The Influence of Dust Deposition, Carbonates and Erosion on the Formation of Clanwilliam Heuweltjies

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Abstract

Heuweltjies (Afrikaans for "little hills") are non-anthropogenic, regularly dispersed earth mounds up to 32 meters in diameter and approximately 1.4 meters in height, that dot about 25% of the land surface of south-western southern Africa. The zoogenic "termite" hypothesis has been widely accepted as a hypothesis of heuweltjie origin. However, the recent "vegetation-patch-erosion" (VPE) hypothesis suggests an equally likely explanation for heuweltjie formation. The aim of this investigation was firstly to determine the influence of dust deposition and carbonates on heuweltjie formation in order to gain insight into the formative process of heuweltjies. The second part of this investigation sought to further test the VPE hypothesis by examining whether erosion alone could give rise to heuweltjies within a reasonable time frame. Soil surveys were conducted on 8 heuweltjies and at 2 inter-heuweltjie areas at depths of up to 0.9m. Textural analysis of soil samples collected from the 8 heuweltjies as well as an additional 11 heuweltjies was conducted. Bulk density was also evaluated for each horizon of each heuweltjie and inter-heuweltjie. Carbonates in all soil samples were determined by acid digestion of soils. A digital elevation model of the Clanwilliam area was constructed and used to obtain heuweltjie area and elevation. There was no difference in average soil texture moving from the centre of a heuweltjie to its periphery (indicating that they formed by layered stratification rather than radially from the centre). There was an apparent difference in texture and carbonates between heuweltjie and inter-heuweltjie zones. Mass of fines (silt and clay) and carbonates were both positively correlated with heuweltjie mass, but were also collinear. Non-parametric regression of heuweltjie mass against both fines and carbonates revealed a clear linear trend. However, the trend between fines and carbonates suggested that fines played a central role in both heuweltjie and carbonate formation and that carbonate took on only a secondary role in heuweltjie formation. Erosion alone would have taken 11000 years to form the heuweltjies. However, some calcretes within heuweltjies have been found to be older than 11000 years, suggesting that erosion has not had a major influence on heuweltjie formation. These findings support the vegetation-patch-erosion hypothesis. However they support dust deposition rather than erosion as a primary contributor to heuweltjie formation.

(1) **Introduction**

Heuweltjies (Afrikaans for “little hills”) are non-anthropogenic, regularly dispersed earth mounds up to 32 meters in diameter and approximately 1.4 meters in height (Francis et al. 2012, Cramer et al. 2012, Moore and Picker 1991, Kunz et al. 2012). They occur in the winter rainfall region of southern Africa; covering approximately 14 – 25% of the landscape of the south-western part of southern Africa and bounded by the Orange river in the north and the town of Oudtshoorn (South Africa) in the south-east (Picker et al. 2007). These heuweltjies form part of a larger tapestry of earth mound patterns found worldwide. They possess a similar spatial patterning to earth mounds elsewhere in the world such as “mima” mounds in Brazil and North America and prairie mounds in Canada (Cramer et al. 2012). However, an essential difference is that heuweltjies present a stratified internal structure while mima and prairie mounds do not (Cox 1984, Moore and Picker 1991). Another interesting characteristic of heuweltjies is that their soils have been found to be different from the soils of the surrounding matrix. Heuweltjies seem to have more fertile soils supporting different vegetation to that of the surrounding landscape (Kunz et al. 2012), possibly due to nutrient inputs from marine aerosols (Midlgey et al. 2012), since the soils on which heuweltjies are found are largely infertile sandy soils (Soderberg and Compton 2007). On observing these patterns one cannot help but wonder how these mounds formed. Thus heuweltjies have received much attention regarding possible mechanisms for their formation.

Ultimately there are two models regarding heuweltjie origin – the zoogenic model and non-zoogenic model. One hypothesis of the zoogenic model proposes that heuweltjies were constructed through the actions of tunnelling rodents such as mole-rats or large fossorial pocket gophers (the Dalquest-Scheffer hypothesis) (Cox 1984). Another more widely accepted zoogenic hypothesis for the origin of heuweltjies is the termite hypothesis. The termite hypothesis proposes that heuweltjies are the result of the nesting activity of the harvester termite *Microhodotermes viator* (Picker et al. 2007). The observation of these termites as well as evidence of their nests in heuweltjies has led to the conclusion that they could have been instrumental in the formation of heuweltjies (Moore and Picker 1991). Their presence has also been used to explain the apparent over-dispersed spatial arrangement of heuweltjies.

The distribution of heuweltjies overlaps with that of M.*viator,* which build nests that are of a similar spatial arrangement to that of heuweltjies (Moore and Picker 1991, Picker et al. 2007). Furthermore, the finer more aerated soil texture of heuweltjies has been attributed to the tunnelling actions of the termites as they displace soil thoughout the heuweltjie (Moore and Picker 1991).

The calcrete present in heuweltjies has also been hypothesised as a result of M.*viator* nesting activity. Harvester termites could produce a hardened upper layer of sand on the heuweltjie, which in turn prevents the leaching of any calcium carbonate in solution, which would then precipitate out as calcite (Potts et al. 2009). The respiration of termites along with the decomposing plant material, could also provide the carbon dioxide necessary for calcite formation (Potts et al. 2009).

The non-zoogenic model of heuweltjie formation invokes the "vegetation-patch-erosion" (VPE) hypothesis as per Cramer et al. (2012). This hypothesis is essentially a combination of the erosion and wind-deposition hypotheses proposed for the formation of mima mounds (Cox 1984). The VPE hypothesis proposes that vegetation patches that form in arid environments retain wind-blown dust and hold onto the soil that they are rooted in; causing differential erosion between the patch and inter-patch areas resulting in the formation of a mound over time (Cramer et al. 2012). The spatial arrangement of heuweltjies is due to the spacing of the vegetation patches. Resource scarcity in an arid landscape would lead to the formation of vegetation patches as each group of plants supports itself via positive feedback processes (creating a favourable micro-climate for other plants to grow) but only up to a certain distance (due to resource scarcity) (Rietkerk and Van de Koppel 2007, Lejeune et al. 1999). Therefore, each patch is limited in its ability to spread over the landscape and is essentially restricted to being a "spot" on the landscape.

Furthermore, the plant roots of these patches have been invoked as a contributing factor to the formation of calcrete (hardened calcium carbonate) only present in heuweltjies, but absent from the inter-heuweltjie regions (Cramer et al. 2012). The carbon in these calcretes has been dated from 4000 to about 30000 years old (Moore and Picker 1991, Midgley et al. 2002, Potts et al. 2009). However, these ages represent only minimum ages since not all heuweltjies contain calcrete (Cramer et al. 2012), and it seems that only heuweltjies of a certain size contain calcrete (Moore and Picker 1991). Thus, if calcrete production follows mound formation, then dating of the calcretes would provide a minimum age of the heuweltjie. Therefore the questions to be addressed are:

1) Does dust deposition and carbonate formation influence the formation of heuweltjies, and if so what do they reveal about how heuweltjies formed?
2) How long would it have taken for erosion to form the heuweltjies (acting alone in the absence of dust deposition) and is it within a feasible time frame?

Thus, invoking the VPE hypothesis, one would expect to find that the heuweltjies are as old as the eroded landscape and that dust deposition and possibly also carbonates (in the form of calcite) are responsible for their formation.

(2) **Methods**

2.1 *Study Site*

Sampling was undertaken in the floodplain of the Clanwilliam dam near the town of Clanwilliam, South Africa (32° 10′ 43″ S, 18° 53′ 28″ E), from the 3rd to the 6th June 2013. The Heuweltjies sampled were situated to the south of the dam (figure 1). Clanwilliam is situated within a winter rainfall region (Cramer et al. 2012), with an underlying geology of Table Mountain Sandstone (Moore and Picker 1991) and vegetation of the Succulent Karoo biome (Cramer et al. 2012).

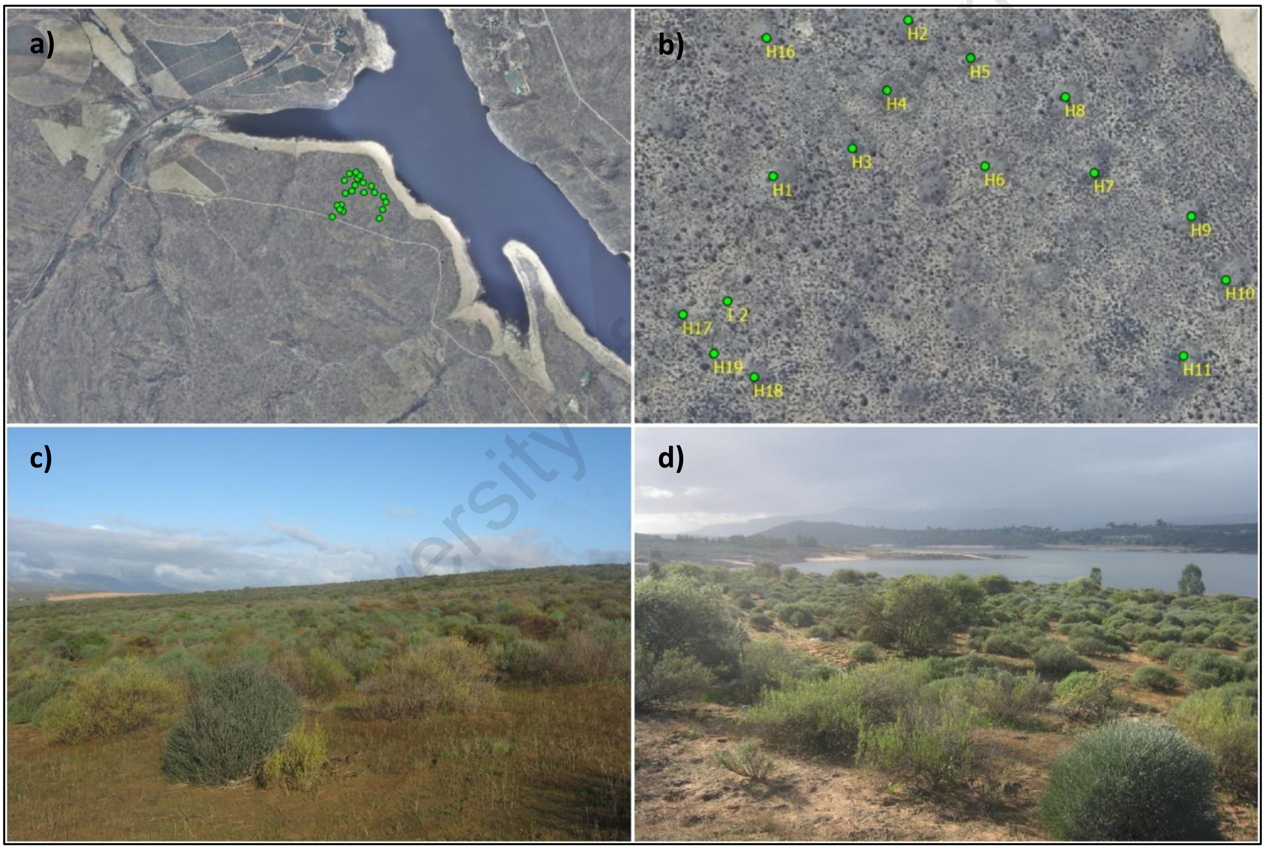

Fig. 1. Study area. a) Overview of Clanwilliam dam and the heuweltjies sampled (green points). b) Heuweltjies (H's) and inter-heuweltjie regions (I's) sampled. c) View from atop a heuweltjie facing away from the dam. d) View from atop a heuweltjie looking across the dam. The sampling area was situated well in the floodplain of the dam and was north of the dirt road that can be seen in a) and b).

2.2 *Heuweltjie Selection and Site Preparation*

Heuweltjies were chosen at random from the heuweltjie H1 (figure 1b), which had been analysed in previous years. The GPS coordinates of each heuweltjie was recorded at what was perceived to be the centre of the heuweltjie, at an accuracy of three meters using a "Garmin GPS Map 60CSx" GPS system. Soil pits were dug at the centre of all heuweltjies. The centre of the heuweltjie was determined by looking for the highest position in the heuweltjie that was also approximately equidistant in all directions towards the periphery of the heuweltjie. Additional soil pits were also dug at an intermediate distance between the heuweltjie centre and edge for heuweltjies H1 to H8 (figure 1b and 2a). Certain heuweltjies, such as H1, H2 and H6 had a second additional soil pit at an intermediate distance of approximately two to three meters away from the centre pit. The pits were dug to bedrock. However, the centre pit of H6 and H8 was only dug to the point at which the soil became too compacted to be broken through with just a shovel and pickaxe.

Fig. 2. Digging a soil pit. a) Digging a soil pit. b) Completed soil pit with pegs inserted demarcating horizons. The pit is labelled CW10 according to an initial labelling order of the heuweltjie pits, and it has been chipped all the way down the length of its face.

2.3 *Soil Survey*

The length of the face of a completed soil pit was made rough by chipping using a soil knife (figure 2b). The knife was then used to gently feel the texture of the soil starting from the top of the face and proceeding downwards. Pegs were inserted where a change in the soil texture was felt (figure 2b). Once all the horizons were demarcated with pegs the thickness of each horizon was recorded and a qualitative categorisation of each horizon was done using the methods and definitions as per Schoeneberger et al. (2002). Horizons were classified as A, B, C or E or a combination of these depending on the characteristics of the layer (Schoeneberger et al. 2002). Horizons were given suffixes such as "k", "t" and "W", to indicate the presence of carbonates, clay or a very sandy horizon, respectively. The soil characteristics examined were boundary, texture, plasticity, structure, roots, gravel, effervescence and colour.

Texture was determined by slightly wetting a small amount (about a tablespoon) of soil with water and kneading it with the hands and then pushing it into a ribbon according to Schoeneberger et al. (2002) to roughly determine the clay, silt and sand composition and assign the soil to a category (sandy clay loam, sandy loam, silty clay loam etc.). The plasticity was determined by taking the same amount of slightly wetted soil and rolling it out into a strand. The minimum diameter of the strand at which it could no longer support itself when held between thumb and forefinger determined the plasticity; and the soil was assigned to a plasticity category (not plastic, slightly plastic, very plastic etc.).

Structure was determined by removing a sample of soil from a horizon using the soil knife and looking at the way in which the soil naturally broke up into large clumps. The soil was then assigned to a category according to the size and edges of the clumps. The density and thickness of roots for each horizon was determined by observation. The percentage of gravel present in the soil was determined by observation. Soil effervescence gave an indication of the presence of carbonates in the soil. Drops of three molar (3M) hydrochloric acid (HCl) were reacted with each soil layer, from the top of the layer to its boundary. The degree of effervescence was recorded (non-effervescent, slightly effervescent, highly effervescent etc.) according to Schoeneberger et al. (2002). The colour of each soil layer was determined using a Munsell® Soil Colour Chart. These charts use three values to distinguish colour – hue (the shade of the colour), value (the lightness or darkness of the colour) and chroma (the intensity of the colour) (Peverill et al. 1999, pp – 62). A ball of soil from each layer was compared against the soil colour chart.

2.4 *Soil Sampling*

Soil samples and bulk density samples were collected from each horizon and stored in plastic ziplock bags. Bulk density samples were collected using a soil core of volume 36cm^3. The core was hammered in at the centre of each soil horizon. There were occasions when the soil was too hard for the core to penetrate. In these cases the spade and soil knife were used to break off two to three clods of hard soil from each horizon. The clods were handled carefully and stored separately from the other samples to avoid damage. Medium sized ziplock bags were filled with soil from each horizon that was either scooped out using a spade or broken off in chunks (where the soil was hard and compacted) using the soil knife and spade. Bulk density samples were only collected from heuweltjies H1 to H8 and from I1 and I2.

2.5 *Soil Processing*

Only soil samples were dried at 25°C for a period of two weeks after which they were ground with a mortar and pestle. Each ground sample was sieved using a 2mm sieve. A representative sample from each of the soils was collected by stirring the soil and then dishing out some soil using a dispersion cup. About forty to fifty grams of each soil was collected in this way. Twenty grams of each of these soils were ground to a finer powdery texture using a hammer mill. Before each sample was fed into the mill, all the compartments that the soil would pass through were cleaned thoroughly with a high-pressure air gun.

2.6 *Particle Analysis*

The soil samples that had been ground and sieved were analysed for particle size using the hydrometer method as per Carter (1993), with some modification. A forty gram representative sample (retrieved by the stirring technique explained above) was weighed out using a “Mettler PE-11” scale. The soil was then mixed with one hundred millilitres of 5% calgon (sodium hexametaphosphate, $(NaPO_3)6$) solution and mixed for five minutes using a hand held blender. The calgon solution was made up of thirty-five grams of calgon granules in one litre of reverse osmosis (RO) water. Calgon acts as a dispersant, aiding in the separation of soil particles in solution. Once blending was completed, the head of the blender was rinsed with RO water into the container holding the mixture of blended soil and calgon.

