LANDSCAPE DENUDATION OR LAND DEGRADATION? INTERROGATING THE GEOMORPHIC PROCESSES OF LANDSCAPE CHANGE IN SOUTHERN AFRICA

Field Guide to the Pre-Conference Excursion:

Edited by Ian Foster & Kate Rowntree

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Graaff-Reinet from the Valley of Desolation (Photo: Libby Foster)

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Preamble

Welcome to the Karoo Field Excursion. We hope you enjoy the experience as much as the academic content of the tour. Detailed route maps are provided as supplements to this guide and the excursion will allow you to experience the culture and heritage, as well as the geomorphic processes operating in the region at timescales ranging from minutes to millennia.

While this guide contains much new material it is also underpinned by information on the geology, climate and land use of the region (see Chapter 1) and a review of earlier palaeoecological studies (Chapter 7) that will provide much useful background to our tour.

This guide is organised around major research themes rather than providing information on specific locations at which we intend to stop. Our tour will take us to many of the sites about which the sections in this guide were written and contributors to the field excursion will use this guide to provide illustrative information and research findings which will hopefully generate lots of debate and discussion as we move around the region.

This guide is organised into four major themes:

1. Background to the Region (Chapter 1)
2. Erosion Processes and Vegetation Controls (Chapters 2, 3 & 4)
3. Post-European Impacts (Chapters 5 & 6)
4. Long term changes (Chapters 7&8).

Many of the recent projects focusing on past and present land degradation in the area of the Karoo around Compassberg started as a result of a chance meeting between Peter Holmes and John Boardman at a conference in Belgium. Peter was finishing his PhD on the Quaternary geology of the area and remarked that no one was working on current geomorphic problems, especially landscape degradation (Holmes, 1998). John Boardman first visited the area in 1999. Since then a series of co-operative projects have involved personnel from the universities of Aberdeen, Cape Town, Leicester, Northampton, Oxford, Sheffield, Rhodes (Grahamstown) and Westminster. Several PhD and MSc students have contributed and funding has come from a variety of sources including Natural Environment Research Council (UK), the Trapnell and Oppenheimer Funds (Oxford) and the British Academy, the South African National Research Foundation and the universities of the personnel involved.

A summary of aims and achievements of the 'Karoo Project' is to be found at:

http://www.eci.ox.ac.uk/research/other/karoo.php

Acknowledgements

We are indebted to many local land owners and managers who have provided us with information on the history of their farms and allowed us access to diaries and weather records and to their reservoirs and catchments in order to undertake the sampling. Their permission to access field sites and their great hospitality are gratefully acknowledged. They include:

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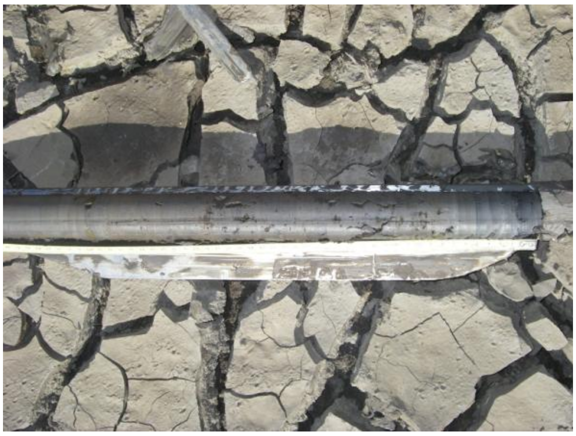
Many of our colleagues and students also contributed to the field work effort including Leanne DuPreez, Roddy Fox, Tim Kinnell, Adrian Pietersen, Breanne Robb & Bennie van der Waal.

Ian Foster & Kate Rowntree **August 2010**

Cranemere Reservoir and Sediment Core (Photos: Libby Foster)



INTRODUCTION TO THE KAROO

Kate Rowntree

1. BACKGROUND

The field excursion takes us to the Sneeuberg Mountains (snow mountains) in the eastern Karoo. Karoo is derived from the Khoi word meaning dry; the Karoo forms a vast dryland in the western interior of South Africa. This region in turn has given its name to the geological supergroup that is exposed over approximately two thirds of the country and to two of the country's seven biomes (the nama Karoo and the succulent Karoo). The Karoo is also famous for its lamb, mohair and ostrich products that have been produced from this semi-arid area for over a century.

The topography of the Sneeuberg Mountains is a complex of basin and range type landforms associated with the Great Escarpment that rises from the Cambedoo plains, lying at an altitude below 800 m between Graaff-Reinet and Pearston, to a height of over 2000 m (Figure 1) . Compassberg mountain forms a distinctive peak at 2502 m, standing up above the surrounding countryside. The two dominant river systems are the Great Fish River to the East and the Sundays River to the west. North of Compassberg the drainage is towards the Orange River. Clarke et al. (2009) provide a detailed account of the physical geography of the Sneeuberg Mountains.

Some useful websites that give further background to the area, its landscape and towns are:

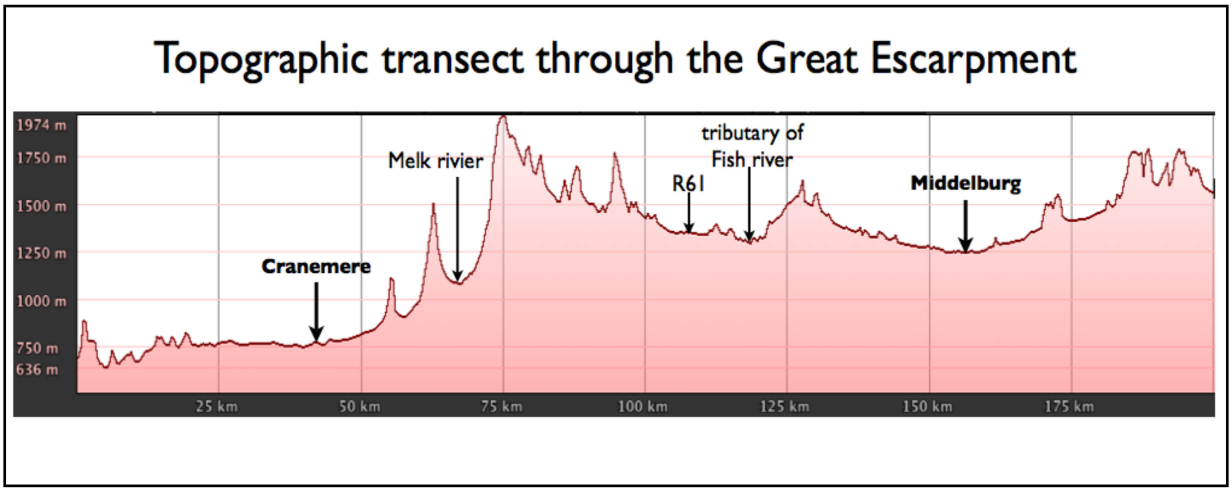
Nieubethesda web sites: www.nieubethesda.co.za/; http://www.nieubethesda.info/; http://www.nieu-bethesda.com/; http://www.nieu-bethesda.com/

Graaff-Reiniet web site: http://www.graaffreinet.co.za/

Open Africa Routes, South Africa, Mid-Karoo route: http://www.openafrica.org/route/mid-karoo-route

Supporting photographs of the region are given in Plate 1.

Figure 1 **Topographic section through the Sneeuberg Mountains (constructed using elevation profile tool in Google Earth).**



2. GEOLOGY

An introduction to the geological history of South Africa, and the associated evolution of life forms, is described by McCarthy & Rubidge (2005). Readers are referred to this elegantly presented book for a more in-depth discussion. A more detailed account of the local geology can be found in the Geological Survey's explanation of Sheet 3224 (Graaff-Reinet). A summary of the geology of the karoo region as described by McCarthy & Rubidge (2005) is given here.

The Karoo Supergoup comprises a succession of alternating sandstones, mudstones and shales deposited during the Late Carboniferous to Jurassic in a basin formed between the emerging Cape Fold Mountains to the South and the Cargonian Highlands to the north east. The Karoo sequence is thickest on the south (maximum 12 km) and thins to the north. The earliest rocks are the Dwyka Tillites deposited when the land that now forms South Africa was located over the South Pole some 310 Ma years ago; the Karoo geological period came to an end with the outpouring of lavas that heralded the breakup of Gondwanaland at around 182 Ma. During this 140 million year period sedimentary rocks were deposited that represent an environment that changed from glacial (Dwyka Group) to fluvio-deltaic (Elliot Group) to semi-arid flood plains and braid plains (Beaufort Group), to sand desert (Stormberg Group). This time period also saw the evolution of the first land plants (Glossopteris and Phyloloceca [horsetails]) and reptiles; the shales and mudstones of the Beaufort Group provide a particularly rich source of early reptilian fossils.

The area that we will visit during the field excursion is underlain by near-horizontal rocks of the Beaufort Group. Sediments of this group were laid down by northward flowing rivers several kilometers wide that meandered across semi-arid floodplains, depositing sands along the river courses and silts over the floodplains, giving rise to the horizontal bands of alternating sandstones, mudstones and shales that can be seen today. These floodplains were home to the many retiles whose fossil remains can be seen in the museums at Ganora, Nieu-Bethesda and Wellwood.

At around 251Ma there occurred a major mass extinction "The Mother of Mass Extinctions" when it is estimated that 96% of species became extinct. This brought to an end the Permian Period and was marked by a distinct change in sedimentary characteristics. The rocks of the Katberg Formation typify braided river systems, possibly due to loss of vegetation caused by the mass extinction. The resulting sandstones are dominated by a single genus of a mammal-like reptile - Lystrosaurus - that was one of few survivors from the Permian. The earliest dinosaurs are found in the overlying Burgersdorp formation whose rocks are thought to be derived from meandering rivers that may represent a better vegetated landscape as life forms diversified again.

The main rocks bearing evidence of dinosaurs belong to the early rocks of the Stormberg Group that outcrop to the east and north of the area to be visited during the field excursion. The uppermost formation of this group is the Clarence whose sand dunes form the impressive cave sandstones of the Golden Gate region.

The Karoo sedimentary sequence was brought to an end with the outpouring of massive basaltic lavas that today cap the Great Escarpment in Lesotho and KwaZulu Natal to the east. If these lavas ever extended over the Karoo region itself, they are no longer evident, but clearly seen in the landscape are the associated doleritic dykes and sills that were intruded into the underlying rocks. These igneous intrusions cap many of the mountains, often giving rise to characteristic 'tafelbergs' (mesa), or form linear ridges standing up above the surrounding sedimentary rocks. They form important groundwater aquifers in an otherwise dry landscape.

Gondwanaland started to break up between 180-160 Ma years ago and isostatic uplift led to a high lying continental interior, the Great Escarpment to the east, and fault bounded basins in the coastal regions. The Cretaceous period, that lasted until 65 Ma years ago (when another mass extinction that wiped out the dinosaurs occurred), was a period of major continental erosion. McCarthy & Rubidge (2005) suggest that the physical landscape of South Africa's interior, and therefore the Karoo, has been little altered since the end of the Cretaceous. Partridge and Maud (1987) believe that a single erosion cycle lasted from the breakup of Gondwanaland to the early Miocene (24 Ma ago), forming a vast undulating surface about 500-700m above sea level. Locally mountains and 'koppies' protected by resistant doleritic caps stand up above this surface. This period of stability was interrupted about 20 Ma years ago when uplift raised the eastern part of the country some 300 m and the western part 150 m. This was followed 5 Ma years ago by a second uplift event that reached 900 m in the east of the country, but less in the interior and the west. These two uplift events caused the dramatic incision of rivers draining the great Escarpment of KwaZulu Natal and Mpumalanga and of the coastal plain of the Southern Cape. McCarthy & Rubidge (2005) do not present any examples of equivalent incision in the Karoo, but it is feasible that canyons such as that through which the upper Sundays River flows near Nieu-Bethesda formed during these periods of uplift.

The thinking presented by McCarthy & Rubidge (2005) suggests that the terrain of the Karoo interior has changed little since the end of the Cretaceous, but the biogeography of the area would have changed dramatically with the conterminous spread of grassland and mammals. By modern times (pre-European settlement) the eastern Karoo is believed to have been dominated by a dynamic mix of grassland and low bush supporting vast herds of grazing ungulates. Karoo vegetation will be described in more detail below.

Although the topography of the Sneeuberg and adjacent plains may not have changed its overall configuration since the end of the Cretaceous, Late Tertiary and Quaternary deposits that mantle the lower hillslopes and valley bottoms (Hill, 1993) play an important role in the hydrology and soil development of the area. Terraces of fluvial gravels, cobbles and occasional boulders with distinct calcrete bands can be found in the tributaries of Sundays River between Graaff-Reinet and Pearston. The oldest of these probably dates to the Miocene (Hill, 1993). Modern alluvium covers many valley floors, though in many cases former valley floor wetlands have become incised by deep 'dongas'. Reports from the 1900s suggests that many of these were initiated at about that time. The lower hillslopes are mantled by scree and colluvial deposits. Formation is ongoing, but the oldest of these features may be Miocene in age (Hill, 1993).

3. CLIMATE & WEATHER

The Sneeuberg region of the Karoo experiences an extreme climate, both in terms of temperature and rainfall. A climate graph for Graaff-Reinet (altitude 752 m) is given in Figure 2. Night time temperatures often drop below freezing in the winter, whereas it is not uncommon for daytime temperatures to exceed 35^{o}C in the summer. Although heavy rain can occur at any time, the wettest months on average are February and March, with the dry winter months of June, July and August often recording no rainfall. Annual rainfall data for seven local stations are given in Table 1. Their location is shown on Map 1 (see field excursion map). These stations can be divided into 'lowland' stations that are located on plains or within mountain basins and 'mountain' stations that are located on the escarpments. Mean annual rainfall for the lowland stations varies from 318 mm at Cranemere to 354 mm at Nieu-Bethesda. Values for the mountain stations are approximately 100 mm higher, ranging from 423 mm at Gordonville to 441 mm at Struishoek.

Mean annual rainfall figures hide a considerable inter-annual variability. Coefficients of variation range from 26 to 39% (Table 1). There is evidence to suggest that regional rainfall has increased slightly since 1950 (Table 1), but there has been no consistent change in the coefficient of variation.

The pattern of long-term variability is shown in Figure 3. The lowland stations all show a similar pattern. Above average annual totals characterize the end of the nineteenth century, whereas a series of severe droughts were experienced during the first 30 years of the twentieth century. The late sixties to early seventies also experienced a number of severe droughts, but for the next twenty years the region experienced some of the wettest years on record. Droughts occurred again in 1991 and 1993, but since then rainfall has generally been high. The records for the mountain sites show more inter-station variability. The extreme rainfall that fell in March 1974 is not seen in the rainfall record at these two stations. In contrast, 1973 was a particularly wet year at Gordonville. The year 1974 is remembered for the extensive flooding that occurred on the night of March 2nd. Heavy rain fell over the entire region, causing major floods in Middelburg and Craddock, on the Great Fish River, and Graaff-Reinet on the Sundays River.

Figure 2 Mean monthly climate statistics for Graaff-Reinet (752 m)

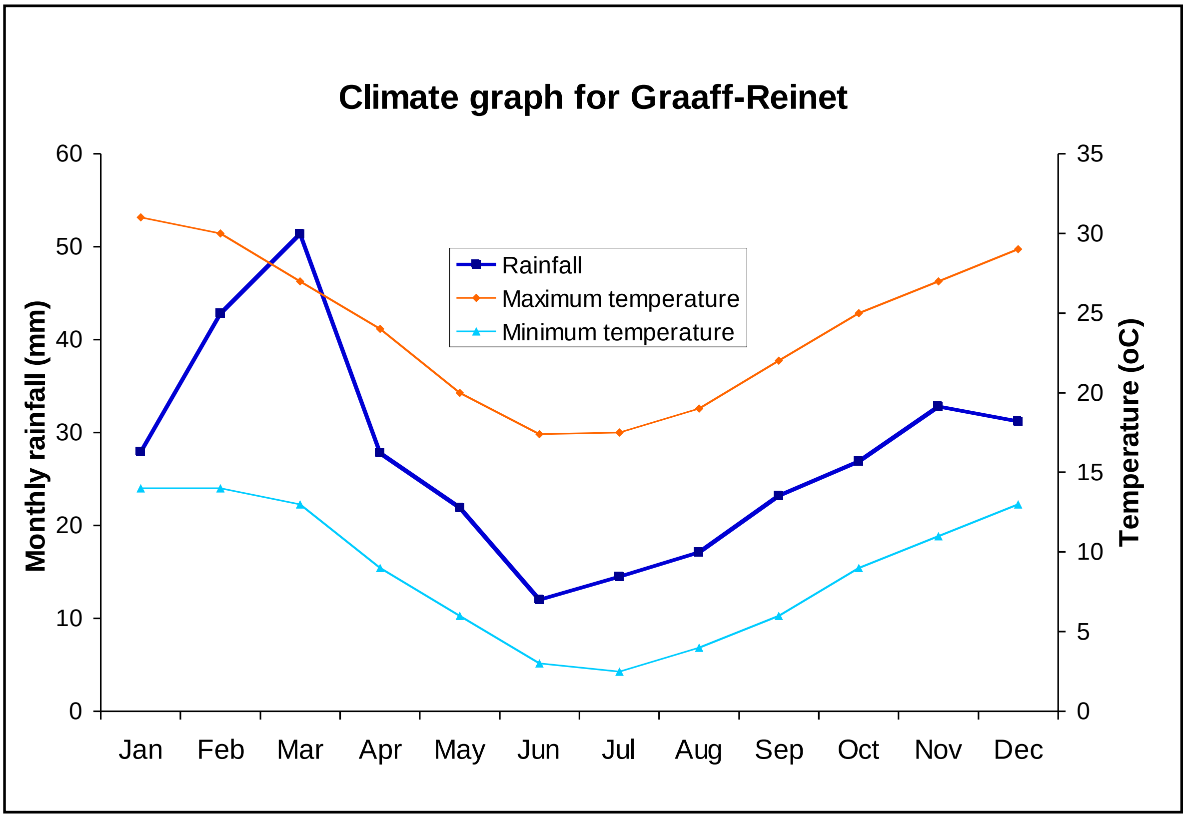
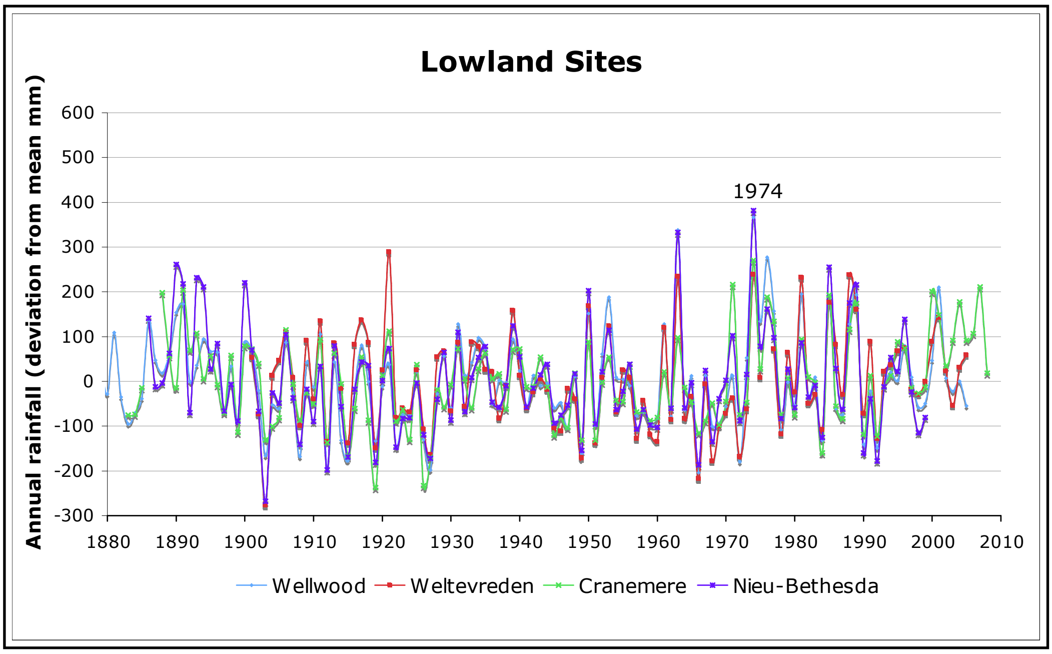


Figure 3 Time series of annual rainfall for two groups of rainfall stations



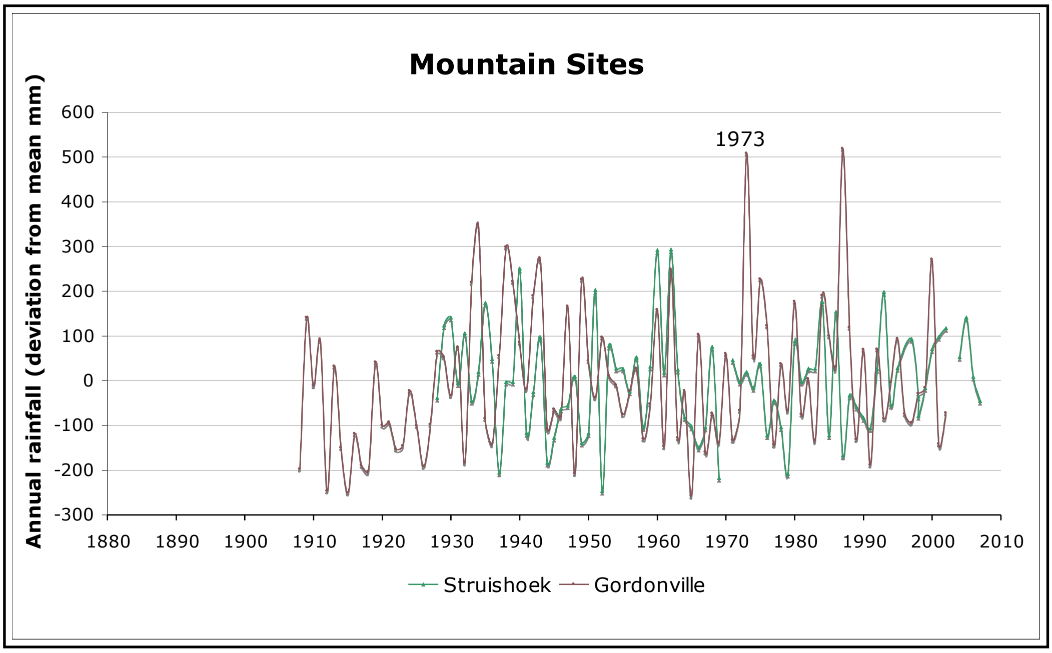


Table 1 Mean annual rainfall statistics for Sneeuberg locations

Long term series							
Station name	Cranemere	Wellwood	Middelburg	Nieu-bethesda	Weltevreden	Struikshoek	Gordonville
altitude (m.a.s.l.)	780	1192	1250	1327	1442	914	1717
Dates	1883-2008	1875-2005	1878-2001	1886-1999	1901-2005	1928-2007	1905-2002
Average	318	340	342	354	353	441	423
standard deviation	98	105	132	116	108	115	157
coefficient of variation (%)	31	31	39	33	31	26	37
Comparison of years prior to and after 1950							
Station name	Cranemere	Wellwood	Middelburg	Nieu-Bethesda	Weltevreden	Struikshoek	Gordonville
Dates	1883-1950	1875-1950	1878-1950	1886-1950	1901-1950	1928-1950	1905-1950
Average	303	331	328	350	348	435	409
standard deviation	91	89	123	111	104	117	159
coefficient of variation (%)	30	27	37	32	30	27	39
Dates	1951-2008	1951-2005	1951-2001	1951-1999	1951-2005	1951-2007	1951-2002
Average	335	354	356	359	357	444	434
standard deviation	104	124	140	124	112	115	156
coefficient of variation (%)	31	35	39	35	31	26	36

Floods and erosion potential are both related to the amount and intensity of storm events. Field observations during storms indicate that runoff on badland slopes can occur during rainfall events of less than 10 mm (see Chapter 2, this guide). A storm of 38 mm in the Compassberg area gave rise to several days of flow in major valley-bottom gully systems. We have not observed storms of greater than 38 mm. Farmers we have talked to indicate that a storm of 10 mm or more is “significant” in terms of wetting the soil and causing local runoff. Few rainfall stations in the Karoo have continuous records so we have to rely on daily rainfall depths to get an indication of intensities.

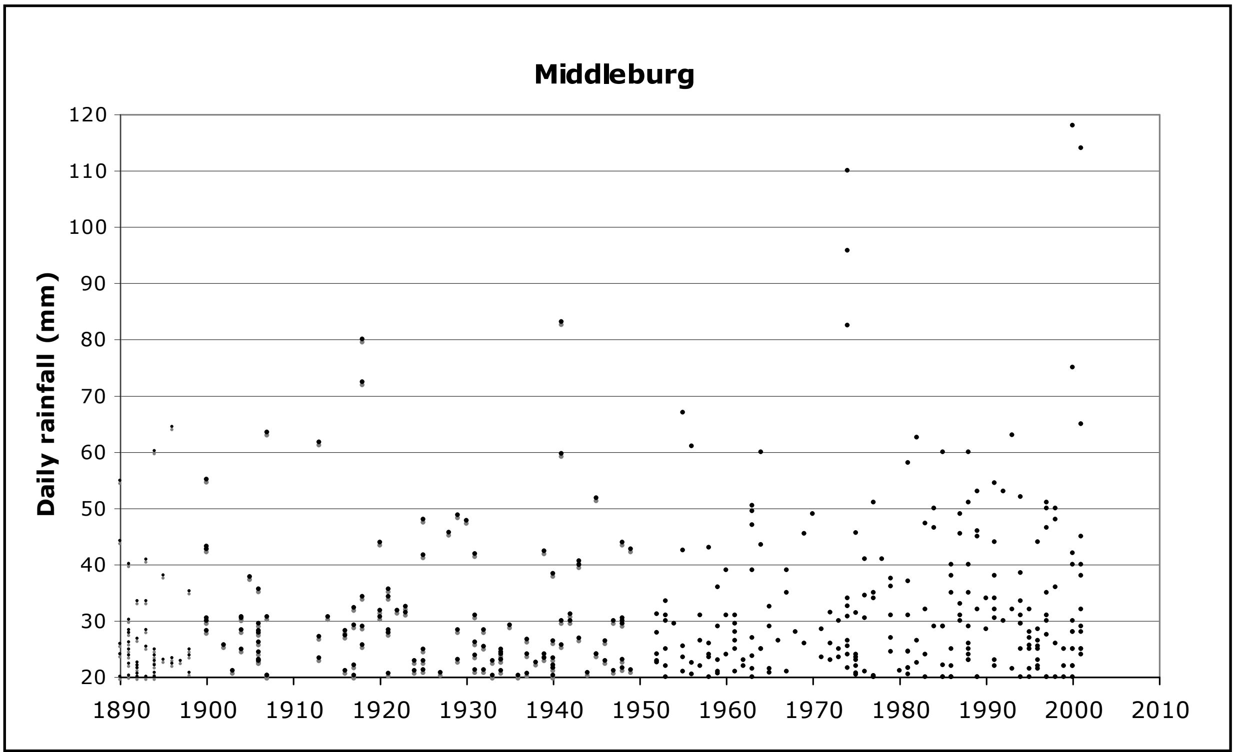
Middleburg and Cranemere both have daily rainfall records dating back to the end of the nineteenth century. These data provide insights into how the character of rain may have changed over the last 120 years (Table 2 and Figures 4 and 5). Taking 1950 as the break point, we can see that although Table 1 indicated that the mean annual rainfall for Middelburg has increased slightly, the data in Table 2 indicate that the number of raindays has decreased. Mean rain per day must therefore have increased. The number of raindays per year at Cranemere has also almost doubled. For both stations the number of days receiving 10 mm or greater has increased significantly, as has the extreme rainfall values. It would appear therefore that at both stations rainfall has become more intense.

Table 2 Daily rainfall distribution at Middelburg and Cranemere

	Middelburg				Cranemere			
Dates	1878-1950	1951-2001	1878-1950	1951-2001	1891-1950	1951-2007	1891-1950	1951-2007
Years	72	51	72	51	60	57	60	57
rain days per year			40	36			23	41
daily rainfall amount (mm)	total number of days greater or equal to given rainfall amount		number of days per year:		total number of days greater or equal to given rainfall amount		number of days per year:	
10	678	620	9.42	12.16	304	463	4.22	9.08
20	225	252	3.13	4.94	87	147	1.21	2.88
30	81	111	1.13	2.18	31	54	0.43	1.06
40	32	53	0.44	1.04	18	20	0.25	0.39
50	13	26	0.18	0.51	5	1	0.07	0.02
60	8	14	0.11	0.27	3	1	0.04	0.02
70	4	6	0.06	0.12	1	1	0.01	0.02
80	2	5	0.03	0.10		1	0.00	0.02
90		4	0.00	0.08		1	0.00	0.02
100		3	0.00	0.06			0.00	0.00
110		3	0.00	0.06			0.00	0.00
max. daily rainfall (mm)			83	118			72.39	98.3

This apparent increase in daily rainfall amounts is also suggested by the data portrayed in Figure 4. All daily rainfall events in excess of 20 mm are plotted as a time series for the two locations. In both cases the number of events between 20 and 40 mm has increased, but perhaps more significantly the extreme events have got bigger. A similar trend is shown by a comparison of the recurrence intervals of extreme events given in Figure 5. These show a distinct upward shift for the more recent data sets.

