4 Landscape and Landforms of the Vredefort Dome: Exposing an Old Wound

Roger L. Gibson and W. Uwe Reimold

Abstract

A striking 100 km-long crescent of ridges and valleys straddling the Vaal River along the border between North West and Free State provinces near the towns of Parys and Vredefort is the most obvious remnant of one of the most remarkable geological events in Earth's history. The Vredefort impact event 2,020 Ma ago into the ancient rocks of the Kaapvaal craton is estimated to have left a crater that was originally at least 250 km wide and over 1 km deep. The crater and its infill of broken and melted rocks have long since been stripped away by erosion, rendering the crater margins largely invisible today. However, a central region of rock that was domed upward during the impact event and that bears numerous scars of the catastrophe is still visible. The crescentic Vredefort Mountainland forms a portion of this geological feature, which is referred to as the Vredefort Dome. The landscape of the Dome owes much of its current dramatic topographic relief to the 300 Ma Dwyka glaciation, evidence of which is now being exhumed by the modern Vaal River. Large potholes, sand-blasted rock pavements and the remnants of ancient dune fields testify to more recent shifts in climate in the Mesozoic and Cenozoic. Part of the Vredefort Dome was inscribed as a UNESCO World Heritage Site in 2005.

Keywords

Climate change • Glacial landforms • Meteorite impact structure • Vaal River • Vredefort Dome

4.1 Introduction

Whilst much of the interior plateau of South Africa is dominated by horizontal strata of the 300–180 Ma Karoo Supergroup that have given rise to its characteristic mesa topography (see Chaps. 1 and 2), the northern parts of South Africa expose a far older and more complex geology that, in turn, contributes to a more varied landscape. The Witwatersrand region that extends westwards from Johannesburg (Fig. 4.1) and forms the great watershed of southern Africa is underlain by rocks that formed more than 2,000 Ma ago, among which are gently-dipping resistant white quartzites that mark the signature cuesta ridges of this region (McCarthy and Rubidge 2005). Sandwiched between the Witwatersrand region and the northern edge of the Karoo Basin, however, is a region in which the rocks display complex, locally annular patterns (Fig. 4.1) that, in turn, have produced a highly unusual landscape. The contorted, broken, displaced and strongly rotated rock layers owe their configuration to a remarkable cataclysmic event ca. 2,020 Ma ago, when an approximately 10 km-wide asteroid hit the Earth and formed a gigantic impact crater, the deeply eroded remnants of which can now be seen in the northern Free State, southern North West and Gauteng provinces (Gibson and Reimold 2008; Reimold and Gibson 2010).

R.L. Gibson (✉) · W.U. Reimold
University of the Witwatersrand, Johannesburg, South Africa
e-mail: roger.gibson@wits.ac.za

