copies of obscure literature. This research was supported, in part, by the Desert Botanical Garden; a generous gift to that institution from Nancy Swanson funded the international travel and fieldwork of J. McAuliffe in 2012. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

**Conflicts of Interest:** The authors declare no conflicts of interest.



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