Figure 4 Time series plots of rain days exceeding 20 mm at Middelburg and Cranemere



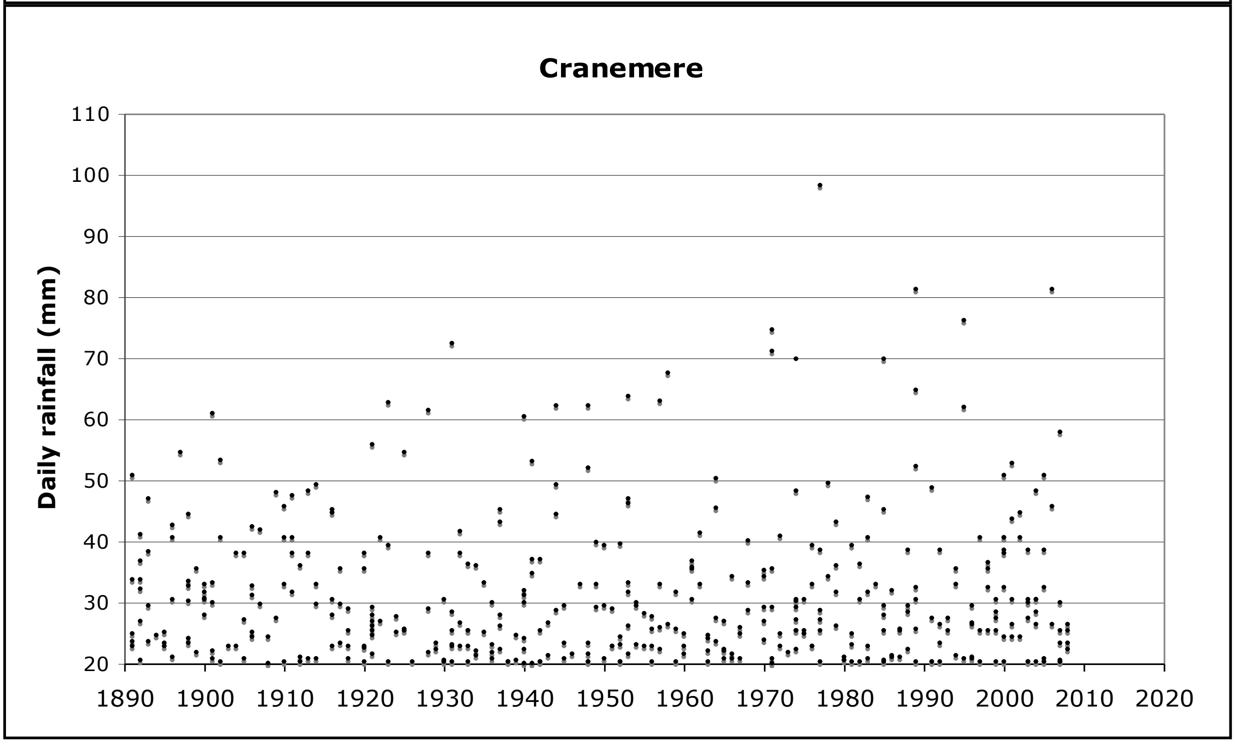
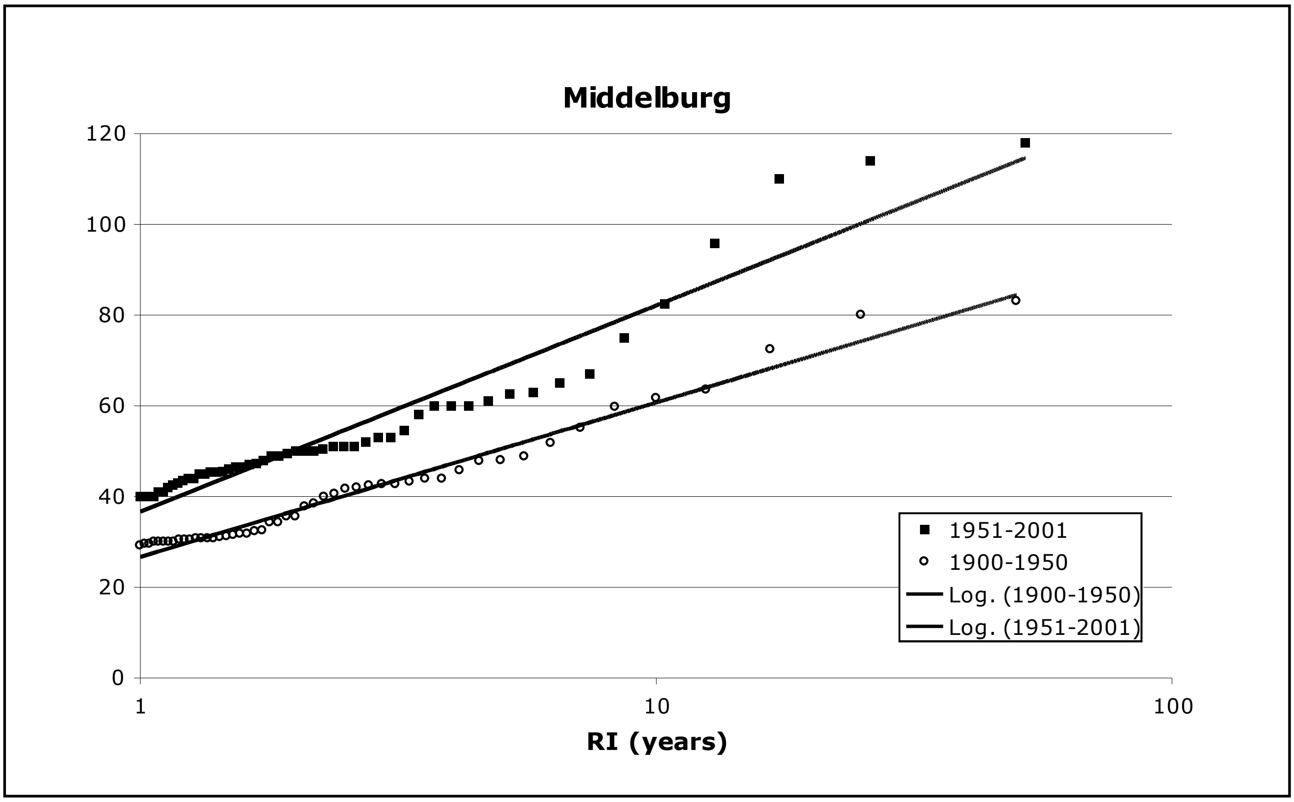
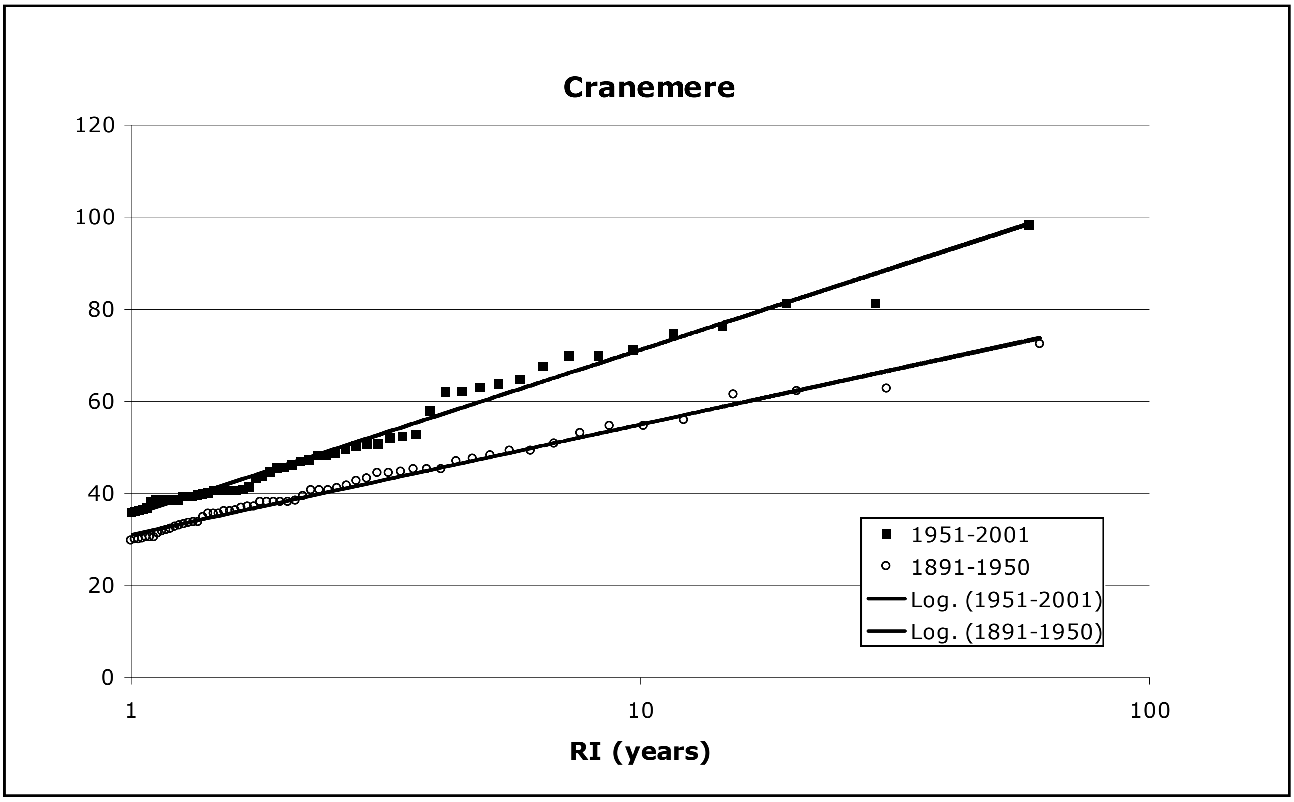


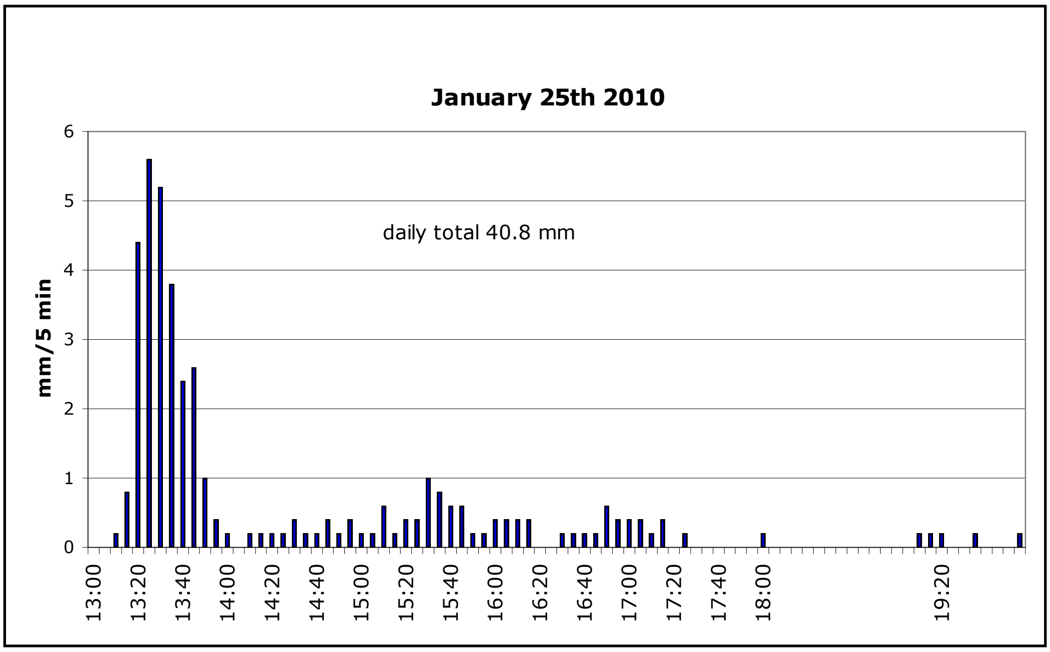
Figure 5 Recurrence intervals for daily rainfall ay Middelburg and Cranemere

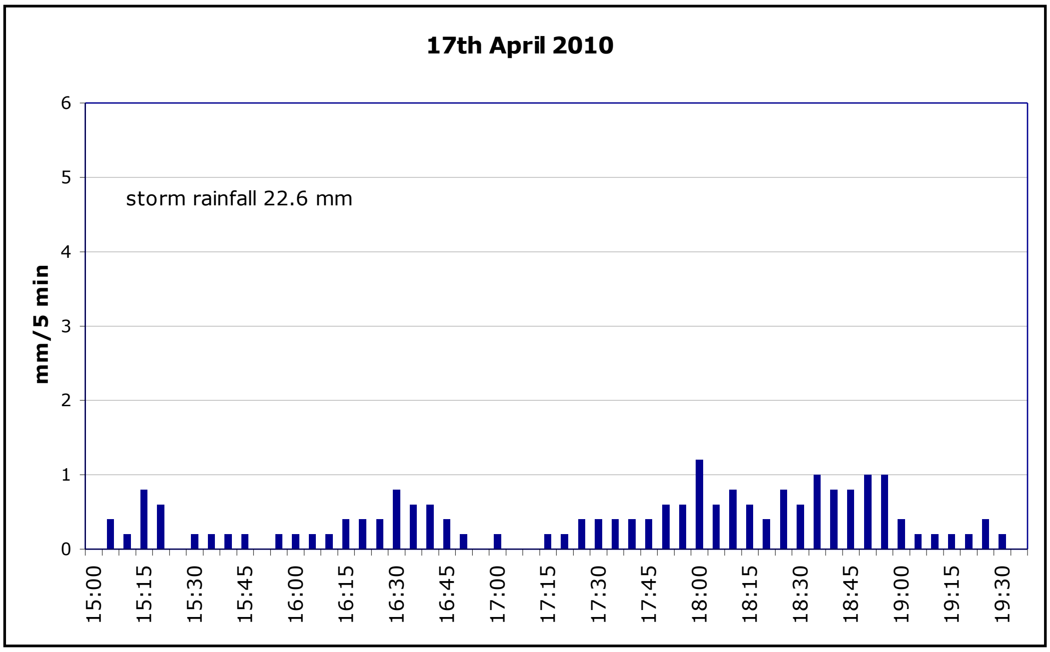




Daily rainfall amounts are not a direct measure of intensity as this depends on how the rain falls over the day. Many Karoo storms are related to thunderstorm activity so are short lived. This is especially true in the summer. According to written observations in the Cranemere rainfall record, the rainfall is dominated by short-lived thunderstorms, often with destructive hail. Spring and autumn rains may be associated with fronts that occasionally extend as far north as this area. An autographic gauge has recently been established at Ganora. Figure 6 presents the daily rainfall for the biggest event recorded since the gauge was established in April 2009, on January 25th 2010, and for a significant autumn rain (17th April 2010).

Figure 6 Five minute rainfall intensity for two storms at Ganora.





4. VEGETATION, LAND USE AND LAND MANAGEMENT

The natural vegetation of the eastern Karoo falls within the nama Karoo biome and consists of a mix of grass and low shrub with scattered trees or denser tree patches where water availability is increased as along stream courses. Shearing (1994) identifies three topographic regions in this area, each with its own distinctive veld types (Table 3). The Sneeuberg Mountains are considered by Clarke et al. (2009) to be a centre of endemism on the Great Escarpment.

Table 3 Veld types for three regions associated with the Sneeuberg area (Compiled from Shearing 1994)

Great Escarpment	**Great Karoo**	**Little Karoo**
	Topographic features	
High lying and low lying inland areas consisting of low mountains with shallow stony soils plus occasional lowlands with deeper soils	Undulating plains, lowlands and hills	Deep ravines that receive an annual rainfall of 250-300 mm
	Typical veld types	
karroid merxmuelera mountain veld - formerly more grassy, dominated by low shrubs; semi-succulent vegetation found especially in doleritic areas false karroid broken veld - taller, denser and slightly less desert-like than Karroid broken veld	karroid broken veld - succulents scarce, numerous grass species, lack of soil development leads to sparse vegetation and stunted shrubs on hills. Thornveld along streams and rivers. Annual rainfall 150-200mm central lower karoo - grass dominated region with *Pentzia incana* and some succulents (*Mesembryanthemaceae*) . false central lower karoo - lacks trees and shrubs, similar species to Central Lower Karoo, but less dense	succulent mountain scrub - dense scrub dominated by Portulacaria afra (spekboom)

Karoo is Khoi for dry (Palmer, 1993), and the dry nature of the Karoo has been reported for at least 250 years, since the first European settlers recorded conditions during their northward trek from Cape Town (Palmer,1993). Karoo vegetation is characteristically patchy, with bare ground or sparse grass occupying the areas between bushes. Grass cover is dependent on both rainfall and grazing management, and is highly variable in time and space (Essler *et al.,* 2006). There is debate over whether or not this area of the Karoo was ever dominated by grasses but, according to Essler *at al.* (2006), the total ground cover in an area with a mean annual rainfall of 300 mm would not be expected to exceed 40% in an average rainfall year, with grass making up only one third of this. It thus appears that bush similar to that present today is the natural condition of the Karoo plains. Chapter 7 (this guide) takes this debate further by examining palaeoecological evidence for long-term vegetation change.

Karoo vegetation provides grazing for both natural and domestic herbivores, so that the condition of the vegetation is largely a reflection of grazing activities and rainfall. Overgrazing has been widely blamed for the condition of the veld over the last 100 years and for the consequent land degradation (Hoffman & Todd, 2000; Dean & Macdonald, 1994; Dean *et al*., 1995). It therefore makes sense to consider vegetation cover and grazing practices together. Detailed land use records for individual farms are often not available, although local farmers have generously allowed us access to farm records, diaries and family correspondence and have provided information about known cultivation history and significant land use change.

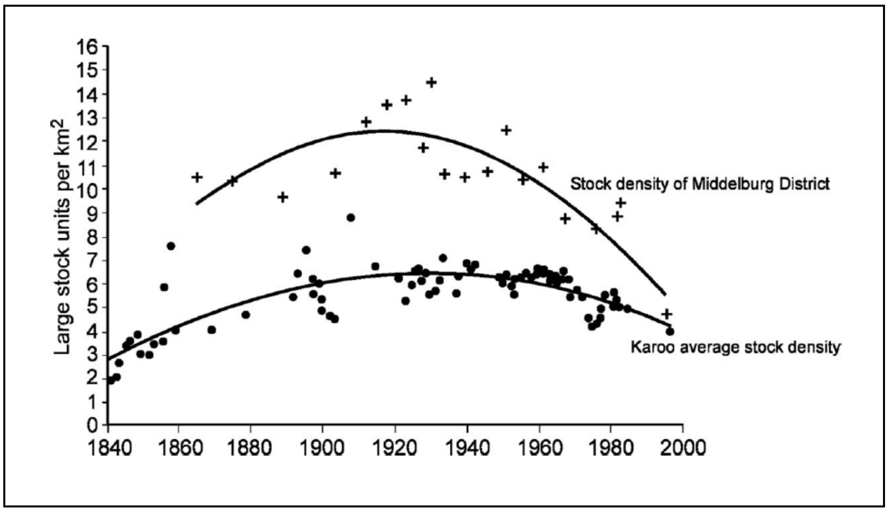
When Europeans first visited the area in the mid-eighteenth century the Karoo plains carried dense herds of ungulates. Migrating herds of springbok were reported in their millions (Palmer 1993). These herds would have supported the indigenous San people who lived as hunter gatherers. Another group of grazers that swarmed through the Karoo periodically were the locusts (Palmer, 1993). In both cases grazing pressures would have been intense, but only for a short time period, so it is thought that the vegetation would have had time to recover before the next migration or swarm.

The first farmers of European origin were the ‘trek boers’, who herded livestock on a nomadic basis (Roche, 2008). Settled agriculture dates from the mid-nineteenth century. One of the first farms in the region was Cranemere. The first farmer to settle here permanently augmented the water supply by building a low dam across a water course in 1843. Since then dams and farmsteads have proliferated across the Karoo. At the turn of the century a new innovation, wind pumps, allowed access to groundwater stored in the dolerite aquifers, bringing about further change to the potential to exploit the landscape. Wind pumps provided a constant supply of water for livestock, hence enabling an increase in stock numbers (Archer, 2000). At the same time stock movement was restricted as farmers built fences around their properties and later subdivided their farms into grazing camps (Archer, 2000). In this way stock numbers on any particular area of a farm could be controlled and stock rotated between camps. Additional feed during dry periods can be provided by the irrigation of fodder crops such as lucerne in the valley bottoms and lower footslopes. Intricate networks of irrigation furrows, some now abandoned, can be seen leading water from dams or boreholes onto the fields. Wheat, for subsistence, was another crop cultivated under rain-fed conditions. If a good crop could be produced one year in three it would be sufficient to keep a farm provided in flower (Neil Sheard pers. com.). With the improvement in road transport and access to shops most land cultivated for wheat was abandoned by the 1980s.

Sheep numbers in the Karoo peaked in the late nineteenth and first half of the twentieth century’s (Hoffman et al., 1999). In the Middelburg magisterial district stock densities have been around twice the Karoo average for nearly 100 years (Keay-Bright & Boardman, 2006) – suggestive of severe environmental stress (Figure 7). Early signs of erosion were clearly evident by 1900. Gordon, Director of Irrigation for the Cape of Good Hope, was one of a number of others who spoke passionately about the evils of soil erosion in the first decade of the twentieth Century (Gordon, 1904). Some of the reduction in numbers after the 1930s was due to an increasing awareness of the link between high stock numbers and land degradation that resulted in the promotion of different conservation-based grazing strategies. Numbers are also linked to economic factors such as the wool price, which peaked in the 1930s.

It is important to distinguish between veld degradation (degradation of the grazing capacity of the vegetation cover) and land degradation associated with soil erosion. While soil erosion is strongly linked to the physical characteristics such as percentage cover and basal area, veld condition depends as much on the species mix as on their cover. Shrubs such as *Rhizogozum trichotomum* (driedoring), *Lycium* spp. (kriedoring), *Psopis* (mesquite), *Elytropappus rhinocerotis* (rhinoceros bush) and *Euryops* spp. (resin bush) may provide a good cover, but are of little grazing value (Shearing, 1994).

Figure 7 Stocking rates in the Middelberg District in comparison with the Karroo Average (after Boardman et al., 2010).



A recent trend has been to move from livestock farming to private game farming. This normally involves the amalgamation of several adjacent farms, removal of internal fences to allow the game to roam freely within the area of the farm and the construction a new boundary game fence that prevents any migration away from or onto the farm. New water features are created to attract game to viewing points. The environmental implications of this major land management change are as yet unknown. A recent study by Chesterman (2009) indicates that there may be a number of negative impacts. The new managers often lack the inter-generational knowledge of the livestock farmers, they may be more concerned with promoting tourism than veld management, and the lack of internal fences means that it is difficult to control the spatial pattern of grazing within the farm. As stock numbers build up overgrazing may again become a serious problem.

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Plate 1 Weather, geology and vegetation of the Karoo

Unstable conditions on 8th December 2007 resulted in severe hail damage at Cranemere

Storm over Compassberg

Dolerite dykes and sills form caps and ridges

Mountain vegetation

Sparse vegetation on lowlands

2. DEGRADED AREAS AND BADLANDS

John Boardman

1. INTRODUCTION

Severely degraded areas or badlands are characterised by closely spaced gullies, little remaining interfluve areas and only remnants of the original vegetation, usually a few shrubs. Badlands are developed in colluvium and relief is up to 2 m with bedrock shale, sandstone and occasional dolerite forming a barrier to further erosion. Badlands are located on gently sloping footslopes and occasionally on valley bottoms. The footslope location is related to runoff from upslope rocky areas and the presence of colluvium which is easily eroded.

There are also badlands which have formed on formerly cultivated land in valley bottoms most notably that around the abandoned threshing floor on Aandrus Farm (Fig 4, Keay-Bright & Boardman 2007). This particular area of degradation has formed since cessation of cultivation ca. 1925. In contrast, formerly cultivated land in the Compassberg Dam catchment (See Chapter 5, this guide) which was probably farmed until ca. 1974 is not yet degraded; this resilience may be related to the presence of broad, gently sloping terraces. Degraded areas are therefore related either to footslope colluvium or to formerly cultivated land.

2. MAPPING DEGRADATION

Degraded areas were mapped from the 1945 air photographs and compared with those on 2002 photographs (Keay-Bright & Boardman, 2006). There had been a decline of 15% in area. This is likely due to reduced stocking densities which have been declining in the Middelburg Magisterial District since the 1930s (Timm Hoffman personal communication, Figure 10, Keay-Bright & Boardman, 2006 and Figure 7, Chapter 1 this guide). It is unlikely to be due to change in rainfall patterns since the local trend is for an increase in rainfall amount on rain days (see Chapter 1, this guide). Despite the decline in area, degraded areas remain extremely active geomorphologically (see below and Figure 1).

Figure 1 Compassberg badlands: erosion pin site 2

3. EROSION RATES ON BADLANDS

Methods of assessing erosion rates on badlands are described in Keay-Bright & Boardman (2009); these include measurement of loss of soil around stone pedestals and shrubs (Pteronia tricephala) but this was not felt to be as reliable as the use of erosion pins. Arrays of 25 erosion pins were inserted 1 or 2 m apart at ten sites in the Compassberg area on severely degraded land or badlands (Figure 2). The sites were chosen to give a range of topographic and lithologic variables (Table 1). The measurements were carried out during 12 visits (2001-10). Damaged or lost pins were replaced. The pins are 335 mm long and 3mm in diameter and were sited within the badlands at interfluve, footslope, channel and side-wall locations. The majority of pins show soil loss (erosion) over the period of measurement, a minority show gains (deposition). It is therefore possible to estimate net rates of erosion for each array of pins.

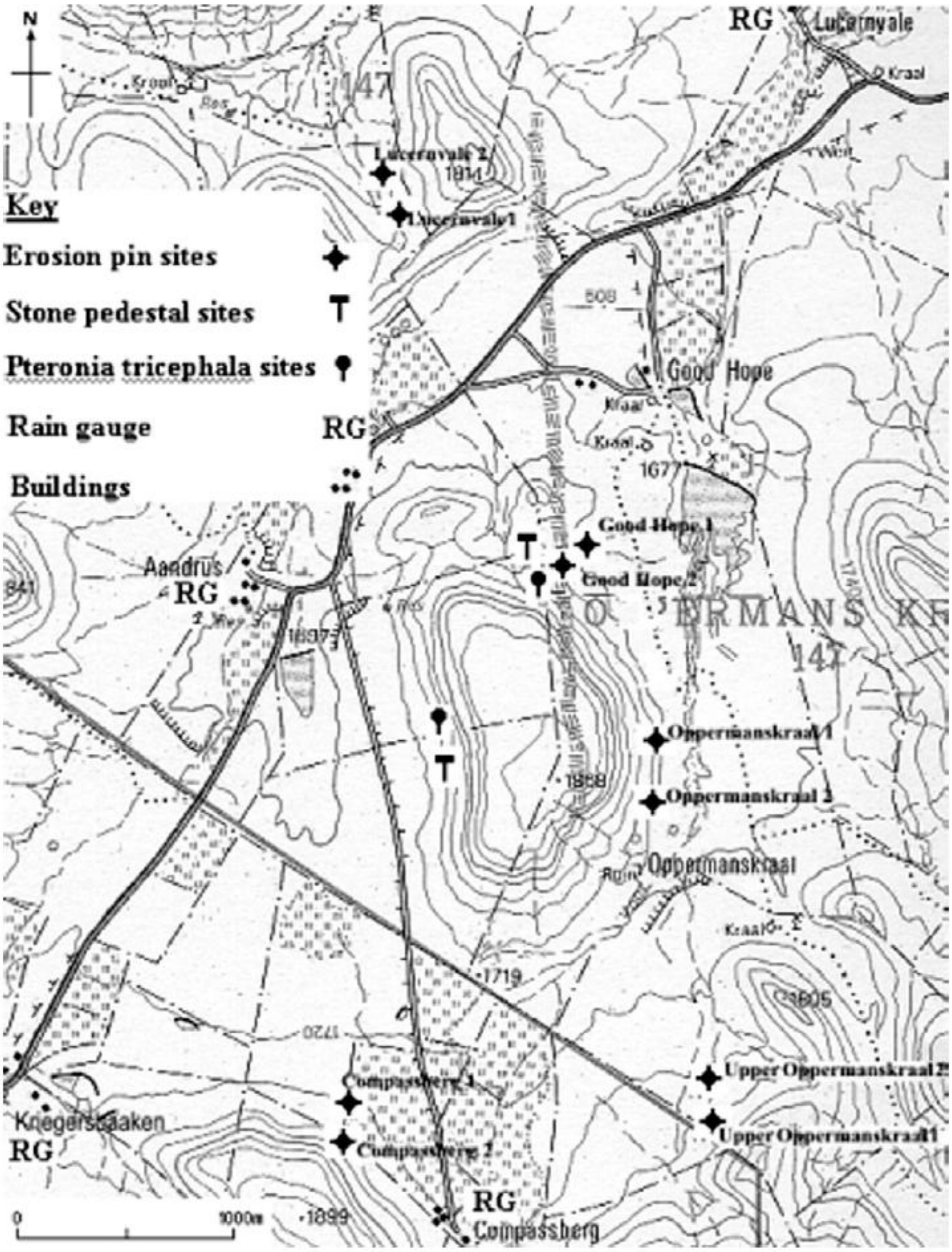
Table 1 Description of erosion pin sites at Good Hope and Compassberg Farms

Site	**Description**
Good Hope 1	Across small gully and broad, gently sloping interfluves (4 degs). Gully very stony (sandstone) with shale bedrock at shallow depth outcropping in channels. Relief 0.6 – 1.0 m. Colluvium appears thin on interfluves and in sidewalls (60-80cm). Little vegetation, a few shrubs on interfluves.
Good Hope 2	Flattish interfluves (4 deg slope) with shrubs with exposed roots; few stones. Relief 1.5m. Clayey, shale-derived colluvium. Steep gully sidewalls, a little grass in channels. No bedrock exposed. No stones in channel. Undissected interfluve upslope of site, rill head working into it with pattern of shallow channels.
Compassberg 1	Flattish interfluve (2 degs), very compact and little vegetation. Colluvium 60 cm depth overlying shale outcropping in channels. Max relief 0.85 cm. Some vegetation recolonising channels and footslopes. Gully heads sometime form arches and then collapse. Very few stones in colluvium or on surface. Runoff event: see Fig 4 Boardman and Foster (2009).
Compassberg 2	Relatively stoneless colluvium generally 1.2 m thick overlying shale. Max relief 1.5 m. Many signs of sidewall collapse and channel downcutting to shale.

Similar erosion pin networks were established in the Ganora catchment in 2007 at sites located on Figure 2 (Chapter 5, this guide).

Erosion pin sites at Good Hope and Compassberg will be visited. Good Hope 1 site shows the lowest rates of erosion and Compassberg 2 the highest (Table 2). These differences probably relate to more active runoff processes, thicker colluvium and steeper side-wall slopes at the latter site.

Figure 2 Location of erosion measurement sites in the Compassberg area (after Keay-Bright and Boardman, 2009).



Net loss for the two Good Hope sites is ca. 3 and 5 mm y^{-1} respectively. This translates into 51 and 85 t ha^{-1} y^{-1} using a measured bulk density from the badland surface of 1.7 g cm^{-2}. Sediment sampling of runoff in the main channel draining the Good Hope badlands during an 11 mm rainfall event suggests a rate of sediment loss from the badlands of 54.8 t ha^{-1} y^{-1} which is in line with estimates from erosion pins (Keay-Bright & Boardman 2009). However, it is noteworthy that rates of deposition in two local reservoirs (Dams 7 and 10 at

Compassberg Farm) are estimated at 1.2 t ha^{-1} y-1 and 3.6 t ha-1 y^{-1} respectively. The discrepancy is due to storage of eroded sediments in fans between badland sites and valley bottoms. Also the two quoted reservoirs do not have badlands in their catchments. A more apt comparison is with the Ganora Farm reservoir with 15% badland area where deposition rates are 6.6 t ha^{-1} y^{-1} (Boardman et al, 2010; Rowntree & Foster, In Press).

Table 2 Average annual loss for eroding pins in the Compassberg sites

Site and years of record	Annual average loss (mm)
Good Hope 1 (9)	7.56
Good Hope 2 (9)	11.99
Compassberg 1 (9)	10.70
Compassberg 2 (9)	17.25
Oppermanskraal 1 (8)	11.90
Oppermanskraal 2 (8)	7.65
Low Upper Oppermanskraal (8)	9.27
Up Upper Oppermanskraal (8)	9.71
Low Lucernvale (8)	9.29
Up Lucernvale (8)	10.60

The results of the erosion pin measurements for the badland sites at Ganora are given in Table 3. The soil loss rates indicate that the badland crests and midslopes continue to be significant sites of erosion, especially during wet periods such as during the first two months of 2008 when 195 mm of rainfall was recorded at Ganora farm (J.P Steynberg pers. comm.). The erosion rates for Ganora are similar to those reported by Keay-Bright & Boardman (2009) in other upland areas nearby (Table 2).

Table 3 Erosion pin measurements for badland sites in the Ganora catchment (Rowntree & Foster, In Press)

Average mm surface lowering over 20 month period Jan '07 to Sep '08

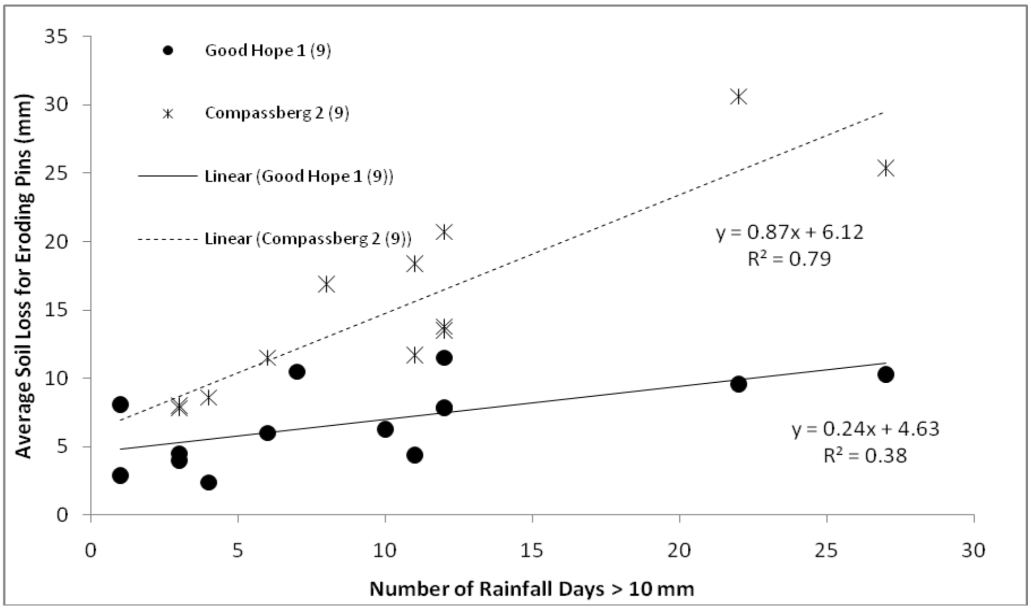
crests	midslopes	channel
-5.85	-4.69	+9.13

Average mm surface lowering over two month period from 10.01.08 to 17.03.08

crests	midslopes	channel
-5.46	-4.59	+0.8

Runoff on these badland areas has been observed in response to rainfall events as low as 10 mm (e.g. Fig 12 in Keay-Bright & Boardman, 2006). Sediment samples have been obtained from runoff in such events. Erosion amounts as estimated from pins in two of the Compassberg sites are correlated with the number of days on which rainfall exceeds 10 mm (Figure 3). That they are not better correlated is due to the fact that weathering prepares the badland surfaces for removal by runoff. Weathering history prior to rainfall is therefore a control on amounts eroded. We can only speculate that wetting and drying and frost action in the presence of moisture are potent weathering agents. Shale stones and boulders found on the surface of the alluvial fan at Compassberg Farm reservoir transported whole in the flood of January 2010 had disintegrated due to weathering a month later.

Figure 3 Average soil loss at Good Hope 1 and Compassberg 2 erosion pin sites for periods of time of varying length, plotted against rainfall for each period. Rainfall data from Compassberg Farm.



4. CONCLUSION

Some major issues remain to be resolved. In particular the age of the gully systems: all that is known is that their present form pre-dates 1945.

- There seems good circumstantial evidence that degradation has been strongly influenced in the past by excessive stock numbers, particularly in the period 1900-1950 (Keay-Bright & Boardman, 2007).
- We have no information about the role of fire, managed or otherwise, but recently observed fires suggest that if followed by rainfall the impact may be significant (Figure 4). Ongoing research is looking at charcoal records preserved in the dam 7 sediments at Compassberg (see Chapter 6, this guide).
- Similarly the impact of droughts on vegetation cover and therefore on erosion is not clear. It may be that farm diaries could be used to explore this relationship.
- The possibility of restoration of degraded ground is problematic. Degradation often implies the loss of A and B soil horizons. Methods of restoration involving removal or decrease in numbers of stock, or faster rotation systems, are extremely controversial (Keay-Bright & Boardman, 2007). Lag times between reduction in stock numbers and a discernible decrease in sediment transport to the reservoirs appear to be long e.g. >50 years (see Chapter 5, this guide).
- Taking a long-term view, the striking fact is that colluvium in the area is exclusively Holocene in age and that older sediments are confined to small areas in valley bottoms (Holmes, 1998). This pattern suggests that under interglacial conditions, weathering and erosion leads to accumulation of thick sequences of colluvium, alluvium and vlei deposits. During glacial stage conditions, these sediments are redistributed and removed from upland slopes and valleys. However, the latter part of

the present interglacial has been different in that human influence has led to extensive surface disturbance and erosion. This is clearly a very simplified model which is open for discussion.

Figure 4 Effects of fire

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3. RAINFALL SIMULATION EXPERIMENTS

Tony Parsons, John Boardman, Peter Holmes

1. INTRODUCTION

Rainfall simulation experiments have been used in a number of instances to help quantify some of the differences in fluxes that characterise the two stable states of the grassland-shrubland ecogeomorphic system (e.g. Abrahams *et al*. 1995; Parsons *et al*. 1996; Schlesinger *et al*. 1999). In the study undertaken here, we sought to identify differences in runoff and sediment fluxes from the grassland, shrubland, and abandoned cultivated land. A variety of rainfall-simulation techniques is available; here we used an Amsterdam drip-type simulator (Bowyer-Bower & Burt, 1989), and we conducted rainfall simulation experiments on twenty-two 0.5-m by 1.0-m runoff plots (Figure 1). The average intensity of the simulated rainfall in the experiments was 25.2 mm/hr, the median drop size was 0.67 mm and the fall height was 140 cm, giving a kinetic energy of the simulated rainfall of 0.089 J m^{-2} s^{-1}. Rainfall intensities for individual experiments ranged from 15.6 to 35.5 mm/hr. With the exceptions of plots 10, 11 and 20, which had durations of 40, 45 and 60 minutes respectively, all simulations ran for 30 minutes. As soon as runoff began, it was collected in one-minute contiguous samples from the outlet of the plot. After each experiment the volume of water in each sample was determined by transferring it to a measuring cylinder. The total runoff from each plot was subsequently collected into a large bottle, allowed to settle, decanted and oven dried at 105˚ C. The weight of the remaining sediment was then recorded. Prior to each experiment, a soil sample was taken from a depth of 5 cm adjacent to the plot, for subsequent determination of antecedent soil moisture. After each experiment, the percentage of the plot covered by vegetation, stones equal to or larger than 5 mm diameter, stones 2 - < 5 mm diameter and particles smaller than 2mm was determined by grid sampling of 100 points over the plot. In addition, the gradient of each plot was measured.