W.U. Reimold
Museum Für Naturkunde, Berlin, Germany

W.U. Reimold
Humboldt-Universität Berlin, Berlin, Germany

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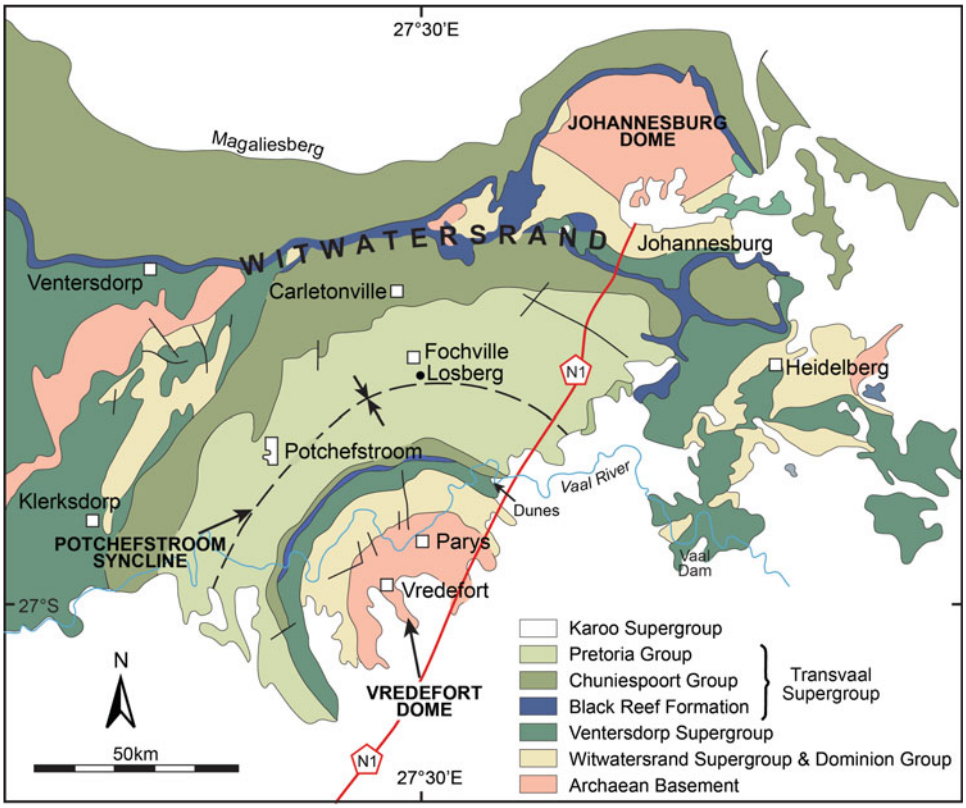

Fig. 4.1 Simplified geological map of the exposed portion of the Vredefort impact structure, with the Vredefort Dome at its centre. The Potchefstroom Syncline marks the outer limit of the Dome. The limits of the original crater may have lain close to, or even beyond, the Witwatersrand. The southern and southeastern parts of the impact structure are hidden beneath a thin veneer of Karoo Supergroup rocks

4.2 Geological Setting

The Vredefort Dome is a region of strongly upturned rock formations centered approximately 15 km south of Parys (Fig. 4.1; Gibson and Reimold 2008). The term "dome" is used here in a geological, rather than geomorphological, sense, in that the landscape is not marked by a central topographic high point; instead, the term describes the arrangement of rock formations that illustrate by both their geometry and their relative ages that old, originally deeply buried, rocks have risen in the centre, pushing aside and rotating the overlying layers (Figs. 4.1 and 4.2). The steep dips of strata within the dome region gradually give way outwards to more gentle dips which are initially centrifugal but, at greater radial distances, switch to centripetal near the towns of Potchefstroom and Fochville (Fig. 4.1). This reversal marks the axial hinge line of the Potchefstroom Syncline, which is the outer limit of the Vredefort Dome. The Dome is thus almost 90 km wide, although most of its southern half presently lies hidden beneath a thin veneer of younger Karoo Supergroup rocks (Fig. 4.1).

The rocks forming the Vredefort Dome span almost one-third of Earth's history (Gibson and Reimold 2008). In the centre lie predominantly granitic gneisses, most of which crystallised from magmas deep below a volcanic arc about 3,100 Ma ago, but which also include even older sea-floor basalts and mudrocks that are now highly metamorphosed gneisses. These coarse crystalline Archaean gneisses define the 40 km-wide *core* of the Dome. Surrounding this core is a 20–25 km wide *collar* of metamorphosed layered sedimentary and volcanic rocks that range in age from 3,074 to 2,100 Ma and that comprise (in order of decreasing age and increasing distance from the centre of the Dome) the Dominion Group and the Witwatersrand, Ventersdorp and Transvaal Supergroups (Gibson and Reimold 2008). The combined original vertical thickness of these rocks is estimated to have been 12–15 km. The Dominion Group and Ventersdorp Supergroup comprise metamorphosed basalt lava flows, whereas the Witwatersrand Supergroup (quartzite, metamorphosed shale, iron formation and conglomerate) and Transvaal Supergroup (dolomite, quartzite and shale) represent sedimentary sequences, but also contain a few thin lava layers, numerous intrusive dolerite sills and several