The mixture was then transferred to a one litre measuring cylinder. Any soil that was left in the mixing container was rinsed into the measuring cylinder using RO water. The cylinder was then left to stand on a level surface out of direct sunlight and more RO water was added to the water column of the cylinder to increase its length to about thirty-six centimetres. The hydrometer reading of a cylinder containing just RO water and calgon (a blank) was recorded. The water column of each cylinder was then disturbed by shaking and mixing them end-to-end, using parafilm as a lid to avoid spillage. Once a cylinder was set down, a forty second timer was immediately started and the hydrometer inserted into the water column.

The hydrometer reading was recorded once the timer alarm went off after forty seconds had passed. It takes about seven hours for larger soil particles such as silt and sand to settle out of the water column leaving clay in suspension (Carter 1993). Therefore, the hydrometer reading was recorded again seven hours later. The percentage of clay, silt and sand was then determined using the following equations:

$$\text{Sand} = 100 - \frac{(R_{40} - R_l) \times 100}{(Sample\ Weight \times Oven\ Dry\ Fraction)}$$

$$\text{Clay} = \frac{(R_7 - R_l) \times 100}{(Sample\ Weight \times Oven\ Dry\ Fraction)}$$

$$\text{Silt} = 100 - (\text{sand} + \text{clay})$$

R_{40} = Hydrometer reading after 40 seconds

R_l = Blank hydrometer reading

R_7 = Hydrometer reading after 7 hours

Oven Dry Fraction – the proportion of soil remaining after it has been dried at 25°C for two weeks

2.7 *Bulk Density*

$$\text{Density} = \frac{Mass}{Volume}$$

The mass of the soil core samples was obtained by weighing them on a “Mettler PE-11” scale. The bulk density was then calculated using the equation above. Clod samples were also weighed but their volume was determined using a water-displacement method adapted from Blake and Hartge (1986). A two-hundred millilitre beaker was attached to a retort stand at an angle of about sixty degrees. This arrangement of beaker and retort stand was positioned above the “Mettler PE-11” scale upon which a five-hundred millilitre beaker was placed directly below the two-hundred millilitre beaker. Each clod was then sealed using a saran solution (a solution of acetone and saran powder).

The solution should not be too thick as this will increase the mass of the clod and thus the amount of water that is displaced. All the clods were placed in hairnets, dipped in the saran solution and hung up to dry. After an hour they were given another dip and left to dry completely. The volume of the clods was determined using water displacement. The two-hundred millilitre beaker was filled with tap water and allowed to overflow slightly. The water that was left after the overflow filled the beaker up to the tip. The water that had fallen into the five-hundred millilitre beaker was discarded and the beaker dried. Each clod was then carefully inserted into the water in the two-hundred millilitre beaker. The clods were left in the hairnets when they were inserted into the water; but the part of the hairnet that was not holding the clod was held out of the water.

The mass of water that fell into the five-hundred millilitre beaker was recorded. One gram is equal to one centimetre cubed. Therefore the mass of the water recorded was converted to volume using this 1:1 ratio of mass to volume. An average mass and volume for clods from the same soil horizon was calculated and bulk density calculated using these average values.

2.8 *Carbonate Analysis*

The amount of carbonate in each soil sample was determined using the method as outlined in Carter (1993), with some modification. The method involves the gravimetric determination of the mass of carbon dioxide released when soils containing carbonates are reacted with a strong acid such as HCl. The balanced chemical equations follow:

Molecular Equation: $\mathbf{CaCO_{3(s)} + 2HCl_{(aq)} \rightarrow CaCl_{2\,(aq)} + CO_{2\,(g)} + H_2O_{(l)}}$

Net Ionic Equation: $\mathbf{CaCO_{3(s)} + 2H^{+}_{(aq)} \rightarrow Ca^{2+}_{(aq)} + CO_{2(g)} + H_2O_{(l)}}$

A three molar (3M) concentration of HCl was made from a 32% (by mass) concentrated solution of HCl with a specific gravity of 1.6 g/cm^3. The morality of the 32% concentrated solution was calculated using the specific gravity and number of moles of HCl present in the 32% solution; which was then used to calculate the volume of RO water needed to dilute the 32% solution to a 3M solution (figure 3). The dilution procedure was carried out in a fume hood.

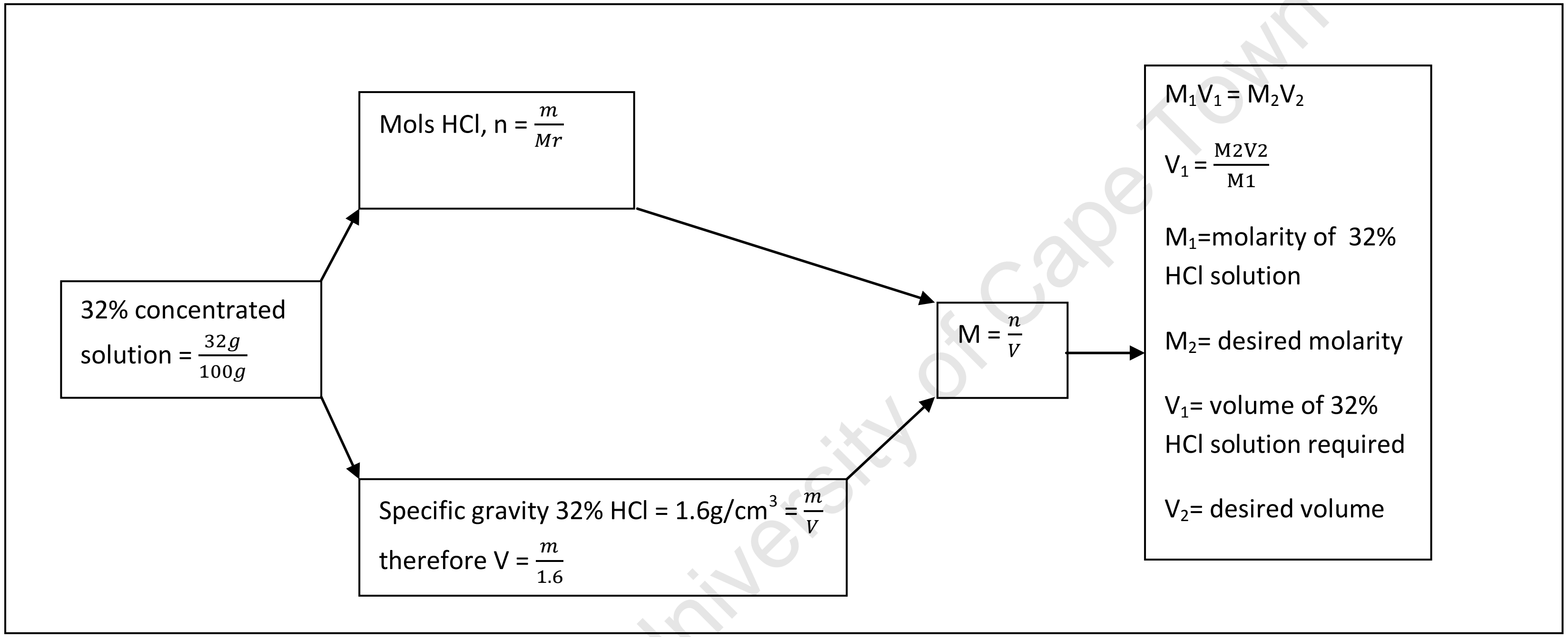

Fig.3. Calculation procedure to determine the volume of concentrated hydrochloric acid (HCl) needed to dilute to a desired volume and molarity of HCl. The mass of the concentrated solution is used to calculate the number of moles and volume of HCl, in order to calculate the molarity of the concentrated solution. This molarity is then used to determine the volume of concentrated HCl needed to mix up a diluted three molar solution of HCl.

The soil samples that had been processed through the hammer mill were used for the carbonate analysis. Five to ten grams of soil were weighed out into glass bottles of known weight. The bottles included caps of which the weight was also known. An empty glass bottle was placed on an analytical scale balance (Shimadzu ATX224) and the scale tared. Ten millilitres of 3M HCl was dispensed into the bottle using a pipette (Eppendorf 10ml pipette), and the weight recorded. The initial weight of each sample before reaction with acid was recorded as the sum of the bottle weight, cap weight, soil weight and weight of ten millilitres of 3M HCl. Each soil sample was then reacted with ten millilitres of acid.

The caps were removed while the acid was being dispensed, and then were replaced loosely after any effervescence of the sample had subsided. After thirty minutes the cap of each sample was removed and the solution swirled to displace any carbon dioxide. The cap was then replaced and the sample weighed on the analytical balance stated above. The reaction between the calcium carbonate and HCl usually takes about two hours to run to completion (Carter 1993). Therefore the samples were left for a further fifteen hours with their caps loosely fitted. After this time they were weighed and found to be at constant weight. The difference between the initial and final weight of the sample gave an indication of the mass of carbon dioxide that was lost during the reaction. This mass of carbon dioxide was converted to mass of calcium carbonate using the molecular equation above. The one to one molar ratio of calcium carbonate to carbon dioxide meant that the number of moles of carbon dioxide was equal to the number of moles of calcium carbonate. Using this information, the mass of carbon dioxide lost was converted to moles using the equation (for moles) in figure 3. The number of moles calculated was then used to determine the mass of calcium carbonate using the same equation in figure 3. The percentage of calcium carbonate in the soil sample was then calculated. This calculation procedure was repeated for all the soil samples.

2.9 *Heuweltjie Elevation and Area*

Heuweltjie elevation data was obtained using a digital elevation model (DEM) (figure 4a). The model was constructed from red-green-blue unrectified images taken during aerial surveys of Clanwilliam, as well as the aerial triangulation results of each of the images. Two images of the area of interest (such as in figure 1a) were superimposed over each other and the elevation position of an arbitrary point was determined using the coordinates of the two pictures (two dimensional- x and y coordinates) and those of the aerial triangulation results (three dimensional – x, y, z and rotational coordinates). This process was repeated for as many points as possible on the stereoscopic image. This point elevation data set (the raw DEM) was then made into a raster data set that could be used in a GIS programme.

The elevations of each point in the final raster DEM was the point in the centre of each grid cell of the DEM. This centre point was calculated as the mean of the other elevation points surrounding that point. Thus the raw DEM data consisting of arbitrary elevation points was converted to a raster data set with an individual point per grid cell. The accuracy of each of these points (the distance between them) was half a meter. The aerial photographs and triangulation results were obtained from the National Geo-Spatial Information[1] centre.

Heuweltjies were digitised by creating a polygon vector layer in Quantum GIS (QGIS Development Team 2013). The vector layer was then added to a raster layer. The raster layer in this case was the red-green-blue rectified map of the area of interest (the Clanwilliam dam area as seen in figure 1a).

Polygons were drawn demarcating the area of each of the heuweltjies of interest and the "zonal statistics" function was used to return the mean area of each of the drawn polygons (heuweltjies). The DEM was then used as a raster layer with the vector layer added. The "zonal statistics" function was then used again to determine mean, maximum and minimum elevation within each of the polygon areas (heuweltjies). The area and elevation values were used to determine the volume of each of the heuweltjies as per the equation, Volume = Area x Height.

The QGIS "terrain analysis" plugin was used to add a hillshade effect to the DEM (figure 4b). Hillshading creates a 3D effect on an elevation layer (such as a DEM) by calculating the aspect and slope of each cell and then simulating the sun's position and assigning a reflectance value to each cell (QGIS Development Team 2013, User Guide, pp -136). The "terrain analysis" plugin was also used to do a slope analysis of the DEM. The slope analysis measures the steepness of each pixel in the DEM relative to its surrounding pixels. The slope values are measured in degrees of inclination such that lighter areas indicate steeper slopes while darker areas indicate less steeper slopes (QGIS Development Team 2013, User Guide)(figure 5). The slopes of each of the heuweltjie areas (figure 5) were calculated using the "zonal statistics" function in QGIS. Another polygon vector layer was made, this time of the inter-slope regions surrounding the heuweltjie areas. Four inter-heuweltjie regions were demarcated around each heuweltjie area and the "zonal statistics" function used to return the slopes of these demarcated areas (Appendix A – figure1).

[1] National Geo-Spatial Information is a component of the department of Rural Development and Land Reform of the Republic of South Africa. Physical Address: Van der Sterr Building, Rhodes Avenue, Mowbray, 7705, Cape Town; Postal Address: Postal Address: Private Bag X10, Mowbray, 7705, Cape Town

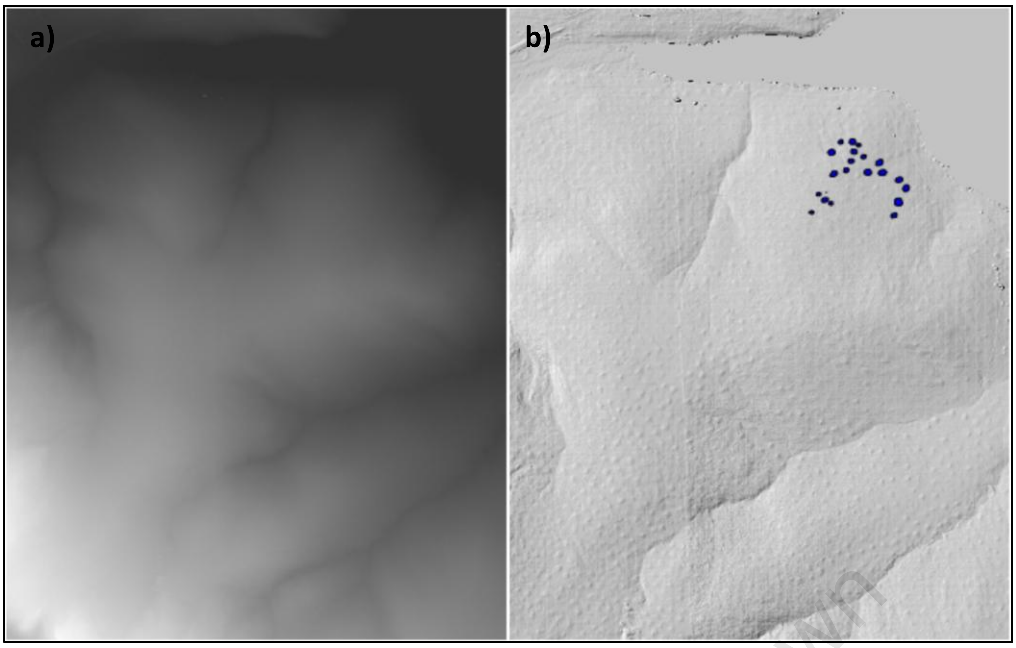

Fig.4. Digital Elevation Model (DEM) used to determine heuweltjie elevation. a) DEM with pixel values stretched over the minimum and maximum b) DEM with hillshade effect. The heuweltjie area vector layer is marked in blue on the hillshade. One can see the heuweltjies as bumps or "pimples" on the hillshade landscape. The area of the hillshade is all of a similar shade of grey, suggesting that the area in which the heuweltjies of interest are situated is quite flat.

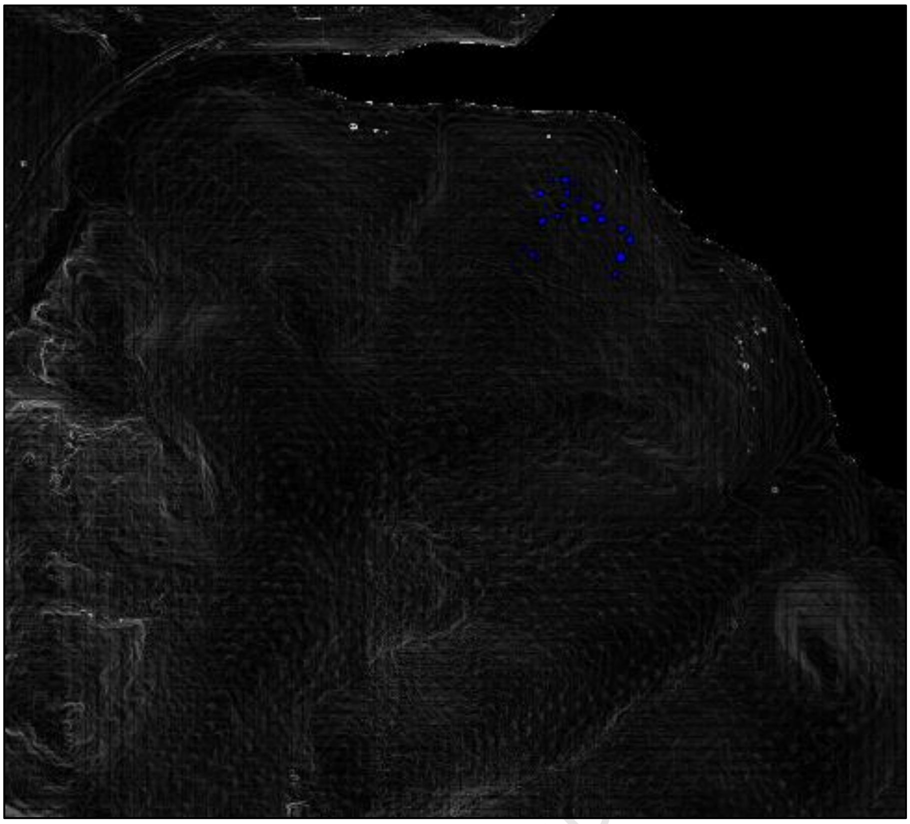

Fig.5. Slope map of DEM. Slope is measured in degrees of inclination. Lighter pixels indicate raised areas with higher angles of inclination relative to their surroundings. One can see that the heuweltjies protrude out of the landscape as they have a steeper slope than the landscape. The landscape has quite a gentle slope given its darker pixel values. The highlighted areas indicate the heuweltjies of this study.