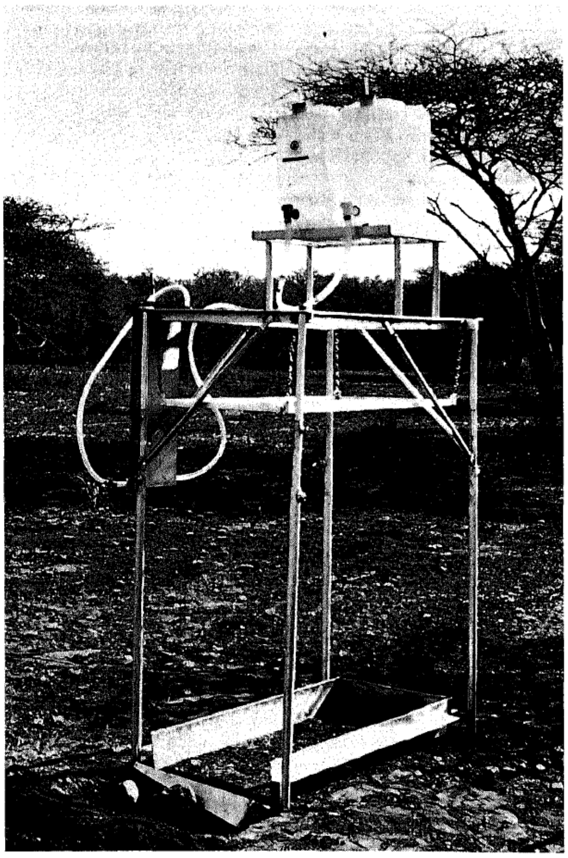
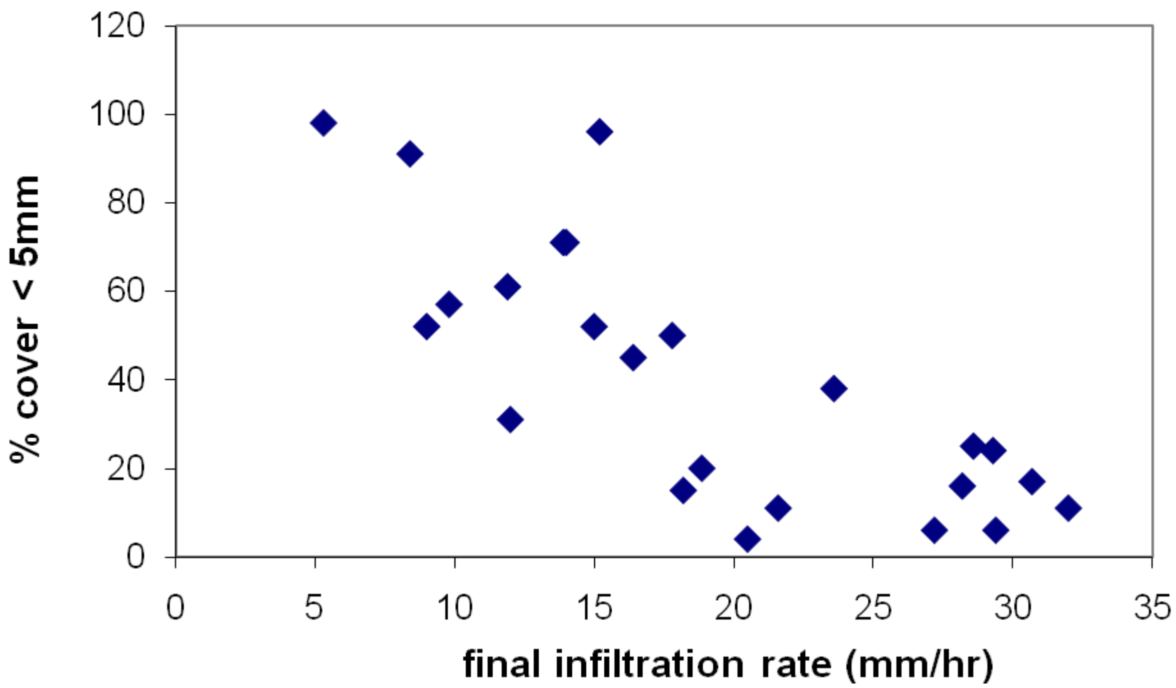


Figure 1 Rainfall simulator used in experiments (after Bowyer-Bower & Burt, 1989)

2. RUNOFF

Vegetation and large stones are positively correlated with the final infiltration rate. Poesen *et al*. (1990) demonstrated that rock fragments may either promote or inhibit infiltration depending on whether they are embedded within the soil surface or lie loose on top of it. At our field sites, they lie loose on the surface and, as Poesen *et al*. found, promote infiltration. Vegetation, likewise, has been observed to promote infiltration (e.g. Abrahams *et al*., 2003), both because of the tendency for fine material to be present around the bases of plants, and for these sites to be preferential locations for burrowing animals and because vegetation reduces raindrop impact and, thereby, inhibits sealing of the soil surface. Greater percentage cover of fine materials denotes the absence of these influences, as well as the greater likelihood of soil sealing which inhibits infiltration. A summary of these effects is demonstrated by the negative relationship between final infiltration rate and the percentage cover of fragments < 5mm (Figure 2).

Figure 2 Final infiltration rate as a function of percentage ground cover < 5 mm (used as an indicator of cover of fine materials)



Using the three independent variables of percentage ground cover of fine particles, antecedent moisture and the rainfall rate, we performed a multiple regression with final infiltration rate as the dependent variable. Antecedent moisture failed to enter the equation at p= 0.95, and the final equation is

$$I = 8.67 + 0.69R - 0.18F5 \quad (1)$$

in which I is final infiltration rate (mm h^{-1}), F5 is percentage of plot surface covered by particles < 5 mm and R is rainfall (mm h^{-1}), and which has an r^2 of 0.83. Of the independent variables, F5 enters the equation first and a simple regression of I on F5 has the form

$$I = 27.48 - 0.21F5 \quad (2)$$

which has an r^2 of 0.58.

Using equation (1), a nominal value for rainfall of 25 mm h^{-1} and measures of the percentage of ground covered by particles < 5mm, it is possible to estimate the infiltration (and runoff) from the grassland and shrubland areas. We obtained the percentage of ground covered by vegetation, stones > 5 mm, stones 2 to < 5mm and particles < 2 mm in the grassland and shrubland communities by sampling every 0.5 m along 50 m transects. Under rainfall at 25 mm h^{-1}, after 30 minutes rainfall the infiltration rate on the grassland would be 23.9 mm h^{-1}, whereas in the shrubland it would be 20.6 mm h^{-1}. Conversely runoff would be 1.1 and 4.4 mm h^{-1}, respectively. The importance of rainfall intensity as a factor influencing infiltration needs to be mentioned here. This result does not imply that rainfall would need to be in excess of 20 mm h^{-1} before runoff would occur on the shrubland. In fact, we observed runoff on the shrubland area during the rainfall event that occurred after the experiment on plot 5, when our measure of peak intensity over a 30-minute period was 10 mm h^{-1}.

Using the same equation and similar transect data from the degraded badland footslopes yields an estimated infiltration rate of 13.9 mm h^{-1} (runoff of 11.1 mm h^{-1}).

3. SEDIMENT YIELD

A similar pattern in the influences of the surface properties of the plot to that observed for the runoff is evident for sediment yield. Fine particles lead to greater sediment production, whereas stones and vegetation are associated with lower sediment production. Total sediment production is also correlated strongly (r = 0.83) with total runoff. Inasmuch as runoff itself is inversely related to infiltration (and hence positively related to sediment yield) this correlation is to be expected. Given the latter relationship, it is inappropriate to include both runoff and percentage of surface fines in a multiple regression to predict sediment loss. Accordingly a simple regression of sediment load on percentage of the plot surface covered by particles smaller than 2 mm has been obtained, as follows

$$S = 0.003\%F2 \qquad (3)$$

in which S is sediment yield (g m^{-2} min^{-1}) and F is the percentage of the plot surface covered by particles finer than 2 mm. This equation has an r^2 of 0.54.

Using the same transect data as before, estimates of sediment production from grassland, shrubland and the degraded sites are 0.034, 0.085 and 0.203 g m^{-2} min^{-1}, respectively.

4. DISCUSSION

The results of these experiments allow us to hypothesise on the geomorphic effects of vegetation change in the Karoo. On hillslopes with stony soils, a change of vegetation from grassland to shrubland leads to a reduction in the proportion of the surface area covered by vegetation and an increase in both the cover by stones and fine particles. In consequence, there is an increase in runoff and erosion rate. However, whereas runoff increases four times, the erosion rate increases only 2.5 times. On the finer-textured footslope soils runoff increases dramatically (tenfold) and the erosion rate increases sixfold. The results imply that the footslope areas which have less stony soils are more susceptible to degradation as a result of vegetation change and it is in these locations that increases in runoff and erosion rates are most significant.

5. CAVEAT

The results obtained here are constrained by the scale of the experiment and the type of rainfall used. They represent relative differences, but not absolute ones. Evidence from elsewhere (e.g. Schlesinger *et al.* 1999, 2000) shows that studies undertaken at different spatial scales and using natural rainfall events may produce quite different values for relative fluxes from different vegetation communities.

Acknowledgement

Much of the information presented here is taken from Boardman *et al*. (2003)

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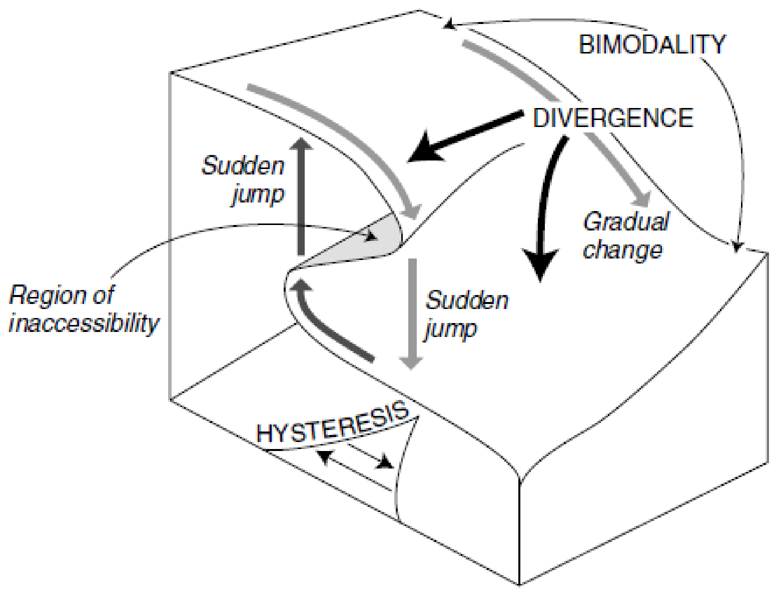
4. VEGETATION AND EROSION

Tony Parsons, Jen Dickie

1. CONTEXT: THE ECOLOGY OF EROSION

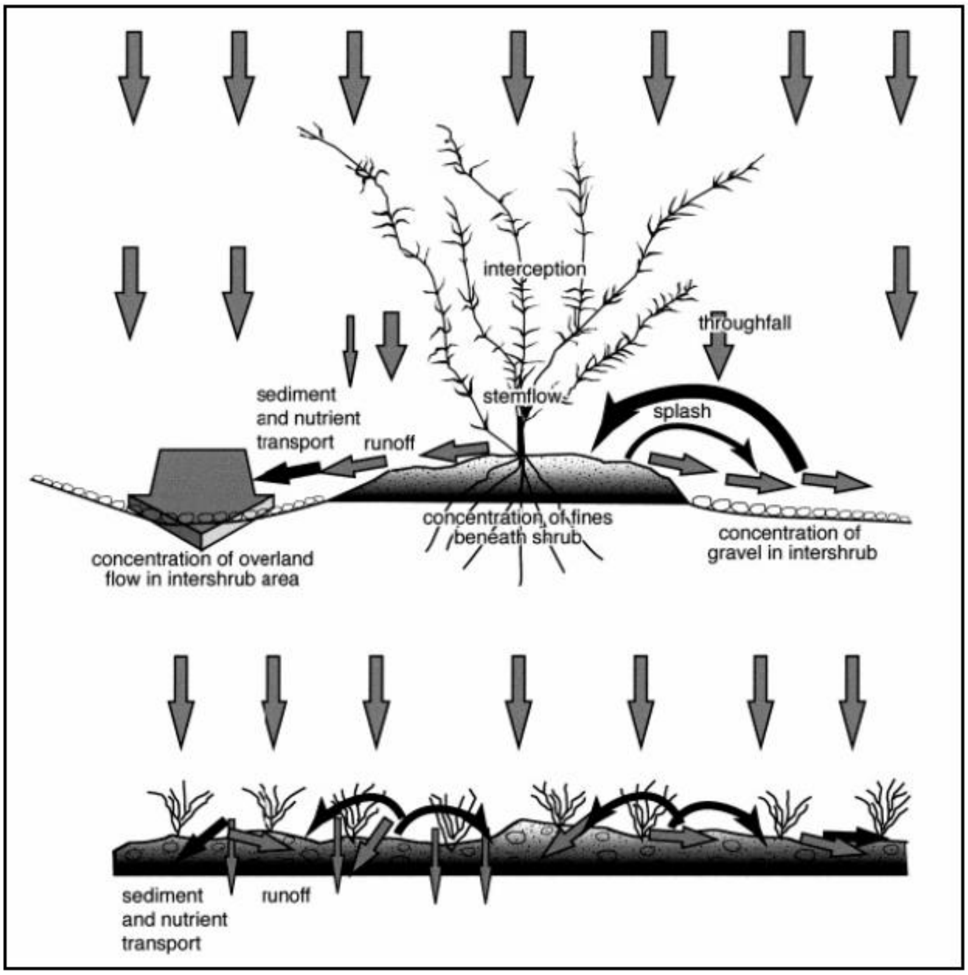
The relationship between vegetation and geomorphic processes is only slowly emerging as one of mutual interdependence, despite the fact that it is now 25 years since Thornes wrote the 'Ecology of Erosion' (Thornes, 1985) in which he argued that the growth of vegetation modified geomorphic processes which, in turn, modify the growth of vegetation. A crucial outcome of such interdependence is the notion that vegetation and geomorphic processes may exist in some sort of equilibrium that may be subject to perturbations, and that these perturbations may drive the ecogeomorphic system into a new equilibrium state. In drylands, a widely observed example of such a shift to a new equilibrium state is the transition from grassland to shrubland. It has been proposed that the dynamics of these grassland-to-shrubland transitions are an example of the notion of thresholds, whereby the perturbation causes the ecogeomorphic system to move to a new stable state (Westoby *et al*. 1989; Laycock, 1991), and that they can be conceptualised within the cusp catastrophe model (Figure 1). There are five properties of grassland to shrubland transitions that have been identified as indicative of cusp catastrophe behaviour (Turnbull *et al.* 2008). They exhibit bimodality in having two distinct stable vegetation states; a region of inaccessibility in which the system is unstable; a tendency to make a sudden jump from one stable state to the next; divergence, whereby a small changes in the governing mechanisms can result in markedly different system behaviour; and hysteresis in which the trajectory of change from grassland to shrubland is different from that in the reverse direction.

Figure 1 Cusp catastrophe model of grassland-shrubland transitions (after Turnbull *et al*. 2008)



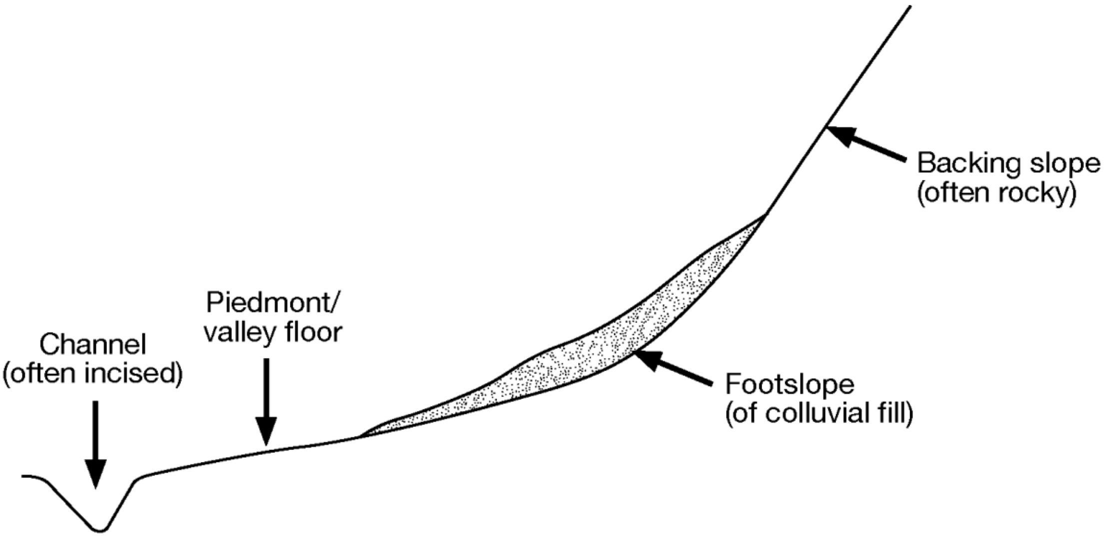
A key concept that has emerged within the study of grassland to shrubland transitions, but one which explains only part of the cusp catastrophe behaviour, is the notion of 'Islands of Fertility' (Charley & West, 1975; Schlesinger *et* al, 2000), which has significant implications for geomorphic processes (Wainwright *et al*, 2000) – see Figure 2. There are two principal shortcomings of the Islands of Fertility model. First, but less important in the context of the short-term past of the Karoo, is that the model provides no way back. Because it emphasises the positive feedback mechanisms of accrual of resources around shrub islands, how such islands may degrade and the landscape revert to grassland is not explained. Secondly, but probably linked to the first problem, is that the model operates only at the plant-interplant scale, and provides no understanding of ecogeomorphic dynamics at a larger, landscape scale.

Figure 2 The basic interactions between vegetation, water movements and erosion on hillslopes, showing differences between shrubland (upper) and grassland (lower). After Wainwright *et al*. (2000)



In the Karoo, we would argue that these landscape-scale ecogeomorphic dynamics are fundamental to understanding the consequences of vegetation change. Typically, hillslope profiles show a backing slope, a colluvial footslope and a piedmont/valley floor (Figure 3). In some senses, it may be argued that the vegetation on the backing hillslope may be regarded as a key driver of the erosional processes downslope. If the backing hillslope is grassland, infiltration is higher and runoff is lower. But if these hillslopes are shrub-covered, their infiltration rates decline and runoff to the colluvial footslopes increases. The impact on the colluvial footslope of this increased runoff from upslope may also depend on the vegetation cover of the footslope, because the same differences of infiltration and runoff will exist there, also.

Figure 3 Schematic Karoo hillslope profile



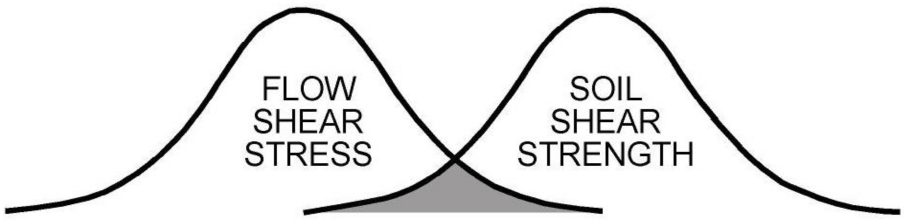
2. THE DYNAMICS OF GULLYING AND THE DEVELOPMENT OF FOOTSLOPE BADLANDS

In many locations, colluvial footslopes have become dissected and now form badlands (Figure 4).

Figure 4 Badlands on a colluvial footslope

Intuitively, it might be thought that increased runoff can explain incision and badland development. However, overland flow depths are typically insufficient to account for sediment entrainment using conventional shear stress: shear strength measurements. Nearing (1991) proposed that this conundrum might be solved by considering the distribution of values of shear strength and shear stress (Figure 5), and Parsons & Wainwright (2006) developed this argument further to determine the probability of flow detachment and channel incision under shrubland and grassland.

Figure 5 Overlapping distributions of shear stress and shear strength (after Nearing, 1991)



Based on this reasoning, Dickie (2006) undertook an extensive sampling programme of soil physical and chemical properties at sites on Karoo grasslands, shrublands and badlands. The study tested the hypothesis that shrub encroachment in dryland environments initiates a change in scale of soil heterogeneity that consequently influences the landscape's biotic and abiotic interactions and potentially the susceptibility of soil to erosion. Using a hierarchical spatial framework, the distribution of soil properties in each of the three landscape types were investigated; comparisons of the spatial patterns were made to determine both the importance of scale, and whether badland development in shrublands are a function of a continued and pronounced redistribution of soil parameters.

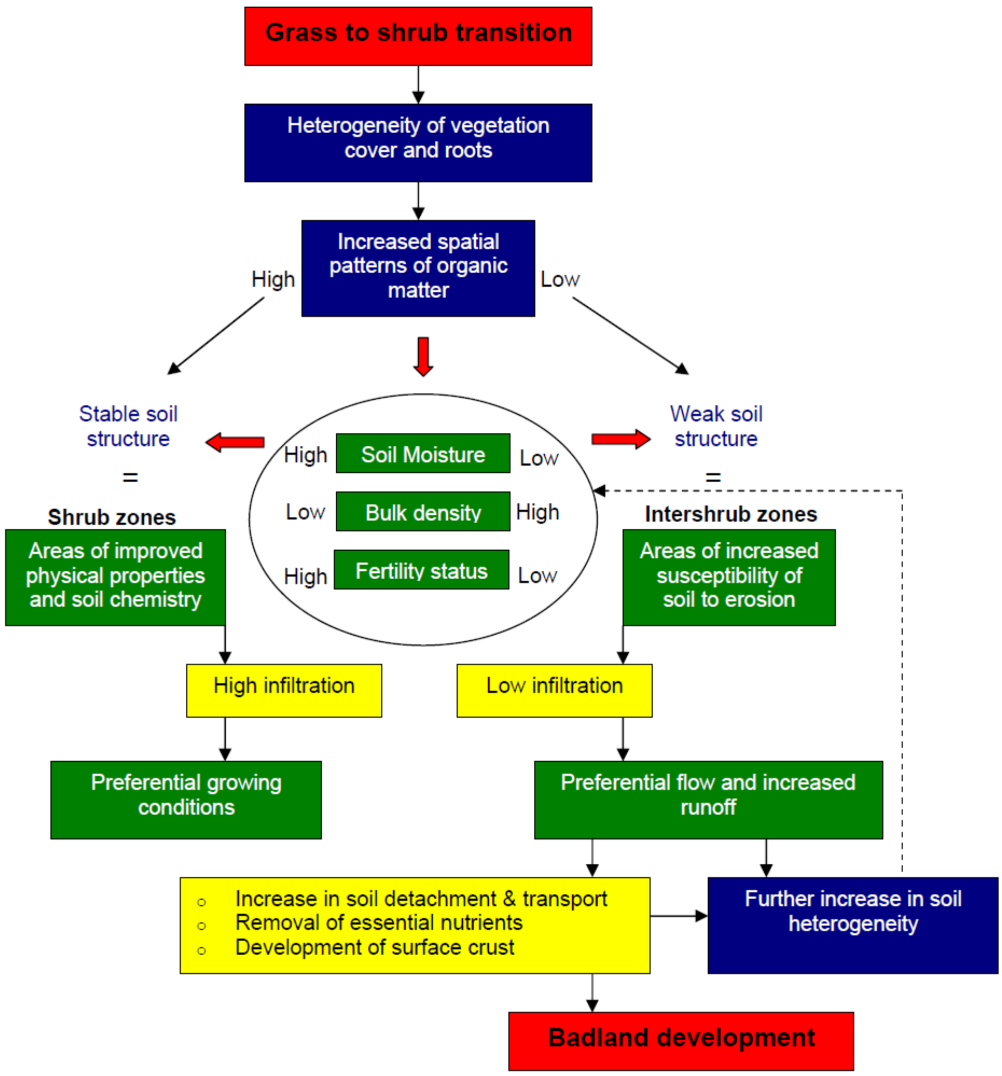
Seven 60m x 60m plots were analysed for bulk density, shear strength, texture, aggregate stability, organic matter content, pH, conductivity and available sodium, calcium, magnesium, potassium and phosphorus content. Geostatistical analyses determined that, at a scale representative of the vegetation community, the grasslands were generally homogenous in their distribution of soil parameters. Shrublands, however, demonstrated an increase in heterogeneity of all soil parameters. Where clear spatial autocorrelation could be identified from the semi-variograms, ranges were reasonably consistent for the physical soil parameters, at around 4-6m. The chemical parameters were more variable. In some cases, traditional autocorrelation analyses could not be performed due to the complexity of the spatial structure; these semi-variograms generally displayed cyclic patterns. The structure of the semi-variograms and additional Moran's I and Geary's C correlograms were used to identify the spatial structure of these soil parameters.

Every physical soil parameter in the shrubland dataset and all parameters in the badland dataset demonstrated some degree of cyclic behaviour. In the shrubland dataset, this was most evident for organic matter content where an average wavelength of 4m was identified. Although the periodicity of other parameters show less consistency, when considered together, the ranges of spatial autocorrelation, periodicity, and the analyses of the correlograms indicate that regular patterns of distribution occur across the landscape. As all the ranges are greater than the maximum diameter of the shrubs (~1.5m), they are most likely to represent the intershrub areas in the landscape. The weak periodicity and spatial autocorrelation displayed by some parameters may be a function of the poorly defined intershrub areas, this is a characteristic of the vegetation structure in the Karoo, where grassland species are commonly found interspersed throughout the karroid *Merxmuellera* mountain veldt shrub species. In the badland landscape the periodicity was even more prevalent; an average wavelength of 8m suggests that, in the absence of significant patches of vegetation, the spatial patterns may be related to the undulating nature of the interfluves and gullies.

Using correlation analyses, it was determined that organic matter is the key component in the plant-soil relationship and hence is the starting point in understanding how the spatial distribution of plants affect the erodibility of soil. Although Geddes & Dunkerley (1999) show that leaf litter and organic matter are redistributed throughout the shrubland landscape by rainsplash, the spatial patterns show evidence of autocorrelation and periodicity suggesting that this process does not redistribute the organic matter significantly.

Instead, it is proposed that a change in organic matter content acts as a catalyst to further changes in the physical and chemical nature of the soil. The conceptual model shown in Figure 6 summarises the processes linking vegetation change and increased erosion, and provides a possible mechanism to explain the development of badlands in some semi-arid environments.

Figure 6. Conceptual model of processes, patterns and interactions connecting vegetation change to the susceptibility of soil to erosion in semi-arid environments (after Dickie, 2006)



The model suggests that two scenarios can occur following bush encroachment: 1. the cycle of plant - soil property interactions can continue in a relatively stable fashion; the spatial heterogeneity becomes more defined in the shrublands, but badlands do not develop. 2. the cycle of plant-soil interactions can continue until the extent of spatial heterogeneity is such that the conditions that inhibit plant growth are predominant in the landscape and badlands develop, as seen in the Karoo. However, the soil type and local conditions determine the areas that are sensitive to further degradation rather than the presumption that all intershrub areas will continue to degrade to this extent. The decrease in mean contents of organic matter and soil moisture and the increase in shear strength and bulk density seen in the Karoo badlands compared to the shrublands demonstrate how the soil properties are adversely affected by loss of vegetation; however, it is the soil type that determines whether a concrete-like crust develops. The crust itself creates a dense soil structure that will not only reduce the infiltration capability and increase surface runoff but also makes it difficult for plants to become re-established. These factors all contribute to the increase in erosion evident in badland landscapes. In summary, if the correct conditions exist, shrubland landscapes can continue to degrade until the intershrub regions become the dominant landform; the landscape becomes inhospitable to plants and hydrological processes lead to conditions that propagate rills and gullies.

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5. CHANGING SEDIMENT YIELDS AND SOURCES FROM AN ANALYSIS OF DATED FARM DAM SEDIMENTS

Ian Foster, Kate Rowntree, John Boardman, Tim Mighall

1. THE CONTEXT

In South Africa, the progressive deterioration of vegetation quality (‘desertification’) is much debated with competing climatic and overgrazing hypotheses (Hoffman & Cowling, 1990; Bond et al., 1994; Hoffman et al., 1995; Hoffman et al., 1999; Hoffman & Ashwell, 2001). Furthermore, the potential for invasive species to alter the hydrological behaviour of former grazing systems in the Eastern Cape has been implicated in regional land degradation, including badland development (Kakembo & Rowntree, 2003). However, less attention has been paid to physical changes to the landscape.

Landscape degradation in the research area (Figure 1 A&B) is characterized by the presence of badlands located on the foot-slopes of upland areas and by gully systems (dongas) located in valley bottoms (Boardman et al., 2003; Keay-Bright & Boardman, 2006). Herding of domestic livestock has probably been a significant management component in parts of the Karoo landscape for at least 2000 years (Elphick, 1985; Bollong & Sampson, 1999). However, it is debatable whether pre-colonial herders caused irreversible damage to the landscape. Lovegrove (1993) suggested that these early communities could have been responsible for some localized overgrazing, whereas Fox (2000) suggested that European settlers were responsible for the dramatic increase in degradation over the last 200 years. Our research has focused on the period since European colonisation, which began in the second half of the eighteenth century (Raper & Boucher, 1988; Newton-King, 1999; Smith,1999).

Since long term erosion and sediment yield data are not available for the Karoo, we have selected and undertaken palaeoenvironmental reconstructions to date in four research catchments with dams and reservoirs at their downstream ends. The overall aim of this part of the research programme is to: (1) reconstruct sediment yield through time by estimating rates of sediment accumulation in the reservoirs (2); qualitatively model changes in sediment sources over time by using geochemical, radionuclide and mineral magnetic signatures of accumulating sediments compared to the signatures of potential sources and (3); use other available secondary data (maps, aerial photographs, satellite imagery, documentary records, weather records) in order to correlate changes in sediment yield with known periods of catchment disturbance or modification.