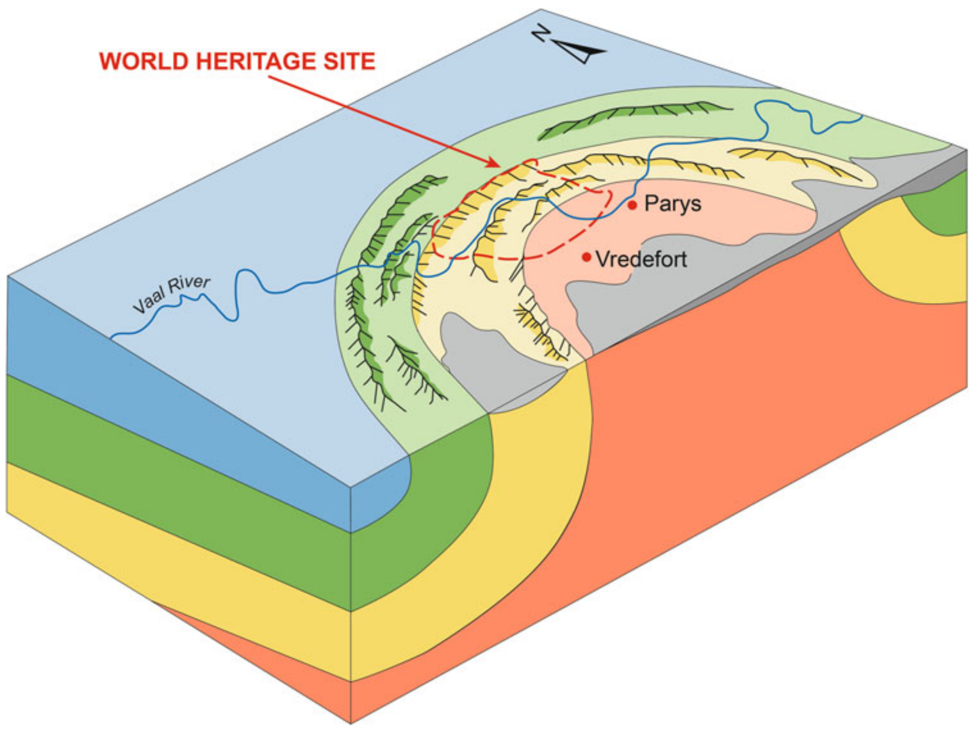

Fig. 4.2 Simplified schematic block diagram of the Vredefort Dome (perspective looking northeast) showing the arrangement of the major rock formations (*orange* = Archaean Basement Complex; *yellow* = Witwatersrand Supergroup and Dominion Group; *green* = Ventersdorp Supergroup; *blue* = Transvaal Supergroup; *grey* = Karoo Supergroup) relative to the Vaal and Vredefort Mountainland. The World Heritage Site occupies only a small portion of the Dome

small granite intrusions. Most of the sedimentary layers have near-vertical dips and are actually inverted in large sections of the collar, so that they dip steeply inwards towards the centre of the Dome (Fig. 4.3a). This overturning reflects the last stage of dome formation, when the dome collapsed downwards and outwards under its own weight. The doming itself was triggered by release of the intense downward compressional forces exerted on the target crust beneath the point of impact. The Dome would have taken no more than a few minutes to form after the impact, but rocks in its core were uplifted by as much as 20–25 km, making its formation one of the most remarkable geological events in Earth's history. It is also one of the few places on Earth where an originally vertical section of Earth's crust more than 20 km deep is now exposed at the surface.