2.10 *Erosion of Heuweltjie Landscape*

The amount of soil that would have had to be removed by erosion from the heuweltjie landscape (figure 6) was determined using the bulk density and depth of the heuweltjie and inter-heuweltjie zones. The average mass per unit area of the heuweltjie and inter-heuweltjie zones was calculated by taking the sum of the product of the bulk density and thickness of each horizon layer. This would give an average mass per unit area value for the heuweltjies and inter-heuweltjie zones. The area to be removed in figure 6 is essentially the mass per unit area of the inter-heuweltjie zone. Therefore the difference between the heuweltjie and inter-heuweltjie mass per unit area should be the amount of soil that would have eroded away. The amount of time that it took to erode away this material was estimated from erosion rate data obtained from Von Blanckenburg (2005) (Appendix A – figure 2, table 1), using the following equation:

$$Erosion\ Rate = \frac{Length\ (m)}{Time\ (Ma)}$$

Each erosion rate was multiplied by the average bulk density (in $kg.m^{-3}$) of all the heuweltjies in order to obtain an estimate of the amount of soil that could be eroded at each erosion rate. The mass per unit area of soil removed from the heuweltjie landscape (figure 6) was then divided by the above estimate of soil removed at a particular erosion rate, to give an indication of the time it took to erode the heuweltjie landscape. The erosion rate data obtained from Von Blanckenburg (2005) was plotted against the amount of time it would take to erode a certain amount of material at each erosion rate.

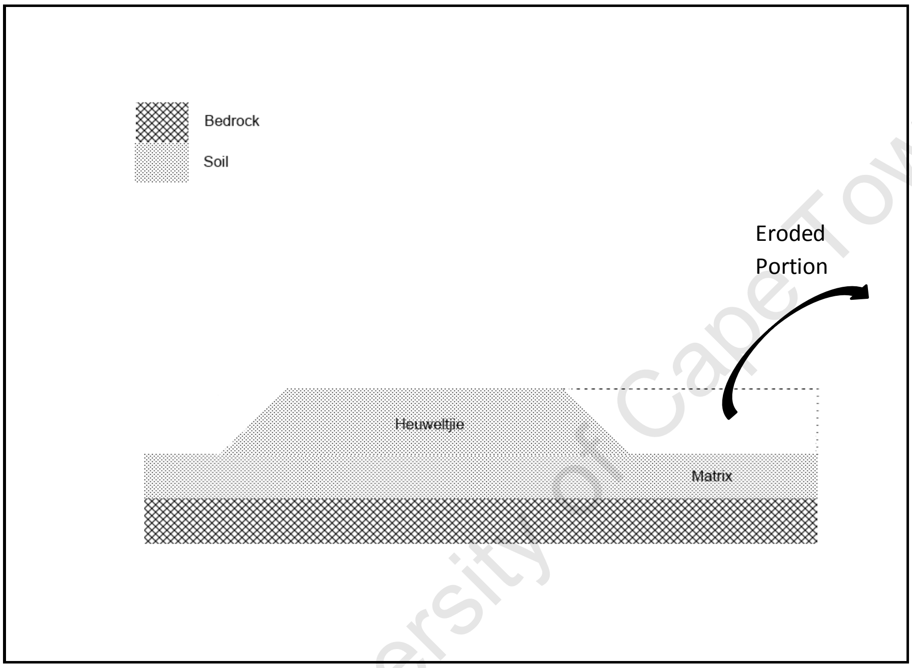

Fig.6. Diagram of heuweltjie and matrix (inter-heuweltjie) soils on a layer of bedrock. The dotted lines and black arrow indicate the area that would have had to erode away over time in order for the heuweltjies to form the mounds they are at present.

2.11 *Texture and Carbonate Calculations*

Soil samples and bulk density samples were collected for each horizon of each heuweltjie (H1-H8) and inter-heuweltjie pit. The weighted average of bulk density, texture and carbonate percentage per pit was calculated by weighting each value by the thickness (as a proportion) of the horizon it came from, and then taking the sum of all the weighted values down the length of the pit. This procedure gave an average pit value of bulk density, texture (%) or carbonate (%).

The relationship between heuweltjie mass, texture and carbonates was of interest to this investigation. Therefore the texture and carbonate percentages per pit were then converted to mass per unit area values as per the equation below:

Mass per unit area ($Kg.m^{-2}$) = Total Pit Bulk Density ($g.cm^{-3}$) x Total Pit Percentage material ($g.100g^{-1}$) x Total Pit Length (cm) x 10

Thus a pit value for texture and carbonate was calculated, and a mean heuweltjie value was calculated by calculating the mean of the pit values for each heuweltjie. The mass of each heuweltjie was also calculated by multiplying its total bulk density (in kilograms per meter squared) by its volume. Carbonate and texture values (in kilograms per meter squared) were converted to mass (in kilograms) by multiplying by the area of the heuweltjie (Appendix A – table 2) (See Appendix C for raw data).

Bulk density samples were not collected for heuweltjies H9 – H19. Therefore the mass of carbonates and texture for heuweltjies H9-H19 was calculated using the average bulk density from heuweltjies H1-H8.

2.12 *Statistical Analysis*

Apparent trends in texture and carbonates between the heuweltjie and inter-heuweltjie zones and within the heuweltjies from centre to edge were investigated for statistical significance using parametric or non-parametric methods depending on whether the data satisfied assumptions of normality and homoscedasticity. The contribution of fine particulates and carbonates to the formation of heuweltjies was of interest to this investigation. Therefore correlation analyses were done between heuweltjie mass and the mass of fine particulate matter and carbonates. The type of correlation analysis that was done (parametric or non-parametric) was determined by whether the data was normally distributed. Data analysis was conducted using the statistical package "Statistica" (Statistica 12, StatSoft Inc., Tulsa, USA), as well as the "ggplot2" package in "R" (32 bit) (R Core Team 2013).

(3) **Results**

3.1 *Heuweltjie Slope and Erosion of the Heuweltjie Landscape*

There was no real difference between the slope of heuweltjies (Mean = 6°, SD = 1.4°) and IH zones (Mean = 5°, SD = 1.05°) ($t=2.24$, $DF=20$, $p=0.04$) (table 1, Appendix A – figure 3, table 3). The amount of soil that needed to be eroded off the heuweltjie landscape was calculated to be 384 kilograms per meter squared. This estimate was calculated by taking the difference between the average heuweltjie and inter-heuweltjie mass per unit area (Appendix A - table 1). The time it would take to remove this amount of soil was estimated to be 11000 years (figure 9). This was based on an estimated erosion rate of 20 meters per million years (Von Blanckenburg 2005) (Appendix A – figure 2) and the average bulk density of heuweltjies H1 to H8 – 1.6 $g.cm^{-3}$ (Appendix A – table 1).

3.2 *Heuweltjie and Inter-heuweltjie Qualitative Structure*

Heuweltjies are qualitatively different from inter-heuweltjie zones. They are deeper and have more fines such as silt and clay than inter-heuweltjie (IH) zones (figures 7 and 8). Both heuweltjies and IHs are very sandy and do not contain rocks within their profile (figures 7 and 8, Appendix B). However, only heuweltjies seem to contain horizons that have accumulated carbonate, and they also have more roots than IH zones (Appendix B).

Soil formation is primarily the result of weathering of parent material (Paton et al. 2002). Sandstone is composed primarily of quartz, which when weathered gives rise to the sandy soils observed in heuweltjies (Paton et al. 1995). The soil colour of most of the horizons in both heuweltjies and IH was a yellow-red hue, with the darker more red colours taking precedence in the upper layers of heuweltjies and in deeper layers in the IH zones (figures 7 and 8). Lighter more yellow colours were found at deeper horizons within the heuweltjies (figures 7 and 8, Appendix B).

Soil Texture and Carbonates of Heuweltjies and Inter-heuweltjie zones

On average, heuweltjies have 50.28, 119.63, 664.76 and 54.07 kilograms per meter squared of clay, silt, sand and carbonate respectively (table 1); while the average heuweltjie size (in terms of volume) is 572 m^3. Although there seems to be quite a substantial difference in texture and carbonates between the heuweltjie and inter-heuweltjies, this difference is only significant for silt content (U (19) = 2, Z = 1.98, p = 0.019) (figure 10) as per a Mann Whitney U-test. There was also no significant difference in carbonates or the amount of clay, silt or sand as one moved from the centre to the edge of the heuweltjies (figure 11).

3.3 *Heuweltjie Mass, Carbonate and Fine Particulate Matter (silt and clay)*

There is a relationship between heuweltjie mass and carbonate and heuweltjie mass and fine particulate matter (the sum of silt and clay) (figure 12a and b). There was also some collinearity between carbonate mass and fine particulate mass (figure 12c). A spearman's rank correlation analysis was undertaken after it was established that there was no bivariate normality between heuweltjie mass (kg) with carbonate mass (kg) and fine particulate mass (Appendix A – figure 4). The correlation analyses revealed that there was a significant positive correlation of carbonate mass ($\rho(17) = 0.69$, $p = 0.001004$) and total fine particulate mass($\rho(17) = 0.75$, $p = 0.0002$) with overall heuweltjie mass. The collinear relationship between carbonate mass and fine particulate mass was also significant ($\rho(17) = 0.77$, $p = 0.0001$). The fitting of a non-parametric regression to the data indicated a linear trend between heuweltjie mass and carbonate mass and fine particulate mass (figure 12 a and b). A similar (generally) linear trend was seen between carbonate mass and fine particulate mass (figure 12c).

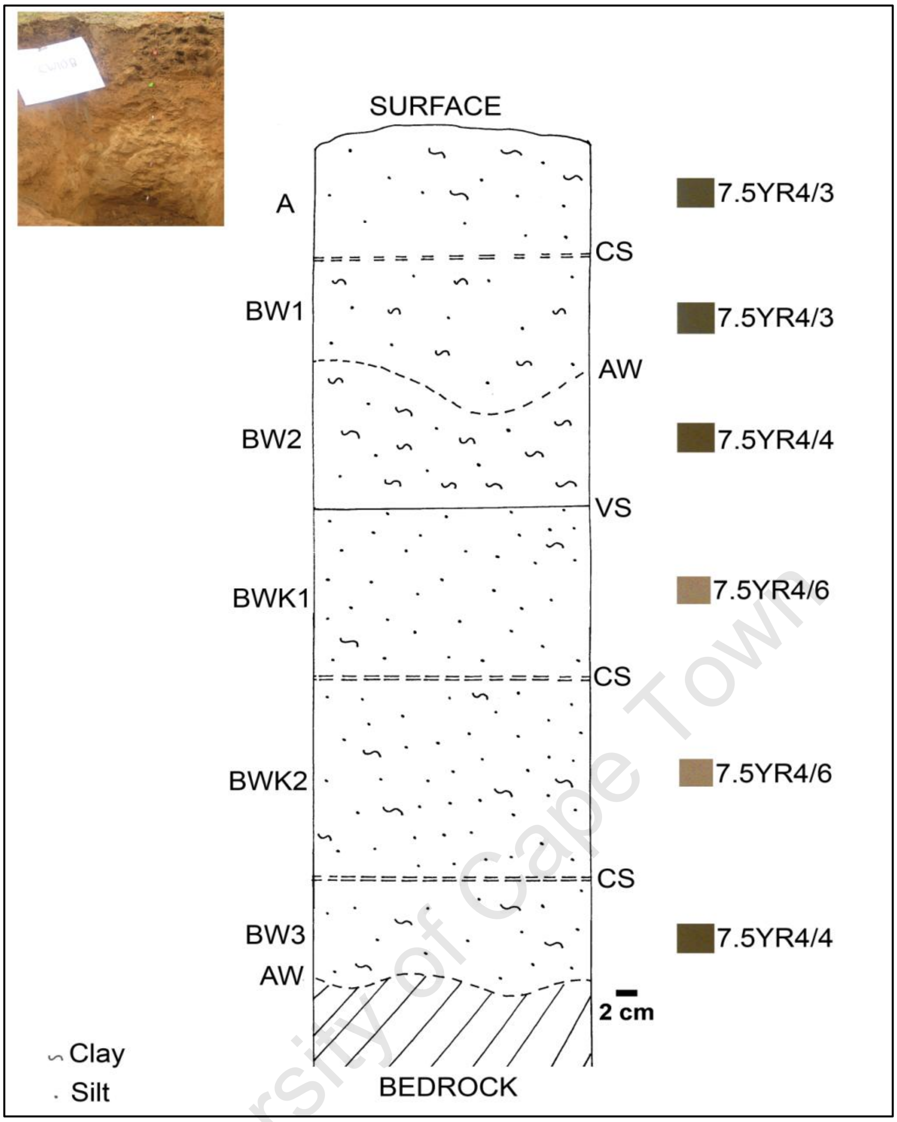

Fig.7. Diagram of a depth profile of heuweltjie H8 (pictured top left). The scale bar is calibrated to depth only. The number of silt and clay particles are drawn proportional to the texture of the horizon. Open white space in each horizon indicates sand particles. Munsell soil colour plates (on the right) indicate the approximate colour of each of the horizons. Horizon layers and transitional boundaries have been designated as per Schoeneberger et al. (2002). The transitional boundaries in this profile are either CS (clear smooth), AW (abrupt wavy) or VS (very abrupt smooth). One can see that the texture down the length of the profile is mostly sandy without any rocks present. The texture changes from a sandy loam to a sandy clay loam then to a sandy clay (BW2). After this horizon the texture becomes a lot more sandy and silty moving to a loamy sand and then finally to a sandy loam once again. The soil colour is quite a dark yellow-red hue in the upper layers but then becomes lighter further down in the more sandy layers where carbonates have accumulated (indicated by the "k" in the horizons).