The four catchments were chosen to represent a range of factors frequently deemed responsible for changing rates of erosion and land degradation. Two catchments (Compassberg Dams 7 and 10; Figure 1C) have well developed donga systems but no badlands. Lying at similar altitudes north of Compassberg, the catchment of dam 7 had rainfed cereal cultivation that peaked in extent in the late 1950s while that of Dam 10 had no evidence of former cultivation. Both, however, had been grazed. The Ganora catchment (Figure 2) is in a similar physiographic setting to that of Dam 7, but has clearly defined dongas and extensive badlands occupying ~ 15% of the total catchment area and has been grazed but not cultivated (Rowntree & Foster, In Press). By contrast, the Cranemere Reservoir (Figure 3) is a much larger catchment with only a small area occupied by mountains (part of the Coetzeesberg). Much of the catchment lies on the plains of Camdeboo, has some former areas of cultivation and has been heavily grazed. However, the catchment has a complex drainage system with clearly defined dongas in some areas that are poorly connected to the main channel (Foster & Rowntree In Press). The main channel itself frequently becomes indistinct and there are several alluvial fans that appear to

Figure 1 **The Research Area. Location of field area in the Eastern Cape (A); Physiography of the Karoo region showing the location of research sites (B) and detail of the Compassberg Dams and Catchments (C).**

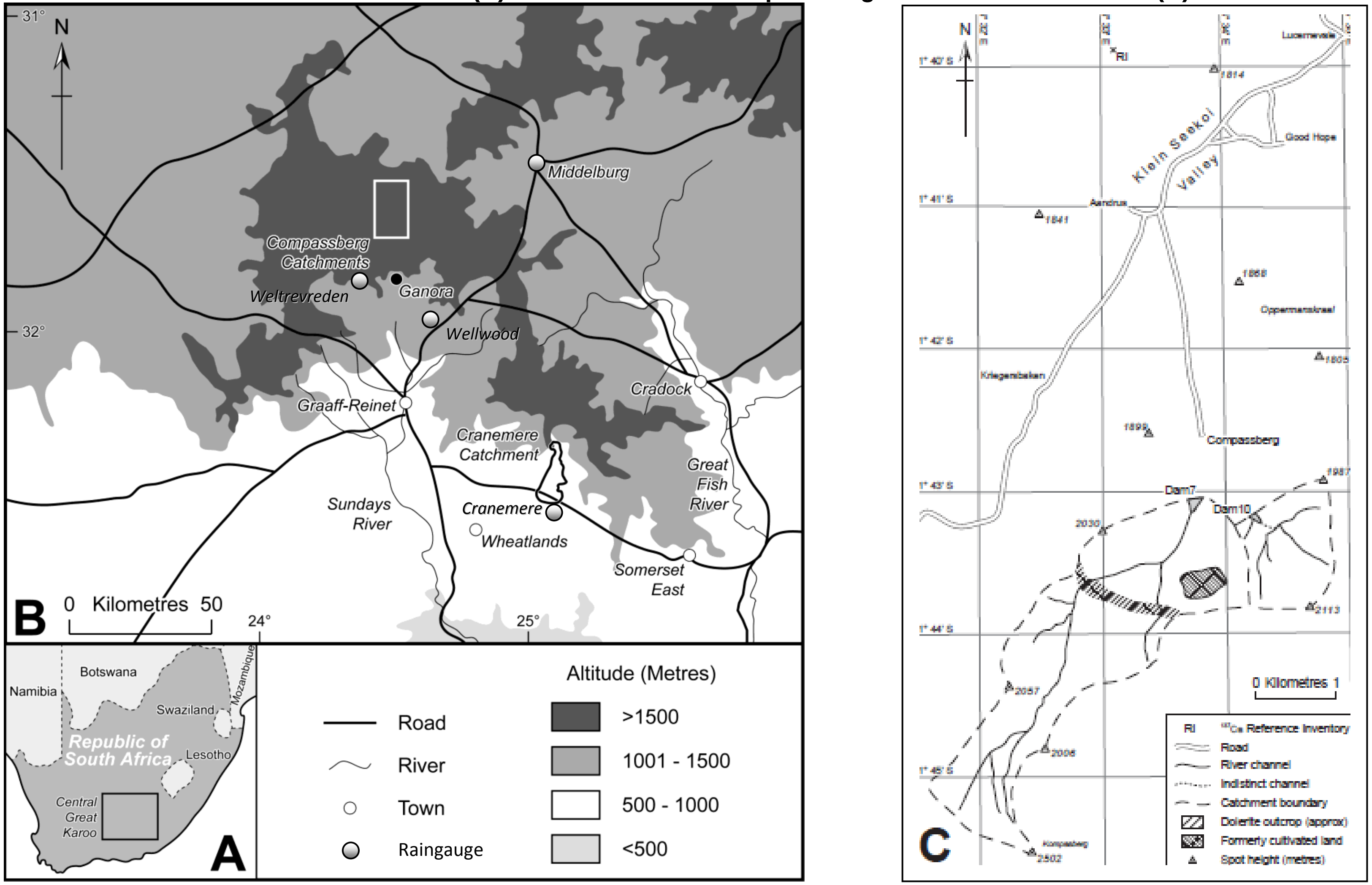


Figure 2 The Ganora Catchment

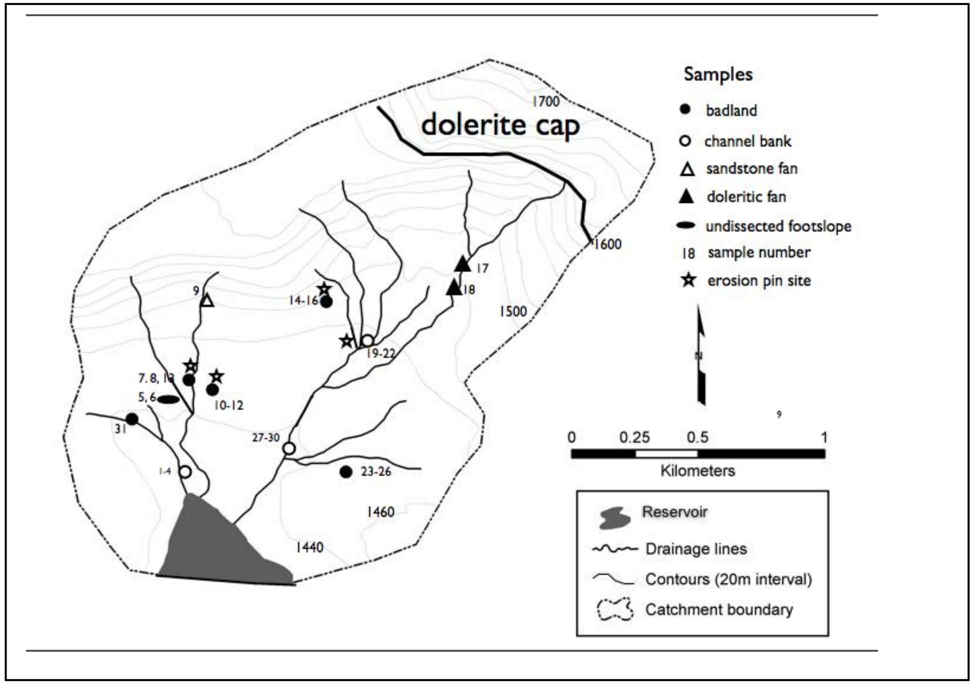
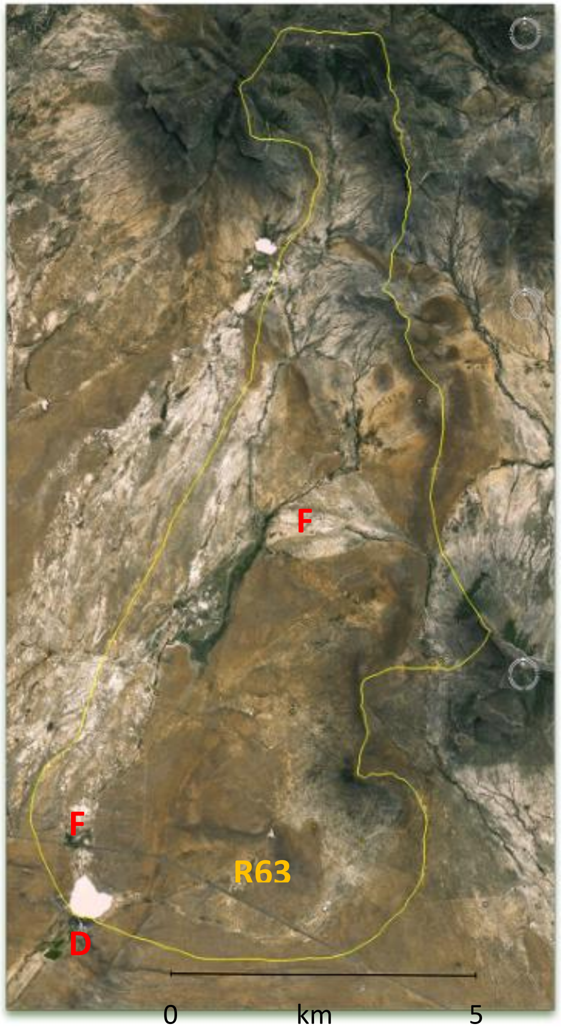


Figure 3 The Cranemere Catchment



Cranemere Catchment

R63 **Main Road Pearston to Graaff Reinet**

D **Cranemere Dam**

F **Alluvial Fan**

be operating as temporary sediment stores within the catchment, either on tributary valleys or on the main channel feeding the reservoir. The main road from Somerset East to Graaff Reinet (R63) runs close to the northern edge of the reservoir and was elevated on a causeway and culverted in 1950.

Three of the four catchments lie within 20 km of each other. Differences between these catchments in terms of erosional response are therefore likely to be independent of weather and climate and are more likely to reflect changes in land management and the internal regulation of sediment delivery (connectivity) within the catchment.

2. FIELD AREA

A general introduction to the geology, soils climate and vegetation of the region has already been given in an earlier section of this guide and will not be repeated here. Details of the four catchments and dams are given in Figures 1-3 and in Table 1.

Table 1 Characteristics of farm dams 7 & 10 at Compassberg, the farm dams at Ganora and Cranemere and their catchments.

Characteristic	Dam 7	Dam 10	Ganora	Cranemere
Catchment area (excluding reservoir) (ha)	630	148	258	5751
Reservoir area (ha)	3.37	1.52	5.23	30.22
Catchment to reservoir area ratio	187:1	98:1	53:1	190:1
Maximum altitude (m)	2502	2113	1741	1507
Minimum altitude (m)	1840	1860	1428	753
Maximum basin relief (m)	662	253	313	754
Relief Ratio*	0.13	0.23	0.15	0.08
Construction Year	~1935	~1935	1910	1843
Sampling Year	2003	2003	2006	2007

*Relief ratio = H/L where H = Maximum basin relief; L = longest dimension of basin parallel to principal drainage line (Schumm, 1956).

3. FIELD METHODS & SECONDARY DATA SOURCES

3.1 The Reservoirs

The sediments in all four reservoirs have been sampled at between1 and10 cm depth increments at approximately the deepest part of the fill between 30 and 50 m from the dam walls using either soil pits or augering (combination of 'Russian' and / or 'Gouge' corers). Sub-samples collected from these individual 'master cores' have been used for dating the fill using a combination of ^{210}Pb and ^{137}Cs and for characterising the fine sediments using a combination of radionuclide, mineral magnetic and geochemical signatures that were compared with similar signatures in potential contributing sources. Additional cores were taken from 7-14 locations in the reservoir fill in order to estimate the thickness of the fill and subsequently calculate its volume and mass. These additional cores were also needed to identify time-synchronous depositional layers in the sediments that were correlated on the basis of either visible stratigraphy (e.g. changes in particle size) or mineral magnetic signatures. Correlation of time synchronous depositional layers was essential in order to subdivide the deposited sediments into time zones from which sediment yields could be reconstructed. In each case the area of sedimentation was surveyed in the field.

3.2 The Catchments

Between 25 and 40 potential source samples were collected from each of the four catchments. These source samples were chosen to represent likely contributions to the sediments accumulating in reservoirs and included, where represented in the catchments, donga sections, formerly cultivated fields, grazed areas, areas that had been recently burned, alluvial fans, and rocky hillslopes with intermittent pockets of soil up to the drainage divide. An example of the sampling strategy used for the Ganora catchment is shown in Figure 2.

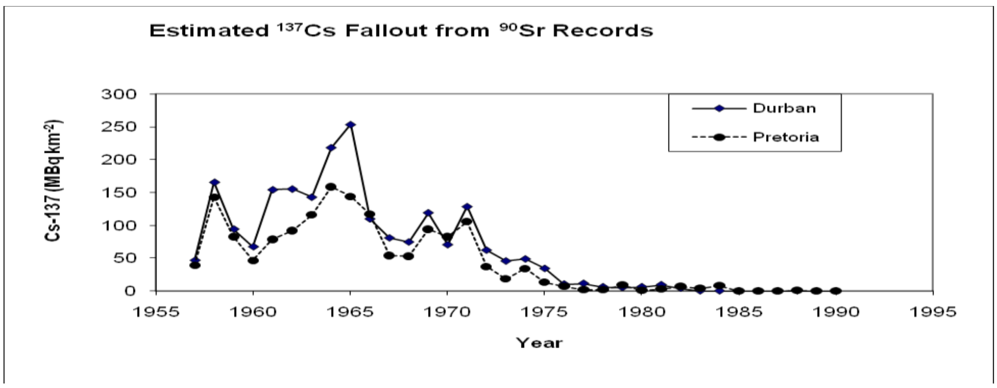
^{137}Cs fallout reference inventories have been obtained from two sites in the Compassberg area at location RI and Lucernevale (Figure 1C) and at Wheatlands on the plains of Camdeboo (Figure 1B). Suitable sites for estimating local fallout inventories are difficult to find. Ideally these sites should be flat (no erosion or deposition) and should not have been disturbed since the onset of ^{137}Cs fallout in the 1950s. Here we have used the floor of a threshing yard, an orchard and the lawn next to a farmhouse in order to obtain samples using either bulk density rings or an Eijkelkamp piston corer to depths of ~ 30 cm in soils that had been pre-wetted using an infiltrometer ring.

3.3 Secondary Data

3.3.1 ^{137}Cs fallout records

There are only 2 known sites in South Africa with available atmospheric radionuclide fallout data (Durban and Pretoria). These are several hundred km away from the research sites and only ^{90}Sr was measured in fallout. We have estimated the ^{137}Cs fallout history from these data assuming the ratio of ^{90}Sr to ^{137}Cs in fallout is ~2.8:1 (Izawa et al. 1961) and the results are shown in Figure 4. The model developed by Walling et al. (nd) was also used to estimate the bomb ^{137}Cs fallout inventory for the region based on the average annual rainfall at Cranemere and Middelberg. This is likely to provide a reasonable estimate of total fallout as there is no evidence that Chernobyl fallout reached Southern Africa.

Figure 4 Reconstructed ^{137}Cs fallout history from Durban and Pretoria



3.3.2 Land use and Rainfall records

Rainfall data and land use history of the area have been reviewed separately by Rowntree (Chapter 1; this guide).

4. LABORATORY ANALYSIS

Laboratory analysis has included:

- Air drying samples (40^{o}C) and calculation of the dry mass of sediment in each subsample from reservoir and reference inventory cores in order to calculate dry bulk density.
- Sieving reference inventory cores to < 2mm fraction; sieving potential source samples to < 250 µm fraction (Compassberg Dams 7 & 10) and <63 µm fraction (Ganora and Cranemere) to match upper particle size limits of sediment deposited in the reservoirs.
- Organic matter content (low temperature loss on ignition (450 ^{o}C for 2 hr)).
- Particle size (dry sieving and Laser Granulometry [Malvern Mastersizer with Hydro 2000 dispersal unit])
- Sediment geochemistry (microwave digestion and Inductively Coupled Plasma) for metals, alkali earths and rare earth elements.
- Gamma emitting radionuclide activities (supported and unsupported ^{210}Pb & ^{137}Cs for dating and sediment flux calculations; primordial radionuclides ^{234}Th, ^{235}U, ^{228}Ac and ^{40}K for sediment source tracing).
- Magnetic susceptibility (Bartington Instruments magnetic susceptibility meter with MS2B dual frequency sensor) and magnetic remanence properties (Molspin ARM demagnetiser, pulse magnetiser and spinner magnetometer).

Full details of the preparation and laboratory analytical methods are given by Foster et al., 2005, 2007, 2008; Boardman et al., 2010; Foster & Rowntree, In Press; Rowntree & Foster In Press).

5. RESULTS

5.1 ^{137}Cs Reference and Reservoir Core Inventories

An example of the downcore trends in ^{137}Cs activity for an undisturbed reference site (Wheatlands Farm) is given in Figure 5. Typically, undisturbed sites show an exponential decrease in activity with depth in the profile by comparison with cultivated sites where cultivation mixes the ^{137}Cs uniformly to the depth of the plough layer. Mixing of ^{137}Cs to depth in the profile in undisturbed sites is usually interpreted as being a consequence of both chemical diffusion and bioturbation. In the case of the profile shown in Figure 5, no ^{137}Cs above the limit of detection is found below 20 cm depth in the profile.

The ^{137}Cs reference inventories are given in Table 2. Comparison with estimates provided by the Walling et al. (nd) global fallout model suggest that the inventories are of the correct order of magnitude and that the lower inventory is associated with the lower rainfall recorded on the plains of Camdeboo in comparison with the upland Compassberg sites.

Fallout in Southern Africa is lower by a factor of between 3 and 4 in comparison with N hemisphere sites for which similar data are available. The reservoir inventories for the dated master cores are also given in Table 2 for comparative purposes and are substantially higher than those of the undisturbed reference sites. Conventionally, the differences are interpreted as the erosion and deposition of ^{137}Cs bearing topsoil from the contributing catchment after the ^{137}Cs has become irreversibly, and preferentially, fixed to the clay minerals in the soil (e.g. Walling & He 1993). However, we cannot discount the possibility that fallout ^{137}Cs was adsorbed by sediment already in transit at the time of fallout and delivered directly to the reservoirs (Dalgleish & Foster, 1996; Parsons & Foster, submitted).

The highest reservoir sediment ^{137}Cs inventory is in Compassberg Dam 7 which is higher than the reference inventory by a factor of ~18.

Figure 5 Downcore ^{137}Cs inventory at Wheatlands Farm, Plains of Camdeboo. (Error bars +/- 1 SD of Counting Errors).

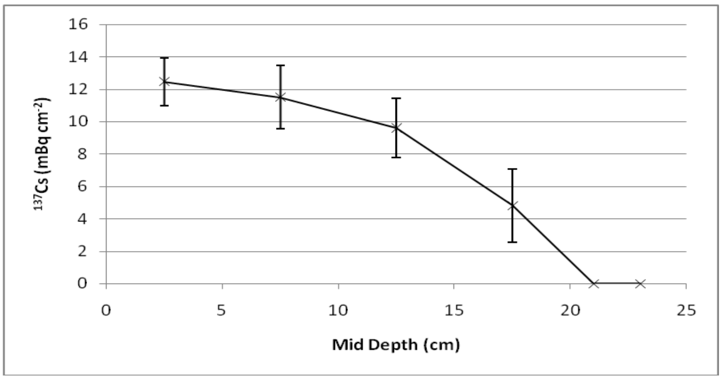


Table 2 Atmospheric Fallout ^{137}Cs Reference Inventories and reservoir sediment inventories (decay corrected to 2007).

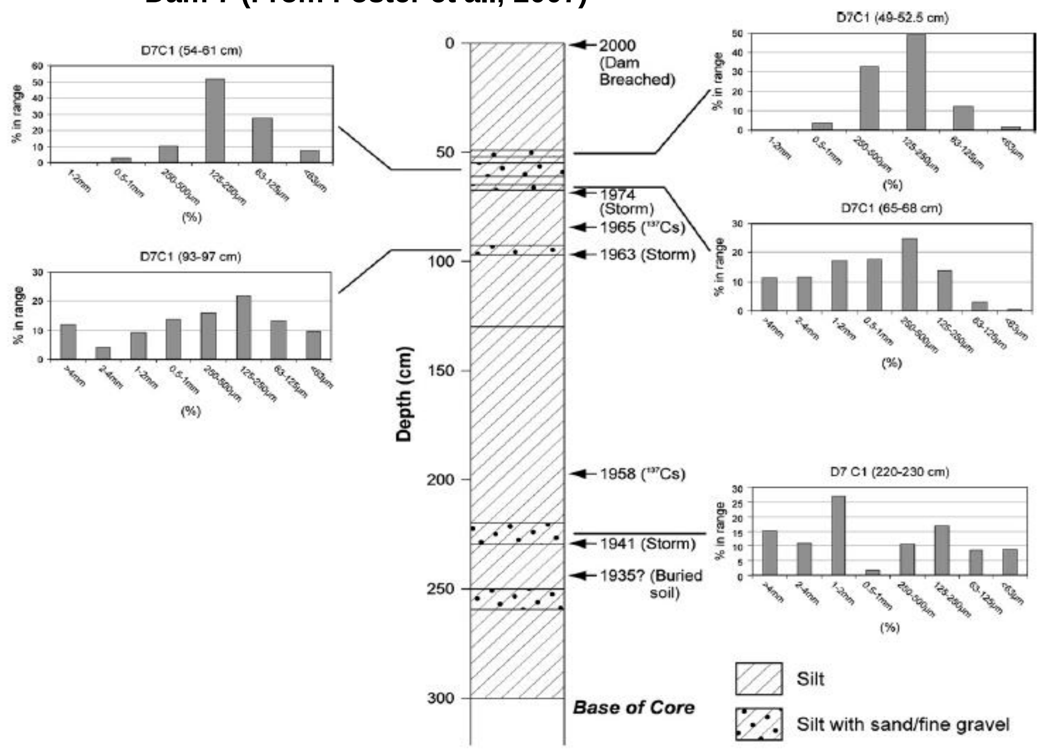
	Measured mBq cm^{-2}	Walling et al. (nd) Model Estimate mBq cm^{-2}
Reference Inventories		
Compassberg (2 sites)	50 +/- 10	48
Wheatlands	38 +/- 8	40
Reservoir Sediment Inventories		
Compassberg		
Dam 7	900 +/- 137	
Dam 10	472 +/- 87	
Ganora	226 +/- 45	
Cranemere	261+/-34	

5.2 Dating the Reservoir Sediments

In the cores from the two Compassberg reservoirs, the pre-impoundment surfaces were identified at ~240cm depth by an increase in organic matter (6–7%), a significant peak in $^{210}Pb_{un}$ and distinctive soil magnetic properties characteristic of topsoils (high χfd%). In the Ganora reservoir, the pre-impoundment surface soil was easily identified as it contained small stones and root hairs while at Cranemere, a gravel was penetrated by the corer below the reservoir sediments. Maximum sediment depth in Ganora and Cranemere was just over 4m.

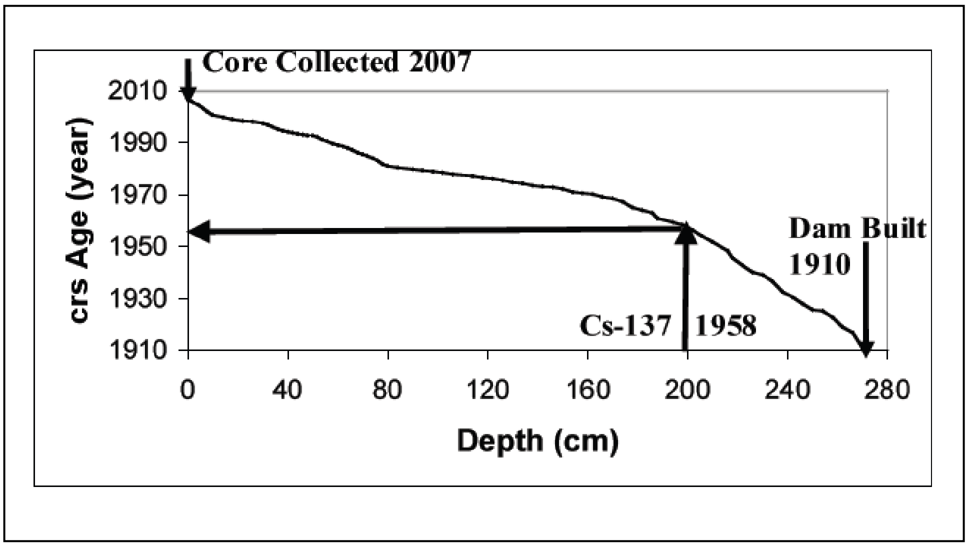
The chronology of the Compassberg reservoir sediment cores was established using the beginning of ^{137}Cs deposition in the southern hemisphere (1958) and its peak fallout in 1965. Gravel layers contained within the reservoir deposits were associated with large storm events that were dated from the rainfall records to 1941, 1963 and 1974 in Dams 7 and 10. An example chronology for Dam 7 is given in Figure 6. Gravel layers were not present in the Ganora or Cranemere farm dam sediments where the coarsest sediments were at the coarse silt/fine sand and fine/coarse silt boundaries respectively. Dam 7 was breached on 24 March 2000 and a gravel layer from this event is present in Dam 10 sediments (Foster et al., 2007). Changes in sedimentation rates can be estimated with some degree of certainty for five periods since 1935 in Dams 7 & 10 at Compassberg.

Figure 6 Dam 7 particle size and ^{137}Cs used to derive the chronology of Dam 7 (From Foster et al., 2007)



By contrast with the Compassberg reservoirs, the sediments in both Ganora and Cranemere reservoirs were much finer and contained a strong and consistent $^{210}Pb_{un}$ record. Using the constant rate of supply 'crs' dating model described by Appleby & Oldfield (1978) and Appleby (2001) sediment depth was related to predicted sediment age and was corroborated independently using the known age of the reservoir (Ganora only) and the first occurrence of ^{137}Cs in the environment (both sites) as exemplified for the Ganora sediment core in Figure 7 (see Foster & Rowntree, In Press; Rowntree & Foster, In Press).

Figure 7 The ^{210}Pb 'crs' predicted depth-age curve for Ganora Reservoir (Based on Rowntree & Foster, In Press).



The core correlation exercise at each of the four sites suggested that the reservoirs had filled with sediment at a relatively uniform rate. From the dated levels in the master core, the total mass of sediment contained in the reservoirs was divided into 5 time zones (Compassberg Dams 7 & 10) and 8 time zones (Ganora and Compassberg) respectively. However, it must be recognised that these small dams are unlikely to trap all of the sediment derived from the catchment and the following section explains how corrections were made to the sediment yield reconstructions by estimating trap efficiency.

5.3 Correcting for Trap Efficiency

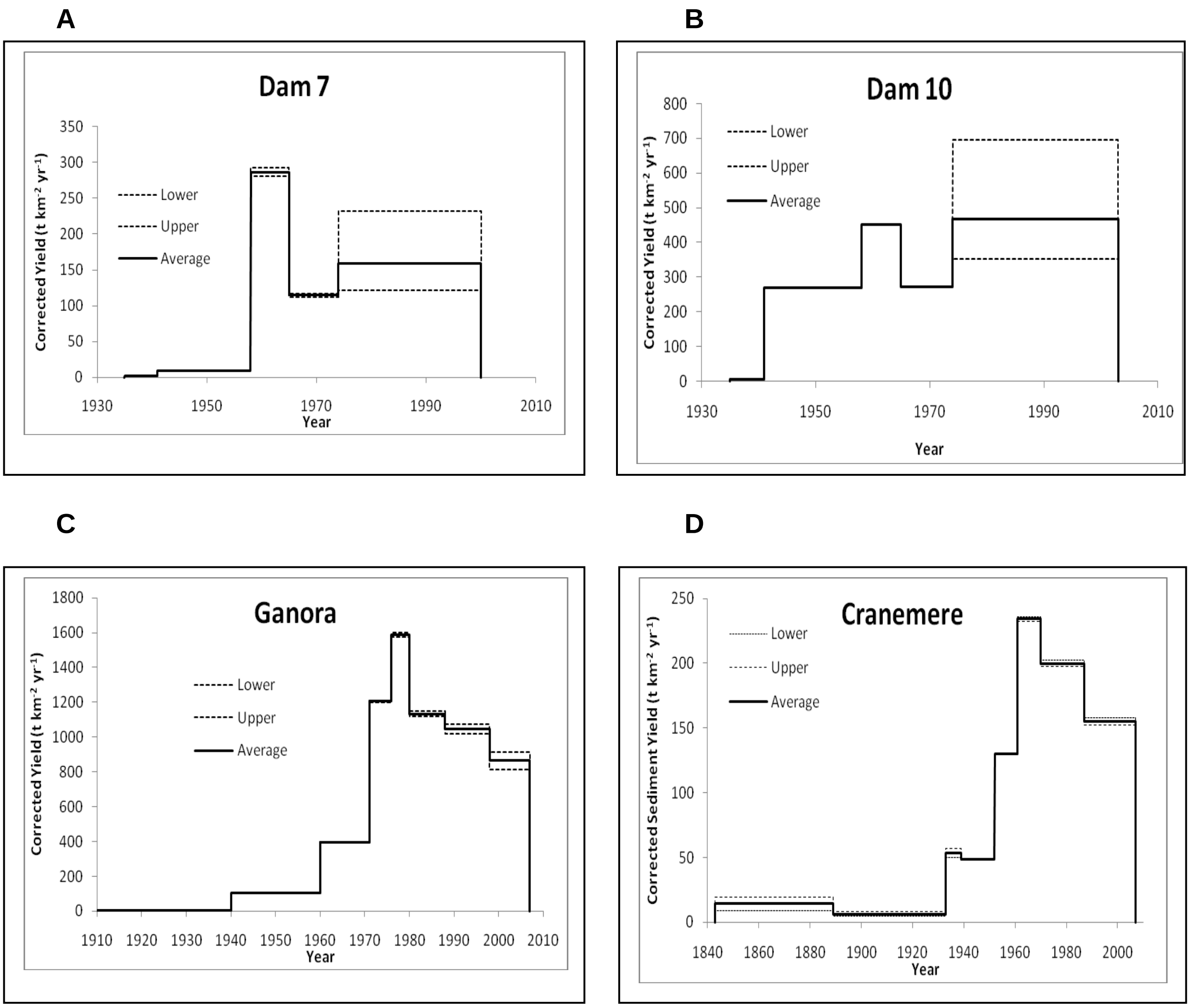
Trap efficiencies (TE) of the four reservoirs have been estimated in order to account for the proportion of sediment that could be lost annually over the outflow and correct the reconstructed sediment yield for these losses. Conventional trap efficiency models require estimates of both the capacity of the reservoir and of the annual inflow and use the ratio of capacity: inflow to model the TE of the reservoir (Heinemann, 1981; Foster et al., 1990). Direct measurement of runoff has not been undertaken at the study sites but runoff ratios for South Africa are low by global standards (5-10%) and, for the Klein Seekoi catchment, the estimate is 5% (Basson et al.,1997; Meadows & Hoffman, 2002). It is likely that the runoff ratio is higher in small catchments and we have therefore used the upper value (10%) in order to provide a conservative estimate of TE for the four reservoirs (see Foster et al., 2008).

Reservoir volumes and volumes of sediment accumulating between dated horizons in the sediment cores were calculated in the following way. TE for the original storage capacity, at different times during phases of sediment accumulation and at the time of survey was estimated from Heinemann's equation 4 (1981), where C/I = Capacity Inflow Ratio:

$$TE = -22 + (119.6C/I) / ((0.012 = (1.02C/I))$$

The volume of sediment accumulating between each time zone was estimated by combining sedimentation rates with trap efficiency estimates. Average, maximum and minimum rates are reported in Figure 8 which use minimum, maximum and average trap efficiency estimates for each time period. These data were subsequently converted to yields using the measured densities of the dam sediments.

Figure 8 Reconstructed Sediment Yields in the four Research Catchments; The Compassberg Catchments (A,B); Ganora (C) and Cranemere (D). All reconstructions are corrected for trap efficiency and show the range of uncertainty associated with minimum and maximum trap efficiency estimates (See text and Foster et al., 2008 for further details).



While all catchments show an increase in sediment yield in the latter part of the 20th century, the exact timing of major increases and the peak rates are not consistent in time. Since the region has probably experienced similar weather conditions over the last 100-200 years, the differences in the temporal erosion patterns suggests that the controls on these increases are related to local catchment / management factors rather than to climate alone (notwithstanding the significant change in the magnitude and frequency of daily rainfall since the 1950s across the region; see Chapter 1, this guide).

All reservoirs show relatively low sedimentation rates for the first decades of the record, which was also the climatically least extreme period in terms of the number of events of >25mm (see Chapter 1, this guide). In Dam 10 an increase in sedimentation rate for 1941–1957 probably reflects an increasing number of rainfall events since there are neither cultivated land nor badlands in the catchment. A significant increase in sedimentation occurs around 1940 (Dam 10), and 1960 (Dam 7 and Ganora). In Dam 7 peak sedimentation in the period 1958–1964 is 8x that in the preceding period; this is in stark contrast to Dam 10 for the same period where cultivation did not occur in the catchment. We suggest therefore that the high rates are related to the extensive area of cultivation in the catchment at this time. In the period since 1974, despite over 3x the number of rainfall events, sedimentation rates have halved as a result, we argue, of declining stocking densities. This trend is also evident at Ganora. In the Dam 10 catchment there has been little decline in sediment yield since the 1960s. Despite the decline in stock numbers in the area increased rainfall intensity appears to override any effects of vegetation recovery in the last 60 years. Declines in sedimentation in Dam 7 and Ganora reservoirs in the latter part of the twentieth century do not approach the low rates at the beginning of the record. We infer that this is due to the continued efficiency of gully systems and the non-recovery of degraded and badland areas despite lower stocking densities. The latter factors may well be offset by the steady increase in rainfall intensity. At Ganora, sediment yields of over 800 t km^{-2} yr^{-1}, evident for the last 50 years, are high for rangelands and we assume this is partly because of the development of badlands and their connection to gully systems (Rowntree & Foster, In Press).

Lowest sediment yields are recorded in the Cranemere catchment. This is unsurprising as the catchment is much larger and of much lower relative relief than the other catchments. There are several opportunities for the internal storage of sediment within the catchment, including small dams in the headwaters (now mostly abandoned / breached) and the presence of alluvial fans and valley floor floodouts in the catchment. The generally low sediment yields for the first 100 years of record dramatically increase in the early 1950s. Three hypotheses were proposed by Foster & Rowntree (In Press) to explain the pattern of sediment yield illustrated in Figure 8D.

- The pattern of sediment yield reflects a lag effect as proposed by Archer (2000), with delayed responses firstly between grazing pressure, degradation of the vegetation cover and soil erosion and secondly between conservation practices and recovery.
- Increased sediment yields after 1950 are due to changes in weather patterns that have resulted in increased rainfall energy, greater erosivity and flooding.
- Increased sediment yields after 1950 are due to changes in connectivity between sediment sources and the reservoir.

It is reasonable to assume a time lag within a process-response system as implied by Archer (2000). The question is how long a lag is reasonable? The increased sediment yields from the late 1930s are consistent with the hypothesis that high stocking densities up to and including the 1930s would have caused serious land degradation, with some lag between the changes in management systems dating back to the 1890s and increased erosion. It is clear, however, that degradation of vegetation cover and soil erosion had been a concern for many years. Archer himself reports that as early as 1875 Civil Commissioners were commenting on the loss of vegetation cover and a reduction in grazing capacity, nearly sixty years before stock numbers started to decline (Archer 2000). Gordon, Director of Irrigation for the Cape of Good Hope, was one of a number of others who spoke passionately about the evils of soil erosion in the first decade of the twentieth Century (Gordon 1904). There is no evidence from Figure8D that the conservation practices put in place during the 1950s had any impact on erosion rates, as the calculated yields continued to rise, peaking in the early 1970s. It therefore seems unlikely that the delayed response of approximately 40 years between maximum grazing pressure and peak sediment delivery was due to a lag in erosion response. Moreover it is unlikely that there would be such a lag in terms of recovery, though a number of authors do question whether there can be a full recovery within the near future (Dean and Macdonald 1994; Dean et al. 1995; Archer 2000).

There is clear evidence from the Cranemere rainfall record that daily rainfall has become more extreme since 1950, thus increasing both the potential for soil erosion and for floods that would be able to deliver sediment to the reservoir (see Chapter 1, this guide). The floods of the 1970s are more or less coincident with the peak sediment yield. The most notable flood occurred on March 3rd 1974, coincident with widespread flooding over the Eastern and Northern Cape. 70 mm fell at Cranemere over a two day period. Although not especially intense (a daily maximum of 98 mm was recorded in 1977), the storm fell on a wet landscape that had already received 115 mm in January and 113 in February. Water a metre deep flowed over the dam overspill at Cranemere. Although this storm resulted in intense runoff, family correspondence indicates that soil erosion was not severe due to the good vegetation cover resulting from the rain over the previous two months. This raises the question – did these floods cause widespread soil erosion, or were they responsible for mobilizing stores of sediment that had been accumulating over a longer time period?

The third hypothesis relates to changes in connectivity within the catchment. Field evidence indicates that the immediate result of catchment erosion was the transport of sediment onto fans and into the valley floor; that is, into local sediment sinks. There are documentary reports of a wetland upstream of the main road that runs across the northern edge of the reservoir. The extremely fine sediments deposited in the reservoir suggest that there has generally been insufficient energy to transfer even fine sand sized material to the dam, yet field observations indicate that sand sized material is widely distributed in intermediate storage locations such as fans and alluvial deposits within the catchment. The reconstruction of the road and construction of culverts in the early 1950s would have had the immediate effect of connecting the reservoir to local valley floor sediment stores, which could then find their way into the reservoir during large flood events. A significant rise in yields after the mid 1950s is apparent from Figure 8D. Peak yields in the 1970s would be consistent with the series of heavy storms that occurred in that decade, including the severe flood event of 1974. Significant reworking of sediment stores would have taken place during these floods. Current research is calculating at rates of sedimentation in the sediment sink upstream of the main road that runs across the northern edge of the reservoir. Here we are using 137Cs to provide a chronology and will examine the particle size distribution of sediment contained within the sink. Preliminary results, if available, will be described on the field excursion.