In addition to the obvious structural disturbance of the rock layers (Fig. 4.3a), the rocks in the Vredefort Dome bear witness to the immense forces caused by the impact and its aftermath—distinctive shatter cones and intense fracturing of the rocks, as well as veins and dykes of impact-formed melt rock that are laden with fragments (xenoliths) of the target rocks (Fig. 4.3b), are abundant. Much of the evidence of impact is, however, microscopic-thin (less than 0.001 mm across), closely-spaced, planar lamellae in quartz and zircon crystals, and dense mineral variants (polymorphs) of quartz called coesite and stishovite testify to intense shock pressures that can only be explained by a sudden, violent, high-pressure, shock event. Although an impact origin for the Dome was proposed as early as the 1930s, alternative hypotheses, such as upwelling of a magma diapir or intersecting fault and fold structures, held sway until the latter parts of the last century, particularly among local geologists (see review in Reimold and Gibson 2010).

The 2,020 ± 5 Ma age of the impact event is a composite of the results of several studies based on analysis of U–Pb (uranium and lead) isotope ratios in zircon crystals extracted from a variety of melt-rocks that formed as a result of the impact (Gibson and Reimold 2008).

Another consequence of the impact was intense heating of the rocks by the energy from the shock wave, which metamorphosed and annealed the rocks. The unusual intensity and broad extent of these metamorphic changes (Gibson et al. 1998), together with considerations of the uplift and erosional history of the region (McCarthy et al. 1990), suggest that the rocks presently exposed at the surface were still buried as much as 8–10 km below the surface of the crater immediately after the impact event. Consequently, the modern landscape of the Dome bears no relation to the original crater. The extreme amount of erosion is one of the primary reasons why the decades-long debate about the

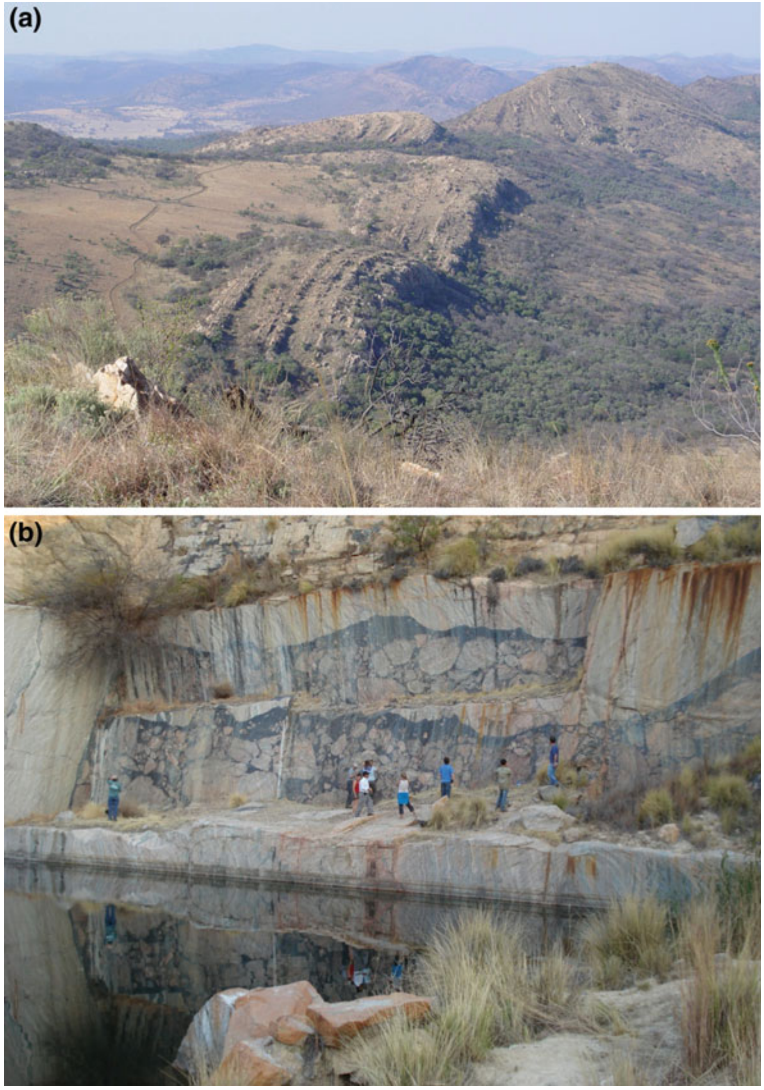

Fig. 4.3 **a** View to the east along the inner collar of the Dome, showing the upturned and strongly disrupted quartzite layers of the lower Witwatersrand Supergroup. Dips are generally steep, and directed towards the centre of the Dome (*right*). **b** Large pseudotachylitic breccia dyke in granite from Leeukop Quarry. The *dark grey* matrix is recrystallised melt. It contains fragments of varying sizes derived from the adjacent wallrocks (*Photographs* R Gibson)

