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The character, origin and palaeoenvironmental significance of the Wonderkrater spring mound, South Africa

T.S. McCarthy [a,*], W.N. Ellery [b], L. Backwell [c], P. Marren [a,1], B. de Klerk [c], S. Tooth [e], D. Brandt [a], S. Woodborne [d]

[a] School of Geosciences, University of the Witwatersrand, P.O. Box 3, WITS 2050, Johannesburg, South Africa
[b] Department of Environmental Science, Rhodes University, Grahamstown 6140, South Africa
[c] Bernard Price Institute for Palaeontological Research, University of the Witwatersrand, P.O. Box 3, WITS 2050, South Africa
[d] CSIR Environmentek, P.O. Box 395, Pretoria 0001, South Africa
[e] Institute of Geography and Earth Sciences, Aberystwyth University, Aberystwyth SY23 3DB, United Kingdom

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ABSTRACT

Wonderkrater is a spring mound consisting entirely of peat in excess of 8 m thick. It has yielded a pollen record extending back over 35,000 years, which has provided one of the very few proxy climatic records for the interior of southern Africa in the Late Pleistocene and Holocene. The current investigation of the morphology and sedimentology of the site has revealed that the peat mound formed due to artesian conditions at the spring, but that accumulation of the thick peat succession was made possible because of clastic sedimentation on the surrounding piedmont which in turn was brought about by aggradation on the adjacent Nyl River floodplain. The peat mound has remained elevated relative to the surrounding piedmont for most of the 35,000 year period. Aggradation of the mound was slower during the Late Pleistocene than the Holocene (0.06–0.1 m/1000 year and 0.2–0.38 m/1000 year, respectively). Controlled archaeological excavations yielded a diverse late Pleistocene fauna preserved in peat and sand in the mound. A 1 m thick, coarse sand horizon at the base of the peat deposit contained a rich Middle Stone Age (>30 k year) lithic assemblage. The MSA sand layer likely represents an arid phase, suggesting the site's antiquity as a place of refuge for Quaternary animals and the people that hunted them.

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1. Introduction

Spring mounds have been described from many parts of the world. In their most common form, the mound is constructed from calcium carbonate precipitated from the spring water, perhaps with a contribution from aeolian dust. This type of mound is very widespread in the Great Artesian Basin of eastern Australia (Boyd and Luly, 2005). Equally common are spring mounds constructed from siliceous material, which are typically associated with geothermal springs, often in volcanic provinces. Less common are spring mounds constructed from peat, although examples have been described from Tasmania (Macphail et al., 2001), eastern Australia (Boyd and Luly, 2005), East Africa (Ashley et al., 2002; Owen et al., 2004) and the USA (e.g. Glasser et al., 1996). Peat normally accumulates below water as this reduces the rate of organic matter decomposition, and since water forms a horizontal surface, very special conditions are necessary to form a peat mound above the general terrain level, perhaps the most important being artesian conditions. Ashley et al. (2002) proposed the name 'artesian blister wetland' for the east African peat spring mounds, because artesian pressure sustains a small pool of water in the top of those mounds.

Spring sites have yielded important archaeological and palaeoenvironmental information. Examples include recovery of the skull of an archaic *Homo sapiens* and associated fauna from the Florisbad spring in South Africa (Dreyer, 1938), and evidence enabling the construction of the Holocene climatic record of the southwestern USA from the Montezuma Well (Blinn et al., 1994). But perhaps the most famous of the world's peat spring mounds is Wonderkrater, situated in the Limpopo Province of South Africa (24°25′50″S, 28°44′36″E) (Fig. 1). This site has yielded pollen samples which have provided an almost continuous record of the vegetation, and by inference, the climate of central southern Africa extending back over the past 35,000 years (Scott, 1982, 1989, 1999; Scott and Vogel, 1983; Scott and Thackeray, 1987; Scott et al., 2003). Although the palynology of the peat mound has received detailed attention, a comprehensive geomorphic study of the mound has never been undertaken. The present study was carried out to rectify this deficiency and also because it was evident that the Wonderkrater site could provide important insights into the geomorphological development of the region and especially of

* Corresponding author. Tel.: +27 11 7176558; fax: +27 11 7176579.
E-mail address: terence.mccarthy@wits.ac.za (T.S. McCarthy).
[1] Present address: Department of Geography, University of Melbourne, Melbourne, Australia.

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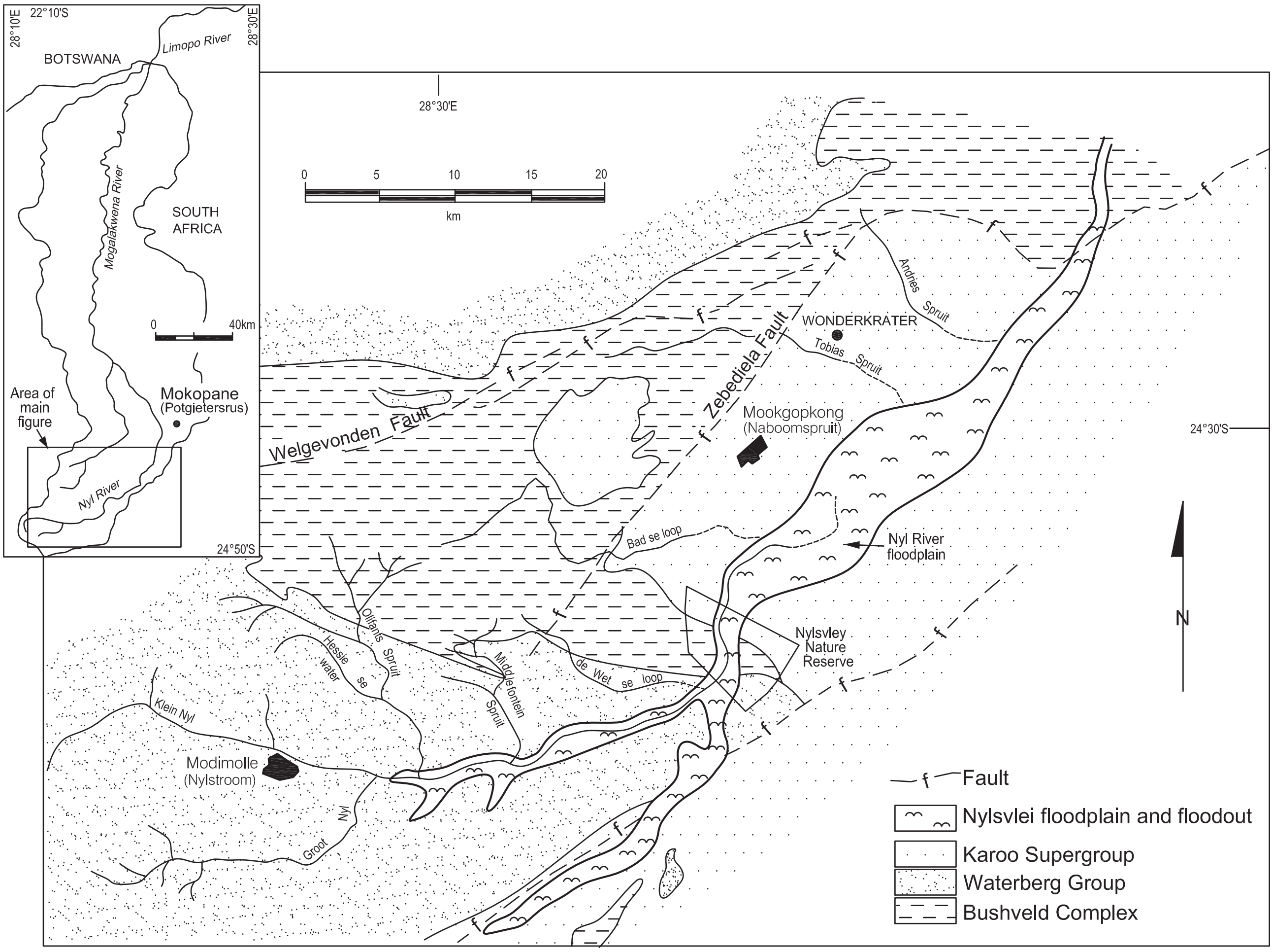

Fig. 1. Location and regional geology of the Wonderkrater spring mound.

the adjacent Nyl River floodplain (Scholes and Walker, 1993; Tooth et al., 2002), which hosts the Nylsvley Nature Reserve, an important RAMSAR site.

2. Geological setting

The study area is underlain by granites, felsites and mafic rocks of the early Proterozoic Bushveld Complex. These are unconformably overlain by horizontally-bedded sandstones of the mid-Proterozoic Waterberg Group, and sandstones, mudstones and basalts of the Permo-Triassic Karoo Supergroup (Fig. 1; Wagner, 1927; Geological Survey, 1978). The Karoo strata generally underlie topographically lower ground, partly a consequence of large-scale regional faulting, but also owing to considerable relief in the land surface upon which Karoo deposition occurred (King, 1942; McCarthy and Allan, 2007).

