ARTICLE IN PRESS

Quaternary International xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

E.M. van Zinderen Bakker (1907–2002) and the study of African Quaternary palaeoenvironments

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ARTICLE INFO

Keywords:
Africa
Palynology
Quaternary vegetation history
Pioneering research
Conceptual climate models

ABSTRACT

The scientific contributions of E.M. van Zinderen Bakker (1907–2002) included the introduction of pollen analysis to Quaternary studies in South Africa. His palaeoecological theories evolved while performing palynological research in Southern Africa (the Maluti Mountains, Florisbad, Aliwal North, the Namib Desert), East Africa (Kalambo Falls, Mount Kenya, Cherangani Hills) and on the subantarctic islands (Marion and Prince Edward Islands). He was involved in the first radiocarbon dating from South Africa at Florisbad. Due to quantitative palynological studies he abandoned Wayland's (1929) Pluvial Theory that was generally accepted in the 1960s. He correlated observations of climate changes in Africa to data from marine borehole-cores and climatic fluctuations in the Northern Hemisphere. His observations led to the proposal that global temperature fluctuations are the primary cause of palaeoenvironmental changes. His studies culminated in a conceptual paleoecological model for the Last Glacial Maximum (LGM). Initially he based the model on symmetrical contraction of climatic belts about the equator that shifted the mid-latitude westerly wind system northward to increase the area receiving winter rainfall but later adjusted this by proposing a mechanism of westerly wind system intensification. He suggested that at this time grasslands had spread over wider areas in Southern Africa and that the tropical rain forests in the equatorial region fragmented. For interglacial periods he suggested that a southward shift of the Intertropical Convergence Zone (ITCZ) resulted in widespread humidity in the Congo Basin while large areas of the interior of Southern Africa became arid. Some of his ideas, especially his conceptual models of Quaternary vegetation and climate, are still relevant to the explanation of recent discoveries.

1. Introduction

Scholars studying the Cenozoic palaeo-environments of Africa inevitably come across the name Eduard Meine van Zinderen Bakker (hereafter vZB).

In his autobiography *Reminiscences of biological travels in Africa and to South Polar Islands*, (van Zinderen Bakker, 1993), he describes himself as a naturalist with an interest in Quaternary geology, historical topics like the origins of agriculture in Africa (van Zinderen Bakker, 1972a), botany (e.g., van Zinderen Bakker, 1967a, 1967b, 1967c, 1981), ecology (van Zinderen Bakker, 1978a), mycology (van Zinderen Bakker, 1935), ornithology (van Zinderen Bakker, 1950), and numerous other aspects of nature with an emphasis on the tropics especially Africa and the Dutch East Indies (van Zinderen Bakker, 1993; Meadows, 2015).

vZB was born in 1907 in Opsterland, the Netherlands, and died in 2002 in Somerset West, South Africa. He graduated in 1935 with a PhD in Botany (Mycology) at the University of Amsterdam, and taught biology at the Grammar School and Royal College in Apeldoorn from 1932 to 1946 (van Zinderen Bakker, 1935; Coetzee, 2001, 2002). In the Netherlands, his interest in palynology, and Quaternary climate change was stimulated by F. Florschütz (1887–1965), a pioneer of Quaternary pollen analysis. During this time, vZB trained and stimulated students including W. van Zeist (1924–2016), who became one of the most influential palaeoecologists working in the Near East (Van Zeist and Bottema, 1991; van Zinderen Bakker, 1993). During the 1930s and 1940s, prior to emigrating, vZB investigated the ecology of wetlands of the Netherlands, but already intended to explore Africa (van Zinderen Bakker, 1993) where he eventually made an important contribution to the palaeoenvironmental investigation of several sites (Fig. 1).

In 1947, after vZB had already published several articles and two books about his diverse research interests (e.g., van Zinderen Bakker, 1942, 1947), he emigrated to Bloemfontein, South Africa (Fig. 1), apparently following many other Dutch citizens who after WW II were looking for new opportunities away from the post-war conditions. He stayed in Bloemfontein until his retirement where he served as consul of

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https://doi.org/10.1016/j.quaint.2018.04.017
Received 17 October 2017; Received in revised form 26 March 2018; Accepted 8 April 2018
1040-6182/

Please cite this article as: Neumann, F.H., Quaternary International (2018), https://doi.org/10.1016/j.quaint.2018.04.017

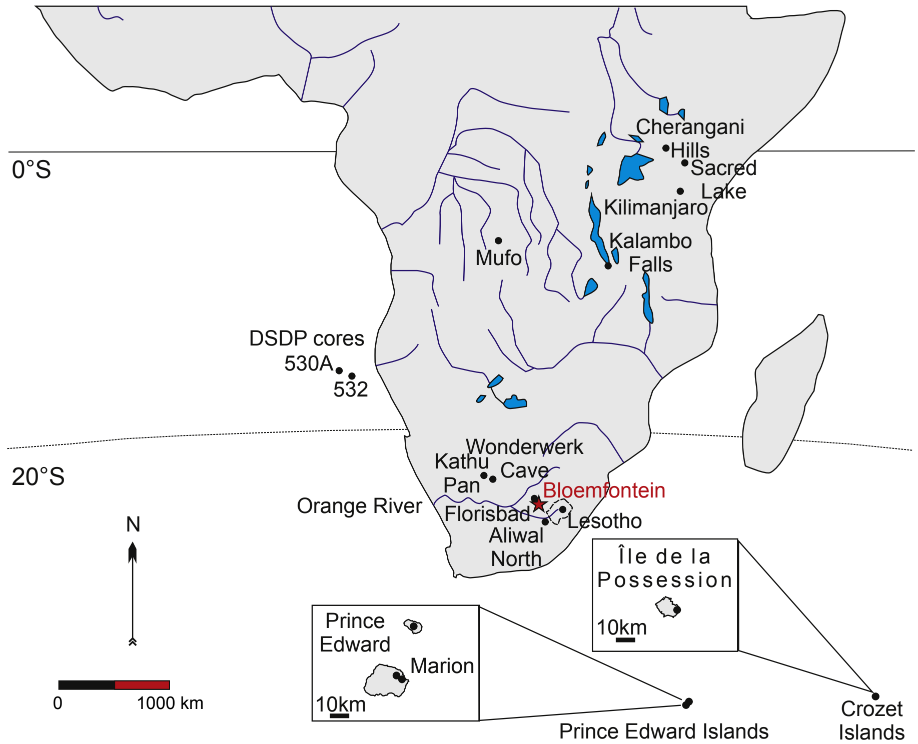

Fig. 1. Sketch map of Sub-Saharan Africa, showing key Quaternary sites where van Zinderen Bakker worked.

the Netherlands for some time. He first worked as a lecturer and later on as Professor of Botany (1947–1972) at the University of the Orange Free State (UOFS, now the University of the Free State or UFS), where he started the first palynological laboratory with a pollen reference collection for Southern and East Africa (Fig. 2A). On his retirement from the Botany Department, vZB was instrumental in forming the Institute of Environmental Sciences at the UOFS and was appointed as its director from 1973 to 1976 but stayed on as research officer until 1988 (Coetzee, 2001, 2002). When he arrived in Bloemfontein, palaeoenvironmental studies in Sub-Saharan Africa were negligible in comparison with those in the Northern Hemisphere (Meadows, 2015). At the time the continent was recognised for its importance in human evolution following discoveries at Taung and Sterkfontein (Woodward, 1921; Dart, 1925; Dryer, 1935) but not for palaeoclimatic studies. Before vZB's arrival on the sub-continent the only existing palynostratigraphical report was on crater deposits of Banke/Namaqualand (Kirchheimer, 1934), which are now considered to be of either uppermost Cretaceous or Paleocene age (Scholtz, 1985). Very few pollen-morphological studies were available (Garside, 1946; Le Roux, unpublished, in van Zinderen Bakker, 1951b). vZB started to address the lack of understanding of long-term global climate change and its mechanisms by applying palynology as a tool in palaeoenvironmental studies.

At UOFS, vZB introduced palynology to the study of the Quaternary in Southern Africa. Being familiar with the glacial periods and their effects on vegetation in Middle Europe (van Zinderen Bakker, 1942), his primary goal was to look for evidence of the last ice age in Africa (van Zinderen Bakker, 1993). Due to the scarcity of pollen archives in South Africa, with exceptions that included the swamps in the Maluti Mountains in Lesotho and the thermal spring deposits at Florisbad (van Zinderen Bakker, 1955b, 1957, Figs. 1 and 2B), vZB ventured into the tropical regions of Southern Rhodesia (now Zimbabwe) and Katanga (now Democratic Republic of Congo) and later further to Kenya (Fig. 2C) and Ethiopia (e.g., van Zinderen Bakker, 1969a; Meadows, 2015). The physiography allowed him to achieve his ultimate aim of studying the climate and vegetation history of East Africa by coring crater lakes and swamps (van Zinderen Bakker, 1962b, 1993). Later, he expanded his palynological studies to the subantarctic islands (Marion and Prince Edward Islands, Fig. 1) (van Zinderen Bakker, 1969b). His scientific interests brought him in contact with other disciplines including geomorphology, radiometric dating, archaeology and climatology. His efforts and dedication later led to Cenozoic environmental studies in Southern and East Africa (van Zinderen Bakker and Mercer, 1986, see Neumann and Bamford, 2015 for a recent review).

Shortly after his arrival in South Africa, vZB started publishing reports under the name *Palynology of Africa* in order to promote palaeosciences (van Zinderen Bakker, 1951a, 1953a, 1955b, 1958a, 1958b, 1960a, 1962a, 1964). They featured news of Quaternary and Cenozoic research activities from across Africa by various international researchers. He established and edited the series *Palaeoecology of Africa* in 1966 which was published by A.A. Balkema. The first volume was a reissue of the first eight reports. Afterwards the title of the series included the *Surrounding Islands* reflecting his expanding interest sparked by his first biological expedition to Marion Island in 1965/1966. Later volumes included papers contributed by different authors. His collaborator, J.A. Coetzee, whose doctoral thesis became the third volume (Coetzee, 1967), and others assisted vZB with editing until 1987 when K. Heine (Regensburg) took over (Vol. 18–27). After 2005 CRC Press/Balkema (Taylor & Francis) became the publisher and J. Runge (Frankfurt) the editor, introducing the current sub-title of *Landscape Evolution and Palaeoenvironments* for the book series (Vol. 28–34) (Runge, 2017).