original magnitude of the Vredefort impact event and diameter of the crater is unlikely to ever be fully resolved (Gibson and Reimold 2008).

The region contains little evidence of geological activity for almost 1,700 Ma following the impact, until the formation of the Karoo basin. The exceptions are narrow dykes of intrusive granite in the northern collar related to the 1,250 Ma Pilanesberg volcanic complex (see Chap. 5) and a large 1,100 Ma (Reimold et al. 2000) gabbro sill, up to 100 m thick, that is exposed along the Vaal River upstream of Parys. It is likely that the exhumation of the Dome was sporadic in the 2,000 Ma since the crater formed and that periods of erosion were punctuated by periods of burial beneath younger, now vanished, sedimentary sequences.

4.3 Landscape of the Vredefort Dome

The Vredefort Dome is only partially exposed: its southern half is largely covered by a thin veneer of Karoo Supergroup sediments, minor volcanic layers and dolerite, for the most part no more than a few tens of metres thick. What many people mistake for the edge of the Dome is, in fact, the outer edge of the Vredefort Mountainland, which lies between 20 and 30 km from the centre of the Dome, whereas the geological limit—defined as the distance at which the pre-impact sedimentary and volcanic rock layers show no clear structural disturbance or rotation to steeper orientations that can be attributed to the impact—lies 40–45 km from the centre (Potchefstroom Syncline in Fig. 4.1), corresponding to the approximate trace of the Mooi River (Figs. 4.1 and 4.4). Comparison with the well-preserved craters on the Moon and other planets suggests that the original Vredefort crater would have been between 2 and 4 times this diameter, i.e., between 180 and 360 km wide. A 250–300 km diameter is typically favoured, although no direct evidence of the crater margins remains today.

Processed SRTM (Shuttle Radar Tomography Mission) images (e.g. Fig. 4.4) illustrate the contrasting landscapes in the Dome. The core of the Dome is dominated by gently rolling topography at an elevation of approximately 1,410–1,430 m a.s.l., but rising to 1,540 m a.s.l. northeastwards and westwards towards the collar. Topographic relief is more subdued away from the Vaal River towards the south. A few small dome-shaped hills exposing the granite bedrock rise up to 30 m above their surroundings. The Inlandsee Pan, a shallow ephemeral lake, is a well-known local feature formed in a topographic depression 1.5 × 2.5 km wide, at 1,406 m a.s.l.

The Vredefort Mountainland (Afrikaans: *Bergland*), *sensu stricto*, corresponds to the inner and middle parts of the geological collar that lie between 20 and 30 km from the centre of the Dome. The highest point in the inner collar lies at Thwane (1,658 m a.s.l.) in the west-northwestern collar, where the most rugged topography (~150 m vertical relief) is also found; however, the highest point overall (1,676 m a.s.l.) lies north of the Vaal River in the northern collar. Towards the southwest and southeast both the maximum elevation and relief diminish, before the rocks disappear beneath the Karoo rocks.