The Wonderkrater spring is just one of a line of springs that occur along a fault juxtaposing the Karoo Supergroup rocks against the Bushveld Complex granite (Fig. 1) (Scott, 1982; Temperley, 1975). The fault is one of a series of splays which fan out from the Zebediela Fault, a major east–west striking fracture zone that coincides with the larger Thabazimbi–Murchison lineament (TML). The TML represents an ancient suture in the Kaapvaal Craton, and has experienced repeated tectonic movement since the Archaean, primarily as a strike-slip fault (du Plessis and Walraven, 1990; Martin, 1990; du Plessis, 1991). The last major activity on the faults associated with the TML appears to have been during the Neogene subsidence of the Bushveld Basin (du Toit, 1933; Partridge and Maud, 1987), which resulted in down-faulting of the Karoo strata and the formation of the trough-like synclinal feature that hosts the Springbok Flats and the Nylsvlei floodplain. Isolated seismic events along the TML suggest that it may still be active (Fernandez and du Plessis, 1992).

Several springs are developed along the faults in the region, and many of them are classified as thermal springs (temperature >25 °C; Kent, 1949). The most famous is Warmbad, situated to the southwest of Wonderkrater on a parallel fault system, which has a water temperature of 36 ± 4 °C (Mazor and Vehagen, 1983). The geothermal character arises from deep, slow circulation of meteoric water (Kent, 1949; Mazor and Vehagen, 1983). The estimated turnover time for the water in the Warmbad spring is about 19,000 years (Mazor and Vehagen, 1983). The Wonderkrater spring appears to be of ambient temperature, although a thermal spring is developed on the same fault a few kilometers to the north (Constantia). The model age for the spring water at Wonderkrater (based on ^{14}C) suggests that the spring water fell as rain 17,289 years ago (S. Talma, pers. comm.).

Although circulation of the meteoric water is clearly very slow, how the discharge at the spring responds to variations in recharge is not known. It is likely, however, that discharge responds rapidly to changes in recharge because pressure is transmitted more rapidly through the aquifer than the water itself. Thus, an increase in recharge would be fairly rapidly expressed by an increase in discharge even though the circulation rate remains slow.

3. Climate

The mean annual rainfall in the area is about 630 mm, but is very variable and over the past 90 years has ranged from 250 mm to 1100 mm (Scholes and Walker, 1993). Annual potential evaporation is about 2400 mm, resulting in a net water deficit. About 60% of the rain falls in the austral summer as localized convective thunderstorms and the reminder as a result of widespread frontal systems.

4. Regional geomorphology

The region is characterized by two distinct terrains. To the east of Wonderkrater lies the Springbok Flats, a vast, featureless plain lying at an elevation of about 1000 m amsl, with a very poorly developed drainage network. This region is largely underlain by rocks of the Karoo Supergroup. To the north and west lie the Waterberg Mountains, which are underlain predominantly by the resistant sandstones of the Waterberg Group and rise to an elevation of about 1800 m amsl.

Tributaries arise in the Waterberg ranges and flow predominantly south and east towards the Nyl River and its floodplain, which flows northeast across the Springbok Flats. Many of the tributaries exhibit unusual downstream changes as they approach the Nyl River or its floodplain: the cross sectional areas and depths of their channels become progressively smaller and ultimately the channels disappear completely on unchanneled floodplains termed 'floodouts' (Tooth et al., 2002). In addition, sediment transported by many of the tributaries undergoes a marked downstream decrease in grain size from predominantly gravelly sand in the headwaters and piedmont to silt and mud towards the Nyl River and floodplain (Tooth et al., 2002).

The decrease in cross sectional area of the rivers draining the Waterberg is principally a result of transmission losses into the underlying alluvial sediment (Tooth et al., 2002). Transmission losses are probably about equal to the long term average discharge of the streams, and result in downstream decreases in flow magnitude and frequency, such that defined channels cannot be maintained downstream and floodouts form. In years of above average discharge, flow continues beyond the channel termini as sheet flooding. The most important consequence of this flow and channel behaviour is that most sediment transported from the headwaters of the tributaries is deposited in transit or on the margins of the Nyl floodplain, making this a region of net sediment accumulation.

The Wonderkrater spring is located on the broad pediment–piedmont of the Waterberg range in the region where many smaller tributaries are beginning to lose definition and floodouts are forming, resulting in deposition of veneers of alluvial sediment. These piedmont sediments merge imperceptibly down-slope into the floodplain sediments of the Nyl River. The Nyl River itself exhibits similar behaviour to that of the tributaries, losing definition down-valley and terminating on an extensive, unchannelled floodplain (floodout) up to 5 km wide known as Nylsvlei (Tooth et al., 2002). Discharge across the floodplain occurs as sheet flooding. Toward the Zebediela Fault in the north, the floodplain dramatically narrows and a channel reforms. This channel is termed the Mogalakwena River, and continues to its confluence with the Limpopo River about 100 km to the north. The unchannelled part of the Nyl floodplain is underlain by up to 35 m of alluvium, which consists of coarse, gravelly sand at the base and fines upward to mud-dominated sediment underlying the immediate flood plain surface.

5. Vegetation

The vegetation of the Wonderkrater spring has been described by Scott (1982) as broadly falling within *Combretum* veld that typically occupies the plains of the region, which is dominated by broadleaved deciduous trees and C4 grasses. The alluvial plains surrounding the Wonderkrater spring tend to be dominated by microphyllous woodlands with *Acacia tortilis* and *Acacia karoo* as dominant species, and with *Acacia mellifera* as an important component. The spring itself is dominated by *Phragmites australis*, with hygrophilous grasses and sedges dominating the associated wetland.

6. Methods

Topographic and geomorphic information on the study area surrounding the spring mound were obtained from the 1:10,000 orthophoto map series published by the SA Government Chief Directorate: Surveys and Mapping. Detailed topographic, surface soil, and vegetation maps were made of the spring mound and its immediate surroundings using a plane table and level. Vegetation was sampled in circular plots of 2 m radius where herbaceous plants were dominant, and 5 m radius where woody plants were dominant. Cover was measured using classes of 0–2%, 2.1–5%, 5.1–10%, 10.1–25%, 25.1–50%, and >50% cover. Data were analysed using the cluster analysis algorithm TWINSPAN (Hill, 1979) that divides samples on the basis of indicator species (i.e. those present in 80% or more of the samples in one group and 20% or less of the samples in the other group). Relationships with environmental factors were determined using an indirect gradient analysis approach by tabulating environmental factors for each vegetation type. The area was systematically cored using 8 cm diameter peat and soil augers to obtain subsurface stratigraphic information. This was supplemented with limited excavations. Samples were collected from auger holes and excavations for petrographic and chemical analysis and radiocarbon dating. Mineralogical analyses were carried out using petrographic optical microscopy and X-ray diffraction, and the chemical analyses were performed using X-ray fluorescence spectrometry. The soluble salt content of the peat was determined by measuring its electrical conductivity (when water saturated) using a standard conductivity meter.

Archaeological excavations were carried out using conventional trowel and brush methods, followed by sieving, where possible. Wet peat was excavated using shovels and hand sieves. Activities were recorded using a total station theodolite and cameras.

7. Results

7.1. Local geomorphology

The topography of the area surrounding Wonderkrater is shown in Fig. 2. To the south is the Tobias Spruit, one of the larger tributaries of the Nyl River. To the west are two smaller, unnamed tributaries that disappear on floodouts before reaching the spring mound. During wet periods, their discharge disperses around the spring mainly as sheet flooding with limited flow in poorly-defined depressions. Observations made after heavy rainfall reveal that the sheet flooding around the spring site deposits graded increments of sediment up to about 2 cm thick that range from coarse sand at the base to silt. On slightly raised areas, the deposits are richer in coarse sand, whereas in lower areas, silt tends to dominate.