Building up a palaeoecological working group at UOFS, vZB trained students H.J.W.G. Schalke, M. Welman, J.A. Coetzee, R. Bonnefille and L. Scott (Fig. 2D, left) in Quaternary palynology. His other activities also included the launching of research groups in limnology (rivers, reservoirs, aquatic environments, algae, algal biotechnology, etc.) (van Zinderen Bakker, 1965a, 1974; Grobbelaar, 2008), terrestrial ecology (e.g., van Zinderen Bakker, 1978a), geomorphology including glacial and periglacial processes (van Zinderen Bakker, 1965b; 1971, 1978a), transmission electron microscopy (Coetzee, 2008) and subantarctic island biogeography (van Zinderen Bakker, 1978a). He therefore also

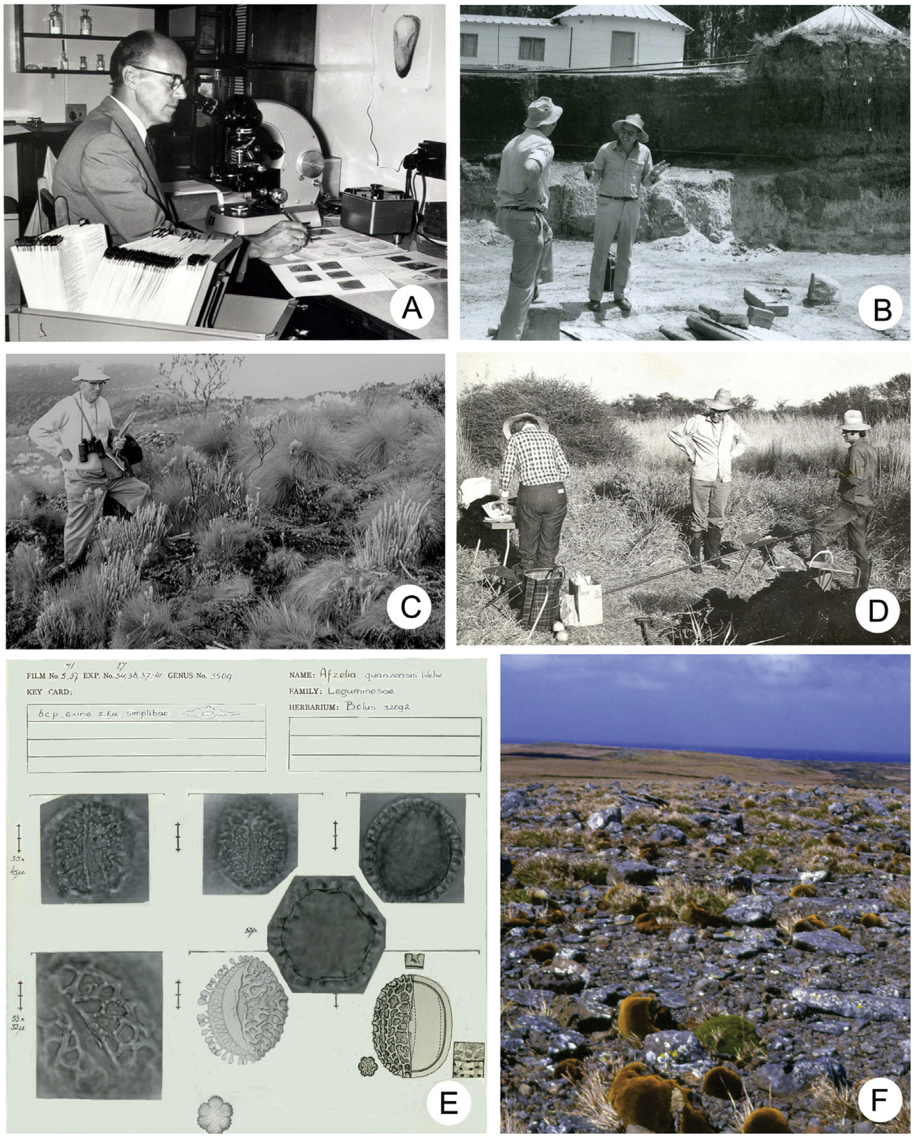

Fig. 2. A: E.M. van Zinderen Bakker c. 1960 in his laboratory (courtesy of the Department of Plant Sciences, UFS), B: R. Clarke (left) & K.W. Butzer (right) at Florisbad, 1982 (photograph Louis Scott collection), **C**: E.M. van Zinderen Bakker, alpine region above the Teleki valley on the west side to Mt. Kenya in December 1970 (photograph E.M. van Zinderen Bakker Jr. collection), D: E.M. van Zinderen Bakker (center), J. Coetzee (left) and L. Scott (right) coring at Wonderkrater 1974 (photograph courtesy of Department of Plant Sciences, UFS), E: LM photos and drawings of pollen grains of *Afzelia quanzensis* in vZB's card system of the pollen reference collection (lower right corner: pasted from Erdtmann, 1952), F: Vegetation on Marion Island incl. *Azorella selago* cushions 1965 (courtesy of Antarctic Legacy of South Africa).

supervised students in other fields than palynology ranging from ecology (B.J. Huntley, V.R. Smith, E.M. van Zinderen Bakker Jr., D.B. Muller) and periglacial processes (K.J. Hall) to fresh water algal studies (W.E. Scott, F.R. Schoeman, J.U. Grobbelaar). Without this groundwork of vZB in his early years, his and his successor's contributions to the study of palaeoenvironments in Africa would not have been possible.

After he established a palynological laboratory at UOFS (Fig. 2A), he realized, in light of the huge diversity of African pollen types (van Zinderen Bakker, 1963), the value of modern reference data for interpreting fossil pollen and collected and obtained anthers from herbaria in Africa and abroad to establish a large pollen and spore reference collection including photographs (e.g., *Afzelia quanzensis*, Fig. 2A, E), which is housed at the Department of Plant Sciences at the University of the Free State holding > 5000 slides. After vZB introduced palynology as a proxy to the scientific community in South Africa (van Zinderen Bakker, 1951c), he also employed methods of pollen processing (Erdtmann and Erdtmann, 1933; Erdtmann, 1952) and outlined challenges to the discipline in Southern Africa since there is a scarcity of potential archives where suitable lakes and peats do not form readily in the oxidizing, dry environment of this country. vZB showed the potential not only for palaeoecological investigations but also for taxonomical studies by indicating in his early work that, for instance, pollen of certain Proteaceae shows greater resemblance to Australian proteaceous pollen than to any of the South African genera in this family which had been studied up to then (van Zinderen Bakker, 1951a, 1951b, 1951c). With J.A. Coetzee, vZB produced the first publication on modern pollen distribution in South Africa (Coetzee and van Zinderen Bakker, 1952). Pollen morphological descriptions were published in the book series *South African Pollen Grains and Spores* (van Zinderen Bakker, 1953b, 1956; van Zinderen Bakker and Coetzee, 1959; van Zinderen Bakker, 1970) and together with J.A. Coetzee, he introduced electron microscope investigations to the Department of Botany, which helped further in the identification of fossil pollen (e.g., Coetzee and Praglowski, 1984).

In vZB's holistic view on vegetation history, he investigated the origins of current biomes that involved pre-Quaternary studies, which, are not discussed in detail in this paper (but see Neumann and Bamford, 2015). He also promoted palaeo-palynology when he collaborated with the Southern Oil Exploration Corporation (SOEKOR) on Cretaceous deposits (Scott, 1971, 1976), secondly with the Atomic Energy Board on Palaeozoic uranium deposits (Horowitz, 1976) and thirdly with the Geological Survey of South Africa to investigate Cainozoic deposits in the Western Cape (Coetzee, 1978, 1983; Coetzee and Muller, 1984; Coetzee and Rogers, 1982; van Zinderen Bakker, 1978c; van Zinderen Bakker and Mercer, 1986). His interests included the Sahara (Van Zinderen Bakker and Maley, 1978) and Namib Deserts (van Zinderen

Bakker, 1975, 1984a), which led him to get involved in the Deep Sea Drilling Project (DSDP cores 530A & 532) off the Namibian coast in Atlantic Ocean deposits (van Zinderen Bakker, 1984b) that was advantageous for his venture into research on the Western Cape Neogene deposits (e.g., Van Zinderen Bakker and Mercer, 1986) (Fig. 1).

vZB's extensive fields of research were funded by the Council for Scientific and Industrial Research (CSIR) through a Palynological Research Unit.

The aim of this contribution is to show the following:

- How vZB's ideas on Quaternary, vegetation and climate change have evolved,
- How these were implemented into the hypotheses of contemporary researchers from various disciplines including archaeology and
- How some of vZB's suggestions are still of importance in current research and might therefore still inspire new concepts to refine African palaeoecology.

2. Quaternary palaeoecology

2.1. The Sub-Saharan setting in Africa

The physiogeography and climatic conditions of Sub-Saharan Africa show extreme spatial variations that determined the few available sites like swamps or lakes that preserved deposits with fossil pollen suitable for palynology.

The climates of Sub-Saharan Africa range from humid to hyper-arid. Belts of diminishing precipitation are arranged in a circular pattern around the Gulf of Guinea on the equator. The current South African climate is characterized by mid-latitude anticyclones over the southern Atlantic and Indian Ocean (Tyson, 1986; van Zinderen Bakker and Coetzee, 1988). The cold Benguela Current along the southwest African coast is distinguished by upwelling, while the warm Agulhas Current flows along the east coast from Mozambique around the southern part of the continent. The western half of the subcontinent is consequently arid to semi-arid and the eastern half more humid with a subtropical climate influenced by the seasonal migration of the ITCZ to give summer rain, especially with moisture derived from the Indian Ocean. The south-western Cape with a Mediterranean type climate is influenced by cyclonic winter rain and has dry summers (van Zinderen Bakker, 1969c). Northwards along the western coast of Africa, the South Equatorial Counter Current is strongest off the coast of Ghana. The West African monsoon brings moisture towards the Congo Basin (van Zinderen Bakker, 1976). Monsoonal activities are coupled to the seasonal migration of the ITCZ across the African continent (van Zinderen Bakker, 1976).

The diverse landscapes include dambos in moist depressions along water courses (Krasilnikov et al., 2009). Some areas are dominated by lowland basins like the Bengweulu Swamps in Zambia or the Congo Basin with tropical rainforest. In contrast there are also highland "alpine" grasslands on tropical mountains in parts of East Africa or cool, windswept plateaus as in Lesotho. Tropical and subtropical savannas like the Kalahari or the Miombo-woodland in turn show transitions to semi-arid shrublands as in the Karoo or desert vegetation as in the Namib. The East African Rift that developed at the beginning of the Miocene, c. 22–25 million years ago (Ebinger, 2005), is an active continental zone maintaining an extensive series of tectonically impressed valleys and lakes, e.g., Lake Victoria and Lake Tanganyika, and volcanoes such as Mount Kenya (Fig. 1). Many are crater lakes associated with volcanism and are particularly suitable for pollen analysis. In contrast the erosional conditions on the highveld of Southern Africa where there are no volcanic craters, and where sediments are transported directly to the ocean, do not favour the formation of natural lakes and swamps. Therefore in this region, vZB started investigating spring sites, e.g., at Florisbad in the Free State province of South Africa (Fig. 1). Because vZB also realized the potential of palynology on the more humid islands with volcanic craters surrounding Africa, he expanded his activities to include some of them like the Marion and Prince Edward Islands (see 2.4).