In contrast to the Witwatersrand region, the ridges of the Mountainland are highly disjointed and, in places, sinuous as a conseqence of fault displacements and buckling caused by stresses during Dome formation (Fig. 4.3a). All ridges

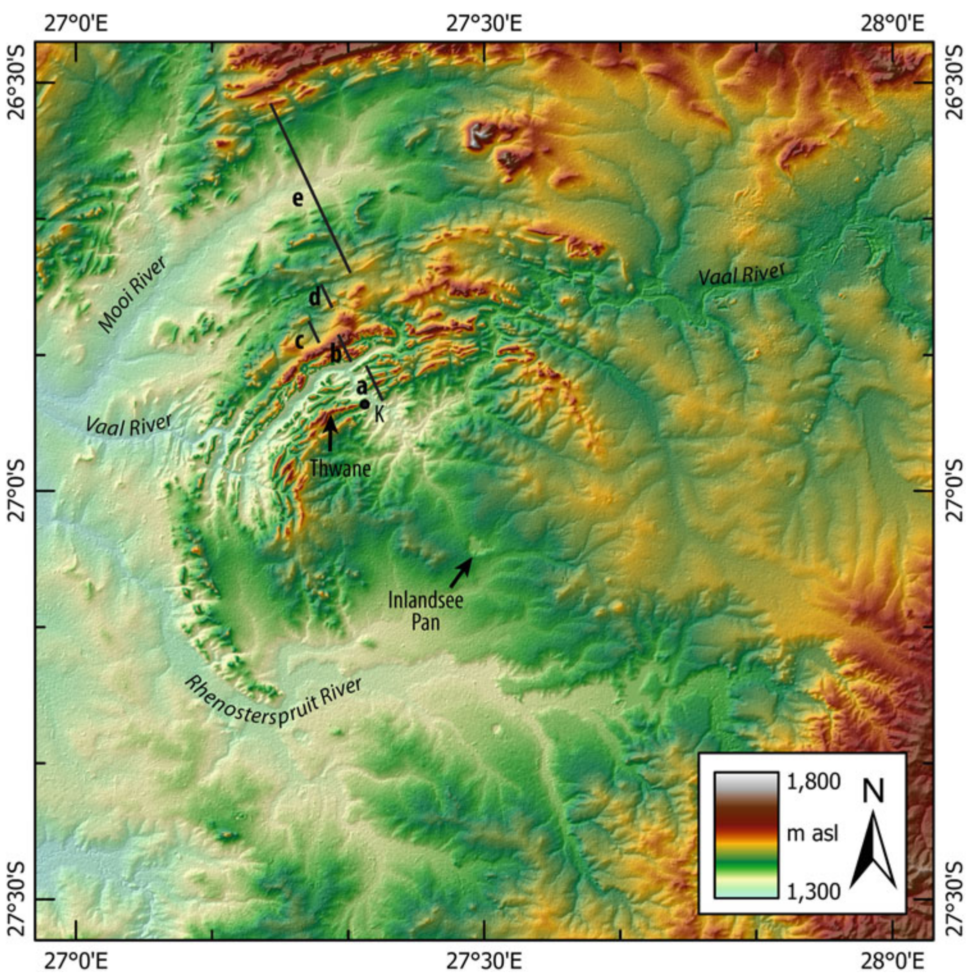

Fig. 4.4 Digital elevation map of the Vredefort Dome from SRTM data (Courtesy M. Rowberry). The image shows the disruption of the normal dendritic drainage pattern of the Vaal River (in the northeast) and Rhenosterspruit River (in the south) by the Dome. The 5 topographic zones (*a–e*) in the collar of the dome and surrounding Potchefstroom Syncline are shown (*K* = Kommandonek)

Fig. 4.5 View towards the northeast along the Venterskroon valley showing a *U-shaped* profile reminiscent of glacial erosion. A small portion of the Vaal River floodplain is seen at *centre-right* (*Photograph* R Gibson)

correspond to outcrops of quartzite, whereas the valleys correspond to meta-shale, meta-basalt and/or meta-dolerite rocks that are more susceptible to chemical weathering. The relative proportions of these rocks play a major role in the type of topography in different parts of the Mountainland, with 5 concentric zones being identifiable beyond the core (Figs. 4.1, 4.2 and 4.4):