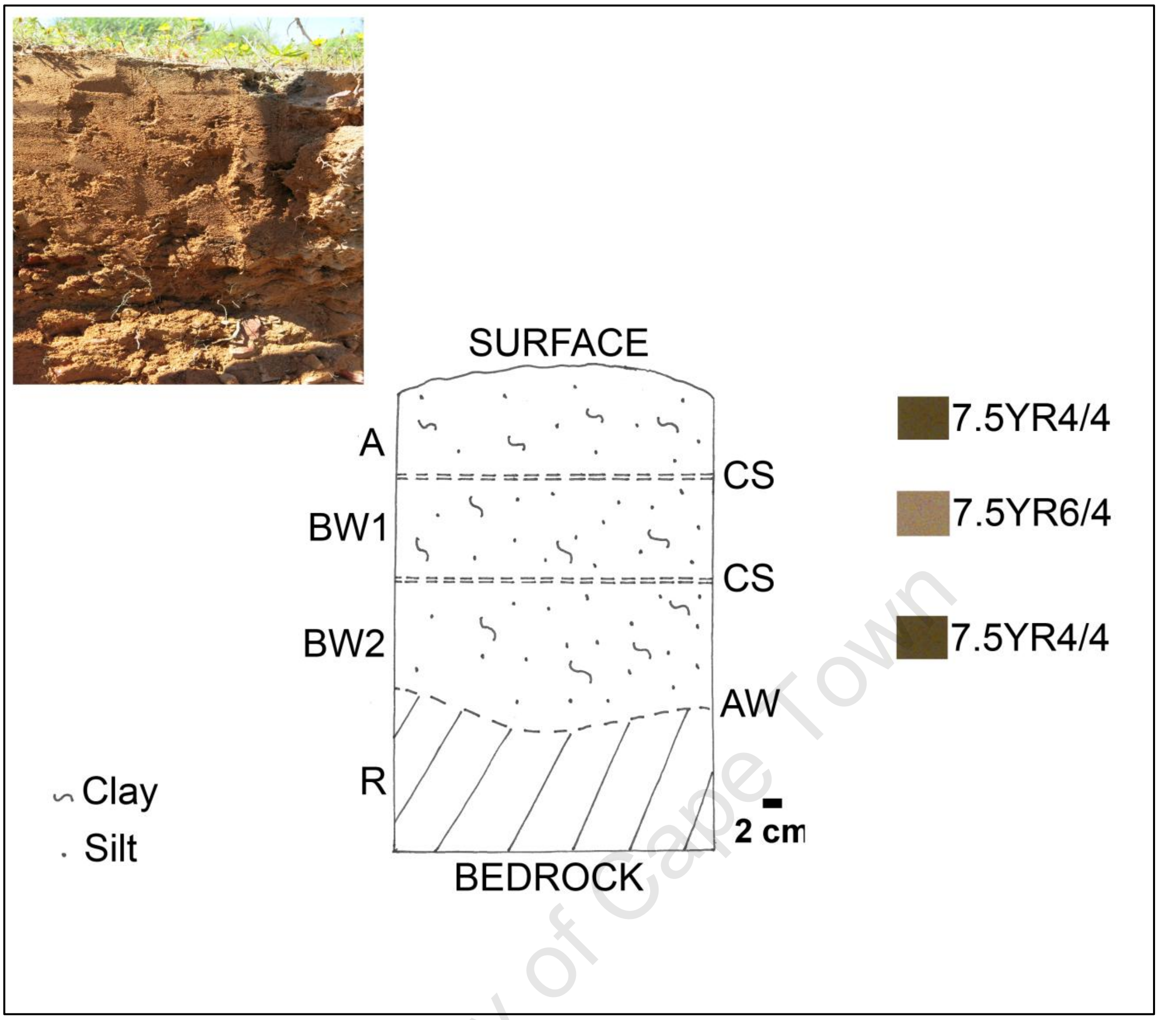

Fig.8. Diagram of depth profile of interheuweltjie zone I1 (pictured top left). The scale bar is calibrated to depth only. The number of silt and clay particles are drawn proportional to the texture of the horizon. Open white space in eahc horizon indicates sand particles. Munsell soil colour plates (on the right) indicate the approximate colour of each of the horizons. Horizon layers and transitional boundaries have been designated as perSchoeneberger et al. (2002). Here one can see that there is no change in texture down the profile. The texture remains a sandy loam with no rocks present. The colour is a continously dark yellow-red hue all the way down the profile.

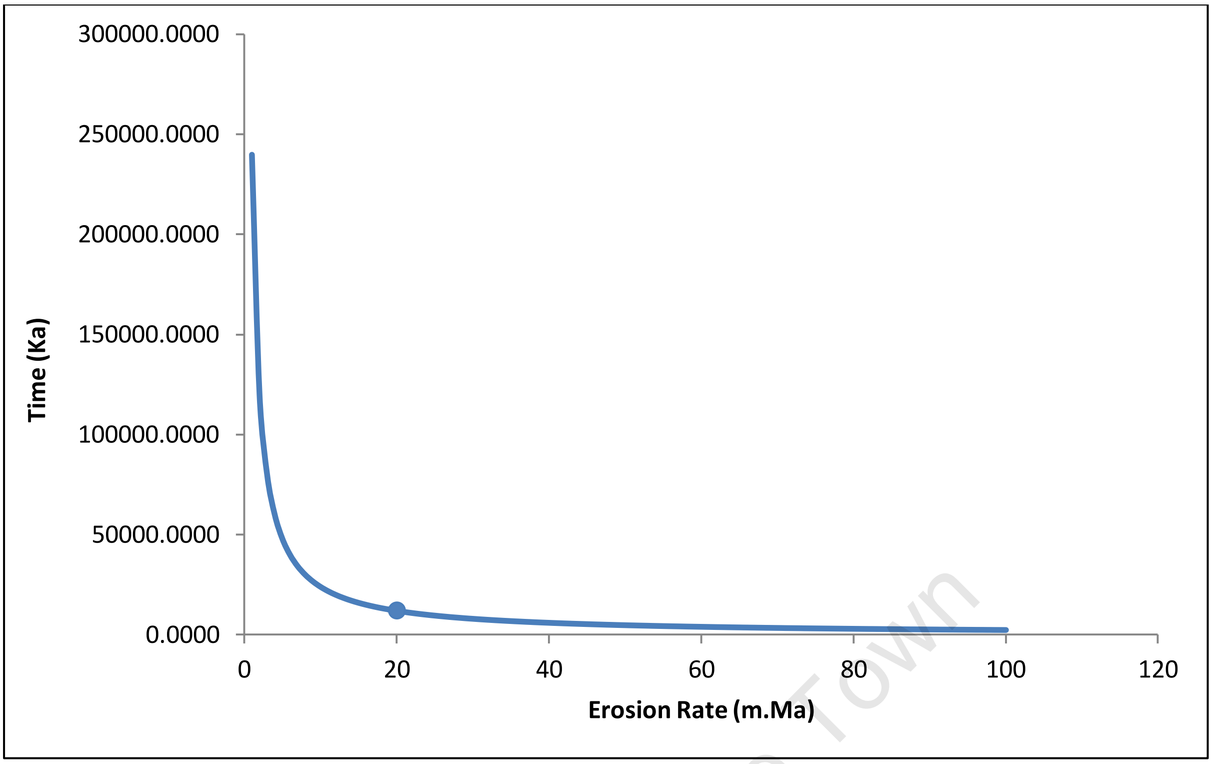

Fig.9. Time taken to erode 384 $kg.m^{-2}$ of soil at different erosion rates. The curve was plotted from erosion rate data presented by Von Blanckenburg (2005). An erosion rate of 20 meters per million years would take approximately 11000 years to erode the heuweltjie landscape down to its present state (indicated by the marker on the line).

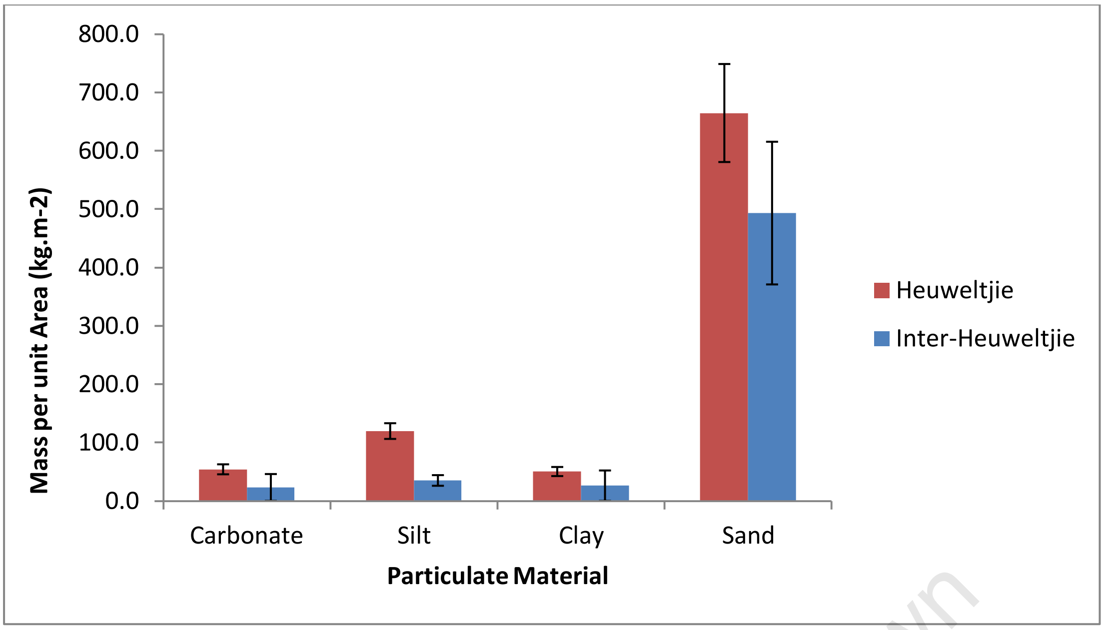

Fig.10. Texture and carbonates of heuweltjie and inter-heuweltjie zones. Means are shown here with standard error. The heuweltjies seem to have greater amounts of soils of all textures as well as carbonate. However, only the amount of silt between heuweltjie and inter-heuweltjie zones was significant as per a non-parametric Mann Whitney U-test (U (19) = 2, Z = 1.98, p = 0.019).

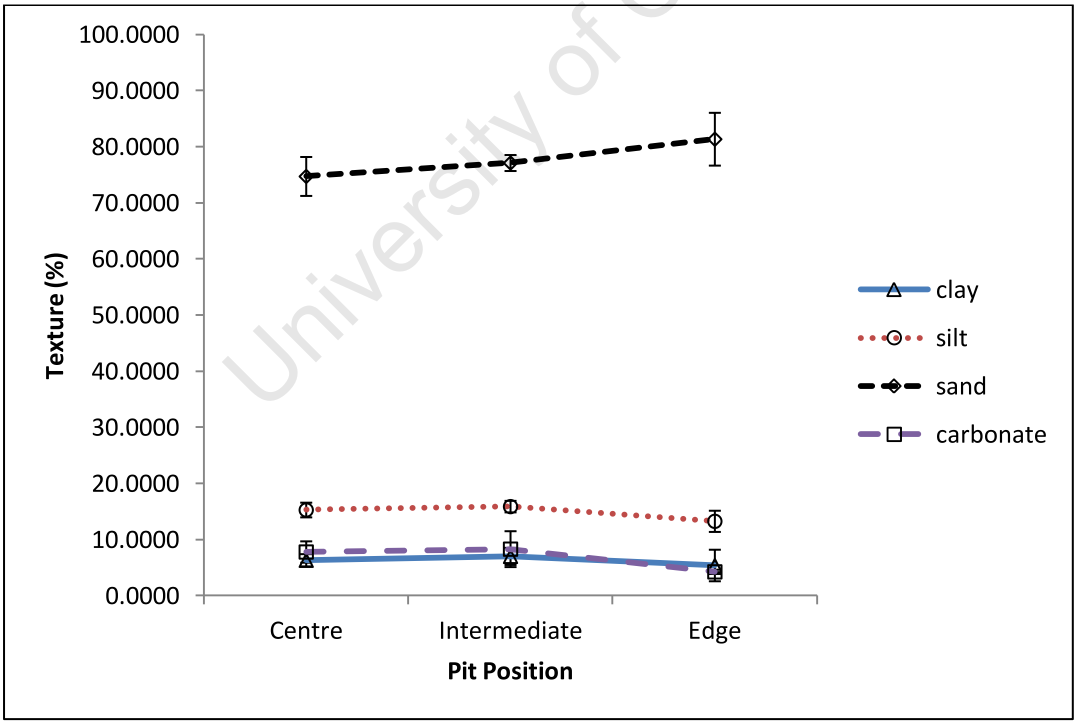

Fig.11. Average soil texture and carbonates (Means ± SE) across all heuweltjies moving from the centre to the edge. There is no difference in the amount of silt, clay and carbonate as one moves from the centre to the edge of the heuweltjie. This was confirmed by a non-

parametric kruskall-wallis test for differences between centre, intermediate and edge groups.

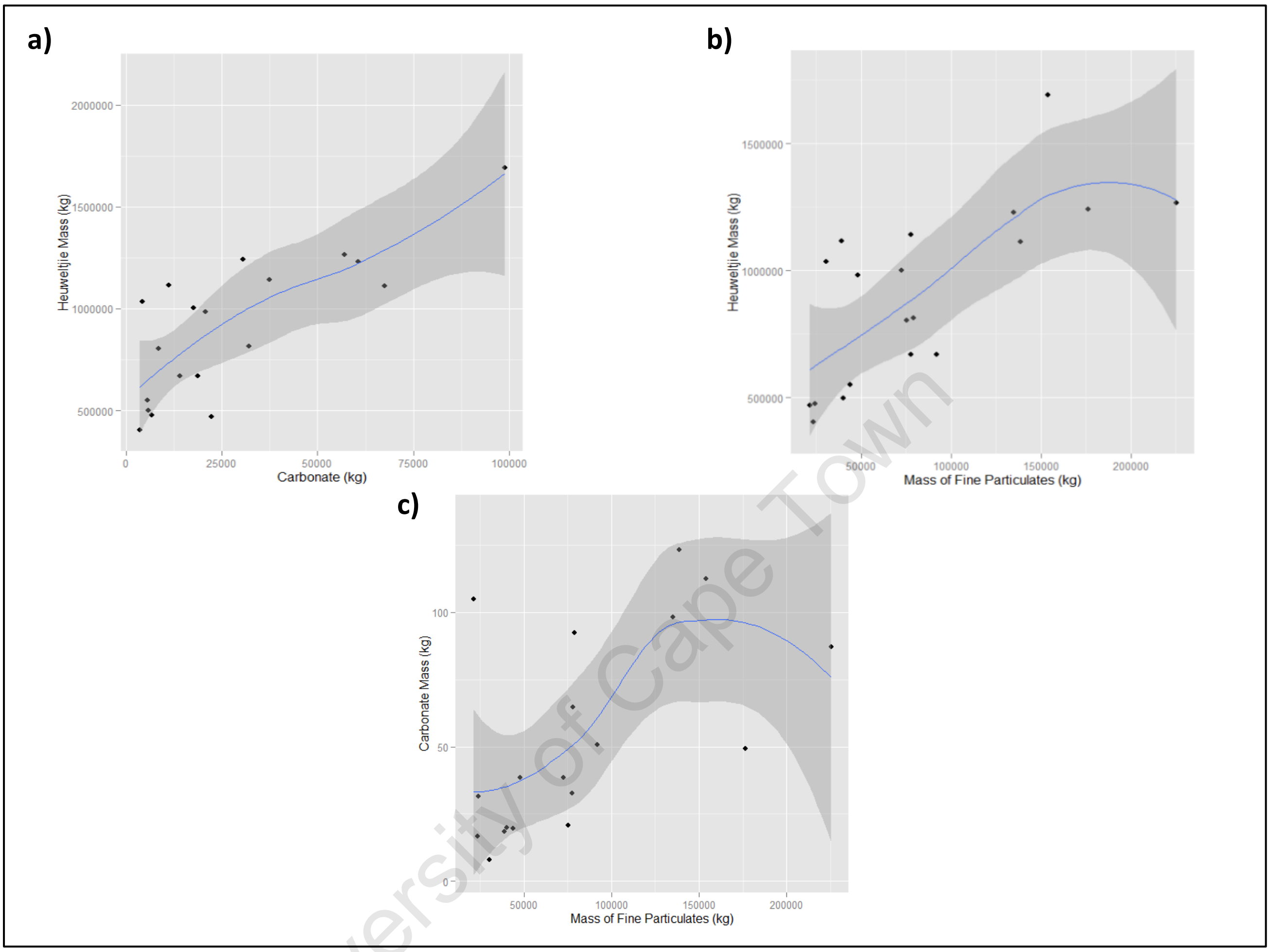

Fig.12. Scatterplots of carbonate mass (a), fine particulates (the sum of silt and clay mass) (b) and carbonate mass against fine particulate mass (c). All the plots have been fitted with a non-parametric local regression. The dark bands indicate 95% confidence bands for these regression lines. The regression line for all plots was fitted with a span of 1. All plots show a general linear trend, including that of carbonates against fine particulates (c). The apparent decrease in carbonates at high amounts of fine particulates is accompanied by high uncertainty. Therefore the overall trend is generally linear. The data for heuweltjie mass against carbonates and against fine particulates is skewed to the right, thus the confidence of estimates is more constrained at lower values of carbonates and fine particulates, with uncertainty increasing at higher estimates. The mass of fine particulates is of higher magnitude than the mass of carbonates. The carbonates have a minimum at about 3000kg (a) while the minimum of fine particulates is at 25000kg (b).

Table 1: Means ± SE of texture and carbonate data. There seem to be substantial differences in texture and carbonates between heuweltjie and inter-heuweltjie zones. The standard error of clay and carbonate for the inter-heuweltjies is equal to the mean. The sample size of the inter-heuweltjies is only two, for clay and carbonate one of the two samples had zero clay and carbonate respectively, resulting in the standard error being equal to the mean. The mean slope value of each heuweltjie and inter-heuweltjie area was calculated from all the elevation points (obtained from a DEM), within a demarcated heuweltjie or inter-heuweltjie area superimposed as a vector layer upon the DEM. The difference in slope between heuweltjie and inter-heuweltjie slope was slightly significant as per Student's t-test for dependent samples ($t=2.24$, $DF=20$, $p=0.04$).