2.2. Southern African palynology and archaeology

vZB introduced palynology as a tool to archaeology in South Africa (van Zinderen Bakker, 1951c). Convinced that elevated and therefore potentially wetter regions were more promising for palynological studies, he became interested in the highlands of Lesotho, which are today characterized by summer rainfall, cool summers, cold winters and grassy vegetation (van Zinderen Bakker, 1955a; Van Zinderen Bakker and Werger, 1974). While his aim was to look for pollen deposits he also took an interest in geomorphology (van Zinderen Bakker, 1965b). He thus contributed to a better knowledge of periglacial phenomena in the Drakensberg region by describing frost soils, e.g., thufur and polygon soils. In addition, he investigated more recent, probably post-glacial, gley soils, brown earths and podzols and the accompanying vegetation types, solifluction processes, the genesis of peat bogs, and their hydrology. He pointed out the great vulnerability of this landscape in the highlands of the Drakensberg due to recent overgrazing which has caused tunnel erosion (van Zinderen Bakker, 1965b).

His earliest palaeoenvironmental study was undertaken here when radiocarbon dating was not yet readily available and the significance of the study in the history of vegetation and environmental changes was therefore unclear. This first palynological study was on a bog in the afroalpine belt of Lesotho at an altitude of c. 3000 m a.s.l. showing a Cyperaceae dominated pollen assemblages indicative of wet conditions at the bottom of an undated 205 cm long profile (van Zinderen Bakker, 1955a). Recent radiocarbon data of geomorphological depressions in Lesotho suggest that these swamps began with pioneer vegetation during the Holocene or Late Glacial period after the climate improved (van Zinderen Bakker and Werger, 1974; Marker, 1991; van Zinderen Bakker, 1993; Fitchett et al., 2017). The radiocarbon date obtained by vZB is 8020 ± 80 yr B.P. (Pta-751) (van Zinderen Bakker, 1955a, 1978b; van Zinderen Bakker and Werger, 1974; van Zinderen Bakker and Coetzee, 1988). Unfortunately, van Zinderen Bakker (1955a) did not provide data about the exact locality of the site. The low growth rate of the peats at about 0.25 mm/year shows that due to the harsh environment, the organic production is very low although decomposition might also be slow due to the high altitude setting (van Zinderen Bakker and Werger, 1974). Until 2017 vZB's pollen study was the only one available from Lesotho but a new Holocene palynological record from the Mafadi wetland indicates cool and humid periods 8140–7580 cal. yr BP and 5500–1100 cal. yr BP, interrupted by warmer, drier periods (Fitchett et al., 2017).

vZB was enthusiastic about close cooperation between archaeologists and botanists (van Zinderen Bakker, 1951c), where fossil pollen might help in establishing chronologies and reconstructing the climate and vegetation during archaeological periods (*"The picture of the life of plants, beasts and man during the Quaternary is obscure and vague …"*, van Zinderen Bakker, 1963). He therefore analysed pollen in thermal spring deposits at Florisbad (Figs. 1 and 2B) and 45 km to the north of Bloemfontein, a locality that produced some of W.F. Libby's first radiocarbon dates (Dryer, 1935; Hoffman, 1955; van Zinderen Bakker, 1957). The site yielded Middle Pleistocene to Holocene archaeological material and fossils that are unique to the grassland biome (Mucina and Rutherford, 2006). The Middle Stone Age (MSA) archaeological remains found at the site several years earlier is associated with a well-known hominid cranium with facial bones and an isolated tooth (Dryer, 1935). The human cranium, described by T.F. Dryer (UOFS) and originally named as *Homo helmei*, is now attributed to either *Homo heidelbergensis* or archaic *Homo sapiens* and is c. 300 000 years old (Clarke, 1985; Kuman and Clarke, 1986; Brink, 1987, 1988; Grün et al., 1996; Kuman et al., 1999; Lewis et al., 2011).

Forty-four years after his 1951c paper, vZB published another article with the same title, summarising the progress in archaeological palynology in Southern Africa and expanding his previous work on Florisbad (van Zinderen Bakker, 1995). In later years there has been some controversy about the depositional processes of this site but despite difficulties with results in initial analyses due to poor preservation as a result of oxidation and inconsistent radiocarbon dates, finer investigation of vZB's work probably still holds promise in resolving some of these questions (Brink, 1987; Douglas, 2006; Rabumbulu, 2011; Toffolo et al., 2017). vZB indicated spring activity phases and changes in vegetation and climate by fluctuations of Cyperaceae and Chenopodiaceae pollen percentages that need to be studied further (van Zinderen Bakker, 1957).

In the early phase of his investigation, vZB adopted the now dismissed Pluvial Theory of Wayland (1929), which biased his interpretations to correlate the then poorly understood Florisbad sequence with the Nakuran and Makalian Wet Phases and the Gamblian Pluvial (van Zinderen Bakker, 1955b, 1960b, 1993, 1995). In reconstructing the degree in which the environment favoured human occupation during the last 140 000 years (van Zinderen Bakker, 1995), studies of palaeolake deposits, zoological remains, palynological data and archaeological evidence from the late Early Stone Age (ESA) onwards were considered. Unconformities in the Florisbad profile and dating limitations for older material prevented an absolute time scale (van Zinderen Bakker, 1995). vZB's (1995) conclusion was that during the time of the Saale glaciation in the Northern Hemisphere, Florisbad was uninhabitable, but that during the warm and humid last interglacial, the spring mound of Florisbad attracted MSA people who lived along the shores of the palaeolake at Soutpan. Although chronometric dates, which include the electron spin resonance (ESR) date from the tooth of the Florisbad cranium of 259 000 ± 35 000 yrs and OSL dates (Grün et al., 1996), were not yet available for age estimates of the Florisbad finds, vZB proposed a sequence of events of cold and dry conditions that prevented human occupation before more favourable environmental conditions supported swampy vegetation with lechwe, hippos, mongoose and clawless otters associated with MSA communities (Brink, 1987, 1988). During the pleniglacial, probably cool and dry conditions returned but later during an arid episode in the Holocene, Later Stone Age (LSA) people re-occupied the site (van Zinderen Bakker, 1995). The Florisbad sequence shows that climate changes took place to form landscapes ranging from “alpine” to temperate and periodically to cold arid conditions (van Zinderen Bakker, 1989). His pollen work was followed by a study on the Holocene deposits that indicated two relatively humid, grassy environmental cycles, c. 6300 cal yr BP and c. 4420 cal yr BP (Scott and Nyakale, 2002). As a result of his experience with spring deposits like those at Florisbad, vZB drilled thermal spring deposits at Aliwal North spa and entrusted their pollen analysis to J. A. Coetzee, which resulted in the first detailed dated pollen record covering the Last Glacial-Interglacial Transition (LGIT) in the dry Karoo region (Coetzee, 1967; van Zinderen Bakker and Butzer, 1973).

vZB followed up his interest in archaeological sites in collaboration with J.D. Clark investigating pollen in sequences in Angola and Zambia (van Zinderen Bakker, 1962b; Clark and van Zinderen Bakker, 1963; van Zinderen Bakker and Clark, 1962). In northeast Angola, at Mufo (Fig. 1), organic sediments dated to c. 38 000 yr BP, featuring dry conditions as shown by pollen typical of open woodland, were deposited together with MSA stone tools (Clark and van Zinderen Bakker, 1963; van Zinderen Bakker and Clark, 1962, 1964). These results show that at c. 15 503 yr BP, cooler and wetter conditions probably developed with montane forest. At c. 6830 yr BP a warm and humid climate developed and c. 4700 yr BP vegetation was similar to todays.

Kalambo Falls, a waterfall at the southeastern shore of Lake Tanganyika (Fig. 1), is one of the most important sites for human evolution in Africa (van Zinderen Bakker and Clark, 1964). The site lies below a plateau covered by *Brachystegia-Julbernardia* woodland with wetlands (Miombo woodland-Dambo grassland mosaic) and relict patches of evergreen forest. Extensive excavations from 1956 to 1966 under J. D. Clark showed the site was continuously occupied for > 250 000 years since the late ESA until modern times. Fifty palynological samples were collected during these excavations covering the period from an estimated c. 60 000 yr BP to the Pleistocene-Holocene transition (van Zinderen Bakker, 1969a). Results suggested that cooler, more humid climatic conditions might have prevailed in the past (van Zinderen Bakker, 1969a, 1993; Clark, 1972). vZB tentatively correlated the sequence with coeval climatic fluctuations of the European late Pleistocene. At c. 60 000 yr BP, swamp vegetation with high groundwater tables supporting Cyperaceae and Podostemaceae, riparian forest fringing the swamp and a semi-deciduous dry forest occurred, which points to warmer and drier conditions than today. Following a cooler period relatively humid conditions returned c. 27 000–30 000 yr BP with *Combretum* and *Alchornea* (van Zinderen Bakker, 1969a). This period might be correlated with the Paudorf Interstadial in the Northern Hemisphere and is named the Kalambo Interstadial (Coetzee, 1967). The uppermost pollen zone is coeval with the LGM/Mount Kenya Hypothermal and indicates a type of vegetation that is nowadays found c. 800 m above the site with abundant Ericaceae and weakly developed forest. Van Zinderen Bakker (1969a) concluded that it must have been cool and humid and points out that similar conditions for that time period have been described from Angola (Clark and van Zinderen Bakker, 1963).

Later vZB collaborated with P.B. Beaumont at excavations at Kathu Pan (Beaumont et al., 1984) and Wonderwerk Cave west of Kimberley (van Zinderen Bakker, 1982b; Scott and Thackeray, 2015). Located in the savanna biome, Wonderwerk Cave in the southern Kalahari (Fig. 1) has yielded stone tools that were recently shown to be almost two million years old. vZB took samples from the upper profile that included LSA artefacts (Malan and Cooke, 1941; Chazan et al., 2012; van Zinderen Bakker, 1982b). Palynological problems with cave deposits that vZB outlined include the scarcity of pollen, disturbances by human occupants and bioturbation. He suspected burrowing bees were responsible for the high numbers of Asteraceae pollen in the early Holocene in the cave and excluded them from the pollen sum (van Zinderen Bakker, 1982b). A recent revision of the Holocene palynology of Wonderwerk Cave suggested the Asteraceae pollen was from regular deposition and has incorporated vZB's sequence in a more extensive pollen data set that included dung deposits and stalagmite data from the same site (Brook et al., 2010; Scott and Thackeray, 2015). Wonderwerk Cave now provides a record of c. 36 000 years with evidence of cold temperatures and humidity between c. 17 000 and 23 000 yr BP before strong moisture fluctuations lead to aridity in the early Holocene and more humid conditions during the middle Holocene (Brook et al., 2010; Scott and Thackeray, 2015). Overall conditions point to warming of the atmosphere in the Holocene with spreading arboreal vegetation (since c. 7500 yr BP: Thornveld Savanna, van Zinderen Bakker, 1995). The Wonderwerk Cave pollen sequence provides an important link between environment and technological change as it tracks shifts in LSA hunter-gatherers that manufactured stone tools belonging to the Oakhurst Complex and their transition to the later Wilton Complex. vZB believed that a dry period of c. 2000 years occurred before present day climatic conditions were established.