Our interpretation of the changing rates of reservoir sedimentation recognises that sedimentation rates reflect the complex process of erosion, sediment storage and re-working. There was undoubtedly a lag between grazing pressure and sediment delivery to the Cranemere reservoir, similar to those for the two Compassberg catchments and Ganora, but this lag at Cranemere may not have been due so much to a delayed response of erosion to grazing pressure, but rather to the reworking of sediment stored within the catchment in sediment sinks. Meade (1982) gave a similar explanation for the continued high sediment yields from east coast rivers in the United States, despite successful soil conservation measures in the upper catchment. More extreme rainfall events during the last fifty years could have caused further erosion, but would also have increased the potential for reworking of sediment stores. The increased connectivity between the dam and catchment caused by the construction of culverts under the road would have enabled this reworked sediment to be delivered more effectively to the reservoir.

If the above interpretation is correct,Foster & Rowntree (In Press)argue that it is unreasonable to relate the variation in yields to the timing of catchment erosion following peak stocking rates. A more realistic calculation would be to take the average yield from 1938, to even out the effects of storage and reworking following increased connectivity. This would give an average sediment yield over the last 70 years of ~145 t km^{-2} yr^{-1}.

Sediment yield to the reservoirs is high by global standards for predominantly grazed catchments. Average yields since the 1930s are given in Table 3. Dam 10 is probably higher because of the small size of the catchment and the lack of substantial areas of valley bottom storage. It is also dominated by sand- and siltstones that are less resistant to erosion than the dolerites that dominate the Dam 7 catchment. In a temperate environment with twice the annual rainfall, Erskine et al. (2002) report sediment yield contrasts for small basins of 710 (cultivated), 330 (grazed pasture) and 310 t km^{-2} yr^{-1} (woodland). In Tigray, Ethiopia, an area of tropical semi-arid climate with rainfall ~450 mm yr^{-1}, 10 small reservoirs in catchments with high population densities and serious land degradation give sediment yields ranging from 237 to 1817 t km^{-2} yr^{-1} (Haregeweyn et al., 2006).

Table 3 Post-1930s average sediment yields in the four Karoo catchments.

	Catchment area (km^2)	Time span	Sediment yield (t km^{-2} yr^{-1})	Source
Ganora	2.58	1935-2007	654	Rowntree & Foster (In Press)
Dam 10 Compassberg	1.48	1935-2003	357	Boardman *et al.* (2010)
Dam 7 Compassberg	6.3	1935-2000	115	Boardman *et al.* (2010)
Cranemere	57	1938-2007	145	Foster & Rowntree (In Press)

5.5 Sediment Sources

5.5.1 Compassberg Catchments

Modelling of sediment source changes through time in the Compassberg catchments has used geochemical, mineral magnetic and radionuclide signatures in combination (Foster et al., 2007) and the most important loadings on each Component in a

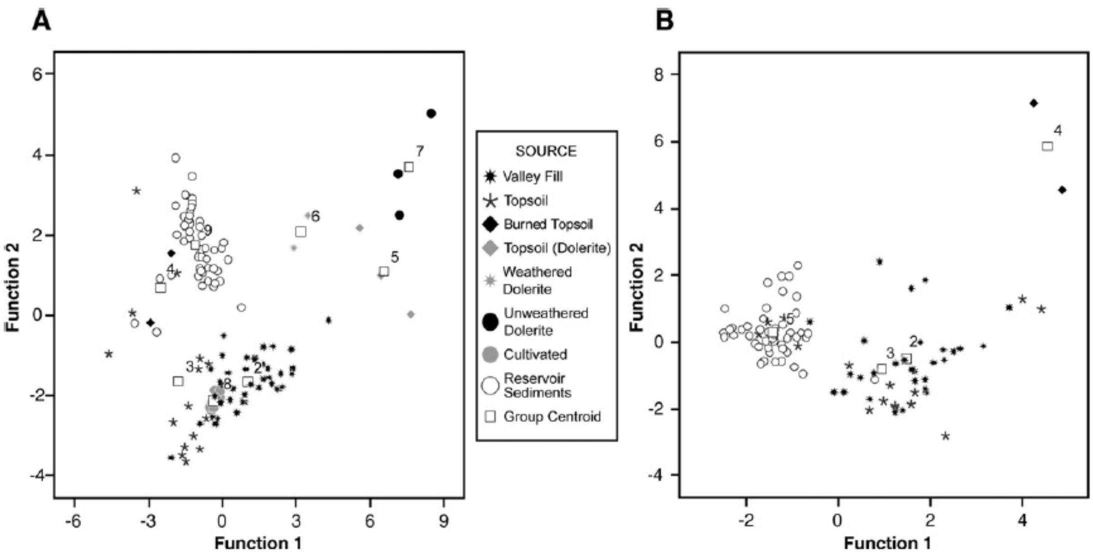
Principal Component Analysis for each of the Dam 7 and Dam 10 catchments are shown in Table 4.

Table 4 Selection of variables best discriminating potential historical sources in the Dam 7 and Dam 10 catchments using Principal Component Analysis

Reservoir 7 Sources	Most significant Variable Loading	**Reservoir 10** Sources	Most significant Variable Loading
Component 1	Ca	Component 1	Xfd(min)
Component 2	IRM0.88T(min)	Component 2	^{40}K
Component 3	Pb	Component 3	Sr
Component 4	Xfd(min)	Component 4	Al
Component 5	Ba	Component 5	HIRM
Component 6	Ni		
Component 7	Fe		

Having objectively selected the individual variables that best represented each of the significant components, each source was characterised and analysed using Discriminant Function Analysis (DFA). Figures 9 A and B show the DFA plots relating the characteristics of the reservoir sediments to those of potential sources for the two Compassberg catchments.

Figure 9 Potential sources contributing to the accumulating sediments in Reservoir 7 (A) and Reservoir 10 (B) (From Foster et al., 2007).



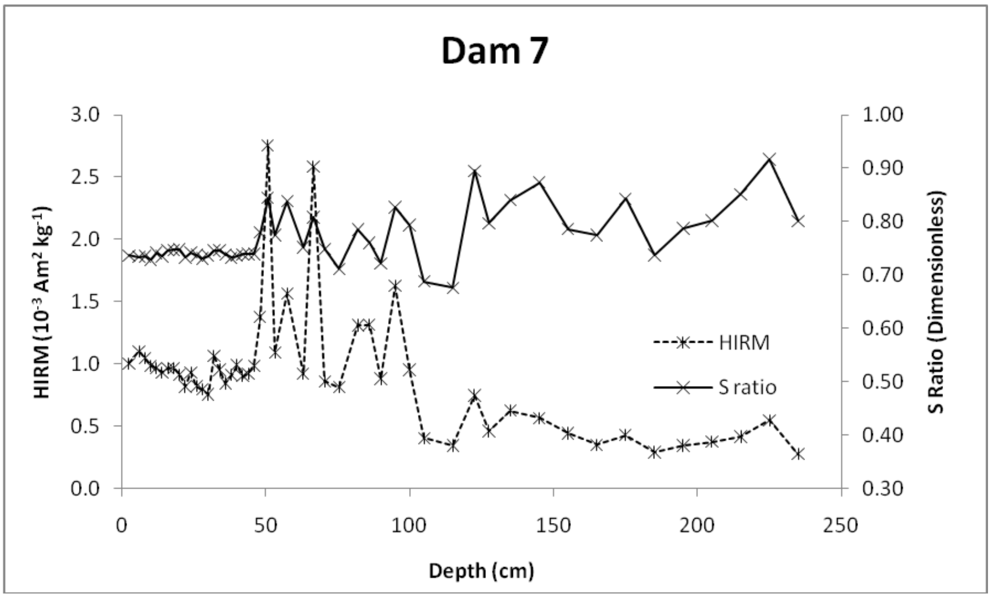
The recent reservoir sediments in both dams do not form a cluster in close proximity to the valley fill samples. This is consistent with the analysis of donga development presented by Keay-Bright and Boardman (2006) who demonstrated that the donga networks had not changed significantly since the 1940s. While these dongas provide excellent landscape connectivity, they do not appear to have been major sources of sediment over the ~70 year period represented by the reservoir sediments. The Dam 10 sediments appear to cluster in close proximity to the small group of sandstone/mudstone topsoils that are known to have been recently affected by vegetation burning, although this is not clearly established in Dam 7 where occasional inputs from dolerite sources are apparent. While there is considerable scatter in the characteristics of the potential source samples, thus precluding the use of quantitative un-mixing models, the evidence presented in Figure 9 suggests that topsoils are the dominant sediment source in both catchments and that these sources have changed little through time.

The above analysis suggests that the majority of the sediment deposited in Dams 7 and 10 came from topsoil sources, although there were occasional inputs from doleritic soils in Dam 7 identified from the disciminant function plots of Figure 9A. These changes in Dam 7 are placed in an historical context in Figure 10 which plots the magnetic parameters HIRM and the S ratio against depth in the sediment column. HIRM values are elevated in the soils developed on dolerite and are especially high in weathered dolerites collected from a road cutting section in the Dam 7 catchment while the S ratio suggests a harder remanence associated with lower values of this parameter. Both signatures are indicative of a greater proportion of hematite-type minerals in the deposited sediments that are likely to be associated with dolerite sources (Walden et al., 1999).

The chronology for the Dam 7 sediments shown in Figure 6 suggests that the change in sediment source, at ~ 100 cm depth in the sediment core, occurred in 1963 following a major storm that produced a distinctive gravel layer within the Dam 7 sediments. This correlates with a sustained change in the magnetic signatures shown in Figure 10 and in all other mineral magnetic, radionuclide and geochemical signatures, including rare earth elements.

One potential explanation for changes in mineral magnetic , geochemical and radionuclide signatures is that of a particle size control (Foster et al., 1998). However, correlations between particle size characteristics of the deposited sediment (SPAN, SSA, D10,D50,D90) and these signatures are not statistically significant in the Dam 7 sediments thereby eliminating the likely effects of particle size on the sedimentary record.

Figure 10 Changes in mineral magnetic signatures in the dam 7 sediments.



The Dam 7 catchment has extensive outcrops of dolerite in addition to the distinctive dolerite ridge shown on Figure 1C that cuts across the main river valley. Most of the southern and northen ridges are dominated by dolerite as is the Compassberg itself. In addition, the boundary between the Dam 7 and 10 catchments also has extensive dolerite outcrops although almost none appears to outcrop within the Dam 10 catchment.

One of the potential dolerite sources that lies in close proximity to Dam 7 and shows evidence of significant erosion lies to the south of the cultivated area of the catchment shown on Figure 1C. Cultivation of this area included the construction of contour bunds that are clearly evident on the Google Earth Image of Figure 11. Also evident on this image are a number of deeply incised but discontinuous gullies that appear to have developed into a drainage network directly linking the dolerite ridge to the dam. These are up to 4 m deep and have been cut in weathered dolerite at the slope foot and extend within a few tens of metres to the drainage divide. While we have yet to establish unequivocal evidence for these gullies to be the dominant source or conveyors of sediment to the dam, their close proximity to the dam and well established connectivity make these possible areas contributing to the change in source signatures in the dam sediments since 1963.

Figure 11 Google Earth Image of the Dam 7 cultivated area.

The Dam 7 catchment has extensive areas of dolerite outcropping close to the channel margins and extending to the headwaters of the Kompasberg itself (Figure 1) unlike the dam 10 catchment which has very little dolerite outcropping in the catchment. Furthermore, we have established that the gullies shown on Figure 11 were also present on the 1945 aerial photographs and, like many others in the region, show no obvious signs of extension since this time.

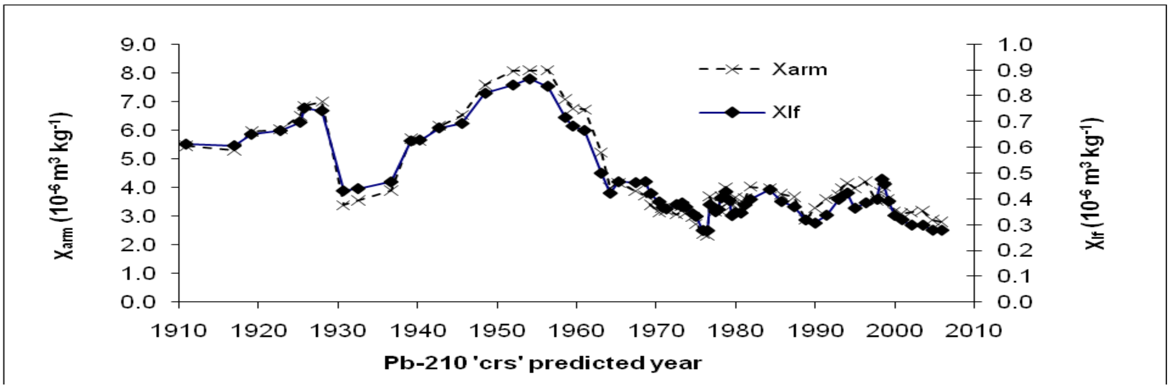
5.5.2 Ganora

By contrast with the Compassberg catchments, analysis of the properties of reservoir sediments in the Ganora reservoir suggest significant source changes through time. This is illustrated in the downcore plots of four magnetic parameters in Figure 12. The magnetic measurements of the sediment core samples were matched with those from 31 samples taken from locations in the catchment representing different source types. These included the badlands, un-dissected footslopes, channel banks, and fans. The fan at the head of the eastern main channel was dominated by doleritic material, that in the western catchment by sandstones. The distribution of source samples is shown in Figure 2 and their magnetic signatures in Table 5.

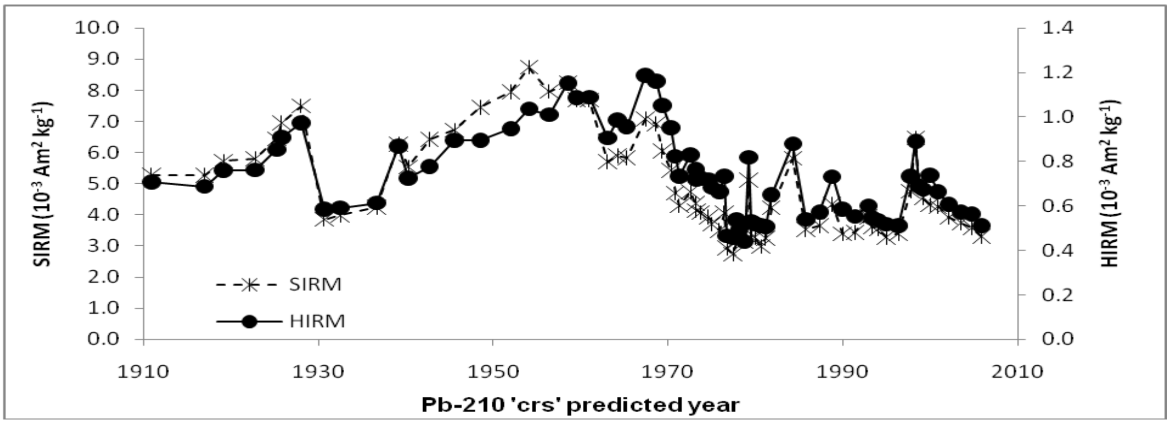
Comparing the values of χlf in Figure 12A with those in Table 5 it can be seen that the sediment delivered to the reservoir in the period up to the late 1950s had high values, similar to those for samples from the doleritic fan. Sediment yield was also low during this period (Figure 8C). An exception regarding the χlf values was in the first half of the 1930s, when values similar to those found for badland soils were measured. After the mid 1960s the χlf values declined, reaching a more or less constant value that seldom exceeded 0.4 10^{-6} m^3 kg^{-1} by 1970. These values are also similar to those of the badland soils from the west of the catchment.

Figure 12 Downcore trends in Xarm and Xlf (A) and SIRM and HIRM (B) in the sediments accumulating in the Ganora reservoir plotted against the ^{210}Pb 'crs' predicted sediment age (After Rowntree & Foster, In Press).

A



B



A similar pattern is shown for the SIRM (Figure 12B), with measured values given in Table 5 for the source samples. One difference is the group of high values of SIRM for the soils developed on a sandstone bench located below the badlands in the western catchment. These values are similar to a group of badland soils above (10 and 12) and may represent local downslope deposits from this source.

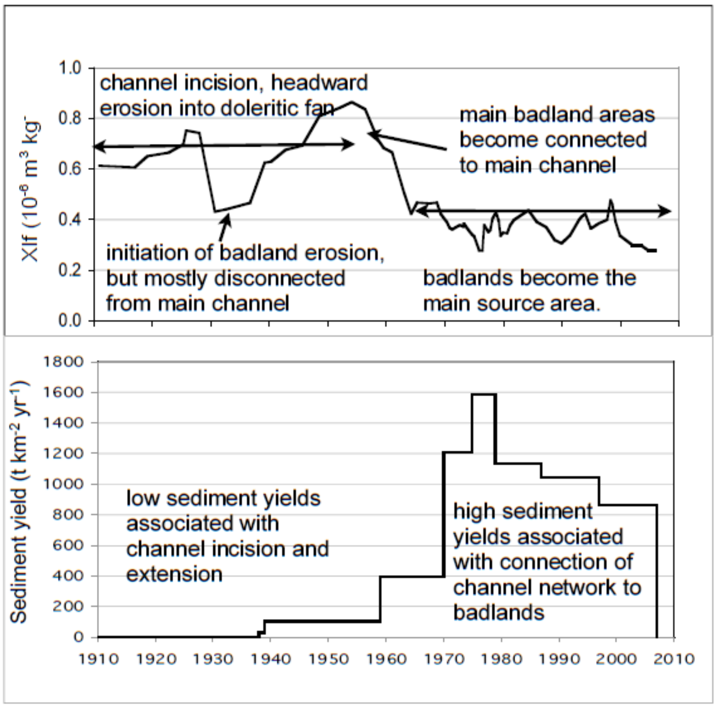
An interpretation of the results (combining an interpretation of both sediment yields and sources) is given in Figure 13. By comparing the χlf values of the core and the source samples, it appears that the main source from 1910 to the mid 1950s was the doleritic fan at the head of the eastern channel. Sediment yield was low throughout this period because headward erosion and incision of one main channel was the primary source. After 1950 it appears that the badlands in the west of the catchment started to contribute, and soon dominated the magnetic signature in the reservoir sediment. Coincident with this shift in source was a rapid increase in sediment yield. The higher yield is also associated with the peak in the ^{137}Cs activities of the reservoir sediment suggesting a significant influx of topsoil.

One question remains. The badlands at Ganora are clearly evident on the 1945 photograph but it was only after 1960 that there was there a rise in the sediment yield and a change in the χlf and other magnetic signatures in the reservoir sediment. There was a drop in χlf values in the 1930s, but no concomitant rise in sediment yields. To explain this pattern it is necessary to look at the channel network itself. We know from aerial photographs that the western channel connected with the main badland area sometime between 1945 and 1966. Thus in 1945 the badlands were poorly connected to the reservoir, but by 1966 they were well connected. Using the evidence from Figure 12 and Table 5, it is suggested that the badland erosion was initiated in the early 1930s (from the drop in χlf and SIRM values in the sediment core), with sediment reaching the reservoir from sources close to the main channels; it was only in the early 1960s, however, that the main badland area started to contribute significant amounts of sediment that also produced the significant increase in sediment yield.

Table 5 Magnetic susceptibility of source samples (Mass Specific Susceptibility - χlf (10^{-6} m^3 kg^{-1})

Western catchment			
Location of sample	Site number	Magnetic susceptibility (χlf) (10^{-6} m^3 kg^{-1}) (values of 0.4 and below are bold faced, 0.6 and above are underlined)	Saturation isothermal remnant magnetism (SIRM) (10^{-3} Am^2 kg^{-1}) (values of 5 and below are bold faced, 8 and above are underlined)
Fan on hillslope	9	0.55	7.00
badland	7, 8, 13 10, 11, 12 14, 15, 16 31	**0.32, 0.16, 0.15** 0.67, 0.54, 0.54 **0.32, 0.23, 0.13** **0.22**	5.87, **1.78. 2.29** 10.01, 6.57, 14.11 **4.67, 0.83, 2.64** **1.86**
sandstone bench	5, 6	0.58, 0.54	12.45, 11.88
channel banks	1, 2, 3, 4	**0.40, 0.39, 0.35, 0.34**	5.36, 5.24, 4.69, 5.49
Eastern catchment (doleritic influence)			
doleritic headwater fan	17, 18 (fan) 19, 21,22 (donga)	0.85, 0.60 0.77, 0.75, 0.72, 0.64	14.16, 22.83 17.68, 12.64, 11.44, 18.88
badland	23, 24, 25, 26	0.67, 0.58, 0.49, 0.43	9.29, 9.50, 5.85, 16.13
channel banks	27, 28, 29, 30	0.55, 0.50, 0.47, 0.46	12.57, 14.55, 11.16, 8.64

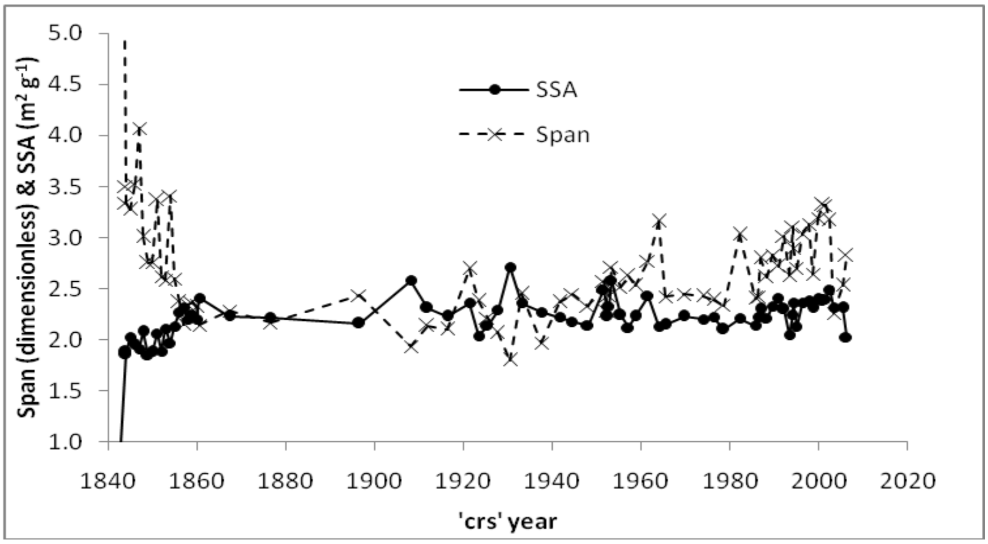
Figure 13 Interpretation of sediment yield changes at Ganora (after Rowntree & Foster, In Press).



5.5.3 Cranemere

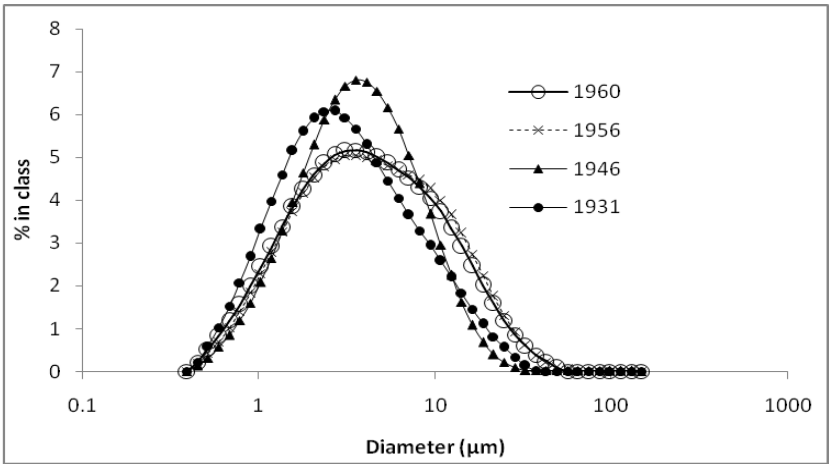
The reservoir sediments at Cranemere date back to the 1840s. Downcore trends in two particle size measures (Span; a sorting index and Specific Surface Area) are given in Figure 14.

Figure 14 Downcore trends in particle size in the Cranemere Reservoir sediments plotted against the chronology derived from ^{137}Cs, the^{210}Pb 'crs' darting model and the known age of the reservoir.



The early history of deposition is associated with sediments of low SSA (coarser sediment) and high Span (poorly sorted sediment) that is likely to represent locally derived material reworked into the reservoir following construction of the dam wall. From the 1850s onwards, Span and SSA remain fairly constant until the early 1950s when there is an increase in Span (more poorly sorted) and a slight decrease in SSA (coarser sediment). This change is further illustrated in Figure 15 which shows the particle size distributions of selected sediment samples before and after 1950.

Figure 15 Selected Particle size distriution curves for the Cranemere Reservoir sediments pre and post 1950.



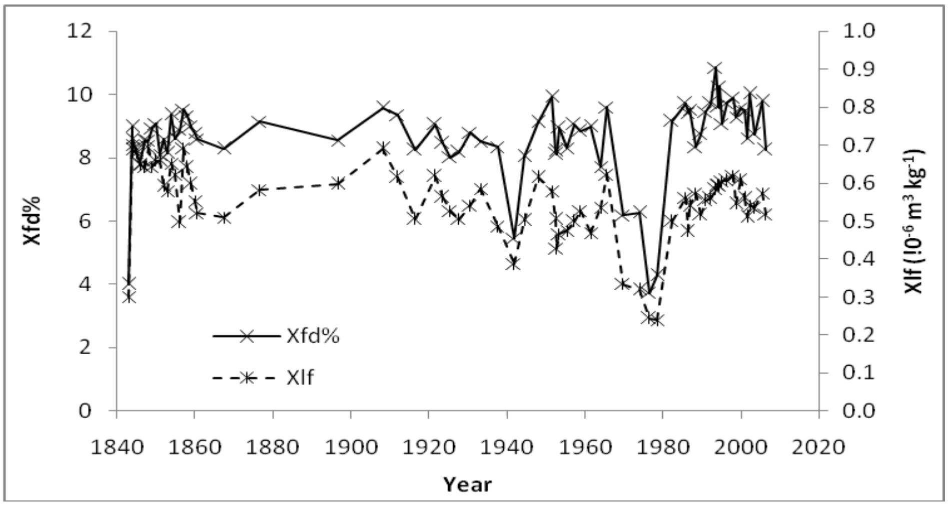
The change appears to have occurred at the time when sediment yields increased dramatically allowing coarser sediments to be delivered to the reservoir after modification to the road causeway and the installation of culverts. However, the dam wall was also raised in 1948 and it remains possible that these coarser sediments could have been delivered as a result of construction work.

Downcore trends in magnetic susceptibility and remanence properties are given in Figure 16. In both cases, the records suggest two major periods when sediment sources changed dating from the late 1930s and the early 1970s respectively.

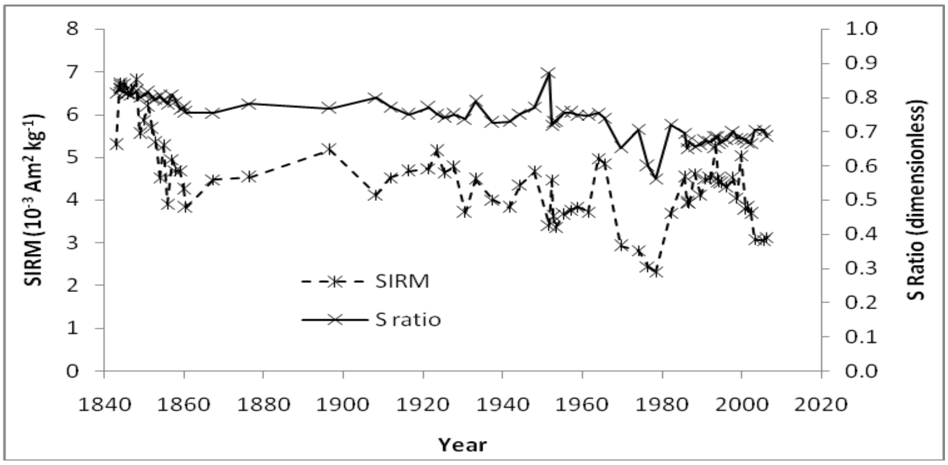
Preliminary analysis of the mineral magnetic characteristics of potential catchment sources shows that the eastern small catchment (Figure 3) is characterised by a combination of sediment sources that have both low susceptibility and low remanence signatures that are not found anywhere in potential source samples collected from the larger western catchment. Undoubtedly, the 1974 floods are most likely to be associated with the most recent and dramatic change in sediment source although the most recent signatures suggest that contributions from this source were relatively short lived. The 1920s and early 30s were periods of sustained drought in the Karoo which broke in the early 1940s with a series of wet years and also recorded extreme daily rainfalls. It is therefore likely that these unsustained changes in sediment source in the Cranemere reservoir sediment record were triggered by extreme rainfall. Unlike Ganora, however, the analysis suggests that changes in sediment source have not been sustained to the present day and that there is no direct link between a specific source contribution and increased sediment yields at Cranemere.

Figure 16 Downcore trends in magnetic susceptibility (A) and magnetic remanence (B) properties of the Cranemere reservoir sediments.

A



B



6. WIDER SIGNIFICANCE

These results exemplify the complex relationship between land use, sediment sources and catchment sediment yield and affirm the framework of structural and functional connectivity within a hierarchy of scales as proposed by Turnbull *et al*. (2008) and Trimble (2010). We need to consider the importance of landscape structure, especially the connectivity between sediment sources and sinks that determines the effective 'partial area' contributing sediment to dongas and reservoirs. In the Compassberg catchments, connectivity was provided by the existing donga networks, although the dongas themselves did not contribute significant amounts of sediment to the reservoirs. In Ganora this was a geomorphic process connecting the channel network to an actively eroding slope area that had high internal connectivity. This increased connectivity since the 1960s resulted in a major and sustained increase in sediment yield. By contrast, the explanation for increased sediment yields since the 1950s at Cranemere is associated with increased connectivity resulting from modifications to a road and associated culverts. Sediment source changes were short lived and probably associated with extreme meteorological events.

The degree of connectivity within the sediment cascade is increasingly recognized as an important driver of geomorphic systems at various scales [e.g.

Fryirs *et al*. (2007) at the catchment scale and Hooke (2003) at the channel scale]. Turnbull *et al*. (2008) consider that both structural and functional connectivity within a hierarchy of scales is key to understanding the dynamics of semi-arid ecosystems that are driven by the movement of water and sediment across hillslopes. There is common acceptance that connectivity can change through time, often as a result of human activity, leading to non-linearities in sediment delivery from source areas (Turnbull *et al*. 2008). Badlands within themselves are highly connected systems, but their downstream impact will depend on their structural connectivity to catchment scale conveyance systems.

Ecologists have called for further investigation into landscape processes in the Karoo, citing the dynamic nature of the vegetation-rainfall response as one factor that makes it hard to decipher the direction of long term trends (Hoffmann and Todd, 2000). Rather than helping to clarify the picture, our research to date has added a further layer of complexity to this landscape, in which catchment scale sediment dynamics are controlled by lags in space and time and in which connectivity plays a key role.

7. FARM RESERVOIRS, SEDIMENT STORES AND BREACHING

Farm reservoirs have been used throughout the Karoo for water storage for stock and irrigation. The oldest reservoir known to us is that at Cranemere (1843) which has been described in some detail above. Most are constructed of earth with rock or concrete spillways, some are stone built. At the present time many are full of sediment and therefore store no surface water, a proportion are breached and are now acting as sources of sediment that is being delivered to downstream sites of storage: channels, floodplains and large reservoirs. We have recently raised the issue of loss of reservoir storage capacity (at a time of concern over water supplies) in major reservoirs due to this unacknowledged and non-quantified sediment source (Boardman et al., 2009).

7.1 Farm reservoirs in the Sneeuberg

Mapping of an area of ca. 80 km^2 revealed the presence of 95 small reservoirs of varying size and age. Of these, 48 are full of sediment and store no water and 28 are breached and are therefore potential sources of sediment loss. Of the total, 18 are constructed of stone and were often built in the 1950s with the help of government grants. Some of these seem to be specifically constructed to reduce erosion along major gullies and all are now full or almost full of sediment (Figure 17).

Figure 17 Dam 36 near Lucernvale farm, built 1980, some water storage capacity remaining.

7.2 Compassberg Farm dam

Considerable work has been done on the sediments at this site (Table 1). Land use historically has been dominated by sheep grazing with former cultivated land on the valley bottom (Figure 11). At present it is full of sediment but the dam was breached on 24th March 2000 as a result of 118 mm of rainfall at Compassberg Farm. The rock-based spillway was clearly unable to cope with excessive flow and overtopping of the earth dam occurred followed by erosion. Since then a gully has started to eat back at the breach into sediments contained within the reservoir.

An extensive gully system debouches into the reservoir at its southern end. As with all gully systems in the area they have changed little in comparison to those on the 1945 air photographs. Estimated volume loss from this system is 105, 400 m^3. It seems unlikely that erosion of gullies has contributed much sediment to the volume trapped in the reservoir (see above).

A boulder, gravel and sand fan overlies fine grained sediments at the southern end of the reservoir as a result of floods from the gully. Most recently, at the end of January 2010, an extremely wet period was reflected in flows of 1.6 m depth and 13 m width in the gully. This resulted in a fresh spread of coarse material on the fan.

7.3 Good Hope Farm reservoir and dam

This major earth-built dam was constructed between 1945 and 1959 to flood an area of deeply incised gullies. The dam is ca. 400 m in length with a stone spillway 30 m in width. The dam wall is up to 5m in height. The valley floor immediately above the dam and up-valley to the now abandoned farm at Oppermanskraal was formerly cultivated (Boardman et al. 2003, Figure 4). Extensive areas were cultivated in 1945 but air photographs for 1959 and 1966 show considerable gullying on this area. By 1980 there was much less cultivated land. Sedimentation has occurred in the reservoir and has spread up the major feeder gully. A crude estimate of sediment stored in the reservoir is 322,800 m^3. The catchment area above the dam is 29.63 km^2 and includes the summit of Kompasberg (2502.7 m).