	Clay ($kg.m^{-2}$)	Sand ($kg.m^{-2}$)	Silt ($kg.m^{-2}$)	Carbonate ($kg.m^{-2}$)	Mean Elevation (m)	Mean Area (m^2)	Overall Mean Slope (°)
Heuweltjie	50.28±7.79	664.76±84	119.63±13.44	54.07±8.57	1.23±0.02	465.42±41.30	6 ± 1.4
Inter-Heuweltjie	26.04±26.04	493.24±122.29	34.98±9.13	22.98±22.98	na	na	5 ± 1.05

(4) Discussion

4.1 *Heuweltjie and Inter-heuweltjie Morphology*

The morphology of heuweltjies and inter-heuweltjies provide clear evidence in support of the argument that depositional and erosion processes could have formed heuweltjies, as posited by the vegetation-patch-erosion hypothesis mentioned above. Both heuweltjies and inter-heuweltjies consist mostly of a sandy loam, which has more sand than clay and silt. Sandy soils are expected in the Clanwilliam area since the underlying geology is sandstone (Soderberg and Compton 2007). However, heuweltjies have more clay and silt ("fines") than inter-heuweltjies. This is apparent from the greater depth to bedrock of the heuweltjies and the fact that they contain horizons with sandy-clay textures, while the inter-heuweltjies do not. Although this difference in texture was found to be statistically non-significant, other studies such as Cramer et al. (2012) and Kunz et al. (2012), which also investigated heuweltjie and inter-heuweltjie texture; found that there was a significant difference in texture, with heuweltjies containing more silt.

Silt forms a large proportion of wind-blown dust (Paton et al. 1995). Thus, together with the qualitative evidence presented here, these observations provide support for the argument that heuweltjie formation is a result of accretion of fines with dust.

The presence of more fines in heuweltjies as opposed to inter-heuweltjies suggests that there must have been some mechanism which retained these particles. The mechanism, as per the VPE hypothesis (Cramer et al. 2012), is that plants retained dust brought in by wind, while their roots helped retain this soil in spite of erosion of the landscape. The non-significant difference in clay content between heuweltjies and inter-heuweltjies is consistent with Cramer et al. (2012) and could serve as further evidence that erosion has indeed played a role in forming these heuweltjies. Clay and silt delivered by wind would have been present across the entire landscape (Soderberg and Compton 2007). Erosion would then act on this landscape, eroding the inter-heuweltjies while vegetation patches retained the fines, forming heuweltjies over time. Therefore, the observation by Moore and Picker (1991) that the shape of heuweltjies is not consistent with downwind deposition could just be due to the deposited material having been eroded away over long (geological) time scales and washed into the river via rainwash (Paton et al. 1995).

The colour of the heuweltjie and inter-heuweltjie horizons also tells a similar story. Soil colour is determined by the type and amounts of iron oxide and organic matter present (Peverill et al. 1999). Thus the yellow-red hue of the heuweltjie and inter-heuweltjies indicate substantial amounts of iron under oxidizing conditions, suggesting a well-drained soil (Peverill et al. 1999). This is expected given the sandy texture of the soils. This along with the fact that heuweltjie horizons show evidence of greater root density and thickness, suggests that heuweltjies could have supported the plant patches that would have been instrumental in dust retention. However, these lightly coloured horizons also contain carbonates in the form of calcretes. These calcretes have been dated from 4000 to 30000 years (Moore and Picker 1991, Potts et al. 2009). Therefore, as mentioned by Cramer et al. (2012), the vegetation on these heuweltjies could have changed over time with the accumulation of carbonates limiting rooting depths. However, the point is that the soil colour could be indicative of conditions once suitable for ample plant growth.

Another major hypothesis for heuweltjie genesis is attributed to the termite *Microhodotermes viator* (Moore and Picker 1991, Picker et al. 2007). The fact that the mounds built by these termites are of similar spacing as that of heuweltjies, and the fact that they build quite large mounds are two of the main reasons this hypothesis has taken hold (Cramer et al. 2012). However, there were no termites present at the study site. Evidence against this and in favour of the vegetation-patch-erosion hypothesis is that the largest of these termite mounds recorded are only one tenth ($27m^3$) of the volume of heuweltjies (Cramer et al. 2012). This is in accordance with the findings of this study, where the average volume of heuweltjies was 572 m^3, which is twenty times larger than some of the largest M.*viator* mounds (as per Cramer et al. 2012).

The spacing of the heuweltjies can also be explained by vegetation patches instead of termites. The plants that first establish themselves in patches create favourable conditions within the patch and for a short distance beyond the patch, allowing for the recruitment of other plant species up to a certain distance from the patch (as resources become limiting), in effect creating a self-reliant "island of fertility" (Lejeune et al. 1999, Rietkerk and Van de Koppel 2007; Cramer et al. 2012). Thus because these patches are resource limited (due to the arid environment), each patch is restricted to a certain amount of space, with the resultant effect being the overdispersed spacing as seen with heuweltjies (Rietkerk and Van de Koppel 2007).

4.2 *Dust Deposition and Carbonates in the Formation of Heuweltjies*

So far it has been established that the heuweltjies have more fines than inter-heuweltjies. Thus one could postulate that the fines in heuweltjies are from dust deposition.

Thus to evaluate the potential influence of fines on heuweltjie formation, the relationship between dust mass (the sum of the mass of silt and clay) and heuweltjie mass was examined. There was a strong positive correlation between heuweltjie mass and fine particulate mass ("dust"). A local non-parametric regression indicated that the relationship between dust and heuweltjie mass can be explained with a linear trend with similar confidence throughout the range of the data. The advantage of a local non-parametric regression is that it highlights the structure of the data, essentially allowing the data to "speak" for itself, in that the orientation and slope of each segment of the fitted curve is dependent on the points nearest to that segment (Jacoby 2000). Thus one could safely say that this data could have come from a population in which the amount of dust is directly proportional to the heuweltjie mass (and thus also size). The mass of carbonates was also significantly positively correlated with heuweltjie mass, and also showed a linear trend. However, after about 65000kg of carbonate the uncertainty of estimates increases greatly. Most of the carbonate data was also only in the range between 3000kg to 35000kg. This indicates that even though heuweltjie mass increases, the amount of increase of carbonates is not of the same magnitude. The general linear trend suggests that a very large heuweltjie (with large volume and mass) could actually only have small amounts of carbonate. Thus heuweltjie mass is only explained by carbonate mass up to a certain mass of carbonate and there is a minimum heuweltjie mass that needs to be achieved before carbonates are produced. This could suggest that after a threshold mass heuweltjies start to lose carbonate.

This is supported by the fact that the amount of dust is highly positively correlated with the amount of carbonate; as well as the fact that the linear trend between carbonate and dust reaches a threshold point at about 150000kg of dust, after which the amount of carbonate declines. This in turn suggests that carbonates could have a more secondary influence on heuweltjie formation and also that dust is instrumental in the formation of carbonates as well as in the formation of the heuweltjies themselves.

Mechanism of Carbonate Formation

The carbonate present in the heuweltjie soils is in the form of calcite (calcium carbonate). The calcium has been proposed to be of marine aerosol origin (Midgley et al. 2012).

Carbonates are a product of carbonate-bicarbonate equilibria (Lal and Kimble 2000) as per the equilibrium equations below:

$CO_2 + H_2O$

$\uparrow\downarrow$

$H_2CO_3 + CaCO_3 \leftrightarrow Ca^{2+} + 2HCO_3^-$

Carbon dioxide reacts with water molecules to make carbonic acid. However, the partial pressure of carbon dioxide determines its solubility in solution (Lal and Kimble 2000). The partial pressure of the carbon dioxide is proportional to the concentration of carbon dioxide (Lal and Kimble 2000). Therefore, in the upper layers of heuweltjies, where the dark colour and high density of roots indicate higher levels of respiration, there could thus be more carbon dioxide (generated from decomposition and root respiration). Therefore, the high concentrations of carbon dioxide would improve the solubility of the carbon dioxide in carbonic acid causing it to dissolve into bicarbonate ions. These ions are then transported deeper into the heuweltjie by percolation (Lal and Kimble. 2000). The decrease in carbon dioxide concentration then causes the precipitation of carbonate at depth (Lal and Kimble 2000). The calcium input into the system causes the precipitation of carbonate and calcium in the form of calcite. Therefore, the formation of carbonates require high pressures (high concentrations) of carbon dioxide (to improve its solubility in water), followed by lower pressures to cause the precipitation of carbonates out of solution.

The texture of heuweltjies although finer than the inter-heuweltjies, still provide good aeration because they are mostly sandy loam soils. This would mean that there should be enough carbon dioxide present at high enough concentration to ensure its solubility in solution. This would allow for bicarbonates to be percolated to greater depths. However, the significantly greater amounts of silt and the greater aggregation of heuweltjie soils (indicated by the blocky structure of the soils, Appendix A – Table 5) could cause conditions reducing the carbon dioxide partial pressure. This in turn would cause the precipitation of carbonates at those depths.

This mechanism could explain the strong trend found between fines and carbonates. It also explains why there seems to be a limit where only heuweltjies of certain mass (and therefore size) can accommodate the formation of carbonates.

Heuweltjies that are too small have too little dust matter to effectively lower the pressure of the carbon dioxide in bicarbonate to allow it to precipitate out as carbonate. This is consistent with Moore and Picker (1991) indicating that only heuweltjies greater than five meters in diameter formed calcrete.

4.3 *Within-Heuweltjie Texture*

The lack of any difference in texture from the centre to the edge of the heuweltjie suggests that they did not form radially from the centre. Instead the internal stratigraphy and finer textures of heuweltjies suggest that they formed by dust deposition, as per the VPE hypothesis. Therefore, if one were to consider the evolutionary sequence of heuweltjies, it would follow a pattern in which erosion and dust deposition build up the heuweltjie and cause the formation of calcrete, which then increases while also increasing the size of the heuweltjie until it reaches a critical mass and stops producing calcrete; at which point the lack of adequate belowground biomass together with erosion but tempered by dust deposition, would eventually lead to the decline of heuweltjies. This proposed evolutionary sequence of heuweltjies has been illustrated below:

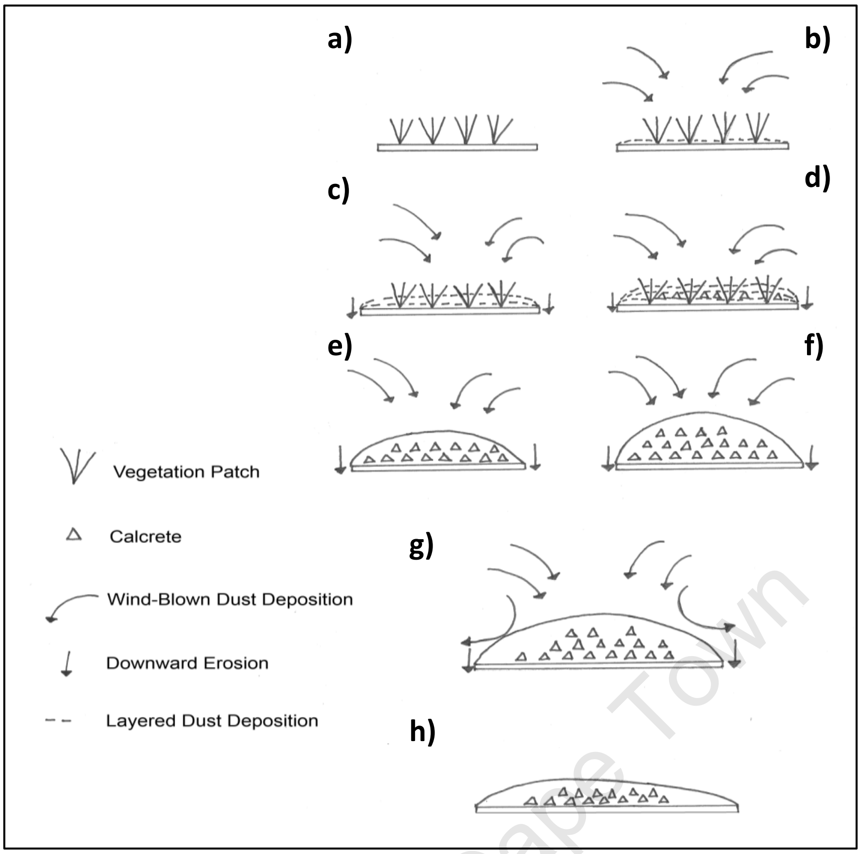

Fig.13. Heuweltjie Evolutionary Sequence. (a) Vegetation patches occur on the landscape. (b) These vegetation patches retain wind-blown dust. (c) The dust accretes in layers while erosion of the landscape takes place. (d) Once a certain amount of dust has accreted the heuweltjie starts producing calcrete. (e) The calcrete continues to form in layers while the processes of accretion and erosion take place as well. (f) The heuweltjie reaches a critical size and stops producing calcrete. (g-h) The lack of deep rooting plants (inhibited by calcrete formation, Cramer et al. 2012) together with erosion (both from wind and rainwash) would erode the heuweltjie away.

4.4 *Erosion and the Heuweltjie Landscape*

One of the aims of this investigation was to determine how long erosion would have taken to form the heuweltjies (acting as a sole agent of formation). If heuweltjies are indeed the remains of ancient vegetation patches due to erosion (as per the VPE hypothesis); then by determining the erosion rate as well as the quantity of soil that would have had to erode off the landscape, one would be able to estimate the time taken to remove that quantity of soil by erosion. The estimated time for erosion to form the Clanwilliam heuweltjies was 11000 years. This estimate was calculated using an erosion rate of twenty meters per million years based on data presented by Von Blanckenburg (2005).

This estimated period of erosion of 11000 years, is more than the 4000 year heuweltjie age calculated by Moore and Picker (1991). However, it is less than the 21000 year old calcrete measured by Midgley et al. (2001). This suggests that erosion alone is not responsible for heuweltjie formation, because calcrete age cannot be older than the time it takes to carve out the heuweltjies by erosion. This is supported by the fact that there was no difference in slope between heuweltjies and inter-heuweltjies. Furthermore, the lack of rocks in heuweltjies and their abundance in inter-heuweltjies proves that erosion has less of an influence on heuweltjie formation than dust deposition. Hence the rate of dust deposition is much faster than the rate of erosion. Therefore, dust could be the primary mechanism building heuweltjies.

4.5 *Conclusions*

Further evidence supporting the vegetation-patch-erosion hypothesis has been presented. Dust deposition could have contributed to the formation of heuweltjies. Heuweltjies do not form radially from the centre but by layering of dust particulates as per the vegetation-patch-erosion hypothesis. This deposition then set up the conditions for carbonates to accumulate in heuweltjies (in the form of calcite), turning them into carbonate "factories". However, the production of calcite seems to decline after a critical mass. This suggests that larger Clanwilliam heuweltjies might have ceased calcite production and are in a state of decline.

Erosion could have aided in the formation of heuweltjies. Erosion alone would have taken 11000 years to form the heuweltjies. However, this is not likely as some calcrete dates from within heuweltjies are older than 11000 years. Thus it is more likely that dust deposition is the primary contributor to heuweltjie formation. Therefore, although VPE invokes erosion as one of its mechanisms of heuweltjie formation, it seems that Clanwilliam heuweltjies have been formed more by the action of dust deposition than erosion.

4.6 *Shortcomings and Further Recommendations*

A better understanding of the evolution of heuweltjies could be attained by examining heuweltjie soils on a regional basis, as this will highlight the importance of factors such as geology on the formation of heuweltjies.

Acknowledgements

I would like to thank Associate Professor Julian Smit of the department of Geomatics, UCT for constructing the digital elevation model of the study site. Also, the staff of the UCT GIS lab for their assistance with GIS issues. Finally, I would like to thank Dr. Lesego Khomo for his unfaltering support, encouragement and patience.