For the Holocene vZB's work at Kathu Pan at the southern margin of the Kalahari (Beaumont et al., 1984), revealed a sequence characterized by grasses and *Acacia karoo* fringing the pan that corroborate findings from Wonderwerk Cave. Circa 7500–4500 yr BP warm and humid conditions were suggested by the presence of pollen that is characteristic of an open grassland with swampy conditions that included Cyperaceae and *Typha*. Circa 4500–2700 yr BP drier conditions than today prevailed when tree elements are absent, indicators for wet habitats were rare and pollen contents were poor. Haline conditions were indicated by pollen of Chenopodiaceae and Crassulaceae (Beaumont et al., 1984). Since c. 2700 yr BP open grassland returned to the site and locally wet conditions are shown by *Typha* and Cyperaceae pollen (Beaumont et al., 1984).

2.3. East African palynology

vZB's interest in pollen studies in the mountainous regions of East Africa might have been influenced by his belief that fossil pollen records are most sensitive in high mountains with steep slopes that create sharp vegetation belt boundaries (compare Bond, 1965). In East Africa where, during pioneering expeditions, he cored lakes and swamps on the Cherangani Hills, Mount Kenya and Kilimanjaro (Fig. 1), he was accompanied by his two young sons, his wife and J.A. Coetzee. They withstood tremendous logistical obstacles by driving all the way from Bloemfontein on poor roads and camping and coring under dangerous conditions (van Zinderen Bakker, 1962b; Coetzee and van Zinderen Bakker, 1967; van Zinderen Bakker, 1993).

vZB investigated high altitude crater lakes as well as peat bogs and swamps, their succession and typical vegetation phenomena, like floating mats overgrown by Cyperaceae and therefore including *Papyrus* rhizomes. vZB believed that the possible genesis of these features was connected to Neogene tectonics, which changed and dammed river courses creating the precondition for vast wetlands and moors (van Zinderen Bakker, 1965b).

He initiated East African palynological studies with the profile at Cherangani Hills that showed a considerable shift to lower elevations in vegetation belts during the LGM (van Zinderen Bakker, 1962b, 1962c, Fig. 1). This was followed by the classic publication by J.A. Coetzee that included a c. 33 000 yr BP profile from Sacred Lake on Mount Kenya, located at 2400 m a.s.l. (Coetzee, 1964, 1967, 2008; Meadows, 2007, Fig. 1). Sacred Lake proved to have one of the longest continuous records retrieved from East Africa covering the last 115 000 yr BP period (Olago, 2001; Street Perrott et al., 1997). A downward shift of c. 1100 m of the vegetation belts occurred c. 27 700–14 000 yr BP during the LGM suggesting that temperatures dropped by c. 5,1–8,8 °C (Coetzee, 1967; Coetzee and van Zinderen Bakker, 1967; van Zinderen Bakker, 1969a). Results from the Cherangani Hills and Sacred Lake led to a study of mountainous vegetation including the current altitudinal distribution of the ericaceous belt in eastern and southern Africa, which vZB postulated probably migrated to lower lying habitats during cool periods over the whole Sub-Saharan transect from the Sudan to the Cape (Van Zinderen Bakker et al., 1970; van Zinderen Bakker and Werger, 1974). Following the work of Van der Hammen (1961) in the Colombian Andes 5° north of the equator, vZB showed that glacial episodes were not exclusively high latitude Northern Hemisphere phenomena but could be demonstrated in tropical regions suggesting they were global phenomena (Scott, 2007). Although vZB's ideas were criticized by Livingstone (1967) and Hedberg (1969), he was convinced that primarily temperature and not only edaphic factors and humidity as proposed by these researchers, was responsible for vegetation change in the East African mountains during the Quaternary (van Zinderen Bakker, 1993).

During the 1950s and 1960s Wayland's (1929) Pluvial Theory was still widely accepted, although based on weak evidence from lakes in the East African Rift, which implied that Northern Hemisphere glaciations coincided with higher precipitation in non-glaciated regions. Geological and palynological research, partly influenced by the studies of vZB, have led to the subsequent abandonment of this theory (Flint, 1957; van Zinderen Bakker, 1960b, 1966; 1982a, 1993; Deacon and Lancaster, 1988).

Studies from the dry belt of Africa north of the equator, e.g., at Lake Chad, have shown that lake levels changed simultaneously in the whole region (van Zinderen Bakker, 1972b). More importantly, during a period coeval with the Last Maximum of the Kenya glaciation (equivalent of the European upper pleniglacial), dry, non-pluvial, conditions prevailed in the region (van Zinderen Bakker, 1972b). According to vZB, arid conditions characterized the LGM over a large region stretching from the southern Sahara to East Africa, and wet conditions occurred during the warm Holocene altithermal (van Zinderen Bakker, 1976, 1993, see section 3).

2.4. Subantarctic islands and Antarctica

vZB organized the first major biological expedition to Marion and Prince Edward Islands in 1965 where he started pollen work together with H. Schalke (Schalke and van Zinderen Bakker, 1967). Under his guidance scientists from various countries studied the palynology, glacial geology, volcanology, limnology, zoology, mineral cycling and the bioenergetics of the islands culminating in a monograph published in 1971 (van Zinderen Bakker et al., 1971). By 1963, intrigued by the influence of the Antarctic glaciation on climate and vegetation in the Southern Hemisphere, vZB initiated palaeoecological studies on several subantarctic islands, namely Marion Island, Prince Edward Island, and the Crozet Islands (van Zinderen Bakker, 1967a, 1967b, 1972c, 1978a; Muller et al., 1967, Figs. 1 and 2F). The Marion and Prince Edward Islands are situated in the southwestern Indian Ocean 1600 km southeast of South Africa and feature a treeless subantarctic vegetation with vascular plants, influenced by an extremely oceanic climate below an altitude of 300 m. Isolated vascular plants (e.g. *Azorella selago*, Fig. 2F) and numerous cryptogams dominate higher altitudes (van Zinderen Bakker, 1967a, 1967b; 1978a, 1978c; Smith and Mucina, 2006).

Fossil pollen sequences from Marion Island revealed a temperature drop of 2–3 °C during the LGM (Schalke and van Zinderen Bakker, 1971; van Zinderen Bakker, 1993). It was suggested by the rounded, smooth periglacial topography with glacial striations on grey lavas that the island was covered by a central ice cap from which a number of small glaciers radiated, while pollen indicated that upland *Azorella* vegetation occupied lower altitudinal positions (Schalke and van Zinderen Bakker, 1967; van Zinderen Bakker, 1969b, 1971; Hall, 1978a, 1978b). According to vZB, Antarctic glaciation influenced the Southern Ocean climate significantly, forcing the Polar Front to the north of Marion Island. While the islands were covered by glaciers, the Antarctic Convergence, an important biogeographic barrier, also shifted allowing icebergs to move 500 km further north than today. vZB inferred from sediment cores (see Brodie, 1965) that during glacial maxima the influence of the Antarctic glaciations reached about 5° further north than during interglacials (van Zinderen Bakker, 1967d). The effect of glacial periods was shown to be of a global scale supporting a view that at the time was not generally accepted by the scientific community (Schalke and van Zinderen Bakker, 1971).

After *Azorella selago* dominated during the LGM, these cushions were accumulating organic matter and volcanic ash, eventually allowing the colonisation of other plants. Since c. 14 000 yr BP climatic conditions improved until c. 12 500 yr BP when the current vegetation was established (van Zinderen Bakker, 1969b) with a dominance of Poaceae and an increase of swamp vegetation like Cyperaceae and Ranunculaceae (Schalke and van Zinderen Bakker, 1967). Decomposing plant matter blocked drainage and led to the development of peats that were probably established at c. 7000 yr BP when major vegetation fluctuations ceased on Marion Island (Schalke and van Zinderen Bakker, 1971; Scott, 1985). Schalke and van Zinderen Bakker (1967) and Scott and van Zinderen Bakker (1985) noted few *Podocarpus*, *Olea*, Combretaceae, fynbos pollen (e.g., Ericaceae, Restionaceae) and *Ephedra* and a single *Nothofagus* grain, evidence of long distance dispersal from Africa and South America. vZB's palynological work on Marion Island was followed by that of his students in the 1980s, e.g., Scott and Hall (1983) on interglacial deposits, Scott (1985) (Holocene sequences) and Scott and Smith's (2008) well dated late Holocene sequence.

A core from Prince Edward Island reached back to c. 5830 yr BP (Schalke and van Zinderen Bakker, 1971). Palynological results are in good agreement with the profiles from Marion Island, showing the development of mire vegetation with an increase of grass pollen towards the top.

vZB described the periglacial geomorphology on Marion and Prince Edward Islands including stone stripes and polygons and assumed permafrost at higher altitudes; needle ice might be responsible for the occurrence of moss balls (van Zinderen Bakker, 1978a; Hall, 1978a).

A profile from Ille de la Possession (Crozet Islands, Fig. 1) gives an age of c. 2830 yr BP and showed pollen spectra, which are also characteristic of mires on Marion Island with Ranunculaceae, Cyperaceae, Poaceae and *Lycopodium magellanicum* (van Zinderen Bakker, 1972c). A change towards drier conditions with *Cotula* and *Tillaea* suggested proximity to the sea in the top of the sequence. The upper few centimetres show limited anthropogenic disturbance (occurrence of *Cerastium*, van Zinderen Bakker, 1972c).

During the South African biological and geological survey of the Marion and Prince Edward Islands, Bouvet Island was also visited. It is the southernmost volcanic island on the Mid-Atlantic Ridge, mostly covered by ice and snow, devoid of vascular plants and containing only moss and lichen (Muller et al., 1967). This island provided vZB with a model of what Marion and Prince Edward Islands might have looked like during the LGM. It was concluded that during the glacial period no organic deposits were formed on Bouvet Island, and the oceanic sediments around the island might be a valuable palaeoclimatological archive that could support this (Muller et al., 1967).

Realizing the important role of Antarctica during the Cainozoic for explaining climatic conditions in Africa, vZB's activities led him to be elected chairman of the Scientific Committee on Antarctic Research (SCAR) from 1972 onwards (van Zinderen Bakker, 1993; Coetzee, 2002). In 1978, as convenor of the SCAR Group of Specialists on Late Cainozoic Studies, he edited the volume *Antarctic Glacial History and World Palaeoenvironments* (van Zinderen Bakker, 1978c). His interests in Antarctica can be seen as closely related to his holistic view of the development of modern biomes in Africa (Zinderen Bakker and Mercer, 1986).