On 21 January 2010 breaching occurred at the dam spillway with much stonework being lost. Below the breach weathered dolerite is extensively eroded down to intact rock. In narrower sections of the deep gorge below the spillway water depths were up to 6 m with spreads of boulders and trees. Rainfall in the area was very localised with over 50 mm at Compassberg Farm and 100 mm at other sites (Dave Gaynor, pers, comm.). Downstream of the dam and gorge, the bridge and road into Lucernvale Farm was washed away on 21st January 2010.

7.4 Estimates of sediment volume in reservoirs

Our interest in the volume of sediment temporarily stored in numerous small reservoirs has led to attempts to find a quick, reasonably accurate and reproducible method of estimation. Estimation of volume based on coring has been carried out at Compassberg Dams 7 and10. This, however, is very time-consuming. Ground Penetrating Radar was unsuccessful, probably due to the fine-grained character of the sediments (Oliver Sass, personal communication). A method based on depth and plan form of sediments shows promise (Table 2).

Table 2 Comparison of volume estimates based on coring and the depth / plan approach.

Reservoir	Volume estimate in Foster et al. (2008) (m^3) based on coring	Depth/plan form approach from Mottram* (m^3)
Compassberg Farm reservoir (Dam 7)	32,400	50,066
Dam 10	27,720	24,210

*from Irrigation Design Manual Fig 5.4 (Mottram, personal communication)

7.5 The impact of stored sediment on large reservoirs

The nearest large reservoir to the Compassberg area is the Nqweba reservoir at Graaff-Reinet with a catchment area of 3,544 km^2.This is on the Sundays River. Extrapolating the mapped density of small dams from Compassberg suggests that there could be 4200 small dams in the catchment. Taking 25,000 m^3 as a conservative average this suggests a figure of 13 M m^3 of stored sediment in the small dams. The average deposition rate in the Nqweba reservoir is 584,906 m^3 y^{-1} with an estimated storage capacity (2010) of about 29 M m^3 (Rooseboom, 1992; Msadala et al., 2009). Without any increase in sediment reaching the reservoir the dam will have a life of about 50 years. A continuation of the upward trend in numbers of intense rainfall events will also affect erosion and sediment transport rates (Keay-Bright and Boardman, 2009, Figure 6; Chapter 1, this guide).

There are many unknowns is this calculation, not least of which is the rate of release of sediment from breached small dams and the delivery ratio of this released sediment to major storage reservoirs. However, the potential impact of this unacknowledged sediment source is clear.

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6. A PALAEOECOLOGICAL STUDY OF THE COMPASSBERG DAM 7 SEDIMENTS

Tim Mighall, Ian Foster, John Boardman

1. INTRODUCTION

A series of studies of erosion, runoff and the development of gullies, badlands and sediment delivery to small farm dams in the Sneeuberg uplands have shown that the semi-arid Karoo is vulnerable to severe landscape change (e.g. Keay-Bright & Boardman 2006; 2007; Boardman et al., 2009; Keay-Bright & Boardman, 2009; Boardman et al., 2010). The causes of land degradation have been well debated with two competing hypotheses: climate or land use changes (e.g. Hoffman et al., 1995; Hoffman et al., 1999; Hoffman & Ashwell, 2001). Land use changes, such as switching from cereal to maize, cultivation on steeper slopes and increase in stock numbers promoting overgrazing, can initiate erosion and they are thought to have played a major role in triggering erosion in the Karoo (Boardman et al., 2010). Farm dams built in the mid 19th century have enabled us to examine such activities over the last 100-200 yrs as they provide an archive of soil erosion (e.g. Foster et al., 2005; Chapter 5, this guide).

This section presents pollen, non-pollen palynomorph (NPPs) and microscopic charcoal from sediments that have infilled a small farm dam in a 6.33 km^2 catchment at Compassberg located in a tributary of the Klein Seekoi River. Dam 7 was constructed in ca. 1935. The data will be used to examine the relationship between soil erosion and the role of vegetation change (e.g. cereal cultivation, conversion of land to pasture) and/or fire. Vegetation changes will be reconstructed using pollen and NPP analysis (including coprophilous fungal spores that provide an index of grazing intensity). Microscopic charcoal will be used to reconstruct local fire histories.

This paper will focus on fungi that are commonly associated with animal dung (van Geel & Aptroot, 2006) that have been widely used as evidence of the presence of herbivores (e.g. van Geel et al., 2003; Mighall et al., 2006; Riera et al., 2006). Modern approaches have shown that a suite of fungal spores can be used as local dung indicators including *Sporormiella*-type (T113), *Cercophora*-type (T112), *Sordaria* (T55A), *Tripterospora*-type (T169), *Chaetomium* (T 7) (Blackford & Innes, 2006; Graf & Chmura, 2006). For example, *Sporormiella*-type is found in sediment where livestock is abundant (e.g. Davis & Shafer, 2006) and it showed the highest correlation with grazing pressure in a study by Cugny et al. (2010). Davis & Shafer (2006) have also suggested that with detailed livestock records it should be possible to establish a quantitative relationship between *Sporormiella*-type percentages in sediments and livestock density. Thus, based on the assumption that the group of coprophilous fungi identified in studies based in north-west Europe are applicable in the southern hemisphere, we aim to use these fungi as a proxy for grazing intensity.

2. METHODS

The dam 7 core was collected and sampled in 2007 according to changes in the stratigraphy. Sub-samples from different stratigraphic units of between 1 and 4 cm thickness were cut from the core. Pollen and microscopic charcoal analyses were undertaken using standard techniques. Samples of 2-3g were prepared for pollen analysis using the procedure described by Barber (1976) with an additional density separation procedure to concentrate the pollen and NPPs (Nakagawa et al., 1998).

At least 200 land pollen grains were counted for each sub-sample. One *Lycopodium clavatum* tablet was added to each sub-sample (Stockmarr, 1971) in order to calculate pollen and charcoal concentrations. Pollen identification was made using the pollen identification keys from Fægri et al. (1989), Moore et al. (1991), the African pollen database developed and maintained by Medias-France, and a pollen type slide collection housed in the at the University of Aberdeen. Pollen preservation was recorded following Cushing (1967) and each pollen grain was classified as either broken, corroded, crushed, or degraded. Pollen grains that had no remaining distinguishing features were categorised as unidentified. Non-pollen palynomorphs were identified using the descriptions and photomicrographs of van Geel (1978), van Geel et al., (2003), Feeser & O'Connell (2009). The pollen and microscopic charcoal data are expressed as percentages of total land pollen (TLP). NPPs are expressed as percentages of total land pollen and NPPs. Charcoal pieces were counted during routine pollen analysis and are divided into size increments: less than 25μm, 25-50μm, 50-75μm and above 75μm to provide a crude index of local to regional fires. A cross denotes one grain or palynomorph.

3. RESULTS

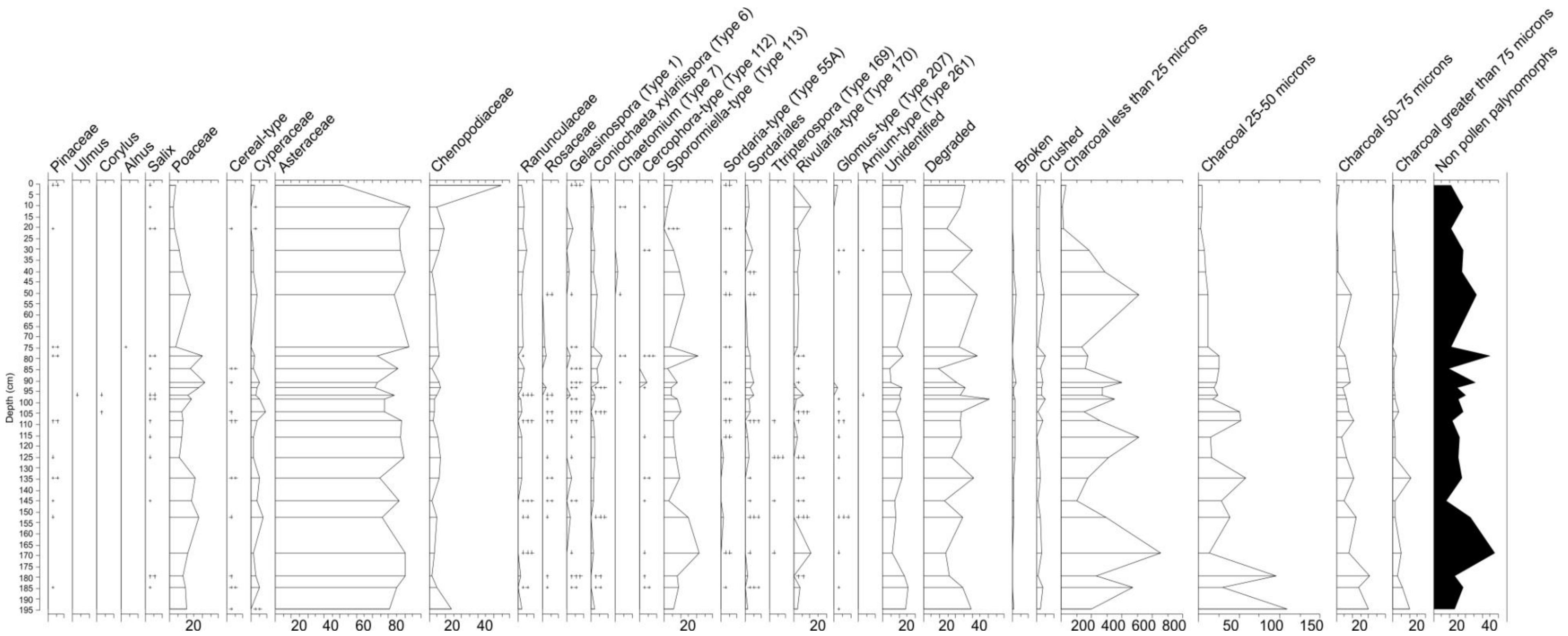
Table 1 presents the stratigraphy of the Dam 7 core. ^{137}Cs and particle size measurements were used to derive a chronology (see Foster et al., 2005; 2007; Chapter 5 this guide for full details). The dam was constructed in 1935. The beginning of ^{137}Cs in 1958 occurred at 200cm and peaks in 1965 at 86 to 85cm. Known storm events of 1941, 1963 and 1974 are identified by gravel layers at 210.5-208.5, 98-91.5 and 68-65cm respectively.

Selected pollen, NPP and microscopic charcoal data for dam 7 is presented in Figure 1. The pollen record is dominated by herbaceous pollen with Asteraceae most abundant and Poaceae, Chenopodiaceae, Cyperaceae and Ranunculaceae well represented. Tree, shrub and dwarf shrub pollen are sparse and their presence can be attributed to long-distance transport. *Salix* is most regularly recorded and is present in the catchment and the dam today. This insect pollinated shrub is a low pollen producer which probably results in its low values and intermittent presence in the pollen diagram. Many pollen grains were unidentifiable and degraded. Degraded pollen grains are characterised by an exine with sculptural and structural details that can only be resolved with difficulty. Lowe & Walker (1997) suggest that degraded pollen grains reflect secondary deposition. Degraded grains are commonly crushed or crumpled which also indicates that they have been transported (Cushing, 1967). The NPPs are dominated by the coprophilous fungi *Sporormiella*-type (T113) and the cyanobacteria, *Rivularia*-type (T170). Sordariales and *Coniochaeta xylariispora* (T6) are regularly recorded.

Table 1 Stratigraphy of the Dam 7 core

Depth from (cm)	to (cm)	Descriptor
0	49	Undifferentiated silt - no mottling
49	52.5	fine sand - no grading
52.5	54	Silt
54	61	fine sand with grey and orange mottling
61	65	silt mottled brownish / red
65	68	coarse gravel pieces to 1.5 cm diameter
68	80	Undifferentiated silt - no mottling
80	80.5	fine sand
80.5	83.5	Undifferentiated silt - no mottling
83.5	84	fine sand
84	84.5	Silt
85	86	Silt
86.5	91.5	coarse silt
91.5	98	coarse sand & gravel
98	109.2	Silt
109.2	109.9	fine sand
109.9	113	Silt
113	115.2	fine sand
115.2	120	Silt
120	125.5	silty clay
125.5	128	fine sand
128	135	silty clay
135	137	coarse sand
137	138.5	silty clay
138.5	139.5	fine sand
139.5	144.7	silty clay
144.7	145.2	fine sand
145.2	149.5	silty clay
149.5	151	fine sand
151	152.4	silty clay
152.4	152.6	fine sand
152.6	176	silty clay
176	176.5	fine sand with charcoal
176.5	180	silty clay
180	180.5	fine sand with charcoal
180.5	201	silty clay
201	201.8	fine sand
201.8	203.3	silty clay
203.3	203.5	fine sand with charcoal
203.5	206	silty clay
206	206.2	v. Thin sand layer
206.2	208.5	silty clay
208.5	210.5	coarse sand and gravel
210.5	220	silty clay

Figure 1 Selected pollen, non pollen palynomorphs and microscopic charcoal from dam 7



4. INTERPRETATION

The lowest two pollen samples are taken from silty clay deposited in ca. 1958, the approximate start of Cs^{137} deposition in dam 7. Both samples record evidence for cultivation (Cereal-type pollen) and grazing (*Cercophora*-type, *Sporormiella*-type). Asteraceae dominate the record whilst Chenopodiaceae percentages decreased. *Rivularia*-type indicates the sediments were deposited in eutrophic water. *Glomus*-type (T207) is indicative of erosion into the dam. The silty clay deposited between 180 and 176.5 cm has a similar pollen and NPP assemblage. Microscopic charcoal values are high, with large pieces of charcoal suggesting that fires were of a local origin. This is confirmed by the presence of visible charcoal bands in the stratigraphy (Table 1).

The silty clay, fine sand and silty clay deposited from 176 to 151 cm contain evidence of increased grazing: higher amounts of Poaceae and *Sporormiella*-type and the presence of *Cercophora*-type. Eutrophication of the dam water is indicated by the increase in heterocysts of *Rivularia*-type at 180-179cm. Cereal-type pollen is recorded in the upper fine sand/silty clay and indicates that these layers may have been derived from the cultivated area.

Grazing pressure is reduced and fire suppressed in the fine sand deposited between 145.2-144.7cm. Poaceae percentages are still relatively high and the presence of coprophilous fungi *Cercophora*-type, *Sporormiella*-type and *Tripterospora*-type indicate the catchment was still being grazed. The dam water is less eutrophic as *Rivularia*-type percentages fall to trace amounts. These conditions persisted during deposition of silty clay and silt between 135 and 115.2 cm. Higher amounts of *Sporormiella*-type and the presence of *Cercophora*-type, Type 55A, Sordariales and *Tripterospora*-type are indicative of grazing, which might account for the decline of Poaceae and the increase of Asteraceae and Chenopodiaceae. Cereal-type pollen is only recorded at 135-134cm. Microscopic charcoal is well represented and the increase in smaller pieces suggests that the region was subjected to more widespread and/or intense fires. *Gelasinospora* also peak and have been associated with charcoal, lignin and dung (Yeloff et al., 2007).

Silt deposited between 109.2 and 98 cm is characterised by lower amounts of Asteraceae and Chenopodiaceae whilst Poaceae and Cyperaceae increased. Grazing indicators *Sporormiella*-type increased and Type 55A, Sordariales and *Tripterospora*-type are all present. Cereal-type pollen is recorded in the lower part of this deposit. Degraded pollen, which frequently reflects secondary deposition (Lowe & Walker, 1997), peaked in this unit.

A major storm in 1963 deposited coarse sand and gravel between 98 and 91.5 cm. Thereafter layers of coarse silt and silt were deposited between 91.5cm and 86.5 cm. These layers are characterised by increased Poaceae and Chenopodiaceae, and decreased Asteraceae. *Rivularia*-type peaked in the lower part of the unit and indicates that the dam water is more eutrophic. Grazing indicators such as *Sporormiella*-type, *Arnium*-type and Sordariales are present. *Glomus*-type peaked. Microscopic charcoal values fall suggesting a reduction in fires.

The undifferentiated silt between 68 and 80 cm can be associated with grazing. It contains higher amounts of Poaceae, Rosaceae, *Sporormiella*-type (T113), and indicators of drier conditions, *Gelasinospora* and *Coniochaeta xylariispora*-type (T6) (Yeloff et al., 2007). Increased percentage of degraded pollen grains indicated that a sizable proportion of the pollen contained in this layer has been transported and possibly re-deposited.

The upper silt is characterised by high Asteraceae pollen. Poaceae and *Sporormiella*-type both decline suggesting reduced grazing pressure as palatable grassland also declined. The main beneficiary is Chenopodiaceae. Microscopic charcoal values fall across the fine sand/silt boundary at 49 cm suggesting that natural fires have declined or that fire has not played a significant role in recent land management.

5. DISCUSSION

Evidence for local grazing is provided by a series of coprophilious fungi: *Cercophora*-type (T112), *Sporormiella*-type (T113), *Tripteropora*-type (T169) (van Geel, 2001; van Geel et al., 2003). van Geel et al (2003) suggest that *Sordaria*-type (Type 55A) and Sordariales spores were produced by various different species belonging to the mainly coprophilous Sordariales. Spore production of these fungi is high but their dispersal is poor as their fruit bodies are located close to the ground (Feeser & O'Connell, 2009). The regular occurrence of coprophilous fungi confirms that the catchment has been grazed continuously over the last 40 years. Stocking rates in the Karoo and Middelburg district show increases from 1840, peaked in the 1920s and have since declined (see Chapter 1, this guide). The record of coprophilous fungi at dam 7 is not totally inconsistent with this general decline but differences do exist. *Sporormiella*-type was most abundant throughout the dam 7 sequence. It achieved its maximum values and might indicate more intense grazing pressure in the catchment between 170 and 150 cm and at 75 cm. Percentages decreased in the uppermost 45 cm which suggests that grazing has been less intense. Poaceae (grass) pollen followed a similar trend, being highest below 80cm, and indicates suitable pasture was available in the catchment. The higher values of *Sporormiella*-type and the presence of other dung fungi such as *Cercophora*-type and *Tripterospora*-type coincides with an increase in sediment yield to dam 7 between 1958 to 1964 (see Boardman et al., 2010) suggesting a causal relationship between grazing and increased erosion.

Studies in South Africa have suggested that high erosion rates are often associated with cultivation (Kakembo & Rowntree, 2003; Sonneveld et al., 2005; Boardman et al., 2010). Evidence for erosion is supported by the presence of *Glomus*-type (T207), especially between the base of the core and 90 cm. Chlamydospores of the soil inhabiting *Glomus*-type is often recorded in lake sediments and has been associated with phases of erosion as a result of drought (López-Sáez et al., 2000) and/or burning and cultivation (van Geel et al., 1989; Argant et al., 2006). Cereal cultivation peaked in the late 1950s in the dam 7 catchment and cereal pollen is present in low quantities during this time, from the base of the core to 80 cm. Cereal pollen is poorly dispersed due to its large size and therefore it is not often found in abundance in lakes, even when close to cultivated areas unless the pathway to transport sediment and cereal pollen from the field to a lake is very efficient (Pittam et al., 2006). The gully systems appear to offer an efficient pathway for transport of sediment to Compassberg dam 7 (Foster et al., 2007). In the 1945 aerial photos there are 4 discontinuous gullies coming into the cultivated area and there is some evidence that these are linked to dam 7 (see Chapter 5, this guide). The cultivated area is also very close to dam 7 but changes in the local topography (construction of contour bunds) might have impeded the delivery of sediment to the dam. The larger dam 7catchment has lower sediment yields compared with the dam 10 catchment. Boardman et al. (2010) suggest that lower absolute yields in dam 7 are a function of the lower sedimentary delivery ratio as the larger catchment has more opportunity to store sediment. Such a scenario would also limit the amount of cereal pollen reaching the dam. Notwithstanding the relative lack of cereal pollen in the dam 7 sediments; its occurrence coincides with increased sedimentation in dam 7 when compared with rates in the uncultivated catchment of dam 10. Thus the record of cereal pollen in dam 7 does lend some support to the suggestion that high erosion rates were linked to cultivation (Kakembo & Rowntree, 2003; Sonneveld et al., 2005; Boardman et al., 2010). However, the coprophilous fungi record suggests that grazing pressure was also significant at Compassberg. The presence of *Glomus*-type in the dam 7 sediments also coincides with more abundant charcoal. Intentional burning as part of a land management strategy may have been employed during this time (cf. Beinart, 2003).

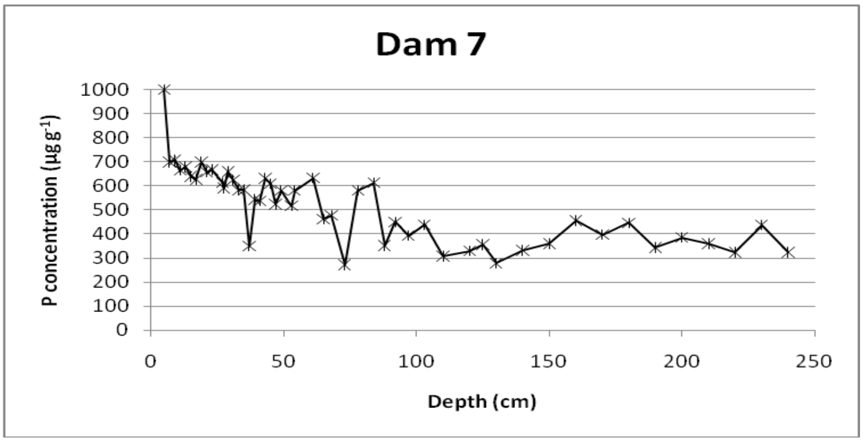
According to van Geel et al. (1996) cyanobacteria are dominant in more eutrophic systems and their dominance can often be explained by increased phosphorus concentrations. The heterocysts of the cyanobacteria *Rivularia*-type are commonly found in lake sediments. They are used as evidence of eutrophication by organic phosphate by Medeanic et al. (2008) and they can be important in nitrogen-depleted environments due to their ability to fix nitrogen (Rull et al., 2008). van Geel et al. (1996) suggest *Rivularia* will bloom in eutrophic, nitrogen-depleted shallow waters. At Dam 7 heterocysts of *Rivularia*-type are relatively abundant in the lowermost part of the core and peaked at 170 cm. It was recorded intermittently with minor peaks at 115 and 100cm and it is continuously present from 70 cm to the surface. These increases can be considered to be an indication of increased nutrient loading, probably as a result of human activity in the catchment.

The increase in trophic status suggested by the palynological evidence presented above appears to be supported by the sedimentary P data shown in Figure 2A for Dam 7. There is a slight increase in P in dam 7 between 175 and 155 cm. Upcore of 100 cm depth there appears to be a sustained increase in sediment P concentration towards the sediment surface punctuated by occasional low concentrations that correlate with documented flood events discussed in Chapter 5 (this guide). A similar trend is not apparent in the sediments of Dam 10 (Figure 2B).

There is no statistically significant correlation between the sediment P concentration and particle size characteristics of the deposited sediments (Figure 3) and we have no evidence that fertilisers have ever been used on the cultivated cereals. Our analysis of the sedimentary P concentrations of potential contributing sources confirms that concentrations are significantly higher in the weathered dolerites and dolerite-derived soils in the area than they are in the donga sidewall sediments and in the sandstone and colluvium-derived topsoils (Foster et al., 2005; 2007). The most likely explanation of the ‘apparent’ increase in eutrophication as indicated by the sedimentary P record is that dolerite-derived topsoils with relatively higher P concentrations than other potential sources have made a more important contribution to the sediments accumulating in the dam since 1963.

Figure 2 **Trends in sediment P concentrations in the sediments of Dams 7 (A) and 10 (B).**

A



B

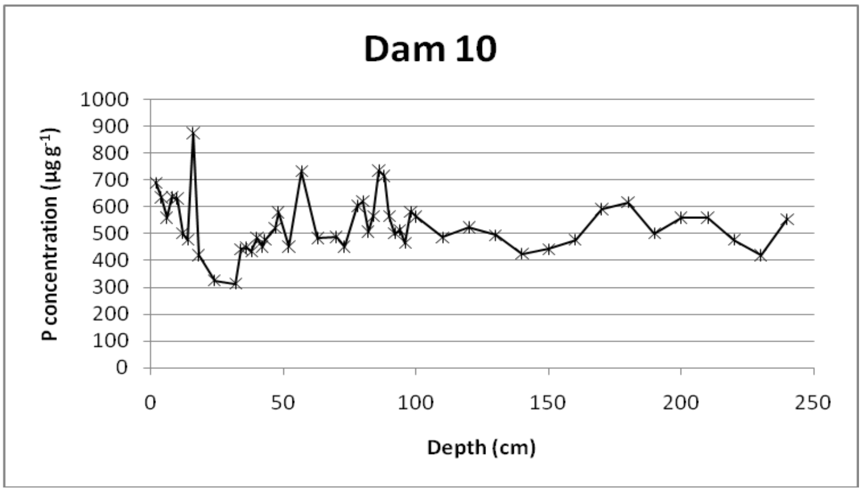
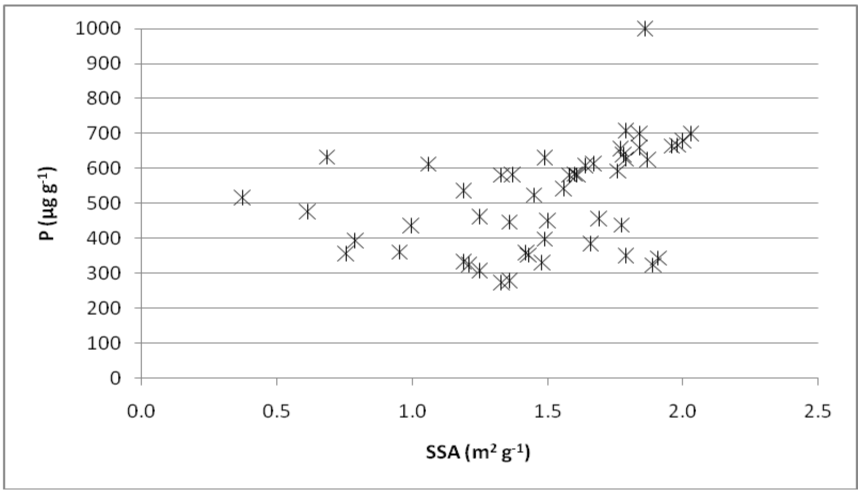


Figure 3 **Relationship between Particle Specific Surface Area (SSA) and sediment-P concentration in the sediments accumulating in Dam 7.**



6. CONCLUSION

The pollen and NPPs from dam 7 presented here provide a record of environmental changes since c. 1958. There is evidence for cereal cultivation and grazing throughout the profile. Both appear to be linked to soil erosion in the catchment. Heterocysts of *Rivularia*-type and P concentrations compare favourably and suggest that the dam water experienced eutrophic conditions. High microscopic charcoal values, especially in the lower 1 m of the core, suggest that fire was ubiquitous in the landscape and probably used as part of a land management strategy.

Further investigations of farm dam sediments and vleis can provide valuable insights into the relationship between human activity, vegetation change, climate change and soil erosion. For example, these archives and the proxy records contained within them can be used to test hypotheses about the causes of long-term and recent land degradation and examine the impact of European farming systems in vulnerable landscapes, including the introduction of alien species.

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7. LATE QUATERNARY PALAEOECOLOGY OF KAROO LANDSCAPES: LONG TERM ECOLOGICAL CHANGE AS A BACKDROP TO HISTORICAL LAND DEGRADATION

Mike Meadows

1. INTRODUCTION

Long term climate changes, in particular associated with the repeated glacial and interglacial cycles of the later part of the Quaternary, have impacted on the vegetation and other environmental characteristics of the Karoo. Quaternary scientists have been at pains to attempt to unravel these environmental dynamics but the details and timing of these important events, especially in arid and semi-arid environments, have proved very cryptic. Therefore, chronologically well-controlled multi-proxy data sets that facilitate reliable reconstructions of changing environments over extended periods remain extremely rare in this part of the world. It is therefore an ongoing frustration that the seemingly dramatic landscape changes that have occurred in the Karoo during the last century or so are difficult to place within a longer-term context. In other words, the absence - or at least presence of only a very limited understanding of longer term environmental change- is a constraint to a more informed perspective on the narrative of land degradation and its associated physical and biological manifestation. In this section, we revisit the reasons for the apparent paucity of palaeoecological evidence in semi-arid environments and then briefly explore some of the more informative sites that do allow us to sketch some of the relevant palaeoenvironmental details.

2. CONSTRAINTS TO A ROBUST PALAEOECOLOGICAL RECORD IN THE KAROO

Traditional Quaternary palaeoecological methods involving the identification of wetlands with suitably long organic sequences rich in pollen, while they have on occasion been applied successfully in the region (see examples below), are not well suited to the high energy fluvial environments that prevail in a region characterised by aridity, extreme climate seasonality and strong erosional forces. Pollen analysis as a tool for palaeoenvironmental reconstruction was developed in the temperate regions of the northern hemisphere for good reason: the relatively cool and moist conditions that favour the accumulation of organic sediments in lakes and wetlands are prominent in such circumstances.

Equivalent conditions are either absent or only intermittently present in places like the Karoo and palaeoecologists have been forced either to abandon the conventional sedimentary archives and turn to alternative sedimentary accumulations (e.g. pan sites, Scott & Brink, 1992; hyrax middens, Scott & Vogel, 1992) or sacrifice temporal and taxonomic resolution in wetland deposits that are only periodically favourable to pollen accumulation resulting in highly fragmented records (e.g. Bousman et al., 1988). There are, accordingly, what Horowitz (1992: 5) refers to as ‘peculiarities of palynology in arid lands. Pollen is often poorly preserved, its taxonomic resolution is poorly understand and the chronology all too often inadequately resolved. This is a bleak picture, although there are several sites across the region that do allow for the development of a coarse-resolution picture of climate and associated vegetation changes that have characterised the later Quaternary.

3. VALLEY-FILL DEPOSITS IN THE KAROO: BLYDEFONTEIN, COMPASSBERG AND NUWEVELDBERG

There are two key valley-bottom sites that have facilitated a tentative late Holocene vegetation history for the region, *viz*. Compassberg (Meadows & Sugden, 1988) and Blydefontein (Bousman et al., 1988). These vegetation histories are supplemented by another palaeoecological reconstruction based on wetland pollen analysis at Nuweveldberg to the east (Sugden & Meadows, 1989), pollen from a hyrax dung midden also at Blydefontein (Bousman & Scott, 1994) and a study of the stable carbon isotope geochemistry of soils (Hoffman et al., 1994; 1995).

3.1 Compassberg

In the upper reaches of the Klein-Seekoerivier, a vlei (31˚ 45’ 37”S; 24˚ 32’ 22”E), some 300m wide is incised by a donga that has exposed some 3m of alluvial sediments within which is a more organic facies interpreted as a palaeosol with a radiocarbon age at its base of 3590± 70 BP (Ptsa 4342). The pollen diagram (Figure 1) shows that the vegetation history, probably representing a few hundred years or so following the initiation of organic sedimentation, is dominated by grasses and sedges (Meadows & Sugden, 1988). Near the base of the layer there are indications of vegetation not markedly different from the *Merxmuellera* mountain veld that characterises the region today. However, Meadows & Sugden (1988) note some interesting changes in pollen frequencies and the upper levels have higher proportions of karroid shrub pollen and lower grass cover consistent with an interpretation of a decrease in available moisture through the sequence. The conclusion reached is that the initiation of the organic facies represents a wetter phase followed by gradual drying of a floodplain pool or wetland.

3.2 Blydefontein

The Blydefontein basin (31˚10’S; 25˚ 04’E) in the upper reaches of the Oorlogspoort River, is similarly situated to Compassberg in that represents headwater valley fills that have been cut by dongas. The well preserved sediments have been intensively investigated by Bousman et al. (1988) and there is better chronological control, through radiocarbon dating, than for any other site in the Karoo as a whole. Several cycles of pool formation and desiccation are apparent in both the sedimentology and palaeoecology (pollen, diatom, molluscs) of the deposits. The pollen diagram for BFS is shown here as Figure 2 and is interpreted as providing evidence for the shifting position of the stream across the floodplain rather than as palaeoclimatic evidence *per se*, although there are some indications of increased grass cover (and therefore effectiveness of summer rainfall) around 1400 BP.

Additional light is cast on the Blydefontein story, in particular for the historical phase, by the analysis of pollen from hyrax middens by Bousman & Scott (1994). The prominence of, and clear inverse relationship between, grass and Asteraceae pollen in the sequence, shown in Figure 3, is notable but reveals that the decline in grass cover that would be expected to arise from overgrazing and disturbance following the colonisation of the region by *trekboers* in the late 1700s actually predates that process by at least a century. Overgrazing cannot account for all the pollen frequency variations illustrated and the conclusion is that both climate change and impacts on the landscape by pre-colonial hunter-gatherer and herder communities are likely contributors to the eastern Cape landscape development over the period in question.

