



The Tsodilo Hills: A Multifaceted World Heritage Site

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Abstract

The Tsodilo Hills are a cluster of three inselbergs rising up over 400 m above the Kalahari Desert in the Ngamiland, NW Botswana, to the west of the Okavango swamps. The exposed succession consists of metamorphosed siliciclastic sedimentary rocks deposited on a marine shelf at a margin of the Congo Craton between ca. 1.90 and 1.1 Ga. The sediments formed a Gilbert-type delta grading towards the open shelf covered with large underwater dunes and influenced by tidal currents. The rocks contain specularite, which was mined and traded throughout Southern Africa from the Late Stone Age up to the nineteenth century. The creativity and culture of the local communities is reflected by over 4000 rock paintings and engravings. A permanent lake, up to 7 m deep, existed between 27,000 and 12,000 years ago adjacent to the hills. The geomorphic features of the Tsodilo Hills document processes of both the physical and chemical modifications of the rocks. Two geological-timescale erosional cycles sculpted the area: (i) continental Dwyka glaciation (the Carboniferous-Permian) when Tsodilo Hills formed nunataks, and (ii) post-Karoo formation of African Surface (the late Cretaceous). Steep slopes of Tsodilo Hills show stepped morphology and some cliffs have flared sides. Silica solution resulted in localised arenisation and karst-like features including phreatic zone-related subartesian well, and vadose zone vertical shaft, horizontal tube and karren.

Keywords

Botswana • Damara Belt • Palaeoproterozoic • Siliciclastic shelf • Geomorphic features • Ancient mining

20.1 Introduction

The Tsodilo Hills form a cluster of inselbergs (Fig. 20.1) located in the north-western corner of the Ngamiland District of Botswana, about 40 km to the west of the Okavango River and rising dramatically by ca. 400 m above a relatively monotonous expanse of the Kalahari Desert (Fig. 20.2). The Tsodilo rock succession is of the Palaeoproterozoic age, whereas the surrounding Kalahari sedimentary cover has been formed and evolving from the Cretaceous to Recent. Exposures of rocks older than the young Kalahari sediments are extremely rare in the region, and therefore the Tsodilo Hills form a unique “window” providing direct access to the ancient strata that belong to the basement complex underlying north-west Botswana.

The exceptional character of the Hills is also reflected by the long human history. This is documented by a staggering world-class collection of over 4,000 rock paintings, prehistoric specularite mining and archaeological discoveries, which testify to the human occupation, evolution of the way of life, work, crafts and arts that started with the first settlers who arrived there in the Middle Stone Age about 100 thousand years ago (Campbell and Robbins 2010). Importantly, the Hills continue to play an important role in the spiritual traditions of the San people. Considering all these unique aspects, the Tsodilo Hills have been inscribed as UNESCO World Heritage Site (International Council on Monuments and Sites (ICOMOS) 2001; Botswana National Museum 2000) and the National Museum of Botswana Complex at Tsodilo was opened by the then President of the Republic, His Excellency Festus Mogae in 2001. Readers

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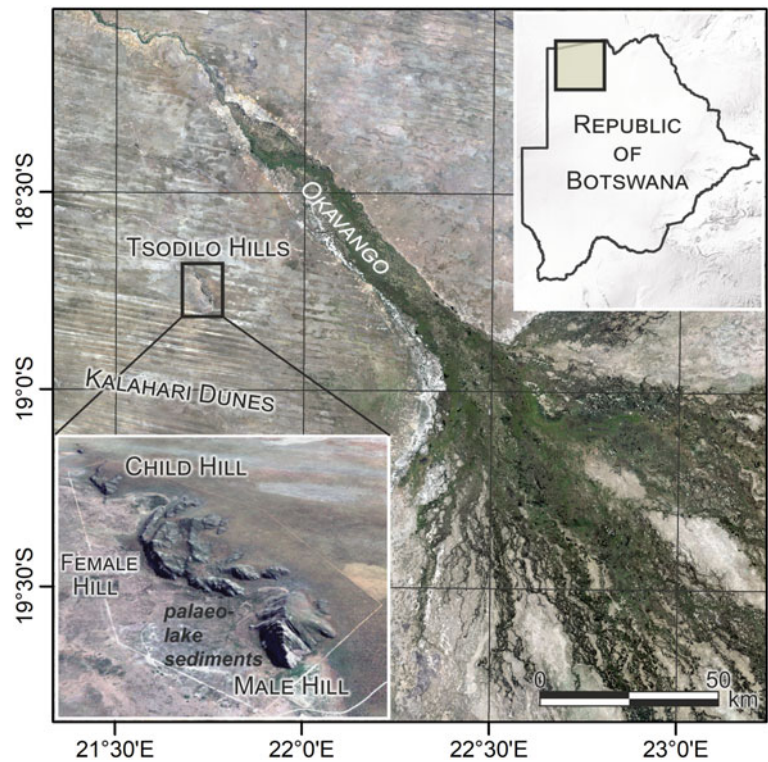
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Fig. 20.1 Low-level aerial photograph showing the Tsodilo inselbergs rising above the expanse of the Kalahari Desert seen from the ESE (Photograph courtesy Els Slots, with permission; all subsequent photographs in this chapter are by Marek Wendorff)

Fig. 20.2 Position of the Tsodilo Hills relative to the Okavango River in NW Botswana (Landsat 8 natural colours composition). Relict seif dunes of the Kalahari Beds are visible on the satellite image as parallel stripes oriented WNW-ESE. Wind shadow devoid of dunes extends to W of the Hills. Inset shows oblique view of the three Hills seen from SW (Sentinel 2 natural colours composition)



interested in details of the rock art, archaeology and historical aspects of human activity are directed to the excellent richly illustrated compendium edited and co-authored by Campbell et al. (2010). Highlights of the Tsodilo Hills appear in a volume published on the occasion of the 35th International Geological Congress, which presents fascinating geological sites of Africa (de Wit and Main 2016).