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APPENDIX A

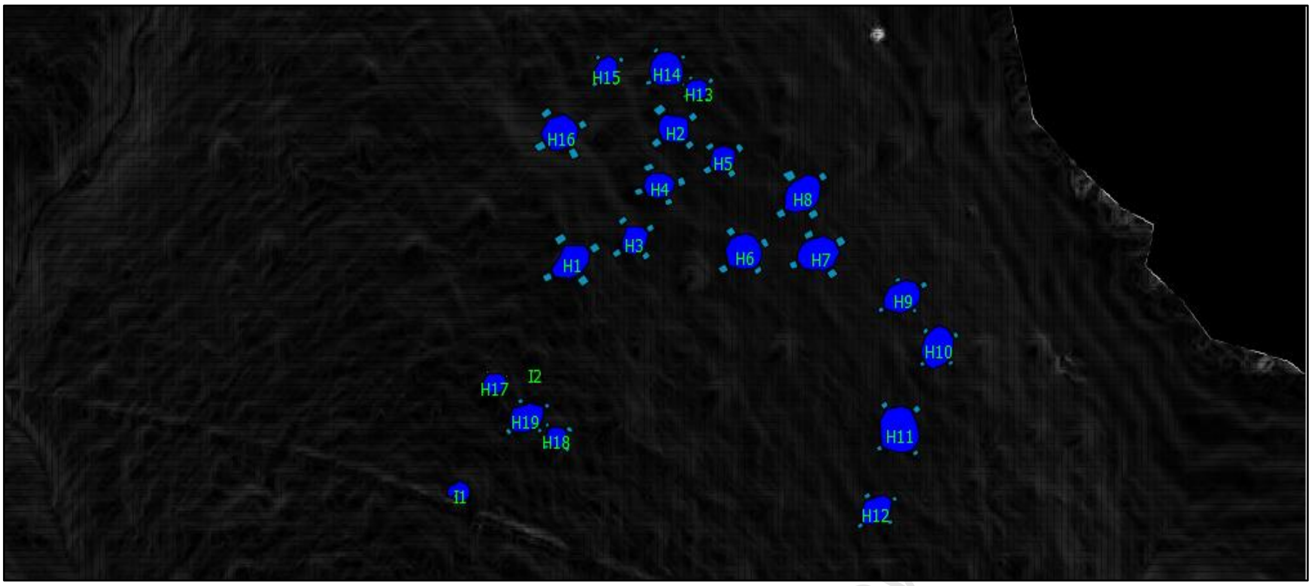

Fig.1. Heuweltjie slope and inter-slope demarcated areas on the slope map. The heuweltjie area vector layer is marked with the heuweltjie number. The area demarcated for I1 is erroneous as I1 is not a heuweltjie but one of the inter-heuweltjie zones sampled. The four blocks surrounding each heuweltjie area indicate the inter-slope vector layer.

Table 1
Comparison of denudation monitors at different time scales

Setting	Authors	Denudation rates [mm ky^{-1}][a]		
		River load gauging 10–100 year	Cosmogenics 10–100 ky	Fission track 1–10 My
Namibian Escarpment, Southern Africa	[22]	–	5–15	3–15
Idaho Mountains, Western USA	[10]	1–12	3–100	50–110
Loire, Allier, Regen, Middle Europe	[11]	2–20	30–60[b]	–
Tropical Highlands Sri Lanka	[26,31]	50–800	5–11[c]	4–15[d]
Arroyo Chavez Basin, New Mexico, USA	[27]	44–380 (Slopes) 1200 (Alluvial Valley Floor)	100	
Yael Nahal Desert Israel	[12]	30	14–28	–
Appalachian Mountains, Eastern USA	[19]	5–50	22–37	10–60
Rio Chagres Basin, Panama	[14]	100	100	

[a] Sediment yields [t km^{-2} year^{-1}] were converted into denudation rates [mm ky^{-1}] using a density of 2.7 t m^{-3}.
[b] Recalculated in [41].
[c] Unperturbed catchments only.
[d] Fission track data inferred by comparison from South India and Madagascar.

Fig.2. Extracted table from Von Blanckenburg (2005). The rates used to determine time to erode 684kg.m^{-2} of soil are the ones highlighted by the green box. A denudation rate of mm.ky^{-1} (millimetres per thousand years) is equivalent to m.Ma^{-1} (meters per million years).

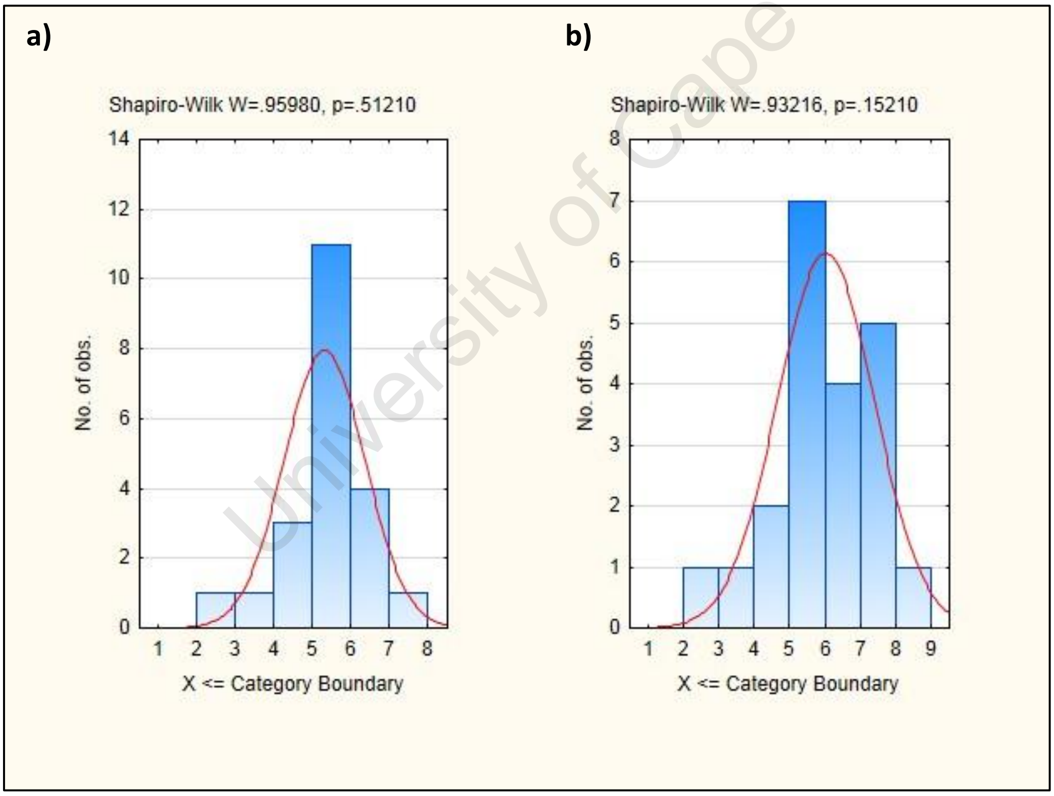

Fig.3. Histograms of the slope of interheuweltjie zones (a) and heuweltjies (b) with an assessment of normality using the Shapiro-Wilk's test. The null hypothesis of the Shapiro-Wilk's test is that the data is normally distributed. Therefore because p>0.05, the null hypothesis is not rejected and one can assume that the data was sampled from a normal distribution.

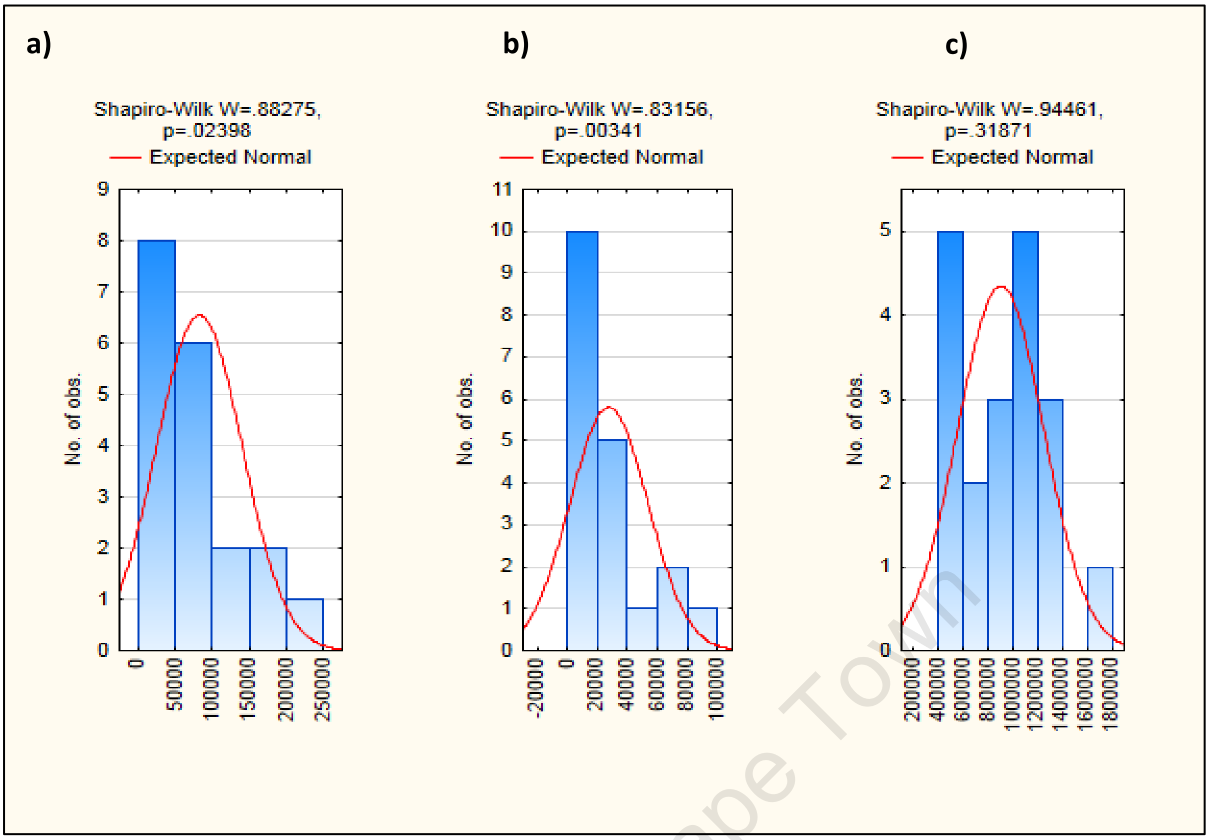

Fig.4. Histograms of fine particulate mass (a) carbonate mass (b) and heuweltjie mass (c) with an assessment of normality using the Shapiro-Wilk's test. Here the null hypothesis that the data was sampled from a normal distribution is rejected for both the carbonate and fine particulate data ($p<0.05$) and is accepted for the heuweltjie mass data ($p>0.05$). The carbonate and particulate data are heavily skewed to the right.

Table 1: The average mass of each heuweltjie including the bulk density and thickness of each horizon. The average mass was calculated by taking the sum of the product of the bulk density and horizon length across all horizons per heuweltjie/inter-heuweltjie; na = no data available.

Heuweltjie (H)/Inter-Heuweltjie (I)	Horizon	Bulk Density ($g.cm^{-3}$)	Horizon Length (cm)	Average Mass ($kg.m^{-2}$)
H1	AB	1.3	7	1373.45
	2Btk1	1.0	9	
	3Bk1	1.3	15	
	3Bk2	1.0	10	
	3Bk3	1.9	30	
	3Bk4	1.7	19	
H2	AB	1.3	7	826.23
	2Bt1	1.2	8	
	3Bt2	0.9	13	
	4Bt3	1.1	13	
	5Btk1	0.9	13	
	6Bw1	1.2	21	
	6Bw2	na	15	
H3	A	1.6	10	1358.73
	BA	1.6	11	
	2Btk1	1.2	15	
	3Bk1	3.0	22	
	3Bk2	1.9	10	

Heuweltjie (H)/Inter-Heuweltjie (I)	Horizon	Bulk Density ($g.cm^{-3}$)	Horizon Length (cm)	Average Mass ($kg.m^{-2}$)
H4	A	1.4	8	1067.68
	Bt1	1.3	8	
	2Btk1	1.3	8	
	2Btk2	1.4	25	
	2Btk3	1.4	18	
	2Btk4	1.4	10	
H5	A	1.5	10	613.40
	Btk1	1.5	13	
	Btk2	1.6	12	
	Btk3	1.2	7	
H6	A	1.4	9	1441.80
	BK1	1.5	11	
	BK2	1.3	15	
	2BKC	2.1	45	
H7	AB	1.4	13	2014.75
	Btk1	1.4	17	
	Btk2	1.3	13	
	Btk3	1.7	19	
	Btk4	1.8	31	
	Btk4	1.8	29	
H8	A	1.5	12	692.14
	Btk1	1.3	12	
	Btk2	1.5	10	
	BC	1.9	11	
H9	na	1.6	5	400.00
	na	1.6	20	
H10	na	1.6	5	320.00
	na	1.6	15	
H11	na	1.6	5	1536.00
	na	1.6	91	
H12	na	1.6	5	640.00
	na	1.6	35	
H13	na	1.6	5	320.00
	na	1.6	15	

Heuweltjie (H)/Inter-Heuweltjie (I)	Horizon	Bulk Density (g.cm^{-3})	Horizon Length (cm)	Average Mass (kg.m^{-2})
H14	na	1.6	5	320.00
	na	1.6	15	
H15	na	1.6	5	640.00
	na	1.6	35	
H16	na	1.6	5	640.00
	na	1.6	35	
H17	na	1.6	5	736.00
	na	1.6	41	
H18	na	1.6	5	896.00
	na	1.6	51	
H19	na	1.6	5	1600.00
	na	1.6	95	
I1	A	1.3	8	356.34
	Bw1	0.9	11	
	Bw2	1.1	13	
	RC	na	na	
I2	A	1.5	10	711.73
	AB	1.4	10	
	Rocky	2.8	15	

Table 2: Mass of textures and carbonates as well as total heuweltjie mass and dust mass. The mass of textures and carbonates of each heuweltjie was converted to kilograms by multiplying by the heuweltjie area. Dust mass is the sum of silt and clay mass; na = no data available.

Heuweltjie (H)/ Inter-Heuweltjie (I)	Area (m^2)	Total Heuweltjie Mass (kg)	Carbonates ($kg.m^{-2}$)	Carbonates (kg)	Silt ($kg.m^{-2}$)	Clay ($kg.m^{-2}$)	Dust Mass ($kg.m^{-2}$)	Dust Mass (kg)	Sand ($kg.m^{-2}$)
H1	547.00	1111800.56	123.18	67379.83	172.74	81.03	253.76	138808.23	780.85
H2	429.00	668156.78	32.71	14034.27	119.25	61.58	180.82	77573.28	453.05
H3	347.00	813214.42	92.39	32060.25	157.59	69.89	227.48	78933.95	959.64
H4	369.00	669281.93	50.72	18716.99	178.73	71.06	249.79	92171.81	561.04
H5	301.00	498650.14	19.93	5999.52	75.60	57.98	133.58	40207.85	305.50
H6	616.00	1228059.71	98.20	60493.72	160.04	59.20	219.24	135054.04	879.54
H7	656.00	1266254.74	87.02	57082.17	222.33	121.31	343.64	225425.49	1051.06
H8	618.00	1240820.75	49.32	30480.68	235.52	50.07	285.59	176494.53	926.12
H9	539.00	983136.00	38.54	20771.44	74.31	14.77	89.08	48012.32	310.92
H10	612.00	1116288.00	18.36	11235.20	53.12	10.56	63.68	38975.04	256.32
H11	880.00	1689600.00	112.27	98800.92	144.01	31.19	175.20	154173.27	1360.80
H12	405.00	803520.00	20.90	8462.61	120.48	65.58	186.06	75354.80	453.94
H13	214.00	404032.00	16.69	3571.67	57.98	51.80	109.78	23492.68	210.22
H14	553.00	1035216.00	7.85	4340.54	40.78	14.25	55.03	30431.22	264.97
H15	291.00	549408.00	19.63	5710.91	133.18	16.90	150.08	43673.40	489.92
H16	580.00	1141440.00	64.61	37476.26	119.45	14.75	134.20	77837.45	505.80
H17	217.00	475664.00	31.53	6843.04	94.80	16.93	111.73	24245.07	624.27
H18	212.00	468096.00	104.92	22242.46	74.32	26.14	100.46	21297.43	795.54
H19	457.00	1001744.00	38.62	17650.25	38.74	120.25	158.99	72660.27	1441.01
I1	na	na	0.00	na	25.85	0.00	na	na	370.95
I2	na	na	45.96	na	44.12	52.08	na	na	615.53

Table 3: Slope values of heuweltjie and inter-heuweltjie zones. The mean slope value of each heuweltjie and inter-heuweltjie area was calculated from all the elevation points (obtained from a DEM). The difference in slope between heuweltjie and inter-heuweltjie slope was slightly significant as per Student's t-test for dependent samples (t=2.24, DF=20, p=0.04); na = no data available.