3. Modelling Quaternary vegetation changes and palaeoclimates in Africa

vZB's multi-disciplinary approach led him to develop a pioneering model to explain Quaternary climatic fluctuations in Southern Africa, which he kept on improving through the years (van Zinderen Bakker, 1975, 1976; 1978b, 1982a), such that this concept is still regularly cited (Chase and Meadows, 2007; Chase et al., 2017). In this way he improved the understanding of how Quaternary vegetation patterns responded to climate fluctuations in Africa (Meadows, 2015; Meadows and Finch, 2016). Realizing that there must be global forces at work in long-term environmental change, vZB started to produce his first conceptual models of mechanisms driving climate change between glacials and interglacials in Southern Africa during the early 1960s (van Zinderen Bakker, 1962c). First vZB observed the current African circulation patterns (see section 2) (Trewartha, 1968) that determine the climate and the extremes of African biogeography (Walter, 1970) and then proposed changes in these systems that may have occurred during glacial periods. vZB focussed on Southern Africa but had a Pan-African perspective.

Limited palynological and other proxy data were available in the 1960s for Southern Africa (see above), e.g., fossil pollen data from the undated peat bogs in Lesotho (van Zinderen Bakker, 1955a), and the crudely dated spring deposits at Florisbad (van Zinderen Bakker, 1957) and Aliwal-North (Coetzee, 1967; van Zinderen Bakker and Butzer, 1973). vZB nevertheless started developing conceptual models to explain possible mechanisms of change between glacials and interglacials, relying on his knowledge of Northern Hemisphere Quaternary studies and newly obtained palynological data from East Africa (van Zinderen Bakker, 1962b; Coetzee, 1967) as well as other available palaeoenvironmental data, e.g., from the Drakensberg region of Lesotho, where periglacial phenomena suggest a drop in temperatures of c. 5.5 °C during glacial periods (Harper, 1969). His models (Figs. 4–7) were further supported by insights into African palaeoecology gained by fieldwork especially when he worked in East Africa at the Cherangani Hills and Mount Kenya (van Zinderen Bakker, 1962b, 1967d; Coetzee, 1964, 2008). In South Africa, vZB's conceptual models were adopted by others in explaining palaeoclimatic mechanisms, e.g., Cockcroft et al. (1987), Tyson (1986) and Chase and Meadows (2007). vZB developed them before attention shifted to orbital parameters, like precession, in explaining Late Quaternary climatic changes (Kutzbach and Street-Perrott, 1985; COHMAP, 1988; Partridge et al., 1997). He adjusted and changed his ideas as new insights became available, e.g., from marine-core studies (Shackleton and Kennett, 1975a, 1975b; van Zinderen Bakker, 1982a). Apart from lowering of vegetation belts during glacial periods, vZB initially relied on the idea of a contraction of circulation and vegetation systems toward the equator as ice cover on the poles spread. In the Southern Ocean this implied that the Polar Front shifted northward and winter rain and fynbos vegetation penetrated deeper into Southern Africa (van Zinderen Bakker, 1976). Later vZB favoured the contention that such changes could be the result of stronger winds of the westerly system in the interior as a result of increased pressure gradients between Antarctica and Africa, as studies on marine deposits suggested (Imbrie et al., 1989; Shackleton and Kennett, 1975a, 1975b; van Zinderen Bakker, 1982a). During his endeavours to reconstruct palaeoclimate, vZB made intense use of a simple model of ecological processes (e.g., van Zinderen Bakker, 1976, 1978b, Fig. 3) that was first introduced by Iversen (1958) for the Northern Hemisphere (Bell and Walker, 1992), starting with a cryocratic phase during the glacial stage and continuing with a protocratic phase at the beginning of an interglacial period. The mesocratic phase corresponded with the climatic optimum whereas the telocratic or oligocratic phases mark the transition to another glacial period with deteriorating climatic conditions (Bell and Walker, 1992). vZB applied this scheme to Southern Africa and used it to create tentative vegetation maps of Africa south of the Sahara during interglacial and glacial maxima (van Zinderen Bakker, 1976, 1978b). These maps and models, which include diagrams of atmospheric and oceanic circulation during glacial and interglacial times, can be viewed as a summary of his thoughts on Quaternary vegetation and climatic fluctuations and deserve special attention. His schematic sketches are redrawn here and slightly amended for consistency from a number of papers to give a synopsis of how he would have envisaged the interglacial and glacial phases in Sub-Saharan Africa (Figs. 4–7).

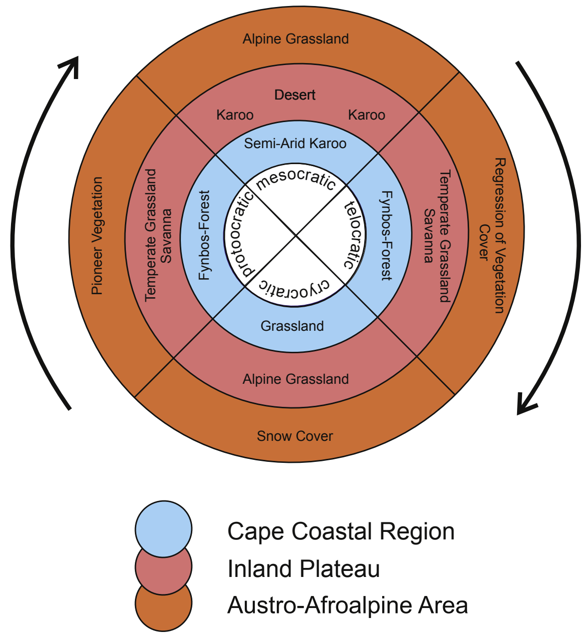

Fig. 3. Ecological model of vegetation types of the full glacial-interglacial cycle of prominent southern African regions (compiled and amended after van Zinderen Bakker, 1976).

It was not always clear what vZB intended to convey in these figures

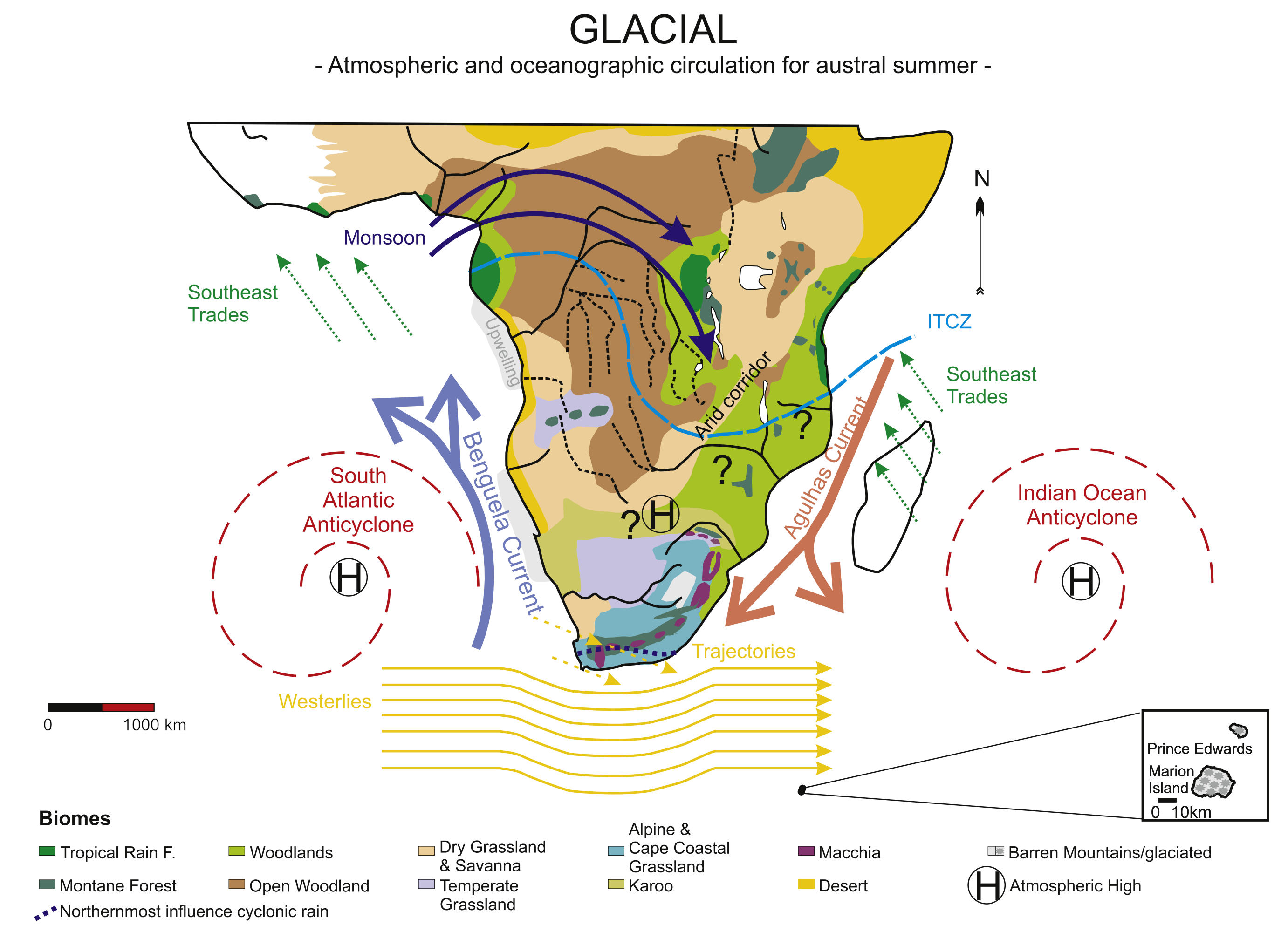

Fig. 4. Tentative vegetation sketch map of Sub-Saharan Africa during a glacial maximum, atmospheric and oceanographic circulation for austral summer. The circulation in the Southern Ocean also applies to Marion and Prince Edwards Islands (inset) (compiled and amended after van Zinderen Bakker, 1976, 1978b).

from the late 1970s but we attempt to interpret them as closely as possible. Together with the discussions below they do not necessarily reflect the authors' opinions about past conditions, which are not fixed. The picture can only become clearer after more extensive evaluation of new and future proxy studies that should include simulation modelling of climates. The discussion below not only follows vZB's maps and publications, but also refers to publications that he used to support his ideas.

3.1. *Last Glacial Maximum (LGM)*

Due to lower sea surface temperatures (SSTs) during the cryocratic phase (at 18 000 yr BP, LGM), evaporation over the tropical oceans decreased by 25–30% in comparison with that during the interglacial and limited the available atmospheric moisture according to Flohn and Nicholson (1980) (van Zinderen Bakker, 1982a). At 18 000 yr BP SSTs along the southern and southwestern coasts of Africa might have been 2–4 °C colder than today (Newell et al., 1981; in van Zinderen Bakker, 1982a).

vZB's palaeoclimatological concepts were supported by a proposed southward expansion of the Sahel during the LGM (Lezine, 1989). In East Africa, forests retreated on the mountains (Hamilton, 1972), whereas in the Kashiru swamp in Burundi grassland and afroalpine elements expanded to lower altitudes (Bonnefille and Riollet, 1988). Cores from lakes in the Rift Valley showed that during cold periods tropical forests were eliminated or replaced by *Podocarpus-Olea* forests and ericaceous heathlands (Sowumni, 1991; Vincens, 1991). In West Africa and the Congo Basin cold and comparably arid environmental conditions during LGM led to a spread of savannas and grasslands (Maley, 1987, 1991). Geological evidence from Ethiopia points to dry and cold conditions during the LGM when the peaks of the Semien Mountains were probably glaciated (Hurni, 1982).