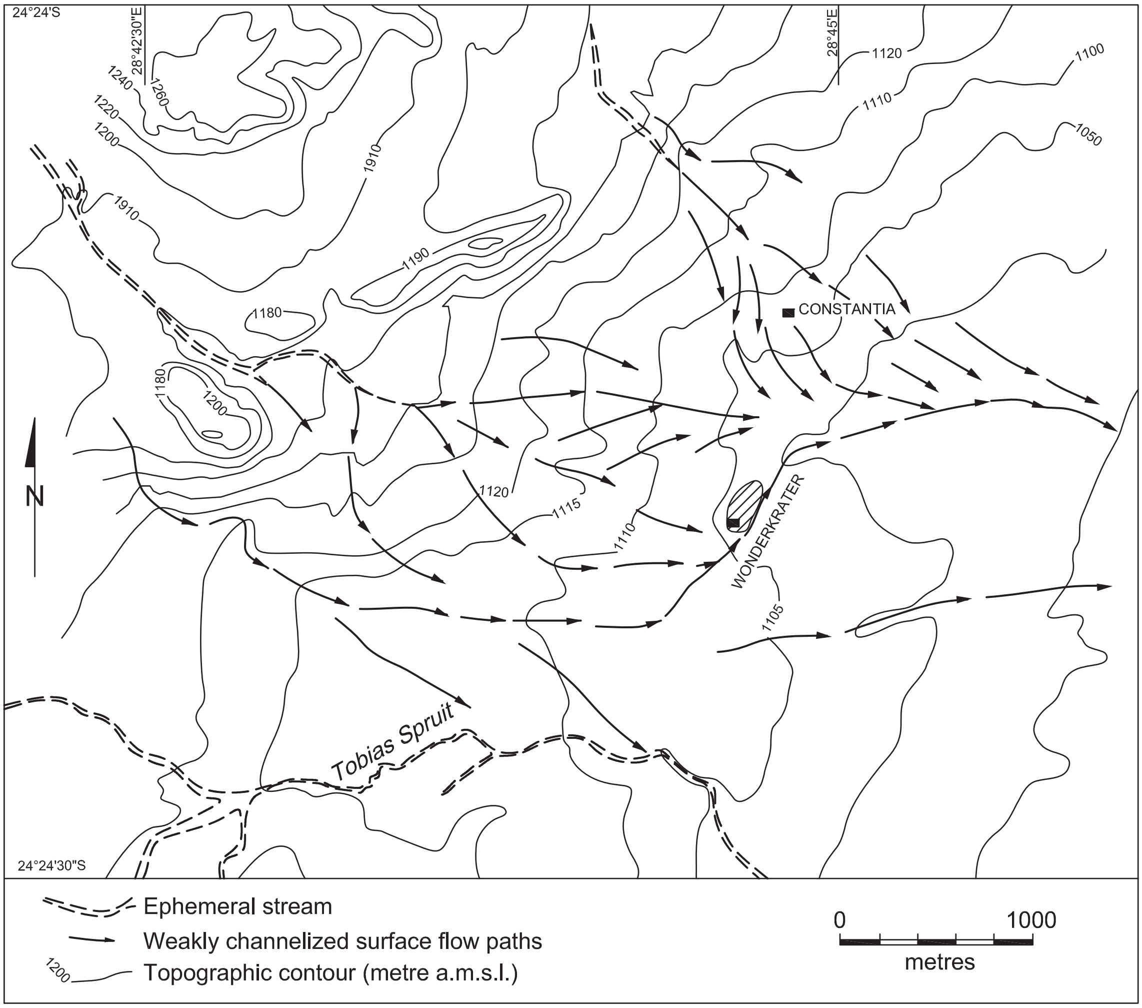

Fig. 2. Topography of the area around the Wonderkrater site.

7.2. Topography of the spring site

The spring mound is irregular in form and about 25,000 m^2 in area (Fig. 3) and rises to a maximum height of about 3.5 m above the surrounding terrain. Fortunately, anthropogenic impact on the mound has not been excessive. Two boreholes were sunk in the southern portion of the mound, one of which is weakly artesian. In this vicinity, a well has also been sunk and contained a pool of water at the time of the survey (November, 2004). Other anthropogenic disturbances include a circular excavation towards the centre of the mound, a shallow shaft on the north western side (Fig. 3) and some trenching on the eastern side (not shown on the map). It appears that the spring may have had much higher discharge in the past as there are remains of a sump system that appears to have collected water from the spring, possibly to supply a swimming pool (now derelict) located a few hundred metres from the site. The area at one time supported a recreational resort, based around the outflows from the spring.

There is a crater-like depression close to the summit of the mound which appears to be of natural origin, and may once have hosted a small pond, perhaps similar to the artesian blister mounds described by Ashley et al. (2002). This crater may have given rise to the name of the spring (‘wondrous crater’ in English). The adjective ‘wondrous’ may have come about because the mound is hydraulically pressurized (see below) and behaves like a quaking bog in the vicinity of the crater, or because of the presence of a pond in the crater at an elevation above the surrounding semi-arid terrain. Currently, the mound appears to be desiccating and deep cracks are forming in its northern flank.

7.3. Surface soils

The surface soils on and around the mound are very diverse. Most of the mound consists of peat (Fig. 4) which is surrounded by black to grey, fine grained material formed by burning of the peat. The soils on the lower, eastern side of the mound consist of black to grey soil, which probably represents a mixture of silty sediment of fluvial origin and peat ash. Where the proportion of fluvially derived fine material (mainly clay) is high, the desiccating soils tend to exhibit shrinkage cracking. The surface soil of most of the terrain surrounding the mound consists of poorly sorted, coarse to medium sand.

7.4. Vegetation

Six distinct vegetation communities were identified and are shown in Fig. 5. *A. mellifera* woodland characterises the sandy alluvial plains surrounding the peat mound. This community has relatively high species diversity (20 species identified, 7.6 spp. per sample). Other woody elements in the community are *A. tortilis, Euclea crispa,* and *Spirostachys africana*. The mound and immediate surroundings is vegetatively diverse, being characterized by five

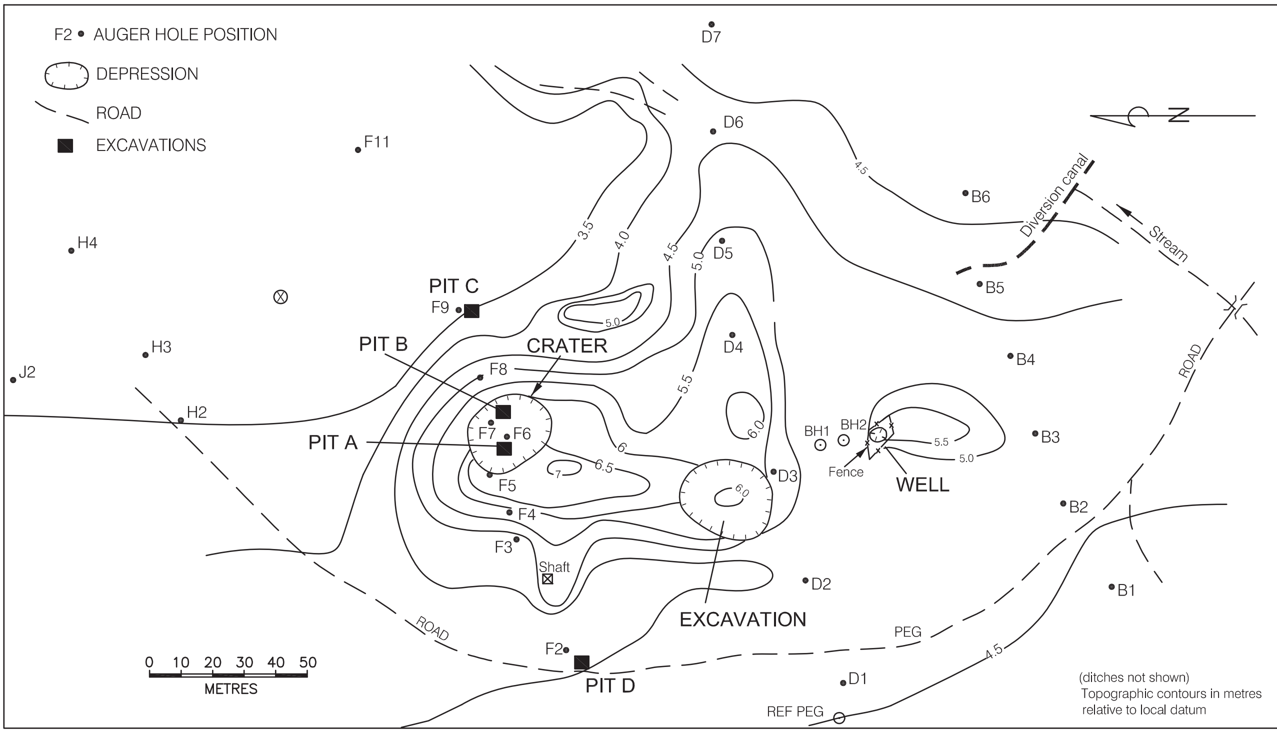

Fig. 3. Topography of the Wonderkrater site.