Heuweltjie/Inter heuweltjie	Mean Slope of Heuweltjie Area (°)	Overall Mean Slope of Heuweltjie Area (°)	Mean Slope of Interheuweltjie Zones (°)	Overall Mean Slope of Interheuweltjie Zone (°)
H1	7	6 ± 1.4	4	5 ± 1.05
H2	6		4	
H3	7		5	
H4	6		6	
H5	6		5	
H6	6		6	
H7	7		6	
H8	7		5	
H9	7		5	
H10	8		5	
H11	6		6	
H12	6		6	
H13	4		6	
H14	6		7	
H15	7		4	
H16	8		6	
H17	6		5	
H18	5		5	
H19	5		5	
I1	na		7	
I2	na		2	

Table 4: Elevation and Areas of heuweltjies. Elevation was calculated from a digital elevation model (DEM) in QGIS. Area was calculated from an aerial photograph in QGIS. Mean±SE is also reported below.

Heuweltjie	Elevation (m)	Mean Elevation (m)	Area (m^2)	Mean Area (m^2)
H1	1.31	1.23±0.02	547	465.42±41.30
H2	1.2		429	
H3	1.27		347	
H4	1.24		369	
H5	1.19		301	
H6	1.22		616	
H7	1.17		656	
H8	1.16		618	
H9	1.14		539	
H10	1.14		612	
H11	1.2		880	
H12	1.24		405	
H13	1.18		214	
H14	1.17		553	
H15	1.18		291	
H16	1.23		580	
H17	1.37		217	
H18	1.38		212	
H19	1.37		457	

APPENDIX B

Qualitative data collected from each soil pit of each heuweltjie and inter-heuweltjie. The root data gives an indication of the density of the roots in a particular horizon as well as the thickness of the roots (fine, medium etc.). The structure of the soil was either sub-angular blocky (sbk) or angular blocky (abk), the size of each structural unit was indicated as either fine (f), very fine (vf), medium (m), coarse (co) or single grain (sg), with a number prefix indicating the strength of units of similar size.

Heuweltjie H1

Pit Position	UTM Easting(m)	UTM Northing(m)	Horizon	Boundary Transition	Texture	Plasticity	Structure	Roots	Gravel (%)	Effervescence HCl	Munsell Moist Colour
Centre	300170	6434222	AB	Abrupt Smooth	Sandy Loam	Non-Plastic	1-2vf,f,abk	Common,Very Fine	0	None	10YR 4/2
			2Btk1	Very Abrupt Wavy	Sandy Clay Loam	Slightly Plastic	2vf,f,abk	Common,Very Fine	0	Very Slight	10YR 3/3
			3Bk1	Clear Smooth	Sandy	Non-Plastic	2m,f,abk	Few,Very Fine	0	Slight	7.5YR 5/6
			3Bk2	Abrupt Smooth	Sandy	Non-Plastic	2m,f,abk	Common,Very Fine,Fine	0	Strong	7.5YR 5/6
			3Bk3	Clear Wavy	Sandy	Non-Plastic	M	-	0	Violent	7.5YR 5/6
			3Bk4	-	Sandy	Non-Plastic	M	-	0	Violent	7.5YR 4/4
Intermediate			A	Abrupt Wavy	Sandy Loam	Slightly Plastic	1vf,f,sbk	Common,Very Fine	0	Very Slight	10YR3/4
			Bk1	Abrupt Smooth	Sandy Loam	Slightly Plastic	1-2m,co,abk	Few,Very Fine	0	Strong	7.5YR4/4
			Bk2	Very Abrupt Smooth	Loamy Sand	Non-Plastic	1vf,f,sbk	Few,Fine,Medium	0	Strong	7.5YR4/4
			2Bk3	-	Sandy	Non-Plastic	3f,sbk	None	0	Very Slight	7.5YR4/5
Edge			A	Clear Smooth	Sandy Loam	Non-Plastic	1f,m,sbk	Many, Very Fine, Fine	0	None	10YR3/4
			Bw1	Clear Smooth	Sandy Loam	Non-Plastic	1m,abk	Common,Very Fine	0	None	10YR3/4
			Bw2	Gradual Smooth	Sandy Loam	Moderately Plastic	1f,vf,sbk	Many, Very Fine,Medium	0	Slight	7.5YR3/4
			Bw3	Very Abrupt Smooth	Sandy Loam	Moderately Plastic	1vf,f,abk	Few,Very Fine,Fine	0	Slight	7.5YR4/4
			2Bk1	-	Sandy	Moderately Plastic	sg,2mgr	Few,Very Fine	60	Violent	7.5YR4/6

Heuweltjie H2

Pit Position	UTM Easting(m)	UTM Northing(m)	Horizon	Boundary Transition	Texture	Plasticity	Structure	Roots	Gravel (%)	Effervescence HCl	Munsell Moist Colour
Centre	300255	6434323	AB	Very Abrupt Smooth	Sandy Clay Loam	Slightly Plastic	2f,sbk	Few,Very Fine,Fine	0	None	-
			2Bt1	Clear Smooth	Sandy Clay Loam	Slightly Plastic	3m,abk	Common,Very Fine,Fine	0	None	-
			3Bt2	Abrupt Smooth	Sandy Clay	Moderately Plastic	2f,abk	Few,Very Fine,Fine	0	Slight	-
			4Bt3	Abrupt Smooth	Sandy Clay	Moderately Plastic	2-3m,f,abk	Few,Very Fine	0	Slight	-
			5Btk1	Abrupt Smooth	Sandy Clay Loam	Slightly Plastic	2-3m,f,abk	Few,Very Fine	0	Strong	-
			6Bw1	Very Abrupt Smooth	Sandy Loam	Non-Plastic	M, 3co,m,abk	Few,Very Fine	0	Slight	-
			6Bw2	-	Sandy	Non-Plastic	3co,abk	-	60	None	-
Intermediate			A	Clear Smooth	Sandy Loam	Non-Plastic	1vf,sbk	Many, Very Fine,F	0	None	7.5YR4/4
			AB	Abrupt Smooth	Sandy Loam	Non-Plastic	1vf,f,m,sbk	Common,Very Fine,F	0	None	7.5YR4/6
			Bw1	Clear Smooth	Sandy Loam	Non-Plastic	1f,m,sbk	Few,Very Fine	0	None	7.5YR4/6
			Bt1	Abrupt Irregular	Sandy Clay Loam	Non-Plastic	1m,sbk	Few,Very Fine	0	None	7.5YR4/4
			Bw2	-	Sandy	Non-Plastic	3m,sbk	None	90	None	7.5YR5/8

Edge			A	Clear Smooth	Sandy Loam	Non-Plastic	1vf,f,sbk	Common,Very Fine,Fine	0	None	7.5YR5/6
			ABw	Clear Smooth	Sandy Loam	Non-Plastic	1vf,f,sbk	Few,Very Fine	0	None	7.5YR5/6
			Bw	-	Sandy Loam	Non-Plastic	1f,sbk	Few,Very Fine	90	None	7.5YR5/4

Heuweltjie H3

Pit Position	UTM Easting(m)	UTM Northing(m)	Horizon	Boundary Transition	Texture	Plasticity	Structure	Roots	Gravel (%)	Effervescence HCl	Munsell Moist Colour
Centre	300221	6434241	A	Clear Wavy	Sandy Loam	Non-Plastic	1vf,f,sbk	Common,Very Fine,Fine	0	None	10YR4/6
			BA	Abrubt Wavy	Sandy Loam	Non-Plastic	1vf,f,sbk	Few,Very Fine	0	None	10YR4/6
			2Btk1	Very Abrupt Smooth	Sandy Clay Loam	Slightly Plastic	1f,abk	Few,Very Fine	0	Very Slight	10YR4/4
			3Bk1	Abrupt Smooth	Sandy Loam	Non-Plastic	M	None	0	Strong/Very Slight	7.5YR4/6
			3Bk2	-	Loamy Sand	Non-Plastic	3m,co,abk	None	0	Very Slight	7.5YR5/6
Intermediate			A	Clear Smooth	Loamy Sand	Non-Plastic	1f,abk	Few,Very Fine	0	None	7.5YR5/4
			Bw1	Clear Smooth	Sandy Loam	Non-Plastic	1f,sbk	Few,Very Fine,f,m	0	None	7.5YR5/6
			Bw2	Clear Smooth	Sandy Loam/Loamy Sand	Non-Plastic	1f,sbk	Few,Very Fine,f,2m	0	None	7.5YR5/6
			Bw2	Very Abrupt Wavy	Sandy	Non-Plastic	1f,sbk	Few, Coarse,Few,Very Fine	0	None	7.5YR5/6
			2Bw3	-	Sandy	Non-Plastic	M	None	0	None	7.5YR4/6

Heuweltjie H4

Pit Position	UTM Easting(m)	UTM Northing(m)	Horizon	Boundary Transition	Texture	Plasticity	Structure	Roots	Gravel (%)	Effervescence HCl	Munsell Moist Colour
Centre	300243	6434279	A	Clear Smooth	Sandy Loam-Sandy Clay Loam	Slightly Plastic	1vf,f,m,sbk	Common,Very Fine, Fine	0	None	10YR3/6
			Bt1	Clear Smooth	Sandy Clay Loam	Slightly Plastic	1vf,f,m,sbk	Many, Very Fine,Fine	0	None	7.5YR3/4
			2Btk1	Abrupt Smooth	Sandy Clay Loam	Slightly Plastic	1,m,sbk	Many, Very Fine,Fine	0	Strong	7.5YR3/3
			2Btk2	Abrupt Smooth	Sandy Clay Loam	Moderately-Slightly Plastic	2m,abk	Many, Very Fine,Fine	0	Strong	7.5YR4/3
			2Btk3	Abrupt Smooth	Sandy Clay Loam	Moderately-Slightly Plastic	2m,abk	Few,Fine	0	Strong	7.5YR4/4
			2Btk4	-	Sandy Clay	Moderately Plastic	1f,m,sbk	Few,Very Fine	0	Strong	7.5YR4/4
Edge			A	Clear Smooth	Sandy Loam	-	1vf,sbk	Few,Very Fine	0	na	10YR5/6
			Bw1	Clear Smooth	Sandy Loam	-	1vf,sbk	Few,Very Fine	0	na	7.5YR5/6
			Bw2	-	Sandy Loam	-	1vf,sbk	Few,Very Fine	0	na	7.5YR5/6

Heuweltjie H5

Pit Position	UTM Easting(m)	UTM Northing(m)	Horizon	Boundary Transition	Texture	Plasticity	Structure	Roots	Gravel (%)	Effervescence HCl	Munsell Moist Colour
Centre	300297	6434301	A	Clear Smooth	Sandy Clay Loam	Slightly Plastic	1f,m,abk	Few,Very Fine,f	0	Very Slight	7.5YR4/3
			Btk1	Abrupt Smooth	Sandy Clay Loam	Moderately Plastic	1vf,f,m,sbk	Few,Very Fine,f	0	Slight	7.5YR4/4
			Btk2	Clear Smooth	Sandy Clay Loam	Slightly Plastic	2f,m,abk	Few,Fine,m	0	Strong	7.5YR3/3
			Btk3	-	Sandy Clay Loam	Slightly Plastic	1f,vf,sbk	Few,Fine	0	Strong	7.5YR4/3
Edge			A	Clear Smooth	Loamy Sand	Non-Plastic	1vf,sbk	Common,Very Fine,Fine	0	None	10YR4/6
			B	Abrubt Wavy	Sandy Loam-Loamy Sand	Non-Plastic	1vf,sbk	Few,Very Fine,Fine	0	None	10YR4/6
			R	-	-	-	M	None	80	None	na

Heuweltjie H6

Pit Position	UTM Easting(m)	UTM Northing(m)	Horizon	Boundary Transition	Texture	Plasticity	Structure	Roots	Gravel (%)	Effervescence HCl	Munsell Moist Colour
Centre	300308	6434231	A	Clear Smooth	Sandy Loam	Non-Plastic	1vf,f,sbk	Many, Very Fine,Fine	0	Very Slight	9.5YR3/4
			Bk1	Clear Smooth	Sandy Loam	Slightly Plastic	1vf,f,m,sbk	Common,Very Fine,F	5	Strong	10YR4/4
			Bk2	Very Abrupt Irregular	Sandy Clay Loam	Slightly Plastic	1f,m,sbk	Few,Very Fine,F	0	Strong	7.5YR3/3
			2BkC	-	Sandy Clay Loam	Slightly Plastic	M	None	0	Violent/None	7.5YR5/6(+WHITE)
Intermediate			A	Clear Smooth	Sandy Clay Loam	Slightly Plastic	1f,vf,m,sbk	Common,Very Fine,Fine	0	SL	10YR3/4
			Btk1	Clear Smooth	Sandy Clay Loam	Slightly Plastic	1vf,f,m,sbk	Common,Very Fine,Fine	0	Strong	10YR3/6
			Bwk1	Gradual Smooth	Sandy Clay Loam	Non-Plastic	1vf,f,sbk	Few,Very Fine,Fine	0	Strong	7.5YR5/6
			Bwk2	Very Abrupt Wavy	Sandy Loam	Non-Plastic	2vf,m,sbk	Few,Very Fine,F	0	Very Slight	7.5YR5/6
			Btk2	-	Sandy Clay Loam	Slightly Plastic	3f,m,abk,M,sg	Few,Very Fine,Fine	50	Strong	7.5YR5/6
Edge			A	Clear Smooth	Sandy Loam	Non-Plastic	1vf,sbk	Few,Very Fine,Fine	0	None	10YR5/8
			Bw1	Abrubt Wavy	Sandy Loam	Non-Plastic	1f,sbk	Few,Very Fine,Fine	0	None	10YR6/6
			BC	-	-	-	-	None	70	None	-

<u>Heuweltjie H7</u>

Pit Position	UTM Easting(m)	UTM Northing(m)	Horizon	Boundary Transition	Texture	Plasticity	Structure	Roots	Gravel (%)	Effervescence HCl	Munsell Moist Colour
Centre	300379	6434228	AB	Gradual Smooth	Sandy Clay Loam	Moderately Plastic	1vf,f,sbk	Few,Very Fine,Fine	0	Very Slight	10YR4/3
			Btk1	Clear Smooth	Sandy Clay Loam	Slightly Plastic	1vf,f,sbk	Common,Very Fine,Fine	0	Slight	10YR4/4
			Btk2	Abrupt Smooth	Sandy Clay Loam	Slightly Plastic	1vf,f,sbk	Few,Very Fine,Fine	0	Strong	10YR4/4
			Btk3	Clear Smooth	Sandy Clay Loam	Slightly Plastic	2vf,f,m,sbk	None	0	Strong	10YR4/4
			Btk4	Abrupt Smooth	Sandy Clay Loam	Slightly Plastic	2,vf,m,f,sbk	None	0	Strong	10YR4/4
			Btk4	-	Sandy Clay Loam	Slightly Plastic	2vf,f,m,sbk	None	0	Strong	10YR4/4
Intermediate			A	Gradual Smooth	Sandy Loam	Non-Plastic	1vf,f,m,sbk	Common,Very Fine,Fine	0	None	7.5YR4/3
			Bw1	Clear Smooth	Sandy Loam	Non-Plastic	1f,m,sbk	Few,Very Fine,Fine	0	None	7.5YR4/3
			Bw2	Clear Smooth	Sandy Loam	Non-Plastic	1f,m,sbk	Few,Very Fine,Fine	0	None	7.4YR3/3
			CR	-	Sandy Loam	Non-Plastic	1vf,f,m,sbk	Few,Very Fine,Fine	40	None	7.5YR4/4

Heuweltjie H8

Pit Position	UTM Easting(m)	UTM Northing(m)	Horizon	Boundary Transition	Texture	Plasticity	Structure	Roots	Gravel (%)	Effervescence HCl	Munsell Moist Colour
Centre	300359	6434277	A	Abrupt Smooth	Sandy Clay Loam	Slightly Plastic	1vf,f,sbk	Many, Very Fine,Fine	0	Very Slight	7.5YR5/3
			Btk1	Clear Smooth	Sandy Clay Loam	Slightly Plastic	1-2f,sbk/abk	Many, Very Fine,Fine	0	Slight	7.5YR5/4
			Btk2	Very Abrupt Wavy	Sandy Loam	Slightly Plastic	2f,sbk,abk	Few,Very Fine,Fine	0	Strong	7.5YR4/4
			BC	-	-	-	3vf,f,sbk	None	0	None	7.5YR5/6
Intermediate			A	Clear Smooth	Sandy Loam	Non-Plastic	1vf,f,m,sbk	Many, Very Fine	0	None	7.5YR4/3
			Bw1	Abrubt Wavy	Sandy Clay Loam	Moderately Plastic	1f,m,sbk	Many, Very Fine	0	None	7.5YR4/3
			Bw2	Very Abrupt Smooth	Sandy Clay	Moderately Plastic	2m,co,abk	Few,Very Fine	0	None	7.5YR4/4
			Bwk1	Clear Smooth	Loamy Sand	Non-Plastic	2-3,m,co,abk	None	0	Very Slight	7.5YR4/6
			Bwk2	Clear Smooth	Loamy Sand	Non-Plastic	2-3,m,co,abk	None	0	Very Slight	7.5YR4/6
			Bw3	Abrubt Wavy	Sandy Loam	Slightly Plastic	2,f,m,sbk	None	0	None	7.5YR4/4
			R	-	-	-	gr,M	None	90	None	-

Inter-Heuweltjie I1

UTM Easting(m)	UTM Northing(m)	Horizon	Boundary Transition	Texture	Plasticity	Structure	Roots	Gravel (%)	Effervescence HCl	Munsell Moist Colour
300083	6434052	A	Clear Smooth	Sandy Loam	Non-Plastic	1-2,f,msbk	Few,Very Fine	0	None	7.5YR 4/4
		Bw1	Clear Smooth	Sandy Loam	Non-Plastic	2f,mabk	Few,Very Fine	0	None	7.5YR 4/6
		Bw2	Abrubt Wavy	Sandy Loam	Non-Plastic	2f,sbk	Few,Very Fine,Medium	0	None	7.5YR 4/4
		RC	-	Sandy Loam	Non-Plastic	1f,sbk, sg,M	Few,Very Fine	95	None	7.5YR 4/4

Inter-Heuweltjie I2

UTM Easting(m)	UTM Northing(m)	Horizon	Boundary Transition	Texture	Plasticity	Structure	Roots	Gravel (%)	Effervescence HCl	Munsell Moist Colour
300142	6434140	A	Clear Smooth	Sandy Loam	Non-Plastic	1vf,f,sbk	Common, Fine	0	None	7.5YR5/4
		AB	Clear Smooth	Sandy Loam	Non-Plastic	1vf,f,sbk	Common, Fine	0	None	7.5YR5/6
		R	-	Sandy Loam+rocky	Non-Plastic	1vf,rocks	Common, Fine,Medium	90	None	7.5YR5/6

APPENDIX C

Tables of texture and carbonate data as well as bulk density of each layer per heuweltjie and inter-heuweltjie. The texture and carbonate data in these tables were converted to mass per unit area as per the procedure described in the methods section, to render the data in Appendix A – table 2.