Antarctic glaciation pushed the Benguela Current and the upwelling zone along the southwestern coast of Africa and the South Atlantic Cyclone northwards (van Zinderen Bakker, 1976, Figs. 4 and 5). Upwelling might have increased due to more vigorous winds, also the northwestern coast of Africa (van Zinderen Bakker, 1982a). In the Sahara, during the LGM c. 18 000 yr BP, a southward shift of the hyperarid zone occurred (van Zinderen Bakker, 1980, 1982a).

Over the southwestern Cape, due to the northward shift and strengthening of the westerlies, winter rainfall penetrated deeper into the interior possibly reaching the southern Namib. As a result, biotas shifted northward so that the southern Namib might have become favourable for human occupation. Hyper-arid conditions and biotas adapted to them might have migrated up the coast into Angola even as far as the Congo, a view supported by evidence of De Ploey (1969) regarding the expansion of the Kalahari sands region (van Zinderen Bakker, 1976, 1978b, 1982a, Figs. 4 and 5). According to vZB's model, the displacement of the ITCZ towards the north was a reason why moist air masses, derived for example from the West African Monsoon, did not reach far into the Congo Basin. Savanna and open woodland invaded much of the present day tropical rainforest area which was retracting to form isolated refuges, e.g., along the coast of Liberia and Cameroon, the Niger delta, eastern Zaire, the East African Rift to the

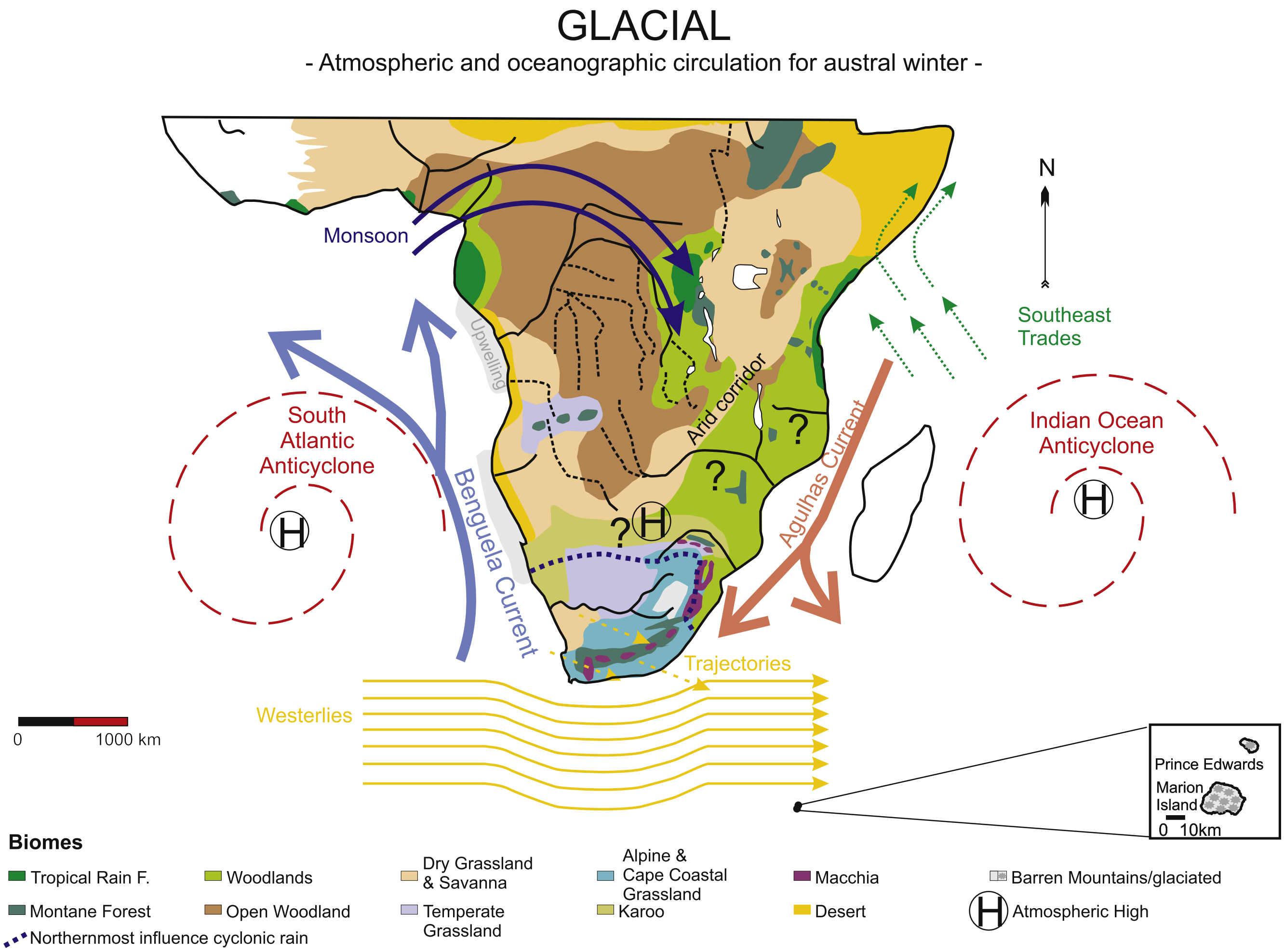

Fig. 5. Tentative vegetation sketch map of Sub-Saharan Africa during a glacial maximum, atmospheric and oceanographic circulation for austral winter. The circulation in the Southern Ocean also applies to Marion and Prince Edwards Islands (inset) (compiled and amended after van Zinderen Bakker, 1976, 1978b).

north of Lake Tanganyika and a narrow strip along the coast of Tanzania (van Zinderen Bakker, 1967d, 1976; 1982a; Hamilton, 1976). This is supported by marine sediment cores from the submerged fan of the Congo River, where, during the LGM, pollen, spores and phytoliths indicate the replacement of tropical rain forest by savanna (Jansen et al., 1984; Caratini and Giresse, 1979 in van Zinderen Bakker and Mercer, 1986). In this context vZB and Mercer emphasised the importance of marine sediment cores which are often more continuous and represent longer time spans than terrestrial archives as was shown in core V16-205, reaching back 2 million years and representing 21 marine oxygen isotope stages (MISs, van Donk, 1976).

Due to increased aridity, lake levels dropped in eastern Africa during the LGM (van Zinderen Bakker, 1972b; van Zinderen Bakker and Mercer, 1986). Woodlands and montane forests reduced in size, although due to decreasing temperatures high altitude vegetation descended by 1000–1100 m (van Zinderen Bakker, 1982a). As a consequence of deteriorating climate, vZB supported the existence of an *arid corridor* stretching from the coasts of Angola and northern Namibia to the Horn of Africa (van Zinderen Bakker, 1976, 1978b, Figs. 4 and 5).

In Lesotho a harsh climate led to the landscape > 3000 m a.s.l. to be barren while in the interior of Southern Africa alpine grasslands expanded. Grassland also occupied the region along the southern coast of South Africa, which experienced a windy and cool climate (van Zinderen Bakker, 1976, 1982a). This was supported by data from Wonderkrater in the central savanna (Fig. 2D), where grassland of the upland kind occurred during the LGM and included some fynbos-like vegetation with Ericaceae and *Stoebe* type pollen (Scott and Vogel, 1978; van Zinderen Bakker, 1982a). This is consistent with cool, subhumid conditions not unlike those prevailing in the Drakensberg region today.

According to Heine (1982), the Kalahari during the LGM was subhumid based on geomorphological evidence and this does not contradict vZB's reconstruction of grasslands for that area (van Zinderen Bakker, 1976). However, van Zinderen Bakker (1982a) emphasizes that central Southern Africa also might have received a certain amount of summer rain during the LGM. He also assumed a refuge in the Karoo outside the range of the winter rains, probably stretching between the Kuiseb River in Namibia and Limpopo Province (van Zinderen Bakker, 1976) (Figs. 4 and 5). In his revised reconstruction for the southeastern coastal region, vZB relied on the assumption by Prell et al. (1980) who proposed that the Agulhas current was weaker and less warm during summer (van Zinderen Bakker, 1982a). vZB reconstructed that the temperature and precipitation conditions were similar to an interglacial but that the area was influenced by the penetration of cold air masses and strong winds during winter, which hampered forest growth. Deacon (1979) and Deacon and Lancaster (1988), based on pollen and charcoal from Boomplaas Cave at the Swartberg Mountains foothills, postulated vegetation cover comprising scrub with dominant *Elytropappus* and grassland c. 22 000–20 000 yr BP and support the reconstruction of grassland for the southern coast and adjacent interior of Africa (van Zinderen Bakker, 1976) (Figs. 4 and 5). He suggested that many rivers and lakes ceased to exist during a glacial maximum.