Figure 1 Pollen diagram for Compassberg (Meadows & Sugden, 1988)

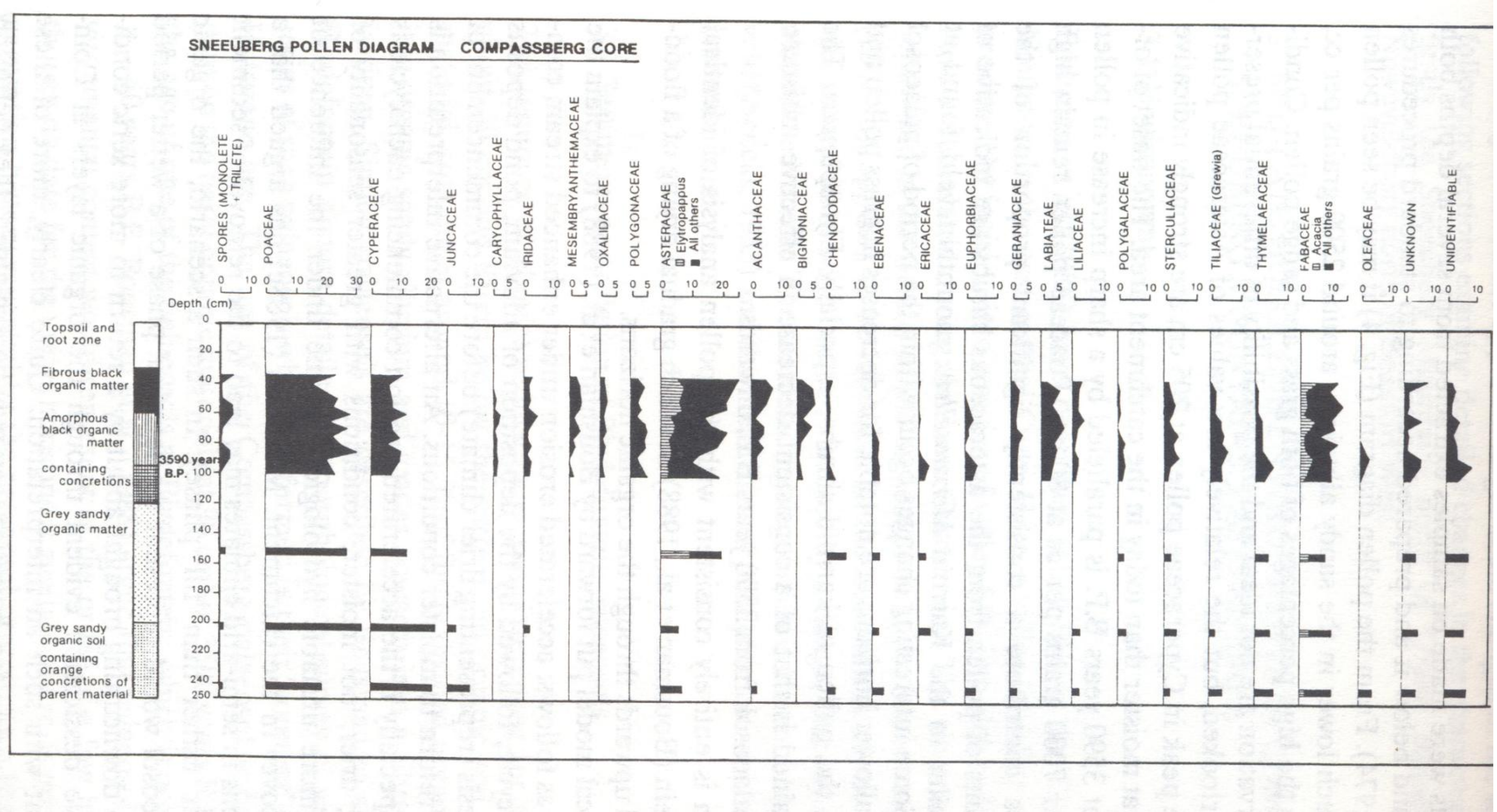


Figure 2 **Pollen diagram for Blydefontein BFS (Bousman et al., 1988)**

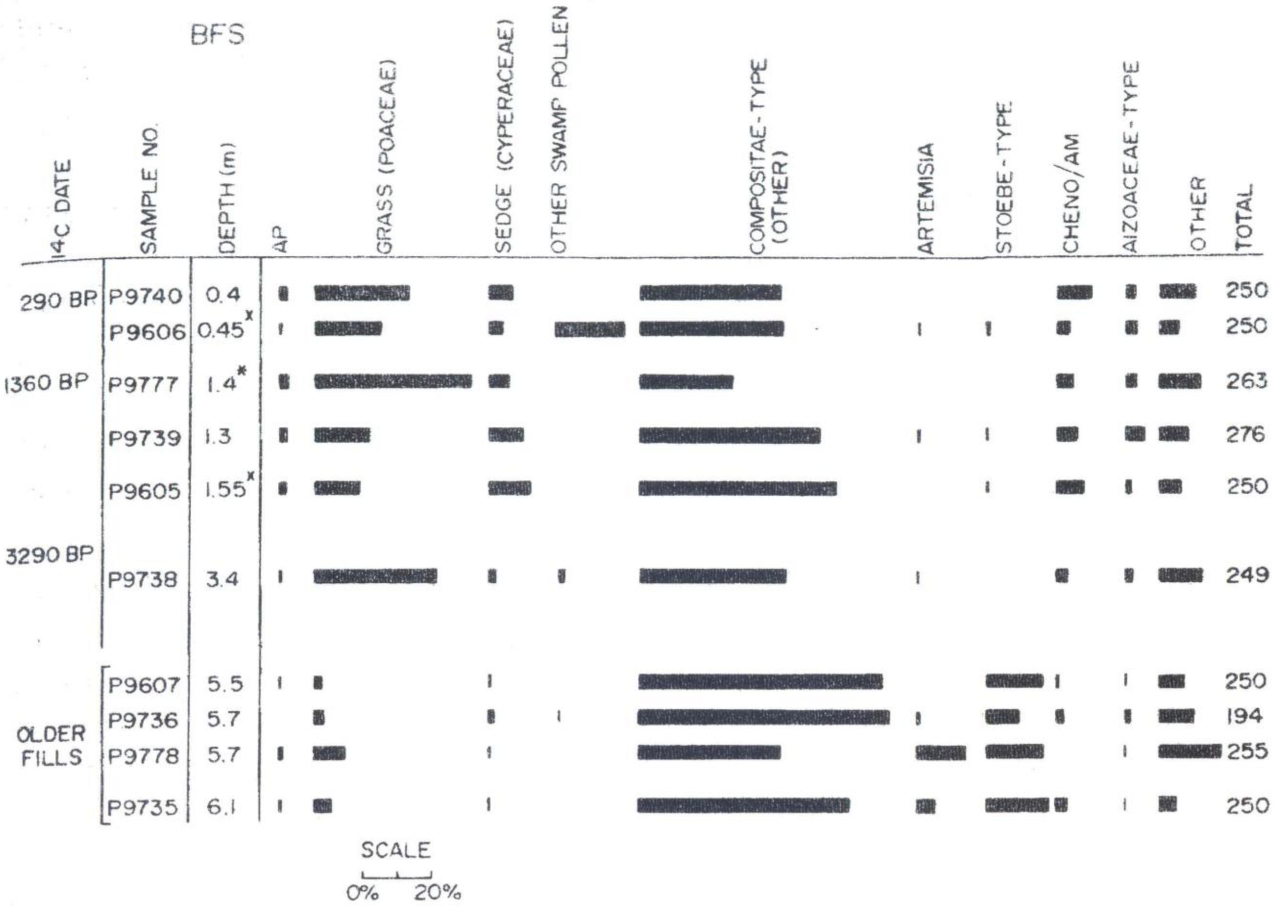
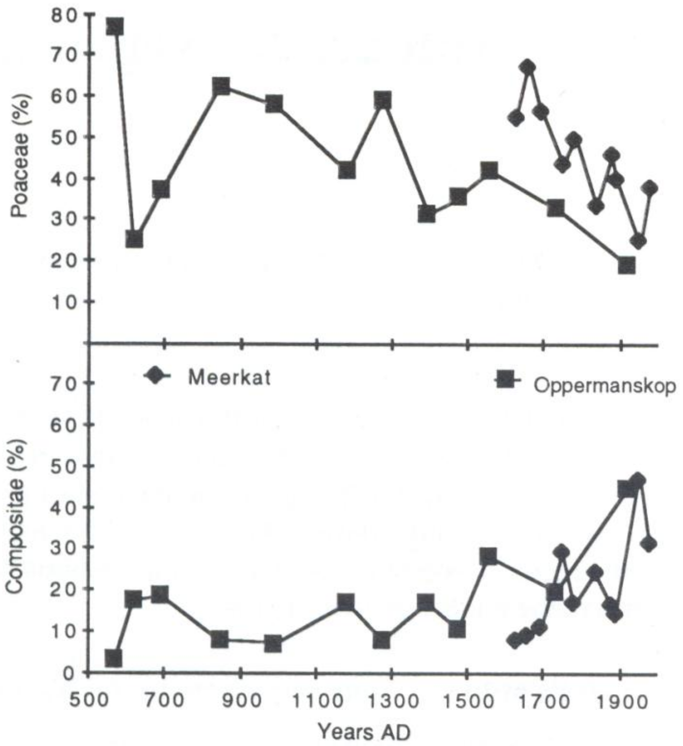


Figure 3 **Changes in Poaceae and Asteraceae (shown here as Compositae) in hyrax dung middens at Blydefontein (Bousman & Scott, 1994).**



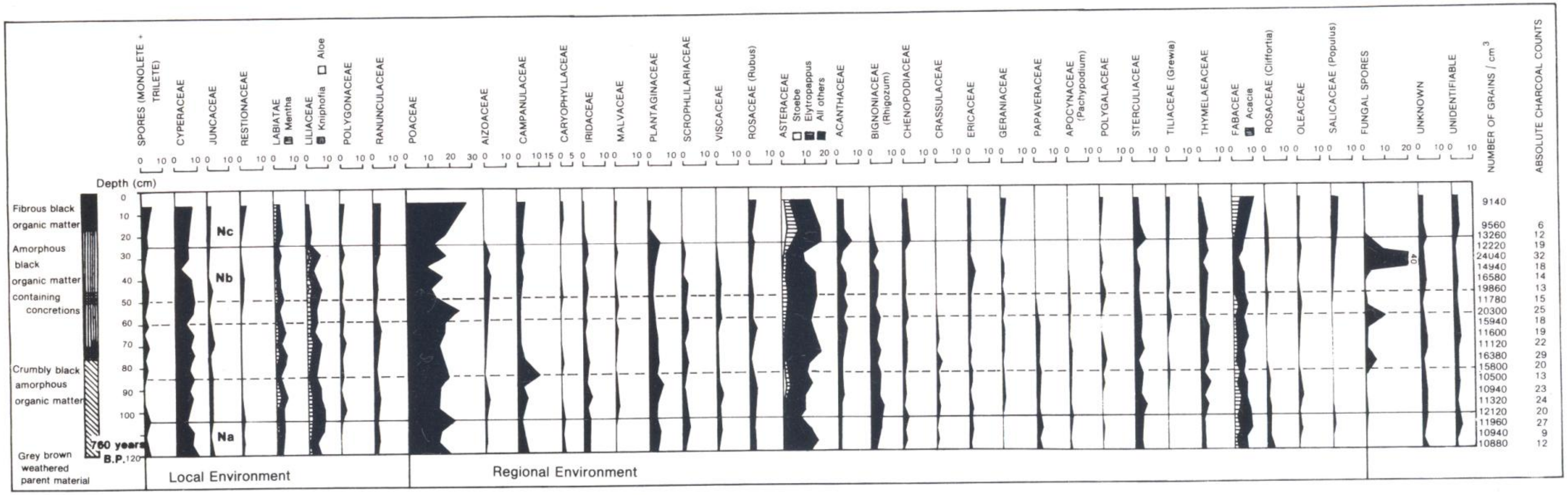
3.3 Nuweveldberg

A wetland sedimentary deposit that accumulated during the last 800 years on the Nuweveldberg plateau near Beaufort West may help to cast further light on the rather fragmented record of vegetation history. Overall, pollen fluctuations at Bokkrall Vlei (32˚15' 55"S; 22˚ 29' 40"E) are minor, but Sugden & Meadows (1989) utilise multivariate statistics on the pollen diagram (Figure 4) to reveal that the upper levels of the sequence represent a disturbed system and that this may well date to the occupation of the region by European colonists.

3.4 Other evidence: stable carbon isotopes in soils

Bond et al. (1994) and Hoffman et al. (1995) have conducted stable carbon isotope analysis at several sites across the Karoo on the basis that a shift from C4 grass-dominated vegetation to C3 shrubland, as expected through over-grazing, should be reflected in changes in isotope geochemistry with soil depth. They conclude that grass cover has indeed declined under grazing pressure within the historical time period but the hypothesis that much of the central Karoo was occupied by grassland prior to the arrival of European settlers cannot be supported.

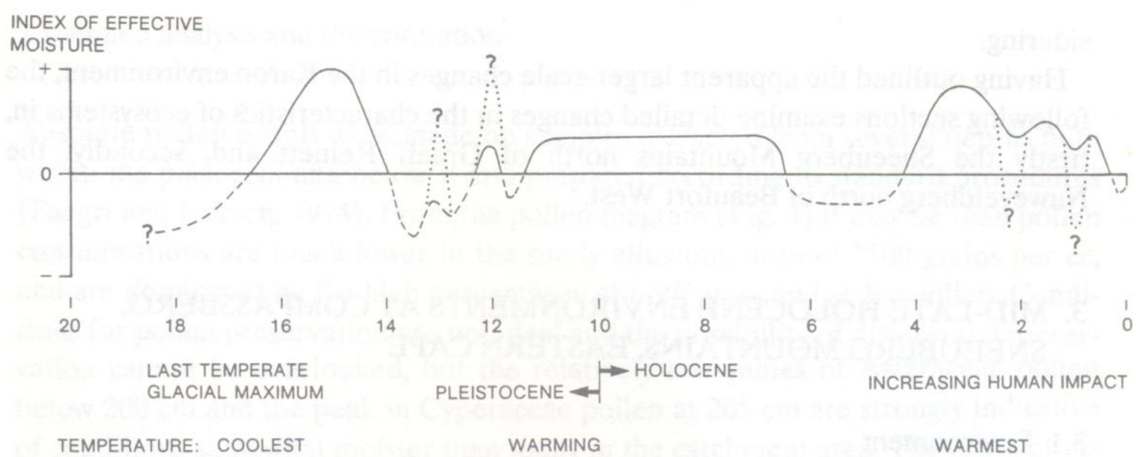
Figure 4 **Pollen diagram for Bokkraal vlei, Nuweveldberg (Sugden & Meadows, 1989)**



4. A PALAEOECOLOGICAL SYNTHESIS?

The longer-term environmental history of the Karoo is far from securely known but there are strong indications that the landscape has been a very dynamic one. Figure 5 offers a tentative summary of some of the changes in effective moisture that have occurred over approximately the past 20k years (Meadows and Watkeys, 1999). The later part of the Holocene appears to have been, on the whole, associated with more mesic conditions, although at several intervals there are periods of markedly drier climates and there is undoubtedly an increased human footprint evident that probably even pre-dates the *trekboer* colonisation phase.

Figure 5 Tentative reconstruction of moisture availability changes over the last 20kyr for the Karoo (Meadows & Watkeys, 1999)



Distinguishing between vegetation and, indeed, broader landscape changes that are a direct consequence of grazing pressure from those that a result of rainfall dynamics remains a key challenge in this region. Certainly, any attempts at unravelling the impacts of people from those of changing climate requires a longer temporal perspective than can be provided by the historical record and an understanding of the sensitivity of these landscapes to future climate change would also benefit from a longer palaeoenvironmental record. Archives such as hyrax middens represent a widespread and chronologically better resolved source of palaeoenvironmental evidence that may yet cast further light on these perplexing issues.

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8. RECONSTRUCTING LONG TERM LAND DEGRADATION IN THE KAROO: A GEOCHEMICAL APPROACH

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1. INTRODUCTION

Severe erosion and land degradation in the South African Karoo have been ascribed to a variety of factors including overgrazing by livestock, inappropriate crop selection and cultivation methods, land abandonment, road construction and extreme floods (e.g. Beinart, 2003; Boardman et al., 2010; Foster et al., 2005; Chapter 1, this guide). Given that large areas of the Karoo have been devoted to livestock agriculture, cereal and market gardening since European colonisation in the early nineteenth century, human-environment interactions have become increasingly important in determining the longevity of the region as a sustainable agricultural resource. Management is therefore crucial in an area that is sensitive to land management, future climate change and abrupt changes in weather. To fully understand the relation between land degradation and human activity, a long term perspective is needed as there has been some debate to whether native herders, including San Bushmen, caused irreversible damage to the Karoo landscape before the arrival of European colonists. San Bushmen lived off the land using a transhumance model of subsistence agriculture. Little is known about their relationship with the natural environment although Elphick (1985) and Bollong & Sampson (1999) suggest that they caused irreversible damage to the landscape for over two millennia whilst Lovegrove (1983) suggests that they could have at least caused local overgrazing. However, as Kraajj & Milton (2005) argue, a paucity of long-term studies exists to test this hypothesis.

Fox (2000) suggests that European colonists, who arrived and settled in the Karoo in the early nineteenth century, are in part, responsible for increased degradation and that this has occurred through a combination of factors including over-stocking of livestock, poor crop selection and cultivation methods, the use of fire as a veld management tool, road construction and extreme floods. Therefore, the exact timing and causes of severe erosion and the development of features associated with land degradation, such as badlands and gullies, are contentious (Kakembo & Rowntree, 2003; Rowntree et al., 2004). Recent studies (e.g. Foster et al., 2005; 2007; Keay-Bright & Boardman 2006; Boardman et al., 2010) have shown that recent farming has indeed had an adverse impact on the landscape, but little is known about the relationship between the earlier bushmen and their land as well as the long term evolution of these culturally modified landscapes (see Chapter 7). This contribution aims to redress the lack of long term information about the impact of early occupants of the region by using records preserved in vleis in the Karoo. Farm dam sediments and vleis provide archives of environmental change which can be reconstructed using biological and geochemical proxies preserved within them. They provide records of microscopic charcoal, pollen and non-pollen palynomorphs (NPPs) and geochemistry alongside ^{137}Cs, ^{210}Pb for dating and mineral magnetic signatures. Preliminary results of geochemical analysis from two vleis at Misty Hills and Compassberg will be presented here.

In this study, geochemistry has been used as a proxy to identify periods of accelerated soil erosion. Lithogenic, conservative and immobile elements, such as Al, Ti, Sc, Sr, Rb and Zr, have been shown to be strongly related to mineral matter (Fábregas

Valcarce et al., 2003) and their presence in peat deposits at high concentrations is most likely to have been result of deposition from eroded catchment soils, or by dry or wet deposition from the atmosphere (Martinez Cortizas et al., 2005).

Based on the assumption that past human impacts on the vegetation must have also induced changes in other components of the landscape (i.e. soils), the main objectives of this research are to:

1) Establish a high-resolution chronology for the accumulation of lithogenic elements and of vegetation changes,
2) Determine the link between vegetation change, human activities and soil erosion and
3) Determine the scale of the impacts (local, regional, extra-regional), 4) to examine competing hypotheses of land degradation in the Karoo.

2. SITE DESCRIPTION AND FIELD METHODS

Two sites were chosen to provide a wider regional setting for this study. A ~1 m deep section was sampled from Compassberg vlei, which is located 2.3 km SW of the catchments of dam 7 (See Chapter 5, this guide). The Compassberg vlei, previously investigated by Meadows & Sugden (1988; described in Chapter 7 of this guide), was sampled from a freshly exposed and clean section cut through the vlei. It contains a record that extends back through the late Holocene. A 0.4m core was also taken from Misty Hills vlei (MHV), ca. 5 km south of Riebeeck-East, and ca 30 km north west from Grahamstown. Duplicate cores were taken using a 50 cm long, 5 cm wide russian corer. The cores were carefully placed in labelled plastic guttering and wrapped in polythene to prevent contamination. In the laboratory, the cores were then cut into 1 cm slices and placed into individual sealed plastic bags ready for further analysis: pollen and non pollen palynomorphs, geochemistry, mineral magnetism, loss-on-ignition and for dating by ^{210}Pb analysis by gamma spectrometry.

3. LABORATORY METHODS

Contiguous samples of 1 or 2 cm thickness from Misty Hills and at 1 or 2 cm intervals at Compassberg vlei have been analysed for geochemistry following the methodology outlined by Martinez Cortizas et al. (2005). All samples were air-dried, milled and homogenised. Fifty seven samples from a core of 101 cm from Compassberg vlei and 37 samples from Misty Hills were analyzed using an XRF energy dispersive miniprobe multi-element analyser (EMMA) housed in the University of Santiago de Compostela, NW Spain. This approach has been chosen because it is non-destructive, less time consuming and more cost-effective compared to other methods of chemical analysis. Despite being a relatively new analytical method, it has already been rigorously tested and therefore the data are completely reliable (Cheburkin & Shotyk, 1996; Weiss et al., 1998). Detectable concentrations of 23 major, minor and trace elements were determined (Si, Al, Fe, K, Ca, Ti, S, Ga, Rb, Sr, Y, Zr, Nb, Cr, Mn, Ni, Cu, Zn, As, Pb, Th, Br, Cl).

^{210}Pb dating has been undertaken on the uppermost samples from each vlei. The methods are described fully elsewhere in this guide (Chapter 5) and in Foster *et al*. (2005).

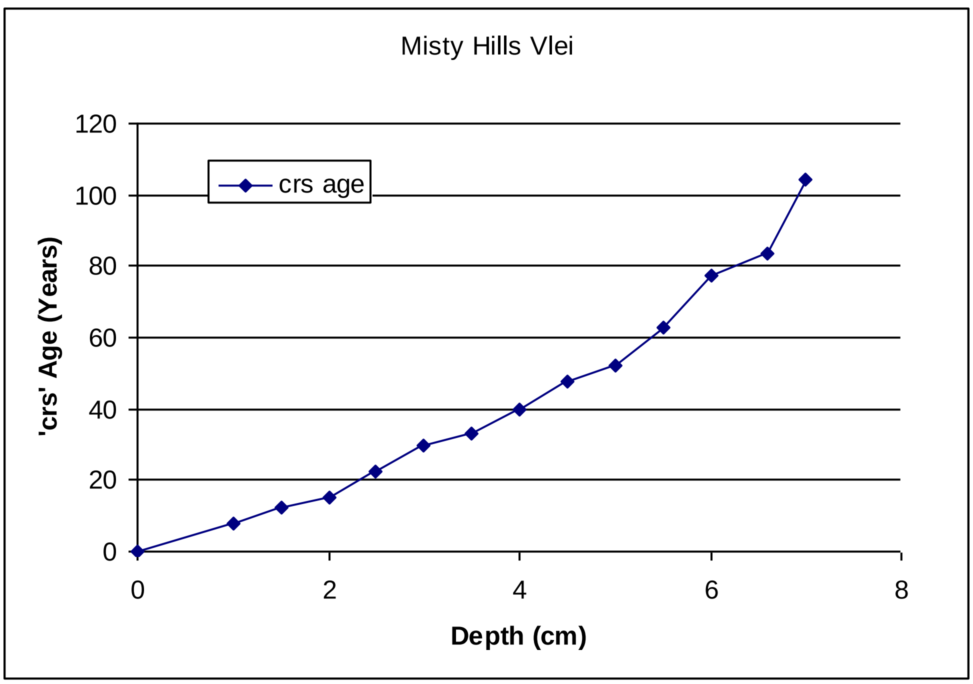
4. RESULTS AND INTERPRETATION

4.1 Misty Hills Vlei (MHV)

4.1.1 Dating

An depth-age plot for the MHV is shown in Figure 1. The CRS ^{210}Pb dating model (Appleby, 2001) was selected as it does not assume constant accumulation rates and the decay of unsupported ^{210}Pb with depth in the core proved to be non-monotonic. The model predicts 7.5 cm of sediment accumulation over ca 105 years. If these rates are extrapolated, the full sequence would span approximately 750 years. Further dating is required to confirm this.

Figure 1 Depth-Age plot for Misty Hills vlei sediment core.



4.1.2 Geochemistry

The concentrations of major and trace elements measured through the MHV sediment column are shown in Figure 2 and a correlation matrix including LOI in Table 1.

Significant positive correlation occurs between the immobile lithogenic elements: Al, Si, Ti, Y, Zr, Cr and K. They all display similar downcore trends: higher concentrations until they decrease in the uppermost 5 cm. Because there is little variation in the concentrations of the lithogenic elements until the top 5 cm, it is difficult to discern any clear patterns of dust deposition that could be attributed to past changes in vegetation and land use. These elements are typically derived from mineral matter and they are likely to have been deposited either by sedimentation, runoff, weathering and/or atmospheric dust deposition (Shotyk, 1988). If atmospheric dust deposition is the primary source, the data suggests that the influx to the MHV has been relatively constant through time. This is unlikely and therefore the record is more likely to have been derived from localized sources, most likely the weathering of bedrock minerals. As K is associated with other lithogenic elements, it appears to be hosted by mineral phases rather than biocycling.

A second cluster of related elements includes Ca, Mn, Fe, Zn, Rb, Br, Sr, S, Ga and Pb. They all display similar downcore profiles. There is little variation until the uppermost 5 cm when concentrations increase. Rb has a slightly different pattern as concentrations fall at the surface. Rb and Sr are elements usually associated with biocycling. The positive correlation of this second cluster with LOI suggests that these elements are organically-bound e.g. Br, Pb, Zn and biophylic e.g. S. This cluster includes Pb suggesting that there might not be any significant contribution from atmospheric deposition (Schofield et al., 2010). The increase of these elements at the vlei surface suggests that they are strongly influenced by organic matter and plant uptake and recycling and possibly oxidation (Shotyk et al., 2003). The pattern of Fe concentrations to that of the organically-bound elements suggests that most of the Fe occurs in Fe-humus complexes. Br is largely derived from ocean spray and rainfall, but its accumulation in soils is related to enzymatic halogenation of organic matter (Biester, 2004; Martínez Cortizas, 2007).

Figure 3 shows the factor loadings and a graph with the fractionation of communality and Figure 4 shows the distribution of the factor scores with depth, obtained by principal components analysis (PCA).

Figure 2 Profiles of selected major and trace elements and LOI from MHV

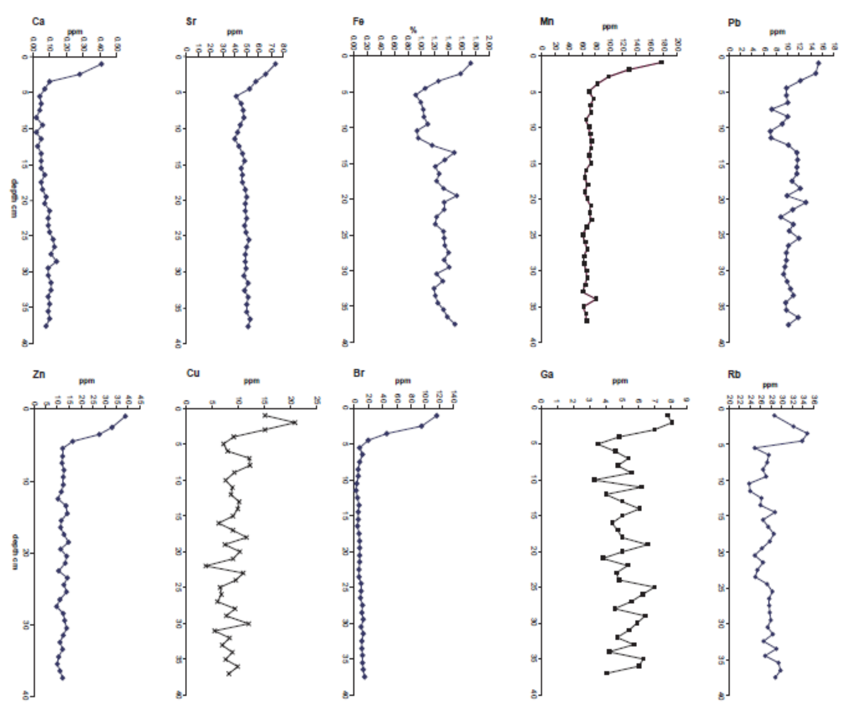


Figure 2 (continued)

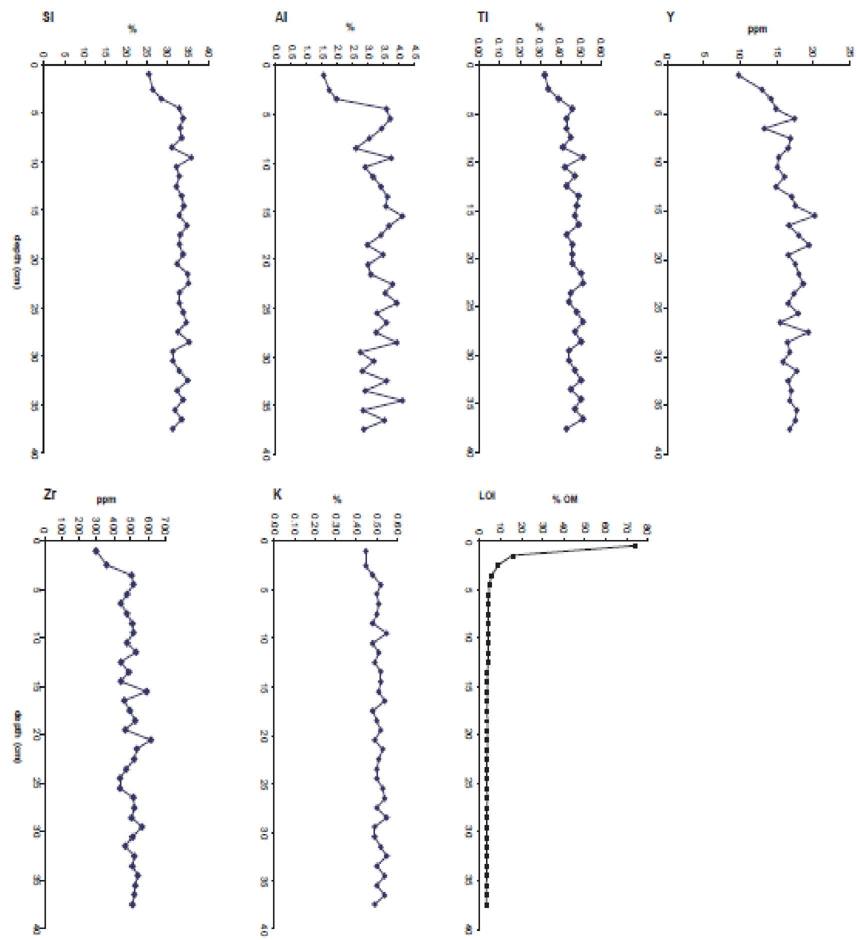
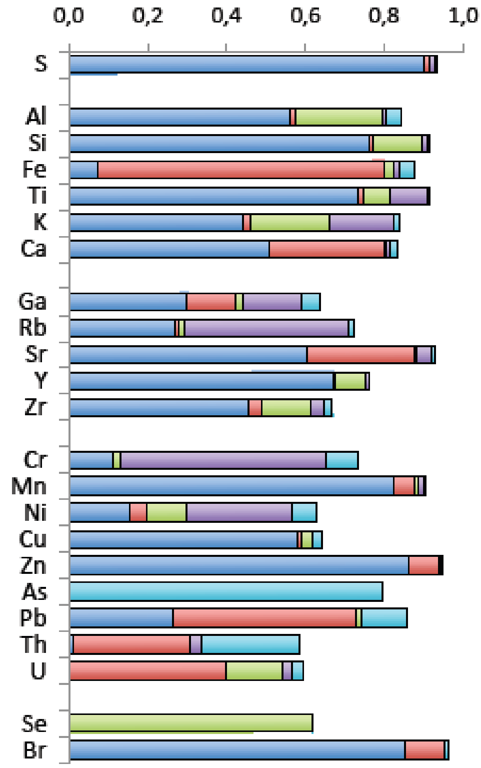


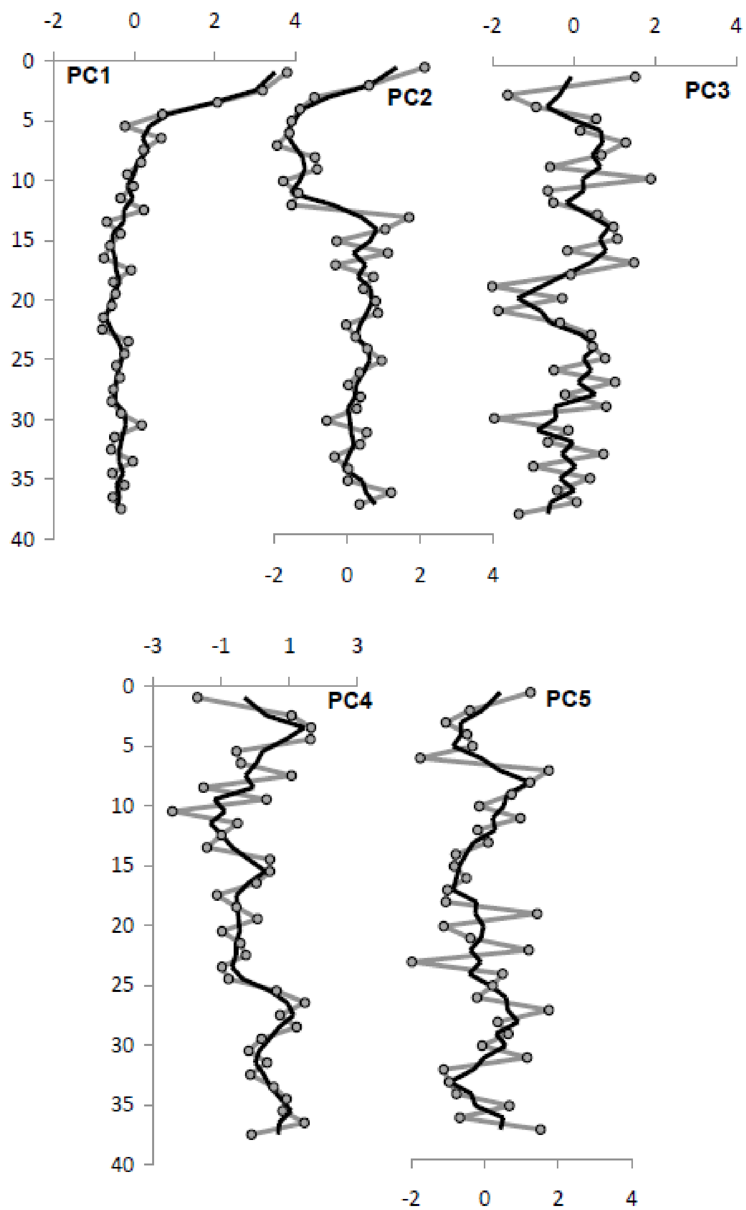
Figure 3 **PCA from MHV: Table with factor loadings and a graph with the fractionation of communality**

	PC1	PC2	PC3	PC4	PC5
Al	-0,75	-0,10	0,47	0,10	-0,20
Si	-0,87	-0,10	0,35	0,12	-0,08
S	0,95	0,12	0,04	0,12	-0,05
K	-0,66	0,14	0,45	0,40	-0,11
Ca	0,71	0,54	0,06	0,10	0,15
Ti	-0,86	0,11	0,26	0,31	-0,05
Cr	-0,33	-0,04	0,13	0,72	0,29
Mn	0,91	0,23	0,10	-0,12	0,05
Fe	0,27	0,85	-0,15	0,12	0,20
Ni	0,39	0,20	0,32	-0,52	0,25
Cu	0,76	0,09	-0,16	0,02	-0,15
Zn	0,93	0,28	-0,07	-0,02	-0,03
Ga	0,55	0,35	-0,14	0,38	0,22
As	0,04	-0,02	0,00	0,00	0,89
Se	0,05	0,02	-0,78	0,04	-0,04
Br	0,92	0,31	-0,04	0,04	0,08
Rb	0,52	0,09	-0,12	0,64	-0,11
Sr	0,78	0,52	-0,08	0,19	0,10
Y	-0,82	0,09	-0,28	0,10	-0,02
Zr	-0,67	-0,19	-0,35	0,19	-0,14
Pb	0,51	0,68	-0,12	0,02	-0,34
Th	-0,11	0,54	0,02	-0,17	-0,50
U	0,00	0,63	0,38	-0,14	-0,16



The first principal component is associated with large positive loadings: S, Mn, Zn, Br, Sr, Cu, and Ca; with moderate positive loadings: Ga, Rb and Pb; with large negative loadings: Si, Ti, Y, Al; and moderate negative loading: Zr. Positive loadings are shown by biophillic and organically-bound elements and negative loadings by immobile major, minor and trace elements. Thus, the distribution of these elements is influenced strongly by organic matter content. The PC1 scores (Figure 4) are higher in the uppermost samples, decreasing sharply until 5 cm, then more slowly until 15 cm, remain low and constant until 23 cm, and then show a small increase and remain almost constant thereafter.