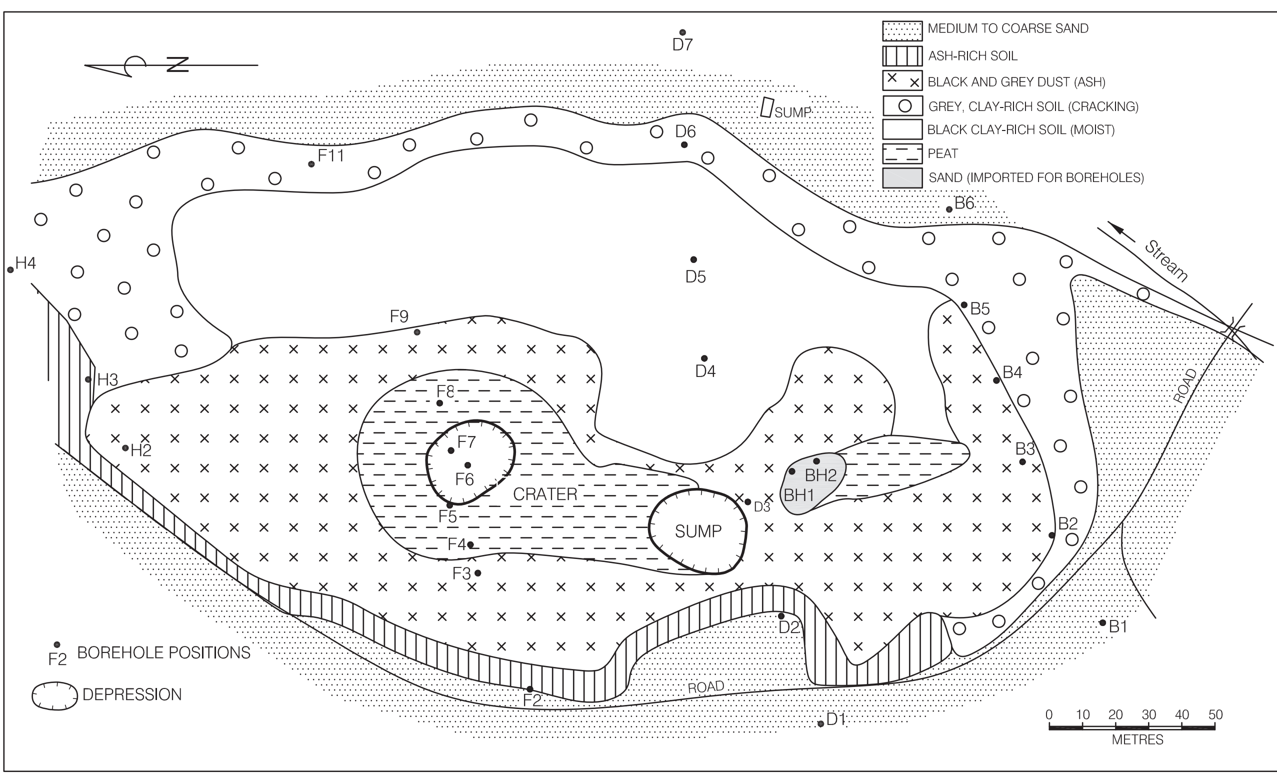

Fig. 4. Surface soils at the Wonderkrater site.

communities. *Sporobolus nitens* grassland is developed at the interface between the mound and the surrounding plains on the upslope side. The supporting soils are a mixture of peat ash and fluvial sand. The community is diverse, with 22 species identified in total and 5.1 spp. per sample. The crest of the mound is surrounded by *A. karoo* woodland. Other woody species present were *A. tortilis, Diospyros lycioides, E. crispa, Rhus lancea, Rhus pyroides,* and *Ziziphus mucronata*. It is quite diverse, with 20 species being identified and a species richness of 7.3 spp. per sample. This community is confined to soils composed primarily of ash, and

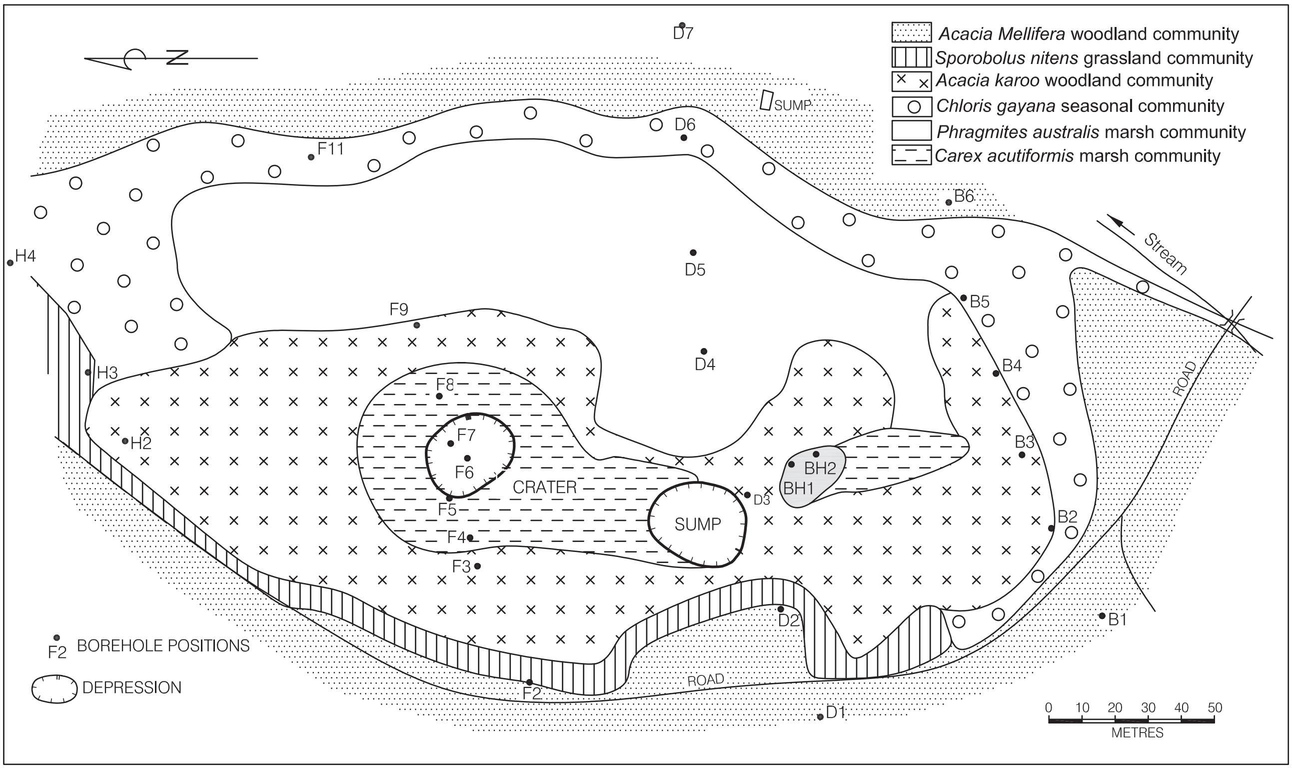

Fig. 5. Vegetation at the Wonderkrater site.

appears to be a pioneer community that develops on the mound following peat burns. The peaty soils on the higher parts of the mound host the *Carex acutiformis* wetland community. Species richness is low with 2.5 spp. per sample and only 10 species identified in total. The eastern foot of the mound is characterized by the *P. australis* wetland community which also has low species richness (3.9 spp. per sample, 12 species in total). This community is restricted to black, clayey soils, rich in peat ash. Finally, the lower-lying, outer fringes on the eastern, down-slope side of the mound are characterized by the *Chloris gayana* wetland community. This community again has low diversity (3.7 spp. per sample, 10 species in total), and occurs on the cracking grey soils characteristic of this area. *C. gayana* is a facultative wetland plant, indicating that this portion of the study area is prone to seasonal flooding.

7.5. Mound stratigraphy and geohydrology

Holes were augered along transects across and adjacent to the mound (see Fig. 3 for locations) in order to assess its gross sedimentology and internal structure. Soil augers tend to mix the excavated material and hence only provide a general indication of the sediment character and stratigraphy. Excavations in selected locations on and around the mound provided better sedimentological and stratigraphic control.

The main textural groups classified during augering consisted of the following: gravel; medium to coarse sand containing minor silt; silt containing coarse to medium sand; black, carbonaceous silt; black peat grading to black peat ash and grey, chalky carbon-free ash; sandy peat. Nine stone tools were also encountered in the auger holes. Wagner (1927) commented on the large number of stone tools littering the surface of the Springbok Flats, and it appears that they may be even more common in the subsurface, judging by the number recovered during augering. The presence of these artifacts prompted a more detailed archaeological investigation of the site (see below).

Auger holes on the mound itself penetrated to a maximum depth of 5 m and encountered mainly of peat interlayered with some carbonaceous ash (Fig. 6). Towards the edges of the mound, grey, chalky peat ash layers became more common, as did sandy and sandy silt layers, suggesting an interfingering relationship of peat, peat ash and clastic material (Fig. 6c). Adjacent to the mound, sand and silty sand dominated the deposit. None of the auger holes encountered the underlying bedrock (the deepest hole adjacent to the mound was 6 m) but based on boreholes drilled for water in the surrounding area, bedrock is encountered at about 8 m depth.

The excavations supported the generalised findings from the augering, and provided further information regarding stratigraphic relationships. A deep excavation on the mound (Pit B) encountered only peat (Figs. 3 and 7), whereas an excavation on the edge of the mound (Pit C) exposed interlayered peat, grey chalky peat ash, and sandy silt (Figs. 3 and 9).