(a) the inner collar (lower Witwatersrand Supergroup and Dominion Group), which comprises mostly meta-shale, ironstone, basalt and dolerite sills, with numerous subsidiary thin quartzite bands up to 50 m thick, is marked by sharply-defined ridges of white quartzite and narrow, steep-sided valleys, with the steepest slopes (in places >45°) directed inward;

(b) the much more homogeneous upper Witwatersrand Supergroup, which is predominantly quartzite with a single meta-shale layer, gives rise to a 3–4 km wide zone of extremely rugged topography cut by narrow gorges that exploit faults or major fractures that cut across the strike of the rocks;

(c) the meta-basalt lavas of the Ventersdorp Supergroup have a much more subdued topography, with their weathering resulting in deep, fertile, soils and scattered, broad, rounded hills, rather than ridges;

(d) the dolomite of the lower Transvaal Supergroup (Chuniespoort Group) is poorly exposed, except where it has been impregnated with more resistant chert that gives rise to rubbly linear outcrops; this terrain is characterised by relatively flat topography known for its sinkholes, caves and water springs, which gives the region its name—*Gatsrand*; and

(e) the upper Transvaal Supergroup (Pretoria Group), which straddles the outer limits of the Dome and contains a similar mix of lithologies to that of the lower Witwatersrand Supergroup. Large-scale basinal folding (seen in the curved and sinuous ridges in Fig. 4.4) obscures the concentric arrangement of the layers around the Dome.

4.4 Fluvial Landforms

The Vredefort Dome preserves highly diverse fluvial patterns (Fig. 4.4) that are dominated, but not exclusively controlled, by the Vaal River. The Vaal River has an average gradient that drops ~ 1 m every 1.5 km across the Dome, but is characterised by a series of local base levels marked by small rapids formed in resistant rocks.

At the macroscale (Fig. 4.1), the Vaal River has a strongly meandering character, despite being incised between 10 and 30 m below its banks. This is consistent with an inherited drainage pattern and explains why the river flows first into and then back out of the Vredefort Mountainland. Despite this, its present path across the Dome is strongly controlled by underlying geology, in this case radial faults related to the impact that cut and displace the collar strata in the northeast, northwest and west, and a concentric foliation in the core gneisses near Parys. Downstream of Kommandonek its northwestward flow across the strata of the inner collar is sharply deflected by the buttress of the Upper Witwatersrand Supergroup and it turns southwestward, parallel to the concentric strike of the collar strata, before exploiting a second fault on the western side of the Dome (Fig. 4.4). The influence of the foliation and fault-related fractures can be seen in the anabranching phenomenon around and downstream of Parys, where the river branches into numerous small linear channels cut into the bedrock.

Tributary rivers and streams in the Dome are ephemeral, although many retain small bodies of standing water throughout the year. Overall, the drainage pattern in the *core* of the Dome is dendritic (Fig. 4.4). Many of the streams in the core of the Dome show strongly sinuous meander characteristics in narrow (usually <100 m wide, but up to 250 m wide in places) marshy ('wetland') overbank areas into which renewed gully incision by up to 2 m has occurred.

The *inner collar* (zones a and b in Fig. 4.4) is dominated by ephemeral streams flowing parallel to the strike of the geological layers and with lower sinuosity than those in the core of the Dome. They are typically incised 3–4 m into thick colluvial deposits containing thin boulder and cobble horizons that locally display a duricrust. In the quartzite-dominated upper Witwatersrand Supergroup (zone b in Fig. 4.4), drainage occurs in linear, narrow, steep-sided, V-shaped valleys and gorges up to several tens of metres deep that are oriented at high angles to the layering and that exploit impact-induced fractures and faults.

Beyond *the Mountainland* at a radial distance of >30 km from the centre of the Dome (zones c, d and e in Fig. 4.4), streams flow either directly into the Vaal (east of the Dome) or into the Rhenosterspruit (south and west) or Mooi River (north), with the latter's course displaying significant geological control.