Figure 4 PCA of MHV geochemistry: distribution of the factor scores with depth.



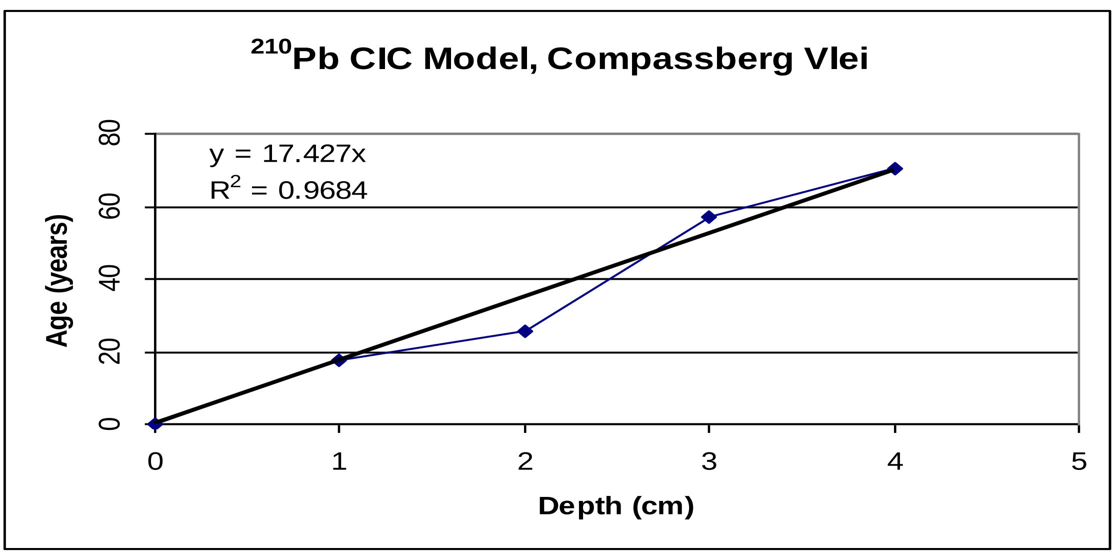
The second component is associated with large positive loadings: Fe; and with moderate positive loadings: Pb, U, Th, Ca, and Sr. In Figure 4 it can be seen that this factor is characterized by relatively higher and constant scores below 13 cm, decrease sharply between 13 and 3 cm (with a small peak between 10-8 cm) and increase abruptly again in the upper two samples. If Fe were the only element in this factor it would suggest that the low concentrations below the surface are related to hydromorphic conditions which encourage Fe leaching, but the presence of other elements suggests this is not the case. Pb, U, Th, Ca and Sr only have part of their variance controlled by this principal component (see the graph in Figure 3: the red section of the bar corresponds to the proportion of the variance associated to PC2; blue to PC1, green to PC3, etc). This means that not all the variations in the concentrations of these elements are exerted by PC2: for example, Ca and Pb have a significant proportion in PC1. They must be hosted in the mineral phase since they are diluted by the presence of organic matter. A second observation is that Pb, Th and U, on one side, and Ca and Sr, on the other, form sets of chemically-related elements. The first belong to an isotopic series and are usually in higher concentrations in materials derived from acid rocks, while Sr has an ionic radius similar to Ca and substitutes it isomorphically in many minerals. Ca and Sr are more abundant in basic and carbonatic rocks, but the concentrations of both elements are comparatively low in MHV. Both are also present in minerals (e.g. plagioclases) common in more acidic lithologies. This indicates a change in the mineralogy pointing to a change in the source of the inorganic material.

4.2 Compassberg:

4.2.1 Dating

The ^{210}Pb CIC model (Appleby,2001) was selected for dating the Compassberg vlei as the depth distribution of unsupported ^{210}Pb was approximately monotonic. The model predicts 4 cm of sediment accumulation over ca 70 years. The data suggests that accumulation rates have stayed fairly constant over the last hundred years or so (Figure 5). Further dating is needed to establish a full chronology for the core. A radiocarbon date of 3590$\pm$70 radiocarbon years BP was by obtained by Meadows and Sugden (1988) from their core suggesting that the record from Compassberg vlei extends back into the late-mid Holocene.

Figure 5 Depth-Age plot for Compassberg vlei.

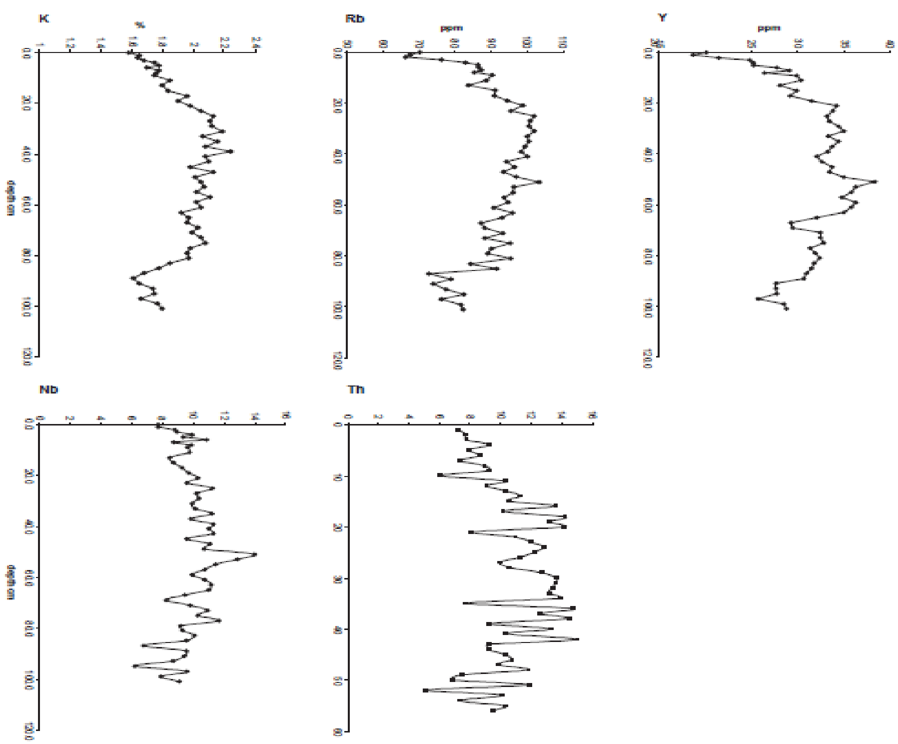


4.2.2 Geochemistry

The samples are mainly composed of mineral matter and the sequence can be considered as a colluvium. Downcore profiles for each element are shown in Figure 6A-C. Six trends can be discerned. Potassium, Y, Nb, Y, and Rb increased in concentration from the base of the profile to approximately 50 cm and then declined towards the surface. Titanium and Zr and, to a lesser extent, Al also decreased in the upper 40 cm but Ti and Zr peaked at the surface. Calcium, Sr, Fe and Cr have elevated concentrations at the base of the profile and in the uppermost 20 cm. Manganese has a similar profile but peaked between 60 and 50 cm and at 23 cm. Bromine and S increased gradually from the base of the core and, with Si, had their highest concentrations in the upper 20 cm. Galium and Cl fluctuated between 7 and 12 and 150 and 650 ppm respectively.

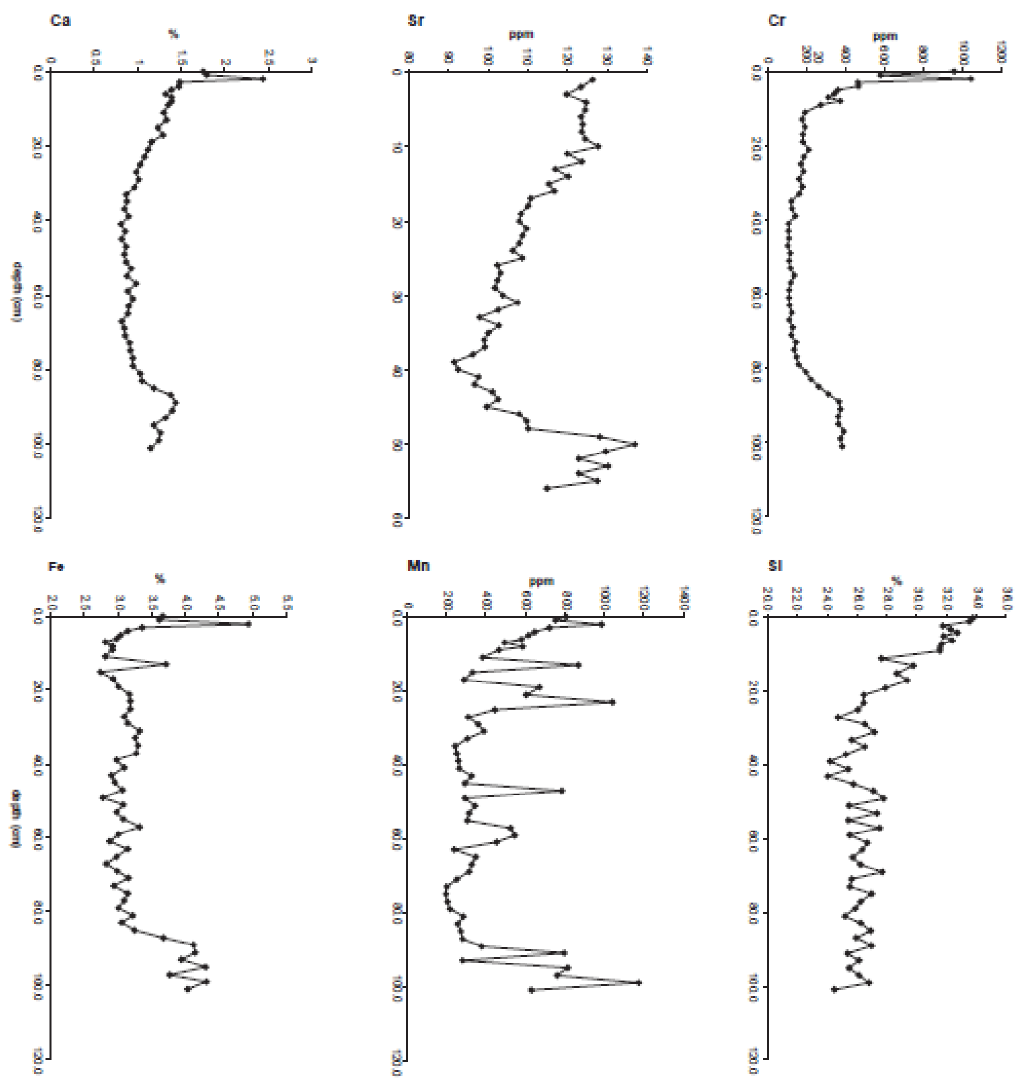
To get insights into the covariation among the determined elements and the possible factors responsible for their distribution (structure of the variance) we performed a factorial analysis by principal components (PCA). The rotated varimax solution provided a more clear association of chemical elements and the results are described below.

Figure 6A **Profiles of selected major and trace elements from Compassberg vlei**



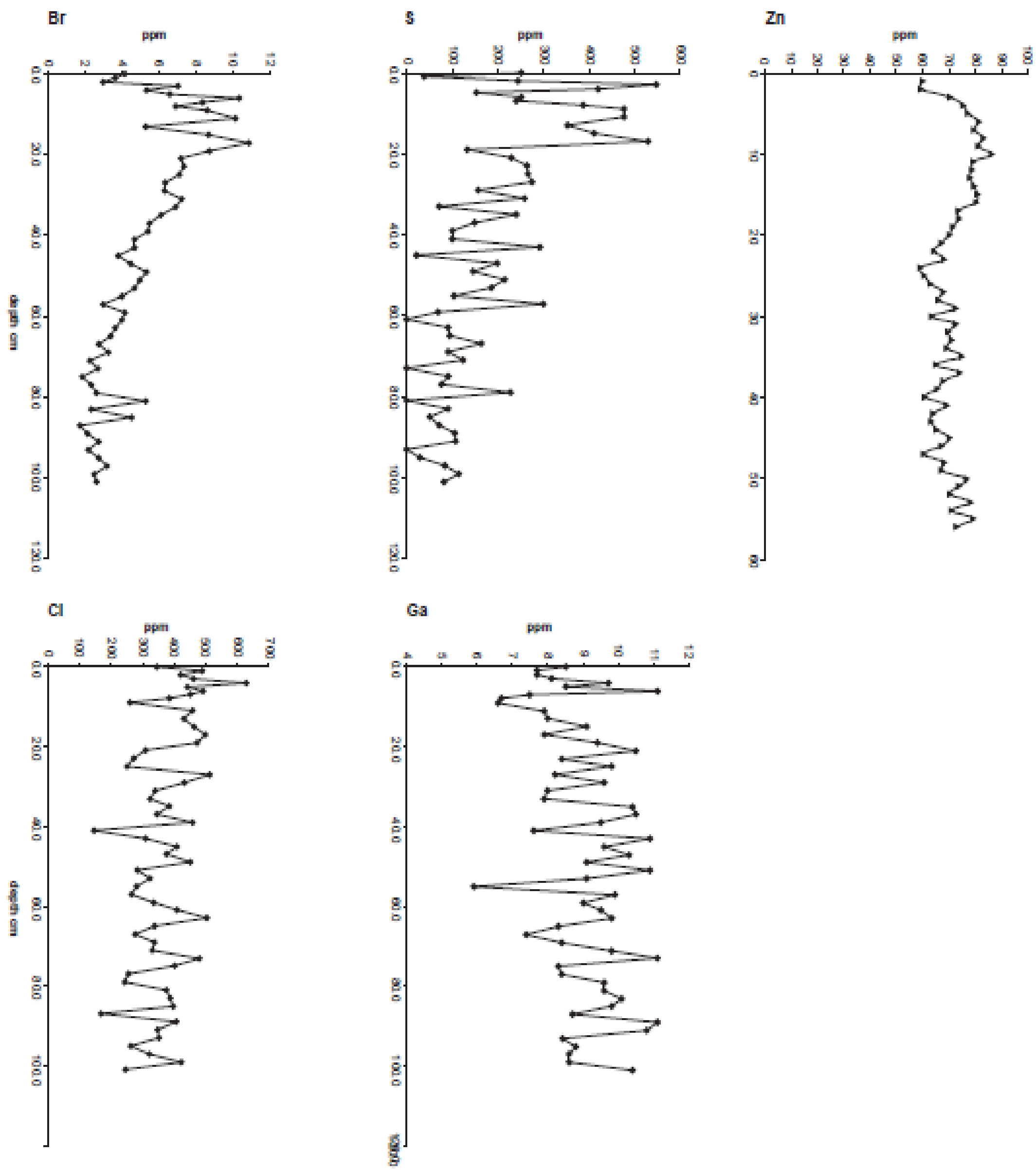
Six principal components explained a 79% of the total variance of the geochemical composition of the samples (Figure 7). The first five PC were considered to be significant since they showed eigenvalues greater than 1. The first principal component, PC1 (33.6% of the variance), shows large positive factor loadings for K, Rb, Y, Nb, and Th, and a moderate loading (i.e. part of the variance) for Pb; large negative loadings were found for Ca, Cr, Sr, and Fe, and moderate negative loadings for Mn and Si (Figure 5). These two groups of elements are usually associated with contrasting mineralogies: the first group is characteristic of acid mineralogies (rich in K-feldspars, for example) while the second group is typical of basic mineralogies (as those of geological materials rich in plagioclase and amphibole). Thus this component may reflect variations in the bulk mineralogical composition of the sediments and points to the presence of two sources for the material, with contrasting geological/mineralogical nature.

Figure 6B Profiles of selected major and trace elements from Compassberg vlei



The second principal component, PC2 (17.7% of the variance), shows large positive loadings for Br, S, Zn, and moderate loading for Si (Figure 7). Titanium shows a large negative loading and Zr a moderate negative loading. Positive loadings are associated to biophilic elements (S) or organically-bound elements (Br, Zn), while the negative loadings correspond to largely conservative elements. This factor seems to be related to the content in organic matter, which may explain the increased concentrations of the biophilic and organically-bound elements, while producing a relative dilution of conservative elements which are not intensively affected by changes in the bulk mineralogy (PC1).

Figure 6C Profiles of selected major and trace elements from Compassberg vlei

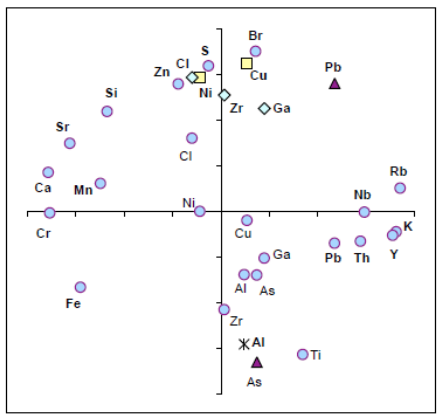


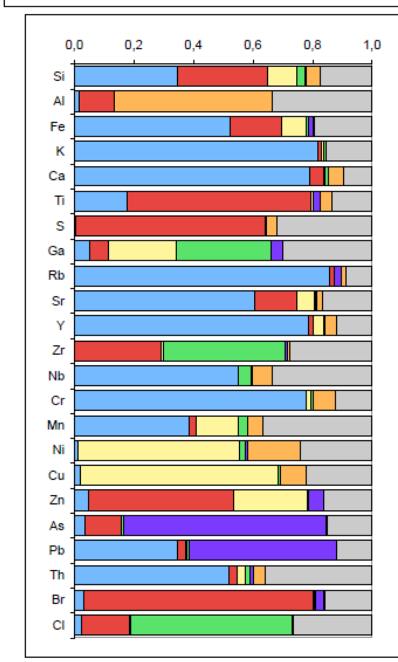
The third principal component, PC3 (9.5% of the variance), shows large positive loadings for Cu and Ni, and a moderate loading for Zn (Figure 7). This component also seems to bear a mineralogical signal linked to metals which are not present in large concentrations in the most abundant minerals.

The fourth principal component, PC4 (6.4% of the variance), shows large positive loadings of Zr and Cl, and a moderate loading of Ga. While the fifth principal component, PC5 (6.1% of the variance), is related to the opposite distribution of Pb (positive loading) and As (negative loading). These two components are also assigned, tentatively, to variations in secondary or trace minerals.

Figure 7 Eigenvalues (Table), Plot of PC1 (x-axis) versus PC2 (y-axis) (top graph) and total variance for each principal component for each element (bottom graph) from Compassberg vlei.

Total	(%)	Cum
7,7	33,6	33,6
4,1	17,7	51,2
2,2	9,5	60,8
1,5	6,4	67,2
1,4	6,1	73,3
1,3	5,6	78,9





The communalities represent the proportion of the variance of each variable (chemical elements in this case) that is explained by the main principal components. In Figure 7 (bottom graph) we have represented the fractionation of the communalities: the different sections of the bars, with different shading, correspond to the fraction of the total variance that is associated to each principal component. The grey bars to the right indicate the proportion of unexplained variance (the variations in the concentrations of the elements that cannot be explained by the significant factors). Fifteen out of the 23 elements analyzed are properly explained by the significant factors, since more than 75% of their variance is associated to them (Si, Fe, K, Ca, Ti, Rb, Sr, Y, Cr, Ni, Cu, Zn, As, Pb, Br); for the other, the proportion of explained variance can be considered also high (63-74%). Some elements have relatively simple controls since almost all their explained variance is associated with only one principal component (large loadings in that principal component: K, Ca, Rb, Sr, Y, Cr, Ti, S, Br, Cu, Ni, As). Others may be affected by more than one process (moderate loadings in more than one principal component: Si, Ga, Zr).

Factor scores are dimensionless values that indicate departures from the average value of the record for the variables associated with the principal component. For an element with positive loadings in a given PC, positive scores indicate concentrations greater than the average of that element in the record (direct proportionality), while for an element with a negative loading the opposite is true (concentrations increasing with negative scores; inverse proportionality). So the scores integrate the signal of all the elements associated to a PC and can be interpreted as an average-normalized measure of the intensity of each factor in the samples.

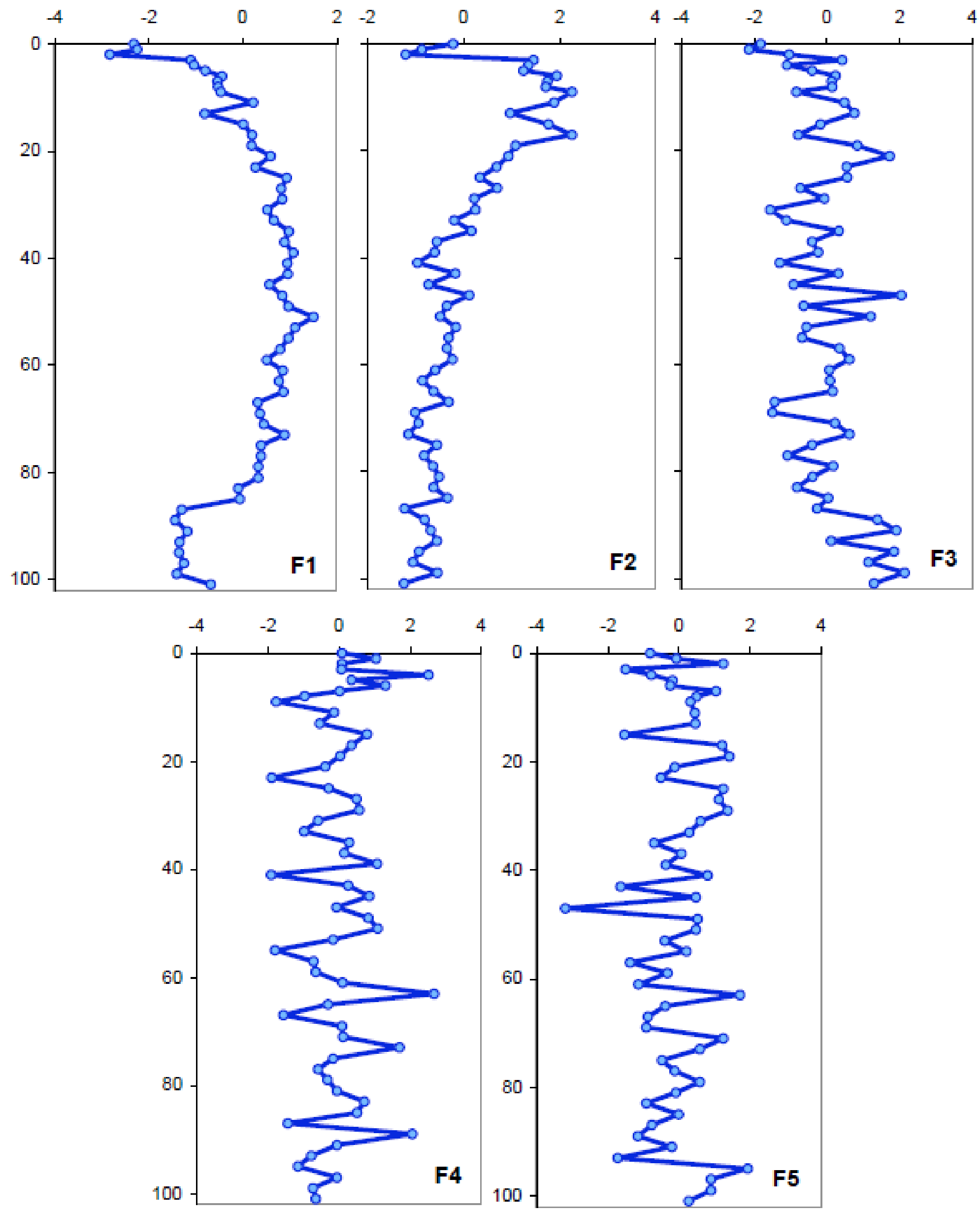
In Figure 8 we show the vertical variation of the factor scores for the five significant principal components.

- Record of PC1 scores: it can be divided into four main sections: I, >85 cm, negative scores: basic minerals predominate; II, 85-35 cm positive and almost constant scores: acid minerals predominate; III, 35-4 cm, a decreasing trend to negative scores: indicative of a progressive change in the bulk mineralogy to a more basic composition; IV, <4 cm, sharp decrease in scores to large negative values: dramatic change to a mineralogy dominated by basic minerals.

- Record of PC2 scores: it can be divided into three main sections: I, > 35 cm, almost stable negative or slightly positive scores: large contents of mineral matter - low content of organic matter; II, 35-4 cm, continuous upwards increase to positive factor scores: increasing content of organic matter; III: <4 cm, sharp decrease in factor scores: largely mineral layer. The first two principal components show large negative scores in the upper sections (IV and III, respectively) of the core and a significant decrease at 13 cm in (sections III and II respectively), in both cases indicating increasing contents of mineral matter with basic mineralogy.

- Records of PC3, PC4 and PC5 scores: these records are characterized by a see-saw pattern around average values (zero score). PC3 has an underlying trend to decreasing values (decreasing concentrations of Cu, Ni, and Zn) to the surface of the core; while PC4 scores show an alternating pattern of positive an negative scores (higher and lower Zr concentrations). This last feature can be related to physical fractionation of particles during transport and sedimentation, since finer sediments may have lower concentrations of Zr and relatively coarser sediments may be enriched in Zr.

Figure 8 **Factor scores (x-axis) versus depth (y-axis) for Compassberg vlei.**



As indicated above, in the graph with the fractionation of the communalities (Figure 7, bottom) the grey bars represent the proportion of the variance of each element which is not controlled by the main factors (bulk mineralogy, organic matter content, etc). This variance can be extracted and represented. The extraction is made by detrending the concentration record of each element from the principal components: first, a regression function between the scores of the principal component and the concentrations of the element is obtained; second, the detrending is done by calculating the normalized statistical residue: (observed - expected concentration)/average of the element in the record, where the expected concentration is obtained from the regression function. These normalized residues represent departures from the average that is not explained by the principal components.

We have applied this calculation to all the elements analyzed in the CBV core. A few examples are represented in Figure 9. Some elements showed the same record of unexplained variance: Ca, Ti, Sr, Cr and Th; Fe and K; or Pb and As (Figure 9). It will be interesting to see if these variations fit with the history of landscape occupation, and if we can find an explanation for their residual variation.

5. PROVISIONAL CONCLUSIONS

5.1 Misty Hills Vlei

The geochemical record shows little change until the uppermost 5 cm. This change is characterised by an increase in organically-bound and biophilic elements and reflects the increase in organic matter. The increase in Pb, Zn and Cu might also partly be the result of increased atmospheric pollution. There is little evidence for past episodes of soil erosion variation as the downcore pattern of the lithogenic elements show little variation.

5.2 Compassberg

The geochemical analysis identified changes in the source of the elements. Two sources are probable: one characterised by acid minerals, one by basic minerals. This may reflect the dominant lithologies of the Karoo: dolerites and sedimentary rocks from the Karoo Supergroup. Four major phases are recorded throughout the sequence.

The shift in sediment source in the 1930s identified in the F1 factor scores is consistent with the hypothesis that high stocking densities up to and including the 1930s would have caused serious land degradation and soil erosion. Rainfall records for the time show this period to be the end of a persistent period of drought (see Chapter 1, this guide). Variations in normalised residues of the lithogenic elements may accord with historical changes in land use.

A full chronology is needed to evaluate the significance of the changes recorded at Compassberg.

Figure 9 Normalised residues of the unexplained variance not explained by Principal Components

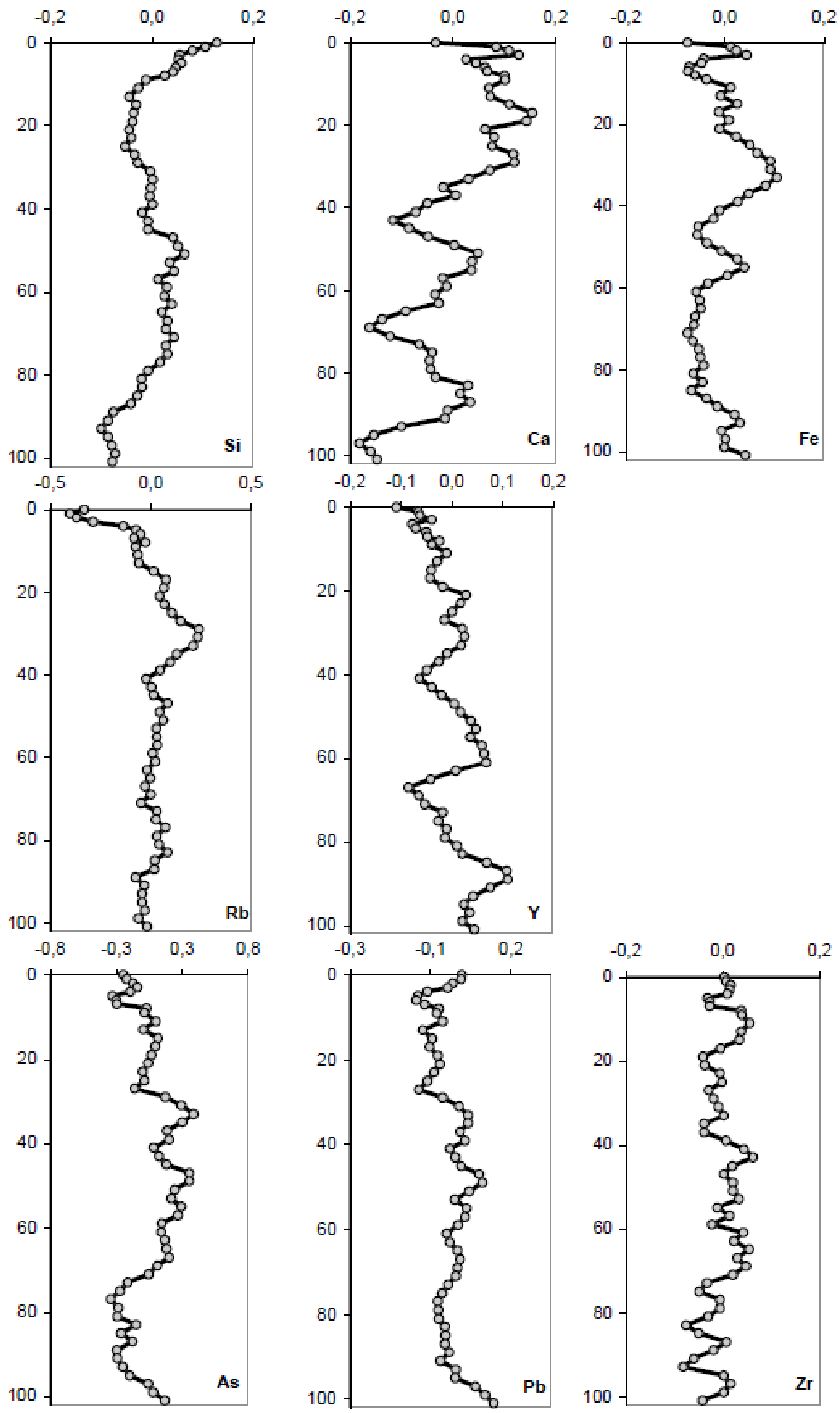


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Table 1 **Correlation matrix for major and trace elements and LOI from Misty Hills vlei (*Insignificant relationship at p=0.05).**

	Al	Si	K	Ca	Ti	Cr	Mn	Fe	Ni	Cu	Zn	Br	Rb	Sr	Y	Zr	Pb	S
Al																		
Si	.850																	
K	.730	.848																
Ca	*.553*	-.637	-3.17															
Ti	.769	.908	.899	-.492														
Cr	.335	.369	.501	*	.482													
Mn	-.653	-.807	-.571	.819	-.747	-.336												
Fe	-.331	-.387	*	.702	*	*	.425											
Ni	-.312	-.333	-.283	.326	-.357	-.309	.501	.196										
Cu	-.612	-.732	-.555	.479	-.675	*	.675	.291	.283									
Zn	-.760	-.846	-.601	.798	-.779	-.357	.925	.480	.423	.782								
Br	-.731	-.844	-.565	.901	-.748	*	.948	.550	.396	.701	.955							
Rb	-.402	-.433	*	.343	-.291	*	.337	.291	-.089	.424	.506	.485						
Sr	-.666	-.732	-.411	.909	-.562	*	.824	.719	.311	.581	.860	.914	.589					
Y	.529	.608	.369	-.572	.641	.338	-.738	-.120	-.432	-.516	-.697	-.708	-.301	-.548				
Zr	.415	.492	.372	-.605	.603	.293	-.658	-.319	-.376	-.382	-.619	-.660	-.206	-.558	.650			
Pb	-.421	-.538	-.296	.635	-.411	-.283	.589	.701	.239	.532	.681	.661	.408	.722	-.243	-.373		
S	-.707	-.825	-.560	.790	-.762	-.300	.921	.413	.334	.739	.947	.963	.557	.837	-.759	-.638	.615	
LOI	-.650	-.764	-.583	.761	-.744	-.372	.953	.340	.625	.616	.889	.897	.259	.735	-.762	-.695	.526	.867