The depth to the water table was measured in the auger holes several days after augering was completed, which allowed sufficient time for the groundwater to equilibrate. Ground water was only encountered in auger holes in the mound area, and those outside of the mound did not intersect the water table. In the case of the D auger transect, the water table formed a broad, gently sloping dome. In the F transect, the ground water dome was much more dramatic: auger hole F6 encountered the water table at a depth of 0.8 m, whereas the water table was not intersected in the adjacent holes 8 m and 10 m away (F7 and F5, respectively) indicating that the water table was deeper than 4 m below surface at these points. An excavation near the site of auger hole F6 (Pit A) partially filled with water (Fig. 8) and remained wet throughout the duration of the excavation, while the adjacent Pit B (Fig. 7) remained relatively dry, although water began entering below a depth of 4 m. The water table therefore forms a steep-sided dome within the peat-dominated portion of the mound. A slightly higher water table would undoubtedly cause flooding of the crater on the mound. The present water table at the apex of the ground water

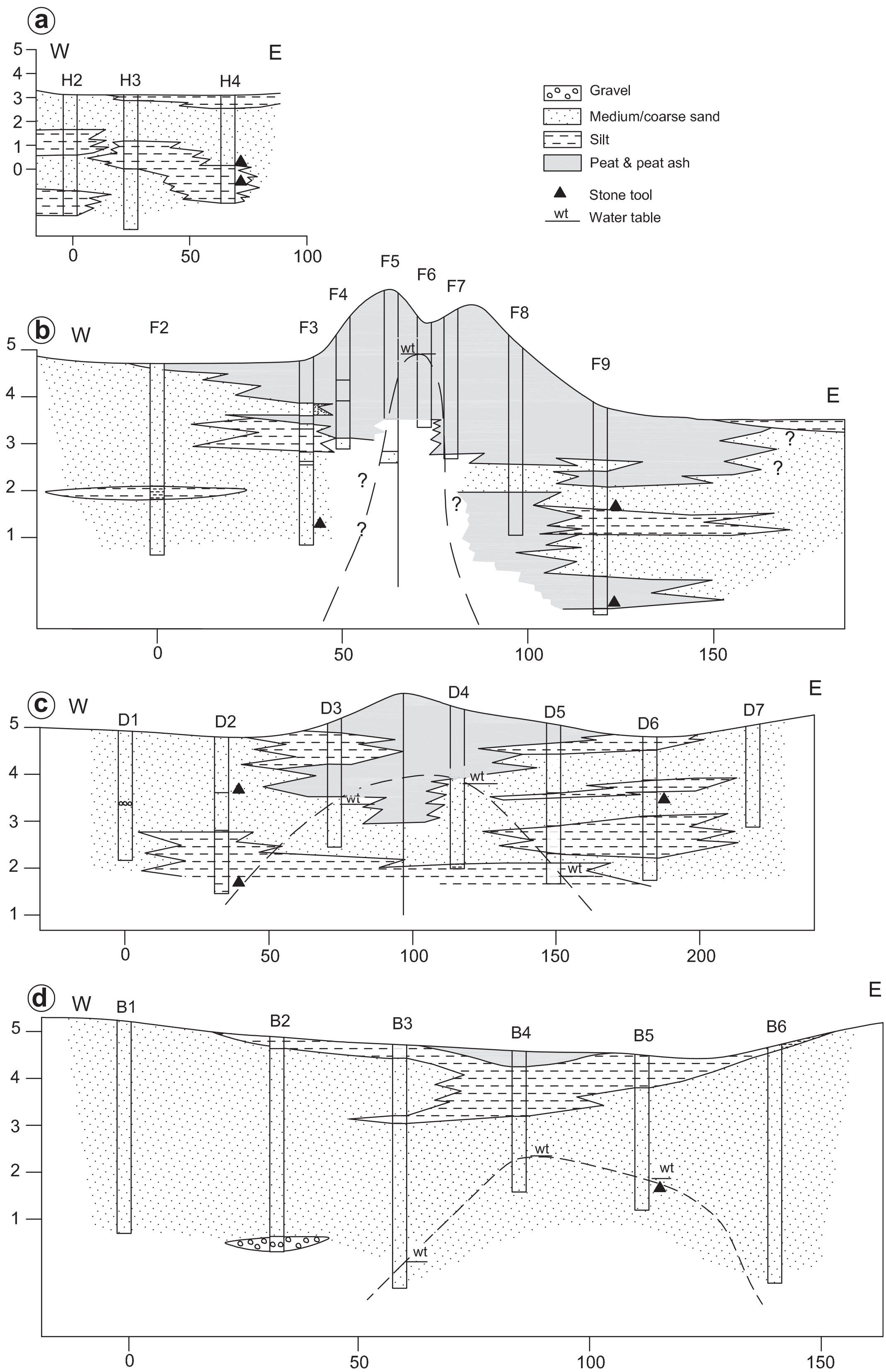

Fig. 6. Cross sections showing subsurface stratigraphic relationships at the Wonderkrater site. See Fig. 3 for locations of the auger lines.

dome is higher than the terrain surrounding the peat mound. The steep slope on the groundwater dome suggests that the peat has a relatively low hydraulic conductivity and evidently is under artesian pressure in the core of the peat mound, resulting in the mound behaving like a quaking bog. Slow outward diffusion of water and capillary creep are evidently normally sufficient to

Fig. 7. The 4 m deep Pit B near the apex of the spring mound. The entire section consisted of peat. See Fig. 3 for location of the excavation.

Fig. 9. The 1.5 m deep Pit C at the foot of the mound showing the interlayering of peat (black), peat ash (white) and clastic sediment (grey). See Fig. 3 for location of the excavation.

Fig. 8. The 1 m deep Pit A in the crater in the peat mound partially, which filled with water to a depth of 80 cm below the edge. See Fig. 3 for location of the excavation.

maintain high enough moisture levels in the outer portions of the mound, thus preventing desiccation and oxidation of the peat by bacteria and fire.

7.6. Archaeological investigations

Four areas were chosen for excavation. Pit A (2 × 2 × 1 m deep) was dug in the centre of the mound; Pit B (3 × 3 × 4 m deep) was dug towards the edge of the crater in the mound apex; Pit C (4 × 4 × 3 m deep) was dug on the dry margin of the mound in black and grey ash deposits; and Pit D (2 × 2 × 0.15 m deep) was dug to the west of the mound (Fig. 3).

Pit A flooded (Fig. 8), yielding little information of archaeological significance. The upper section of Pit B yielded little, but from below a depth of 2.1 m, 53 fossil specimens representing a minimum of nine individuals of different taxa were recovered. A 1 m thick sand layer was encountered commencing at 3 m depth, which contained a well preserved Middle Stone Age (MSA) lithic assemblage. In Pit C on the edge of the mound a coarse sand horizon starting 3 m below surface yielded a well preserved MSA lithic assemblage, whilst Pit D, away from the mound, also yielded a number of MSA lithics. Details of the archaeological investigations, including a faunal analysis, will be published elsewhere (Backwell et al., in preparation).

7.7. Mineralogical composition of the peat

The soluble salt content of the peat was determined by mixing 50 g aliquots of dry peat with 50 ml of deionized water and then measuring the electrical conductivity. The soluble solid content of the peat ranged from 0.2 to 0.9 mass%, with an average of 0.56%. The nature of the solutes was not determined, but most probably consisted mainly of sodium chloride with lesser sodium sulphate, as these are the major solutes in the artesian water from the site (S. Talma, pers. comm.). The artesian water from the borehole analysed by Talma contained about 380 mg/l dissolved solids and therefore was not particularly saline.