Heuweltjie H1

Pit Position	Intial Depth (cm)	Final Depth (cm)	Layer length (cm)	BD ($g.cm^{-3}$)	Total layer length(cm)	Layer Proportion	Clay (%)	Sand (%)	Silt (%)	Carbonate (%)
Centre	0	7	7	1.3	90.0000	0.0778	0.0000	69.6492	30.3508	1.0779
	7	16	9	1.0	90.0000	0.1000	5.0816	72.0514	22.8671	4.4460
	16	31	15	1.3	90.0000	0.1667	5.0932	79.6273	15.2795	8.6360
	31	41	10	1.0	90.0000	0.1111	7.6179	77.1463	15.2358	8.8389
	41	71	30	1.9	90.0000	0.3333	17.8097	61.8365	20.3539	6.8984
	71	90	19	1.7	90.0000	0.2111	12.8786	69.0914	18.0300	10.4810
Intermediate	0	7	7	1.6	46.0000	0.1522	5.2062	66.1599	28.6339	12.4811
	7	18	11	1.4	46.0000	0.2391	2.6261	78.9916	18.3824	65.1953
	18	34	16	1.3	46.0000	0.3478	2.6291	86.8546	10.5164	31.6360
	34	46	12	2.2	46.0000	0.2609	5.3379	83.9863	10.6758	6.2916
Edge	0	8	8	1.4	65.0000	0.1231	7.6695	79.5480	12.7825	6.7997
	8	20	12	1.3	65.0000	0.1846	12.9587	71.4908	15.5505	7.4003
	20	33	13	1.4	65.0000	0.2000	10.3466	71.5468	18.1066	3.2771
	33	43	10	1.2	65.0000	0.1538	2.5683	82.0218	15.4099	3.8031
	43	65	22	1.9	65.0000	0.3385	2.6069	86.9656	10.4275	3.4163

Heuweltjie H2

Pit Position	Intial Depth (cm)	Final Depth (cm)	Layer length (cm)	BD ($g.cm^{-3}$)	Total layer length(cm)	Layer Proportion	Clay (%)	Sand (%)	Silt (%)	Carbonate (%)
Centre	0	7	7	1.3	90.0000	0.0778	0.0000	69.7996	30.2004	0.0679
	7	15	8	1.2	90.0000	0.0889	7.5529	69.7885	22.6586	0.0800
	15	28	13	0.9	90.0000	0.1444	10.1214	67.1055	22.7731	0.9751
	28	41	13	1.1	90.0000	0.1444	10.1387	56.9106	32.9507	7.0921
	41	54	13	0.9	90.0000	0.1444	2.5365	67.0260	30.4375	7.3087
	54	75	21	1.2	90.0000	0.2333	0.0000	82.2128	17.7872	1.9774
	75	90	15	-	90.0000	0.1667	0.0000	89.8258	10.1742	21.4914
Intermediate	0	10	10	1.3	52.0000	0.1923	7.6844	76.9467	15.3689	0.2134
	10	19	9	1.6	52.0000	0.1731	15.4560	69.0881	15.4560	10.7232
	19	36	17	1.4	52.0000	0.3269	15.7862	65.7967	18.4172	0.2668
	36	52	16	1.6	52.0000	0.3077	21.3744	65.2666	13.3590	8.5305
	52+	-	-	0.9	52.0000	-	4.0000	86.0000	10.0000	5.4658
Edge	0	13	13	1.5	20.0000	0.6500	7.6640	74.4533	17.8827	3.7640
	13	20	7	1.5	20.0000	0.3500	12.8521	74.2957	12.8521	2.9990
	20+	-	-	1.7	20.0000	-	7.6789	76.9632	15.3578	1.1536

Heuweltjie H3

Pit Position	Intial Depth (cm)	Final Depth (cm)	Layer length (cm)	BD (g.cm^{-3})	Total layer length(cm)	Layer Proportion	Clay (%)	Sand (%)	Silt (%)	Carbonate (%)
Centre	0	10	10	1.6	68.0000	0.1471	5.0638	79.7448	15.1914	17.4247
	10	21	11	1.6	68.0000	0.1618	10.4395	71.2914	18.2691	3.2944
	21	36	15	1.2	68.0000	0.2206	5.3146	84.0561	10.6293	9.0990
	36	58	22	3.0	68.0000	0.3235	2.6664	86.6681	10.6655	8.8508
	58	68	10	1.9	68.0000	0.1471	6.0924	75.6306	18.2771	2.5329
Edge	0	9	9	1.5	60.0000	0.1500	5.0000	84.5169	10.4831	4.3290
	9	18	9	1.5	60.0000	0.1500	0.0000	85.9424	14.0576	2.8866
	18	31	13	1.7	60.0000	0.2167	5.0398	84.8806	10.0796	1.4410
	31	47	16	1.5	60.0000	0.2667	5.0592	79.7632	15.1776	7.1226
	47	60	13	2.2	60.0000	0.2167	15.6740	71.2644	13.0617	17.2879

Heuweltjie H4

Pit Position	Intial Depth (cm)	Final Depth (cm)	Layer length (cm)	BD (g.cm^{-3})	Total layer length(cm)	Layer Proportion	Clay (%)	Sand (%)	Silt (%)	Carbonate (%)
Centre	0	8	8	1.4	77.0000	0.1039	10.4559	68.6324	20.9118	0.3197
	8	16	8	1.3	77.0000	0.1039	13.0589	68.6586	18.2825	0.7822
	16	24	8	1.3	77.0000	0.1039	15.7928	63.1501	21.0571	6.7718
	24	49	25	1.4	77.0000	0.3247	15.6887	60.7782	23.5331	12.7851
	49	67	18	1.4	77.0000	0.2338	10.5597	60.4013	29.0391	5.0023
	67	77	10	1.4	77.0000	0.1299	2.6194	73.8055	23.5750	9.3943
Edge	0	10	10	1.5	36.0000	0.2778	0.0000	82.2209	17.7791	3.9913
	10	24	14	1.6	36.0000	0.3889	0.0000	79.8082	20.1918	6.4474
	24	36	12	1.5	36.0000	0.3333	7.6617	74.4611	17.8772	1.5434

Heuweltjie H5

Pit Position	Intial Depth (cm)	Final Depth (cm)	Layer length (cm)	BD ($g.cm^{-3}$)	Total layer length(cm)	Layer Proportion	Clay (%)	Sand (%)	Silt (%)	Carbonate (%)
Centre	0	10	10	1.5	42.0000	0.2381	13.0753	71.2343	15.6904	6.7823
	10	23	13	1.5	42.0000	0.3095	16.0393	67.9213	16.0393	9.1669
	23	35	12	1.6	42.0000	0.2857	18.3592	60.6588	20.9820	0.0615
	35	42	7	1.2	42.0000	0.1667	18.4152	65.8003	15.7845	6.4962
Edge	0	14	14	1.3	20.0000	0.7000	5.0643	77.2106	17.7251	1.9646
	14	20	6	1.4	20.0000	0.3000	7.5949	77.2152	15.1899	2.7247

Heuweltjie H6

Pit Position	Intial Depth (cm)	Final Depth (cm)	Layer length (cm)	BD ($g.cm^{-3}$)	Total layer length(cm)	Layer Proportion	Clay (%)	Sand (%)	Silt (%)	Carbonate (%)
Centre	0	9	9	1.4	80.0000	0.1125	7.7399	71.6202	20.6398	6.1823
	9	20	11	1.5	80.0000	0.1375	7.7551	71.5645	20.6804	0.2473
	20	35	15	1.3	80.0000	0.1875	5.2274	76.4767	18.2959	14.5084
	35	80	45	2.1	80.0000	0.5625	5.2290	84.3129	10.4581	18.5176
Intermediate	0	12	12	1.5	90.0000	0.1333	7.7367	66.4741	25.7891	4.9515
	12	29	17	1.5	90.0000	0.1889	5.1594	74.2029	20.6377	8.6888
	29	51	22	1.5	90.0000	0.2444	7.7712	79.2768	12.9520	1.6403
	51	77	26	2.2	90.0000	0.2889	5.1637	84.5089	10.3274	6.4331
	77	90	13	1.4	90.0000	0.1444	5.2100	79.1602	15.6299	4.4615
Edge	0	10	10	1.4	24.0000	0.4167	0.0000	87.3725	12.6275	7.2250
	10	24	14	1.5	24.0000	0.5833	0.0000	92.4150	7.5850	2.8340

Heuweltjie H7

Pit Position	Intial Depth (cm)	Final Depth (cm)	Layer length (cm)	BD ($g.cm^{-3}$)	Total layer length(cm)	Layer Proportion	Clay (%)	Sand (%)	Silt (%)	Carbonate (%)
Centre	0	13	13	1.4	122.0000	0.1066	2.6394	76.2458	21.1149	1.5110
	13	30	17	1.4	122.0000	0.1393	5.2977	76.1602	18.5421	0.2408
	30	43	13	1.3	122.0000	0.1066	2.6319	84.2089	13.1593	9.0051
	43	62	19	1.7	122.0000	0.1557	13.0808	68.6061	18.3131	4.5701
	62	93	31	1.8	122.0000	0.2541	10.6474	70.7198	18.6329	4.4338
	93	122	29	1.8	122.0000	0.2377	8.0463	75.8610	16.0927	9.5088
Intermediate	0	8	8	1.5	47.0000	0.1702	7.6766	79.5292	12.7943	4.4257
	8	22	14	1.7	47.0000	0.2979	10.2701	79.4598	10.2701	3.9662
	22	32	10	1.8	47.0000	0.2128	10.1771	79.6458	10.1771	2.2107
	32	47	15	1.5	47.0000	0.3191	12.8429	74.3142	12.8429	20.0508

Heuweltjie H8

Pit Position	Intial Depth (cm)	Final Depth (cm)	Layer length (cm)	BD ($g.cm^{-3}$)	Total layer length(cm)	Layer Proportion	Clay (%)	Sand (%)	Silt (%)	Carbonate (%)
Centre	0	12	12	1.5	45.0000	0.2667	2.6042	76.5625	20.8333	1.2573
	12	24	12	1.3	45.0000	0.2667	2.6208	73.7918	23.5874	2.7548
	24	34	10	1.5	45.0000	0.2222	2.6118	79.1057	18.2825	5.4290
	34	45	11	1.9	45.0000	0.2444	3.0000	92.0978	4.9022	5.1200
Intermediate	0	11	11	1.6	90.0000	0.1222	5.1052	82.1319	12.7629	2.2532
	11	23	12	1.5	90.0000	0.1333	10.3541	76.7033	12.9426	5.5097
	23	38	15	1.4	90.0000	0.1667	2.6299	78.9607	18.4094	7.6915
	38	56	18	2.2	90.0000	0.2000	2.5931	76.6622	20.7447	4.6250
	56	77	21	2.4	90.0000	0.2333	2.6140	71.2463	26.1397	2.2639
	77	90	13	2.2	90.0000	0.1444	7.8239	66.0964	26.0797	3.7533

Heuweltjie H9 – H19

Heuweltjie	Intial Depth (cm)	Final Depth (cm)	Layer length (cm)	BD (g.cm^{-3})	Total layer length(cm)	Layer Proportion	Clay (%)	Sand (%)	Silt (%)	Carbonate (%)
H9	0	5	5	1.6	90.0000	0.0556	7.7874	74.0422	18.1705	1.8629
H9	70	90	20	1.6	90.0000	0.2222	2.6684	78.6530	18.6786	11.5771
H10	0	5	5	1.6	20.0000	0.2500	5.1319	76.9065	17.9616	0.3901
H10	20	5	15	1.6	20.0000	0.7500	2.6911	81.1625	16.1464	7.5192
H11	0	5	5	1.6	94.0000	0.0532	2.5816	79.3474	18.0710	5.7324
H11	94	5	91	1.6	94.0000	0.9681	2.0000	89.1020	8.8980	40.3961
H12	0	5	5	1.6	40.0000	0.1250	7.7979	71.4078	20.7943	0.2759
H12	40	5	35	1.6	40.0000	0.8750	10.5966	70.8594	18.5440	3.6919
H13	0	5	5	1.6	20.0000	0.2500	10.3082	71.6524	18.0394	7.9216
H13	20	5	15	1.6	20.0000	0.7500	18.1460	63.7080	18.1460	4.3137
H14	0	5	5	1.6	20.0000	0.2500	10.1574	77.1458	12.6968	2.5297
H14	20	5	15	1.6	20.0000	0.7500	2.5518	84.6892	12.7590	2.4272
H15	0	5	5	1.6	40.0000	0.1250	2.5725	79.4196	18.0078	1.5923
H15	40	5	35	1.6	40.0000	0.8750	2.6511	76.1400	21.2089	3.2770
H16	0	5	5	1.6	40.0000	0.1250	0.0000	79.7550	20.2450	7.2694
H16	40	5	35	1.6	40.0000	0.8750	2.6341	78.9274	18.4385	10.4998
H17	0	5	5	1.6	46.0000	0.1087	0.0000	87.3006	12.6994	2.2437
H17	46	5	41	1.6	46.0000	0.8913	2.5805	84.5169	12.9026	4.5335
H18	0	5	5	1.6	56.0000	0.0893	5.1093	84.6720	10.2187	2.2406
H18	56	5	51	1.6	56.0000	0.9107	2.7021	89.1915	8.1064	12.6378
H19	0	5	5	1.6	100.0000	0.0500	5.0429	94.9571	0.0000	7.6458
H19	100	5	95	1.6	100.0000	0.9500	7.6460	89.8053	2.5487	2.1385

Inter-Heuweltjies I1-I2

Heuweltjie	Intial Depth (cm)	Final Depth (cm)	Layer length (cm)	BD (g.cm-3)	Total layer length(cm)	Layer Proportion	Clay (%)	Sand (%)	Silt (%)	Carbonate (%)
I1	0	8	8	1.3	32.0000	0.2500	0.0000	92.4712	7.5288	0.0000
I1	8	19	11	0.9	35.6	35.6	0.0000	92.4686	7.5314	0.0000
I1	19	32	13	1.1	32.0000	0.4063	0.0000	94.9682	5.0318	0.0000
I1	32+	-	-	-	32.0000	-	0.0000	94.9706	5.0294	0.0000
I2	0	10	10	1.5	35.0000	0.2857	7.6351	77.0946	15.2703	7.0047
I2	10	20	10	1.4	35.0000	0.2857	10.2491	87.1887	2.5623	5.5945
I2	20	35	15	2.8	35.0000	0.4286	5.1499	92.2752	2.5749	6.6692