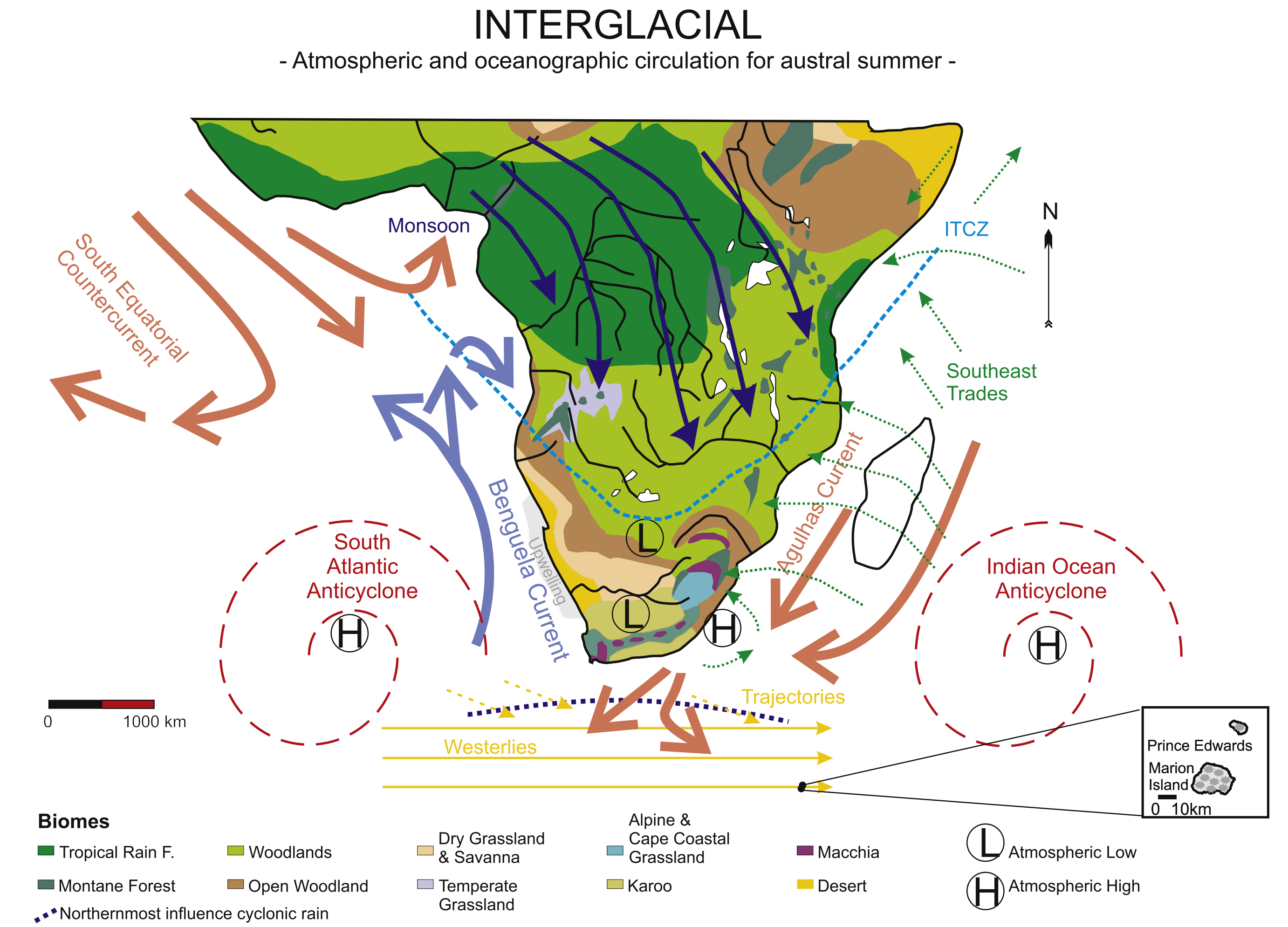

Fig. 6. Tentative vegetation sketch map of Sub-Saharan Africa during an interglacial maximum, atmospheric and oceanographic circulation for austral summer, including Marion and Prince Edwards Islands (compiled and amended after van Zinderen Bakker, 1976, 1978b).

3.2. Interglacial maximum

Changes during an interglacial (protocratic, mesocratic, telocratic phase) were the opposite of the phenomena described above (van Zinderen Bakker, 1976, Fig. 3). During the mesocratic phase, when temperatures peaked, asteraceous Karoo vegetation and desert sand dunes crept towards the interior along the Orange River valley probably occupying the southern half of the Free State (Figs. 6 and 7). Karoo vegetation spread along the southern Cape coastal plain (van Zinderen Bakker, 1978b). During the telocratic phase, in the Cape coastal region, fynbos and forest dominated the landscape whereas in the interior temperate grassland and savanna spread (van Zinderen Bakker, 1978b). In the Austroalpine area during the protocratic phase pioneer vegetation occupied the previously barren landscapes. During the mesocratic stage (as depicted in Figs. 6 and 7) alpine grassland with numerous bogs was present on the high-altitude plateau of Lesotho, while vegetation cover was regressing during the telocratic stage (van Zinderen Bakker, 1978b). Further towards the north, during warm mesocratic conditions, tropical rainfall increased due to a southward shift of the ITCZ and a strong West African monsoon supported vast areas of woodland-savanna (van Zinderen Bakker, 1976, 1978b). The alpine grasslands, under warmer conditions, retracted towards the afro-alpine zone in the highlands of Lesotho (Coetzee, 1967; van Zinderen Bakker, 1976). During protocratic and telocratic periods the coastal plain of Southern Africa was occupied by evergreen forests, whereas an increase in summer rainfall favoured the spread montane forest along higher altitudes probably reaching the Huambo Plateau in Angola (van Zinderen Bakker, 1976). In contrast to the cryocratic phase, the Namib desert moved southwards, maybe even reaching south of the Orange River mouth following a southward shift of the South Atlantic cyclone and the upwelling zone (van Zinderen Bakker, 1976).

Van Zinderen Bakker and Mercer (1986) concluded that the long-term cycle of the repeated spreading of arid conditions with higher occurrences of drier grasslands and deserts during glacial periods and the renewed expansion of forests during interglacials caused the demise of many taxa. It resulted in higher speciation that consequently took place in Africa.

4. Conclusion

4.1. Philosophy

vZB had a holistic approach towards the reconstruction of palaeoclimate and vegetation. This was certainly influenced by his perception of himself as a naturalist and his broad interests that allowed him to cooperate with colleagues from various disciplines. vZB rarely relied on statistics or numerical models, which only became more fashionable later with the development of digital technology (Birks and Birks, 1980; Birks and Gordon, 1985; COHMAP, 1988). He favoured descriptive science with an emphasis on carefully recording, describing, and classifying phenomena he observed in the field. vZB's holistic approach is fitting since he was a pioneer in a field where not much groundwork had been done before his arrival in Africa. He was far from being lost in details and saw problems from a wide perspective that allowed him to

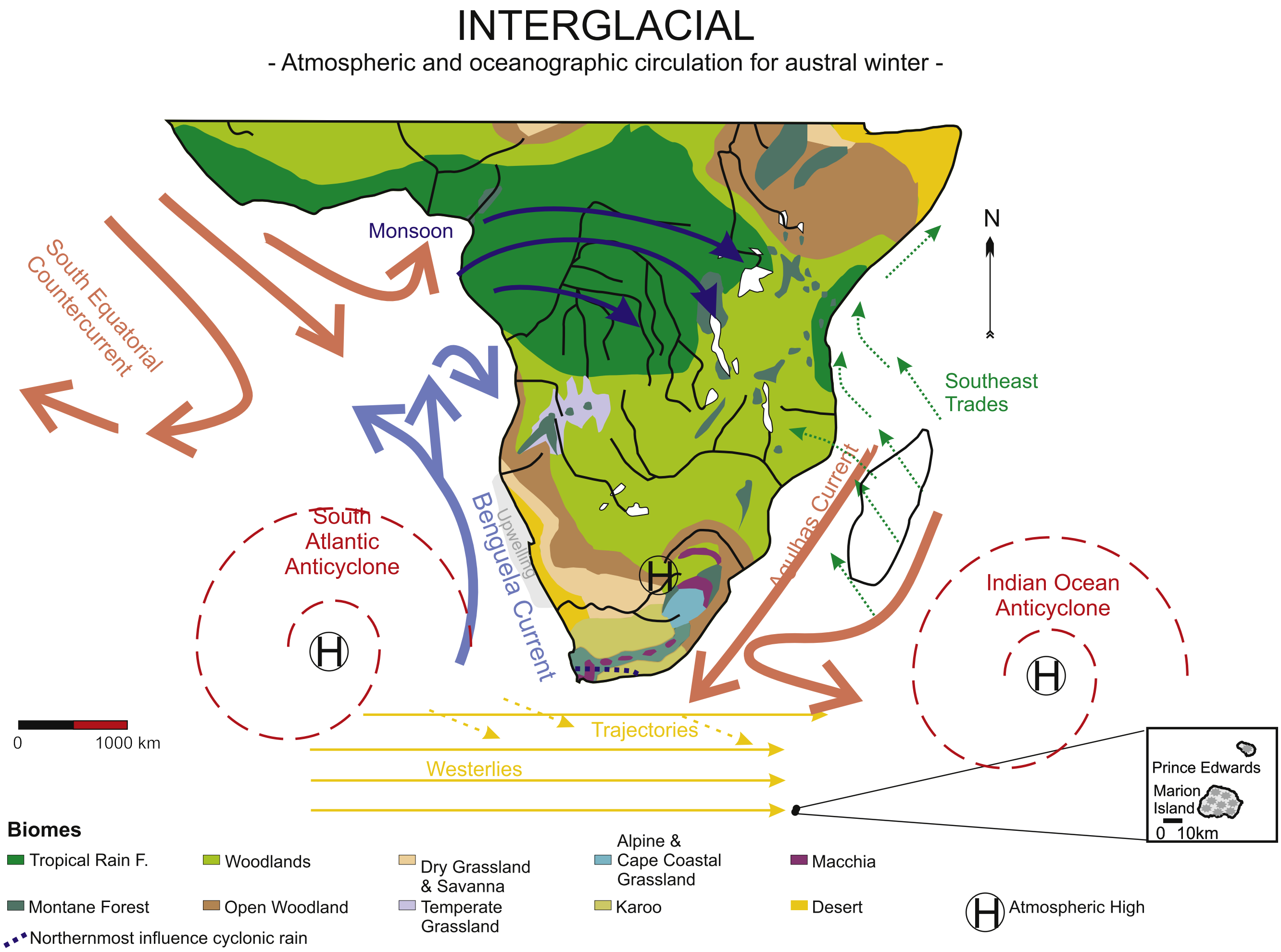

Fig. 7. Tentative vegetation sketch map of Sub-Saharan Africa during an interglacial maximum, atmospheric and oceanographic circulation for austral winter, including Marion and Prince Edwards Islands (compiled and amended after van Zinderen Bakker, 1976, 1978b).

independently develop hypotheses. vZB's approach is modern in the sense that geoscience has to cope with the full complexity of a world in which no single aspect can be explained in isolation but only as a part of systems (compare Sen and Chakrabarti, 2007). His work was the opposite of the often specialist-centred and fragmented thinking of today where the focus is often on the application of methods rather the development of fresh ideas. For example, he was aware that geological sequences from marine archives are more continuous than terrestrial sequences, often cover a much longer time span and give various proxies like oxygen isotope analyses and palaeomagnetism that allow the establishment of more reliable chronologies (van Zinderen Bakker and Mercer, 1986). vZB saw this potential early on although he was focussing on terrestrial archives. Even today knowledge exchange between terrestrial and marine geoscientists is not optimal.