Between Parys and Kommandonek where it re-enters the collar, the Vaal River exhibits a 7.5 km northwest-flowing reach characterised by significant anabranching, induced by fault-related fractures in the bedrock gneiss and metasedimentary rocks. Midway along this reach, the northeast bank of the river comprises a granite pavement containing large potholes 2–3 m in diameter and over 1.5 m deep. The pavement also displays polish and striations consistent with sand abrasion related to strong northwesterly palaeowinds. The latter may be related to arid climatic conditions that also deposited a small dune field alongside the Vaal River in the northeastern part of the Dome (Fig. 4.1).

4.5 Landforms Likely Associated with Glaciation

In the Dome, the smooth, bare and slightly elongated dome-shaped granite hills of the core locally preserve striations, interpreted as gouges caused by rock fragments being carried in moving ice during the Permian Dwyka glaciations and are, thus, interpreted as glacial features. A large boulder of Witwatersrand Supergroup quartzite several metres across was reported by R.J. Hart (personal communication, 1978) during drilling near the Inlandsee Pan, at least 15 km from the nearest quartzite outcrop, pointing to ice as the likely transport mechanism. The pan itself may be a scooped-out glacial erosion feature. The domical granite hills display limited evidence of exfoliation joints, but the preservation of glacial striae on some surfaces suggests that this is not a particularly intense phenomenon. The Venterskroon valley currently being exploited by the Vaal River has a U-shaped profile consistent with glacial erosion (Fig. 4.5).

4.6 Landscape and Human Dynamics

The Vredefort Dome area contains evidence of human settlement extending back at least several thousand years (e.g. stone tools, rock engravings; Reimold and Gibson 2010) and includes traces of significant settlements from the Late Iron Age up to the early nineteenth century. Human impacts on the regional landscape include gold mining in the collar rocks during the late nineteenth and early twentieth centuries, alluvial diamond diggings along the Vaal River, and quarrying for granite dimension stone in the latter part of the 20th century. Whilst not strictly linked to the Dome itself, South Africa's largest bentonite clay deposits are mined from Karoo rocks overlying the Dome in the south.

In the modern era, a renewed threat of gold mining, using open-cast methods, in the mid-1990s, led local landowners to petition Government for Conservancy status that, ultimately, led to the proposal to declare a portion of the Dome a World Heritage Site. Subsequently, in 2005, a 30,000 ha portion of the Vredefort Dome, extending northwestwards from Vredefort and Parys (Fig. 4.2) was inscribed as a UNESCO World Heritage Site, principally in acknowledgement of its global geological significance as the location of the world's largest and oldest confirmed meteorite impact.

Today, the only continuing mining activity in the Dome area is for sand and bentonite. Large areas are now devoted to private game farms that have restocked the area's wildlife, and to eco- and adventure tourism. Judicious use of the region's resources, particularly in the light of the influx of tourists, is the subject of much discussion, and is complicated by jurisdictional issues between two provinces, four municipalities, and the World Heritage Site Management Authority. Of particular concern is the water quality of the Vaal River, which is affected by activities within the Dome area but most notably from the mining and industrial activities upstream. The World Heritage status has assisted with some projects, such as the clearing of alien vegetation from parts of the Vaal River and upgrading of road infrastructure.

4.7 Summary

The geomorphological evolution of the Vredefort Dome provides snapshots of environmental changes in southern Africa extending back 300 Ma. The present erosion cycle is exhuming an older (Permian) glacial landscape that appears to have been little modified by Mesozoic and Cenozoic erosion related to the Vaal River (Fig. 4.5). Pothole evidence suggests that the Vaal River was once considerably larger than at present; however, sand dunes and sand-blasted rock pavements also indicate that considerably drier conditions prevailed even more recently. Whilst the latter is consistent with increased aridity during cold phases of the Quaternary, it is not clear if the former indicates the waning stages of a humid, tropical climate cycle that dominated in southern Africa for much of the Cretaceous Period, or whether it could be Cenozoic in age. Renewed incision of all rivers in the Dome may reflect the strong Cenozoic uplift within the last 20 Ma, particularly since 5 Ma; however, local river base level migration is also likely to be a contributing factor on a more local scale.

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