Samples of peat were combusted in a muffle furnace at 450 °C to determine their ash content. The ash content ranged from 22 to 95 wt.% and averaged 57.9%, reflecting a spectrum ranging from carbonaceous ash to ash-rich peat. The ash content of the peat appears to be spatially random (Fig. 10). The ash from selected samples was chemically analysed. The most abundant constituent was SiO_2, which ranged from 41 wt.% to 80 wt.%, averaging 67.6%. Several of the peat samples contained high calcium concentrations, reflecting abundant calcite. Calcite concentration, calculated by assuming that all of the CaO in the analysis represented calcite, ranged from 8.8 wt.% to 45.9 wt.% and averaged 16.4%. The quartz content of the ash samples (measured by X-ray diffraction) ranged from 1.2 wt.% to 9.0 wt.%., and averaged 3.5%. The alumina content, which reflects largely the clay mineral abundance, ranged from 1.7 wt.% to 6.0 wt.% (average 3.3%)., which represents a clay content ranging from 4.3 wt.% to 15.0 wt.% and averaged 8.4% (assuming all of the clay is kaolinite). The bulk of the silica was thus present in an amorphous form, and petrographic examination revealed abundant phytoliths indicating that they contributed significantly to the silica content, together with some diatoms. The diatoms tended to be confined to discrete horizons, whereas the phytoliths were present throughout. Microscopic examination of

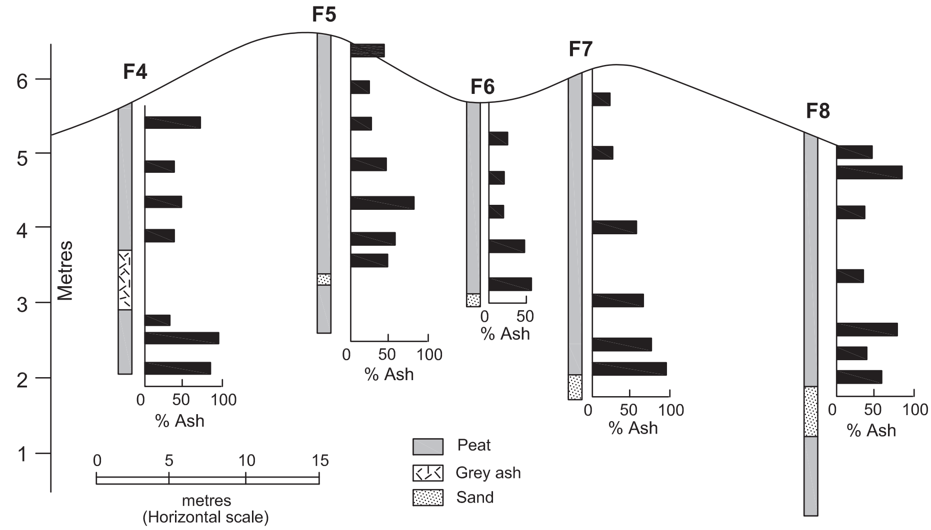

Fig. 10. The ash content of the peat along auger line F.

the grey, chalky layers and dusty surface material encountered at the site revealed that they consist primarily of amorphous silica, largely as phytoliths, and represent burnt peat. Some of the peat exposed in the excavations contained grains of quartz up to 1.5 mm in diameter.

7.8. Peat accumulation rate

Scott et al. (2003) reported the results of ^{14}C age determinations on peat samples down to a depth of about 7 m. The depth versus age relationship of their samples is shown in Fig. 11, and suggests that two linear trends are present in their data. Samples from surface to a depth of about 4.5 m reflect a peat accumulation rate of 0.38 m per 1000 years, whereas samples below 4.5 m appear to define a slower accumulation rate of 0.11 m per 1000 years. The inflection point at about 4.5 m depth corresponds to an age of 12,000 years BP, close to the Holocene–Pleistocene boundary. Whilst the peat accumulation rate for the Holocene is well constrained, that in the deeper section is based on only two samples and must be considered tentative.

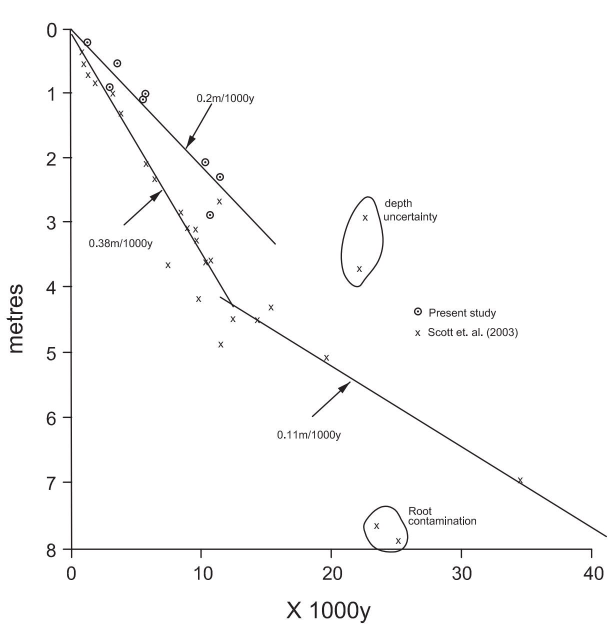

Fig. 11. A plot of calibrated ^{14}C age of the peat as a function of depth. The data from Scott et al. (2003) appear define two trends, whilst the samples collected during the present study define a third.

The ages of samples collected in the upper portion of the peat mound during the present study (Backwell et al., in preparation) are also plotted in Fig. 11. These samples suggest a somewhat slower peat accumulation rate of about 0.2 m per 1000 years during the Holocene. The discrepancy between these accumulation rates is puzzling. We rule out compaction due to loading as a cause, because both trends are linear, and compaction would be a progressive effect, resulting in curved trends of age vs. depth. Errors in depth measurement are also unlikely: Scott et al. (2003) used augering equipment that could not distort the depth in any way (L. Scott, pers. comm.), and the present samples were collected from the vertical face of Pit B (Fig. 7). Scott (1982) reported the presence of a sand layer at a depth of 4.3–4.8 m below the apex of the mound. Although the precise locations of Scott's auger holes are unknown, in the present study a sand layer was found at a depth of 3 m below the apex. If these are indeed the same layer, some 30% shrinkage of the peat is indicated, and this would also explain the discrepancy in the accumulation rates. The most likely cause of shrinkage is a reduction in the artesian pressure as such variations in peat mound height due to artesian pressure fluctuations have been documented elsewhere (e.g. Almendinger et al., 1986). Drying of the peat may also contribute to shrinkage. Rainfall records for the region show relatively elevated precipitation levels in the period 1974–1977 when Scott conducted augering activities at the site (L. Scott, pers. comm.; Tooth et al., 2002).

8. Discussion

The Wonderkrater mound has developed on an artesian spring which taps slowly circulating deep groundwater. Discharge appears to have been higher in the recent past when the spring formed the focus of a recreational resort, but there is currently no surface run-off from the spring mound. The present survey was carried out in a period of average to slightly above average rainfall, so the decline in discharge is more likely due to over exploitation of the aquifer that supplies the spring. Comparison of mound stratigraphy and peat accumulation rates based on samples collected by Scott with those collected during the present study (Fig. 11) are also consistent with a reduction in artesian pressure and shrinkage of the mound.

The mound itself presently rises 3.5 m above the surrounding terrain and consists entirely of ash-rich peat. Clearly, the rate of vegetation growth and peat formation is sufficiently high to create this relief. Peat generally forms under saturated conditions where the surface or near-surface water inhibits oxidation of the organic matter. Raised bog formation – whereby peat accumulation occurs above the groundwater table – generally only occurs in high rainfall areas. To form a peat mound in an area with a negative water balance such as Wonderkrater, the material must be kept more or less continuously moist by the inflow of sufficient groundwater to counter evapotranspirative loss. Water must therefore be forced into the mound under artesian pressure, and this pressure is held because of the low hydraulic conductivity of peat.

The peat contains mineral matter, which is dominated by phytolithic silica, which the plants obtain from dissolved silica in the spring water (18 mg/l, S. Talma, pers. comm.). Insoluble salts make up as much a 1% of the peat by mass and probably arise by evapotranspirative losses from the mound. Calcite, clay, and quartz grains are also present. It is likely that the interstitial water in the mound has become saturated in calcite and possibly silica, which have precipitated to become part of the mineral matter in the peat. The peat presently appears to be quite saline, and is possibly sufficiently so as to become a source of salt for grazing animals in the area (cattle frequently came onto the mound during our excavations). Animals coming to obtain salt on the mound may also import particulate sediment adhering to their skins from mud wallows, and this may be the source of the clay and quartz grains and especially the very coarse sand grains found in the peat (too large to have been transported by wind). It is likely that the salinity of the peat varies with time: during wet periods, discharge from the mound would tend to dissolve and translocate the more soluble of the accumulated salts, whereas at times such as the present, when there is no outflow and the only loss of water is by evapotranspiration, salts probably accumulate in the mound, rendering it more saline. The mound may also have accumulated dust during drier periods, adding to the mineral matter.

The fairly high ash content indicates that oxidation of the peat is substantial. The cause of this oxidation is not clear, but is probably due to a combination of shallow burning and bacterial oxidation. The amount of oxidation has evidently varied, resulting in the wide range in ash content of the peat (22% to 95% by mass, Fig. 10). It is likely that during periods of enhanced artesian discharge the mound would have expanded both laterally and vertically, only to shrink during periods of reduced flow, when the desiccated peat on and around the mound would burn, producing ash layers.