4.2. Evaluation of the palaeoclimatic and palaeovegetation models

vZB influenced thinking in African palaeoclimate studies starting in the 1980s when the Climatology Research Group at the University of the Witwatersrand initiated research into the reconstruction of Quaternary palaeoecology followed by the University of Cape Town (see Cockcroft et al., 1987; Tyson, 1986; Partridge et al., 1997, 1999; Gasse et al., 2008; Chase and Meadows, 2007). Following vZB's model of the late Quaternary, new studies have emerged, some supporting his contentions and others not. In their publication on the late Quaternary, Cockcroft et al. (1987) begin with a model of the present climate, explaining that humid periods are caused by increased tropical atmospheric disturbances and tropical-temperate interaction, and a linkage to the Walker Circulation. Cockcroft et al.'s (1987) model predicts an increase in precipitation over an expanded winter rainfall region at the time of decreased temperatures during the late Quaternary. In contrast, arid periods seemingly result from diminished tropical activity over Southern Africa, equatorward movement of westerlies and temperate perturbations in the westerlies (Cockcroft et al., 1987). They propose that the LGM was associated with northward-displaced circulation conditions similar to those of current dry periods over the summer rainfall region, whereas the extensive moist conditions that prevailed for several thousand years after 9000 yr BP were similar to current humid conditions with minor displacement of circulation features. Cockcroft et al. (1987) notes vZB's reliance on intensification rather than displacement of circulation features (van Zinderen Bakker, 1982a) and that in later papers he even argues that summer rainfall might have prevailed in certain regions during the LGM (van Zinderen Bakker, 1986), which shows general uncertainties between the climate models. Based on his research in the Namib desert, van Zinderen Bakker (1983) revised some of his earlier thoughts and concluded that while westerly circulation during the LGM was intensified, it did not expand equatorward to the degree that he had proposed in van Zinderen Bakker (1967d) (van Zinderen Bakker, 1982a). In contrast to assumptions that during the LGM climatic conditions in Southern Africa were rather dry, geomorphological evidence for lake formation from Alexandersfontein in the dry Northern Cape close to Kimberley points to doubled rainfall at c. 16 000 yr BP (Butzer et al., 1973; van Zinderen Bakker and Butzer, 1973) although the timing is questioned in Partridge and Scott (2000).

Nevertheless, increased rainfall at the time is in agreement with studies by Kent and Gribnitz (1985) showing that palaeolakes in the Northern Cape filled up due to enhanced rainfall between 16 000 and 14 000 yr BP.

Partridge et al. (1999) developed a vegetation model for the Holocene Altithermal and the LGM and suggested this was largely consistent with Cockcroft et al. (1987). Partridge et al. (1997, 1999) further derived a precipitation record from sediment analysis of a c. 200 000 years long record from Tswaing Crater north of Pretoria (Partridge et al., 1997, 1999). The assumption was that summer rainfall was orbitally forced by Southern Hemisphere summer insolation. Partridge et al. (1999) deduced from this record that the interior of South Africa was significantly drier during the LGM (Partridge et al., 1997) and concluded, by reconstructing isohyets, which mean annual precipitation was reduced to c. 50–70% of present day values over much of Southern Africa. For the LGM they reconstruct dry, desert-like conditions for the Kalahari basin, which is not well supported by pollen from the Wonderwerk Cave that indicates more moisture availability during the LGM (Brook et al., 2010; Scott and Thackeray, 2015). This may seem to lend some support to vZB's views in terms of increased moisture availability but the moisture may not necessarily be from winter rainfall as we suggest below.

According to Partridge et al. (1999) areas in the south and east were occupied by dry savanna, shrubs and grasslands whereas tropical rainforest retracted towards the north and evergreen forest occurred in a small area along the KwaZulu-Natal coast. In the mountainous region, the Drakensberg "steppe" vegetation was spreading, and in the south the fynbos biome probably maintained, or even increased, its areal extent due to a larger proportion of winter rain. Partidge's model (Partridge et al., 1999) stands in sharp contrast to vZB's ideas that the Namib desert was displaced towards the north and that grasslands and Karoo vegetation occupied the interior of Southern Africa during a glacial maximum with fynbos restricted to higher altitudes (van Zinderen Bakker, 1976). In both models, only the extent of the tropical rainforest during the LGM is comparable. Partridge's assumption of arid conditions during the LGM in the western half of the sub-continent (with an exception for the southern Cape, Partridge et al., 1999) is contradicted by other findings e.g., Stuut et al. (2002) who suggest that increased moisture occurred on the western margins of Namibia during the glacial period due to enhanced winter rainfall, which is more in accordance with vZB's 1976 model.

Chase and Meadows (2007) was a turning point in interpreting especially the shifts of the Southern African winter rainfall zone during the Late Quaternary. They gave a synopsis/critical discussion of all existing, major models. They divided Southern Africa into three axes, one along the western side, another parallel to the southern coast and a third towards the interior. From Cockcroft et al. (1987) they deduced an even distribution of winter rainfall for the glacial period that occurred south of a line connecting Namibia with Swaziland. Based on the conceptual model by van Zinderen Bakker (1967d, 1976), they reconstructed increasing winter rainfall for southern Namibia, the Kalahari and the western Free State whereas a broad belt along the southern coast, and from Swaziland until northern Namibia would be influenced by interannual rainfall. A third model, discussed by Chase and Meadows (2007), also assumes a larger amount of winter rainfall during the glacial period in a large area covering the Western Cape, Northern Cape and the western half of the Eastern Cape (Heine, 1982). Chase and Meadows (2007) discuss van Zinderen Bakker's (1976) original idea of a northward shift of westerlies opposing Butzer's assumption of stronger rather than displaced westerlies (Gaap escarpment, Alexandersfontein; Butzer et al., 1973, 1978; Butzer, 1984; van Zinderen Bakker and Butzer, 1973). Marine sequences GeoB1711-4 and GeoB1023-5 offshore from South-Western Africa show fluctuations of pollen since > 130 000 and the last c. 18 000 years respectively. Here Restionaceae and desert elements are associated with cool conditions during glacial periods and spreading of grasses during interglacials (Shi et al., 2000, 2001). These marine records are compared in Chase and Meadows (2007) to the Vostok ice core, insolation, and data from the Kalahari region that suggest increased precipitation during the last glacial, c. 50 000–12 000 years ago (Petit et al., 1999; Stuut et al., 2002). Charcoal from Elands Bay Cave on the west coast shows diminishing afromontane forest since the LGM, also underlining cool and wet conditions c. 20 000–12 000 yr BP (Parkington et al., 2000). Chase and Meadows (2007) concluded that during the last glacial period, of which the best documented part is c. 32 000–17 000 yr BP, the winter rainfall zone expanded conforming to vZB's original view.

Scott et al. (2012, 2013), reviewed terrestrial pollen records from Southern Africa during the last 26 000 years and applied principal components analysis to enable comparison. They do not present a climate model but indicate major changes in terrestrial environments due to variations in temperature and moisture in certain regions. During the LGM, a predominantly sub-humid but oscillating climate is indicated, followed by a dry period at the beginning of the Holocene. Scott et al. (2012) underline that climate forcing during the LGM was not uniform in the whole region and moisture changes appeared during different times in different sub-regions. With reference to the Wonderkrater record (Scott, 1999a, 1999b, 2016), there is no evidence for aridity in the central Savanna Biome during MIS 2 or that the available moisture was derived from winter rain. This is in contrast to the conceptual model of vZB (van Zinderen Bakker, 1967d, 1976) where this area is envisaged to be affected by a larger contribution of winter rain, resulting in an interannual rainfall region.

Controversial geomorphological observations pointing to possible glaciers in the Drakensberg region (Mills et al., 2012) together with the spread of Ericaceae and Restionaceae c. 18 000–14 000 yr BP at Mahwaqa in the eastern Drakensberg outliers (Neumann et al., 2014) suggest a shift to more winter rainfall. Increased activity of westerlies (cold fronts), possibly as a result of a northward shift of pressure cells, might have led to higher winter and reduced summer precipitation. This could have created climatic conditions suitable for marginal, short-lived glaciation (Mills et al., 2012) supporting van Zinderen Bakker (1967d, 1976). However, a cooler climate without any shifts in circulation patterns in comparison with the present system may in itself also have created favourable conditions with cool growing seasons for the mentioned fynbos elements (Scott and Neumann, 2018).

4.3. Summary

In conclusion it can be stated that Eduard Meine van Zinderen Bakker contributed significantly to the fields of palynology, palaeoecology and plant ecology of Africa especially in connection to the following aspects:

- vZB's holistic and interdisciplinary perspective promoted interpretations of past conditions at archaeological and palaeontological sites in Africa. He did not focus on one region of the continent but worked at numerous sites in southern and eastern Africa, later extending his interest to the Sahara and Namib deserts and to the subantarctic islands of Marion and Prince Edward. As such he developed a Pan-African view of climate and vegetation changes.
- vZB's hypotheses started with a paucity of information. However, more data gradually became available to his successors due to his groundwork and this may eventually lead to the development of sophisticated numerical simulations of past climate. This process fits a pattern that is not uncommon in science, where initial ideas can be shown to be inaccurate but through persistent work lead to breakthroughs. vZB initiated this process but how close his findings are to those that will eventually effectively describe the climate system in Southern Africa remains to be seen.
- vZB's climate modelling ideas were the first attempt at reconstructing interglacial and glacial climate and vegetation distribution in Southern Africa based on how pollen could be used to

reconstruct vegetation and fluctuations of humidity and temperature. In opposition to contemporaries, e.g., Livingstone (1971) and Hedberg (1969), who stressed local moisture effects, vZB attributed global temperature variations as being the primary cause of profound palaeoenvironmental changes in Africa.

- vZB's (1967d, 1976, 1982a) proposal that a northward displacement of pressure belts during glacial periods in the Southern Hemisphere, especially increased westerly wind activity resulting in higher amounts of winter rainfall over large regions in Southern Africa, is still controversial.
- Due to his own fieldwork and experience, vZB was aware of the advantages and disadvantages of marine sequences and terrestrial deposits, which allowed him to compare and correlate sites and use the benefits from both types of archives on a wide geographical scale.
- vZB abandoned the Pluvial Theory that was used to compare African climate changes with high-latitude Northern Hemisphere sites, soon after obtaining more quantitative studies and improved dating.
- vZB introduced (Quaternary) palynology to the sub-continent, established the first Quaternary palaeoecological research unit in Southern Africa and initiated the first book series (*Palaeoecology of Africa*, ISSN 2372–5907) that focussed specifically on African palaeoecology.

As a consequence, vZB's ideas are still influential and intensively discussed in the Southern African scientific community and worldwide, inspiring Quaternary studies on the sub-continent. His academic heritage, which includes the book series *Palaeoecology of Africa* and the large pollen reference collection at UFS in Bloemfontein, serves as a unique and important base for further research.

Acknowledgements

We declare that we have no significant competing financial, professional or personal interests that might have influenced the performance or presentation of the work described in this manuscript. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. F.N. was funded by a postdoctoral fellowship at UKZN/UFS and L.S. by the NRF (Grant no. 85903). Any opinion, finding, and conclusion or recommendation expressed in this material is that of the authors, and the NRF does not accept any liability in this regard. We are very grateful to the editors of Quaternary International, as well as J. Runge and two anonymous reviewers for their useful suggestions and comments. We thank Eduard van Zinderen Bakker Jr. for reading the manuscript and for the photograph of his father at Mount Kenya. We thank the archive of the Antarctic Legacy of South Africa (http://alp.lib.sun.ac.za) for the use of the photographs in Fig. 2 (B, F).

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