The mound is situated on an extensive piedmont formed by tributaries draining the Waterberg ranges to the north and west of the site. Tributaries rising in these mountains lose discharge downstream and disappear on floodouts, so that during high flow events, they cause extensive sheet flooding in the area around the spring mound. Transported sediment is deposited across a wide area, and consists mainly of coarse to medium sand in the vicinity of the mound, becoming increasingly finer-grained down the regional topographic slope towards the Nyl floodplain. Owing to the relatively shallow depth of flow, size separation of the sediment seems to be poor. Local topographically higher areas accumulate mainly coarse sand, whilst the lower-lying areas host shallow ponds in which silt and mud accumulate. The proximal, western side of the mound is slightly more elevated, and hence the substrate is sand-dominated compared to the eastern side of the mound, which is finer-grained (Figs. 3 and 4). Observations after heavy rainfall events show that individual storm floods deposit composite increments of sediment a few centimeters thick consisting of coarse sand at the base, grading rapidly to silt at the top, probably reflecting waning flow conditions. After the storm has passed, these graded deposits are quickly mixed owing to bioturbation by insects and animals, accounting for the poorly sorted silty sand found during excavation and augering at the site. More than 6 m of relatively homogeneous, medium to coarse silty sand has been deposited on the piedmont in this way in the vicinity of the spring (Fig. 6).

The elevated nature of the spring mound evidently results in the exclusion of clastic sediment, so that clastic sediment has accumulated around the mound while peat forms the mound itself. In periods of higher artesian discharge, the mound would probably enlarge with a concomitantly larger area of exclusion of clastic material. Conversely, during periods of reduced artesian flow, the mound would be smaller, resulting in deposition of clastic sediment closer to the core of the mound. Such changes probably account for the interstratification of peat, peat ash, and clastic sediment observed around the edges of the mound (e.g. Figs. 6 and 9). The core of the mound consists of at least 8 m of peat, with a single intercalated sand layer, indicating that the spring has almost continuously sustained a mound for more than 35,000 years.

The area in which the mound occurs is presently a site of sediment accumulation, but this was not always the case, because the bedrock in the area consists of remnants of Permo-Triassic Karoo Supergroup and Proterozoic basement rocks that have clearly experienced erosional degradation. The unnamed streams that are presently depositing sediment on the piedmont around the spring must have been erosional in the past, and still are in their upper reaches to the west. A cross section based on the actual

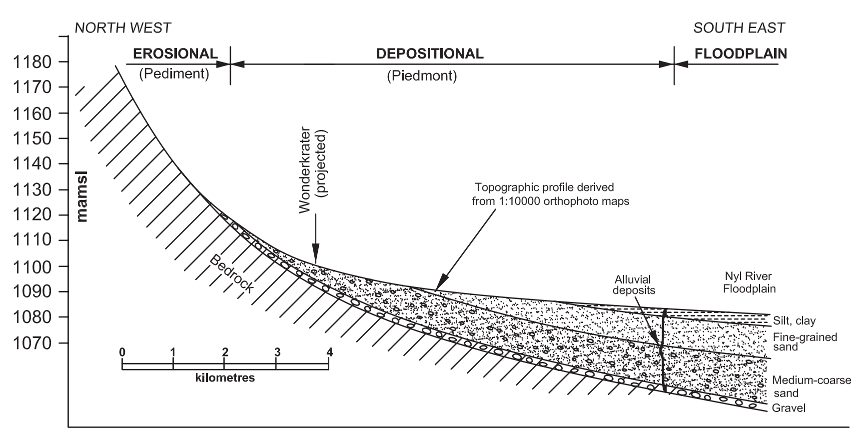

Fig. 12. A topographic profile showing the surface and inferred subsurface relationships between the Wonderkrater site and the adjacent Nyl River floodplain. Elevation data were obtained from published topographic maps and subsurface stratigraphy was obtained from Tooth et al. (2002) and the present study.

topography and the surface and subsurface relationships reported here and by Tooth et al. (2002) is shown in Fig. 12, and illustrates the transition from an erosional pediment to a depositional piedmont which merges down-slope with the Nyl River floodplain. Under conditions where the terrain was undergoing slow erosion, a peat spring mound could form but could not keep growing upwards indefinitely. It would probably reach some equilibrium height determined by the prevailing artesian pressure, but its summit would be gradually lowered in parallel with the erosional lowering of the surrounding terrain. Superimposed on this would be fluctuations in mound height induced by climate changes. Any pollen record the mound may contain would thus probably be very disjointed.

However, accumulation of clastic sediment around such a mound would bring about profound changes because the mound could now continue to grow upwards while maintaining a fairly constant elevation relative to the surrounding area, provided there was sufficient artesian pressure. Such simultaneous sedimentation, together with fluctuations in the size of the mound, would produce the interstratification of clastic and spring sediment observed in the auger holes and trenches around the mound (Figs. 6 and 9), and would enable the mound to continue to grow vertically, creating the potential to preserve a long and coherent pollen and archaeological record. We suggest that it is for this reason that the mound preserves such a great thickness of peat and provides such a coherent pollen record. Its peat accumulation was evidently interrupted only once, prior to about 15,000 years ago (calibrated age from a sample from directly above the sand layer dated by Scott et al., 2003), when a sand layer was deposited over the peat.

We believe that sedimentation in the Nyl River valley may have been the trigger for sedimentation and piedmont formation in the vicinity of the mound. The Nyl River provides the base level for the streams draining the Wonderkrater area, and sediment accumulating in the Nyl valley would cause a decrease in the gradients of the tributary streams, resulting in sediment deposition, initially on the edge of the floodplain but gradually progressing up slope, thus inducing sedimentation as illustrated in Fig. 13. It is thus likely that sedimentation taking place around Wonderkrater is intimately linked with sedimentation on the entire Nyl River flood plain. Hence the peat accumulation rate measured at Wonderkrater may have a far wider significance.

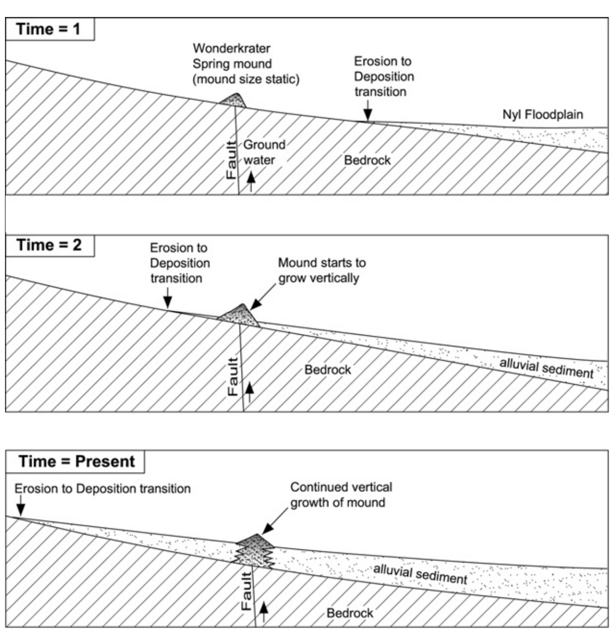

Fig. 13. Schematic diagrams illustrating how sedimentation on the Nyl River floodplain could have ultimately caused sedimentation and aggradation at the Wonderkrater spring site.

From the age determinations reported by Scott et al. (2003), it is evident that the spring mound has been in existence for at least the last 35,000 years, growing upwards at between 0.11 m and about 0.06 m per 1000 years prior to the Holocene and between 0.2 m and 0.38 m per 1000 years during the Holocene (based on the two sets of accumulation rates). Peat accumulation was thus slower during and sometime after the last glacial period, and increased quite suddenly with the onset of the present interglacial about 12,000 years ago. Although this observation requires verification, it is consistent with the inferred generally drier conditions that prevailed during the last glacial maximum (Scott, 1982; Tyson and Partridge, 2000; Holmgren et al., 2003). Wetter conditions in the Holocene would presumably have resulted in expansion of the mound, with concomitant increase in its local relief.

As discussed above, the ability of the mound to continue to grow upwards is dependent on continued clastic sedimentation around the mound, and it is thus tempting to equate the rate of peat accumulation with the clastic sedimentation rate around the mound. Because of the proposed linkage of this local sedimentation with sedimentation on the Nyl floodplain (Fig. 13), it is also tempting to extrapolate these sedimentation rates to the floodplain as a whole.

However, caution is warranted before such inferences and extrapolations are made. Under arid conditions there is less vegetation cover, and hillslope run-off, although less frequent, is more erosive. Hence, given erodible hillslope sediment stores, more rapid clastic sedimentation would be expected on piedmonts during arid periods. At this time, peat aggradation would be slower and relief on the peat mound would be less. It is possible that clastic sedimentation may have outstripped peat accumulation, causing the mound to be overwhelmed, and hence depositing the clastic layer in the peat mound. With the onset of more moist conditions in the Holocene, peat formation would have accelerated and outstripped clastic sedimentation, and the relative relief of the mound would have increased. Hence, it is probably incorrect to the equate peat accumulation rate directly with clastic sedimentation rate, although the order of magnitude of the two rates would probably be similar, which suggests that the clastic sedimentation rate at the site and on the Nyl flood plain is probably around 0.1 m per 1000 years.

9. Conclusions

The Wonderkrater site is firmly entrenched in the archaeological and palaeoclimatic literature of southern Africa because it has been accumulating peat and pollen virtually continuously for the at least the past 35,000 years, and therefore provides a unique window into the climate of the region over this time. This is a particularly important time too, because it straddles the Pleistocene–Holocene transition. The present study has provided new insights into the mechanisms that led to sustained mound growth.

The region around the mound had previously experienced erosional lowering, which stripped off much of the Karoo Supergroup and other strata. The spring was in all probability active during this time, but would not have experienced sustained vertical growth. Rather, it is likely that it would have grown and shrank in response to rainfall fluctuations but with an overall lowering trend in concert with regional degradation.

This situation probably changed as sediment began to accumulate around the spring, forming an extensive piedmont. The spring mound evidently responded by also aggrading vertically. It seems that the mound was able to maintain positive relief with respect to the surrounding piedmont most of the time, except for a period close to the Pleistocene–Holocene transition, when the mound evidently became overwhelmed by clastic sediment, suggesting extremely dry conditions. Although mostly in positive relief, the size of the mound fluctuated, probably in response to variations in rainfall. It evidently expanded during wetter times, but shrank during drier periods, a phenomenon still occurring today, as evidenced by the 30% shrinkage of the mound between the late 1970s and 2007. During drier times, the peat evidently sometimes desiccated and caught fire, leaving layers of ash. Clastic sediments from the surrounding piedmont buried the shrunken peat or ash layers around the mound, resulting in interfingering of clastic sediment, peat and ash on the fringes of the mound.

The onset of aggradation at the Wonderkrater site was most likely caused by a change in local base level, brought about by aggradation on the Nylsvlei floodplain, which resulted in a flattening of gradient on the valley sides and hence induced sediment deposition. The regional events which caused the flood plain to aggrade are beyond the scope of the present paper and will be discussed elsewhere. Sedimentation on the valley sides was probably further enhanced by infiltration losses, resulting in the development of floodouts around the spring mound and elsewhere. The Wonderkrater site is thus fully integrated into its environment and responds to events taking place on a more regional scale. The rate of aggradation of the mound seems to have been lower during the Late Pleistocene than during the Holocene (0.06–0.1 m/1000 year and 0.2–0.38 m/1000 year, respectively).

The aggradation of the mound and surrounding area has created optimum conditions for the preservation of late Pleistocene fossil fauna, and created one of the few MSA sites known in the interior of southern Africa. The spring mound probably attracted game because of its salt content and reliable water supply and provided a refugium for animals and hunters in times of drought. Thus, active sedimentation and mineral-rich spring water may have contributed to the preservation of a multi-proxy record of climate change and human adaption in this region.

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References

Almendinger, J.C., Almendinger, J.C., Glaser, P.H., 1986. Topogrpahic fluctuations across a spring fen and raised bog in the Lost River, peatland, northern Minnesota. Journal of Ecology 74, 393–401.

Ashley, G.M., Goman, M., Hover, V., Owen, R.B., Renaut, R.W., Muasya, A.M., 2002. Artesian blister wetlands, a perennial water resource in the semi-arid Rift Valley of East Africa. Wetlands 22, 686–695.

Blinn, D.W., Hevly, R.H., Davis, O.K., 1994. Continuous Holocene record of diatom stratigraphy, palaeohydrology and anthropogenic activity in a spring mound in southwestern United States. Quaternary Research 42, 197–205.

Boyd, B., Luly, L., 2005. Inland spring mounds. In: Whinam, J., Hope, G. (Eds.), The Peatlands of Australia. Denisia 16, zugleich Kataloge der OÖ. Landsmuseen Neue Serie 2, pp. 19–21.

Dreyer, T.F., 1938. The archaeology of the Florisbad deposits. Argeologiese Navorsing van die Nasionale Museum, Bloemfontein 1, 65–77.

Du Plessis, C.P., Walraven, F., 1990. The tectonic setting of the Bushveld Complex in southern Africa, part 1. Structural deformation and distribution. Tectonophysics 179, 305–319.

Du Plessis, C.P., 1991. Tectonics along the Thabazimbi–Murchison Lineament. Unpublished PhD Thesis, University of the Witwatersrand, Johannesburg, South Africa.

Du Toit, A.L., 1933. Crustal movement as a factor in the geographical evolution of South Africa. South African Geographical Journal 16, 3–20.

Fernandez, L.M., du Plessis, A., 1992. Seismic hazard maps for southern Africa. South African Government Printer, Pretoria.

Glasser, P.H., Bennett, P.C., Slegel, D.I., Romanowicz, E.A., 1996. Palaeo-reversals in groundwater flow and peatland development at Lost River, Minnesota, USA. The Holocene 6, 413–421.

Geological Survey, 1978. 1:250,000 Geological Map, 2428 Nylstroom, South African Geological Survey, Pretoria.

Hill, M.O., 1979. TWINSPAN–A FORTRAN 4 program for arranging multivariate data in an ordered two-way table by classification of the individuals and attributes. Cornell University, Ithaca, NY.

Holmgren, K., Lee-Thorpe, J.A., Cooper, G.R.J., Lundblad, K., Partridge, T.C., Scott, L., Sithaldeen, R., Talma, A.S., Tyson, P.D., 2003. Persistent millennial-scale climatic variability over the past 25,000 years in Southern Africa. Quaternary Science Reviews 22, 2311–2326.

Kent, L.E., 1949. The thermal waters of the Union of South Africa and South West Africa. Transactions of the Geological Society of South Africa 52, 231–264.

King, L.C., 1942. South African Scenery. Oliver and Boyd, London. 340pp.

Macphail, M.K., Pemberton, M., Jacobsen, G., 2001. Australian Journal of Earth Sciences 46, 667–677.

Martin, D. McB., 1990. Early Proterozoic syndepositional tectonics along the Thabazimbi–Murchison Lineament. Unpublished MSc Thesis, Unoversity of the Witwatersrand, Johannesburg, South Africa.

Mazor, E., Vehagen, B.Th., 1983. Dissolved ions, stable and radioactive isotopes and noble gases in thermal waters of South Africa. Journal of Hydrology 63, 315–329.

McCarthy, T.S., Allan, J.G., 2007. A possible new alluvial diamond field related to the Klipspringer kimberlite swarm, South Africa. South African Journal of Geology 110, 503–510.

Owen, R.B., Renaut, R.W., Hover, V.C., Ashley, G.M., Muasya, A.M., 2004. Swamps, springs and diatoms: wetlands of the semi-arid Bogoria–Baringo Rift, Kenya. Hydrobiologia 518, 59–78.

Partridge, T.C., Maud, R.R., 1987. Geomorphic evolution of southern Africa since the Mesozoic. South African Journal of Geology 90, 179–208.

Scholes, R.J., Walker, B.H., 1993. An African Savanna: Synthesis of the Nylsvley Study. Cambridge University Press, Cambridge.

Scott, L., 1982. A Late Quaternary pollen record from the Transvaal Bushveld, South Africa. Quaternary Research 17, 339–370.

Scott, L., 1989. Climatic conditions in southern Africa since the last Glacial maximum, inferred from pollen analysis. Palaeogeography, Palaeoclimatology, Palaeoecology 70, 345–353.

Scott, L., 1999. The vegetation history and climate in the Savanna Biome, South Africa, since 190,000 ka: a comparison of pollen data from the Tswaing Crater (the Pretoria saltpan) and Wonderkrater. Quaternary International 57–58, 215–223.

Scott, L., Vogel, J.C., 1983. Late quaternary pollen profile from the Transvaal highveld, South Africa. South African Journal of Science 79, 266–272.

Scott, L., Thackeray, J.F., 1987. Multivariate analysis of Late Pleistocene and Holocene pollen spectra from Wonderkrater, Transvaal, South Africa. South African Journal of Science 83, 93–98.

Scott, L., Holmgren, K., Talma, A.S., Woodborne, S., Vogel, J.C., 2003. Age interpretation of the Wonderkrater spring sediments and vegetation change in the Savanna Biome, Limpopo Province, South Africa. South African Journal of Science 99, 484–488.

Temperley, B.N., 1975. The Welgovended fault of the central Transvaal and its thermal water. Groundwater Series 2, Geological Survey of South Africa, Pretoria.

Tooth, S., McCarthy, T.S., Hancox, P.J., Brandt, D., Buckely, K., Nortje, E., McQuade, S., 2002. The geomorphology of the Nyl River and floodplain in the semi-arid Northern Province, South Africa. South African Geographical Journal 84, 226–237.

Tyson, P.D., Partridge, T.C., 2000. Evolution of cenozoic climates. In: Partridge, T.C., Maud, R.R. (Eds.), The Cenozoic Geology of Southern Africa. Oxford University Press, Oxford, pp. 371–387.

Wagner, P.A., 1927. The geology of the north-eastern part of the Springbok Flats and surrounding country. Explanation of Sheet 17 (Springbok Flats). South African Geological Survey, 104pp.