The aim of this chapter is to summarise the recent state of knowledge of the geological makeup of the Tsodilo Hills, with emphasis on features of their metamorphosed sedimentary rocks, which preserve a multitude of primary sedimentary structures and textures. These characteristics document the processes of deposition, their evolution in time and space, and therefore provide insights into the palaeo-landscape and sedimentary environments in which Tsodilo Hills strata were formed. A brief discussion of geomorphic features and relations is followed by a summary of the ancient mining and rock art enclosed to emphasise the extent to which the geological resources combined with a period of hospitable climate influenced the ancient industry, economic activity, creativity and culture.

20.2 Environmental Setting

The Tsodilo Hills represent a morphological feature unique to the landscape of NW Botswana. Steep slopes and precipitous cliffs of the inselbergs expose a succession of resistant to weathering metamorphosed sedimentary rocks of the Proterozoic age. By contrast, the surrounding relatively monotonous landscape of the Kalahari Desert is underlain by Cretaceous-to-Recent in age Kalahari sediments.

Three main hills of the Tsodilo cluster are called Nxum Ngxo (Male), Nxum Di (Female) and Picannin (Child) in the local San People language and occupy an area of about 3×10 kms. Male Hill is the highest peak rising 1,395 m a.s.l. and about 420 m above the surrounding Kalahari Desert, which extends at an elevation of ca 1000 m a.s.l. (Fig. 20.1). Female Hill occupies an area almost three times broader and the highest of its several peaks rises about 300 m above the surrounding plains. Child Hill, 1.7 km north of Male, is only 40 m high. About 2.1 km to the north-west lies a very small hill, called Grandchild.

Geologically, the Tsodilo Hills lie in the Damara Belt—one of the arms of the Pan-African system of several Neoproterozoic orogenic belts that traverse the African continent. The Damara Belt extends from Namibia in the southwest, crosses northwest Botswana and southern Angola, and continues to Zambia and the DRC to the northeast, where it is known as the Lufilian Arc, or the Katanga Belt (Fig. 20.3). These two orogenic segments are the erosional remnants of a large mountain belt that resulted from a continental collision between the Kalahari Craton in

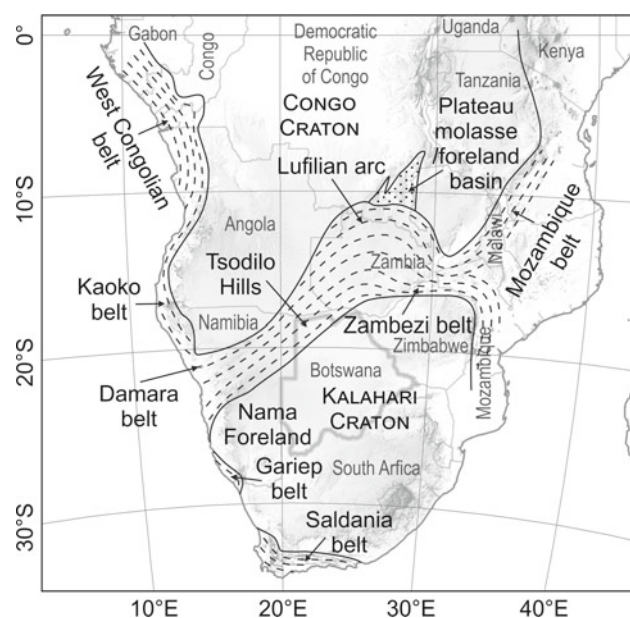


Fig. 20.3 Regional position of the Tsodilo Hills in the framework of the Neoproterozoic-Lower Palaeozoic Pan-African belts and cratons of Central and Southern Africa

the south and the Congo Craton in the north at the time of assembly of the Gondwana Supercontinent, at the turn of the Precambrian and Palaeozoic eras (Rogers et al. 1995; Unrug 1996).

The surrounding Kalahari Group sediments rest directly upon the Proterozoic basement rocks and attain a maximum thickness in excess of 300 m in the Okavango graben to the east of the Tsodilo Hills (Fig. 20.2). Regionally, the Kalahari strata are formed by laterally and vertically variable facies of continental deposits: gravels and conglomerates, sands and sandstones, marls, evaporites, as well as duricrusts - calcrete, silcrete and ferricrete (Thomas and Shaw 1991). These are covered by now inactive, partly degraded and vegetated linear dunes, which rise up to 25 m in height, are usually spaced 1–2.5 km apart and constitute the predominant landscape feature surrounding Tsodilo Hills (Carney et al. 1994; Thomas and Shaw 1991). The linear dune sands of the north-west Ngamiland rest directly upon the Precambrian basement units (McFarlane et al. 2005, 2010; McFarlane and Eckardt 2006), which contrasts with central Botswana where they are underlain by the Karoo Supergroup strata spanning Carboniferous/Permian to Late Triassic Periods (Carney et al. 1994; Key and Ayers 2000).

The Tsodilo Hills presently have a semi-arid climate. However, the sedimentary record of a palaeolake adjacent to the Hills and archaeological research document much wetter periods, which are discussed later. The annual average rainfall can reach about 560 mm; November to March are the wettest months, with January's maximum of 134.9 mm. The dry period extends from April to October, with the driest

June–July (0 mm). The average monthly temperature varies very widely from a maximum of over 30 °C during the day between September and April (34.3 °C in November) to 26.0 °C in July (Botswana National Museum 2000), and may fall down to below freezing point in the winter period (Brook 2010).

20.3 Geology of the Tsodilo Hills

20.3.1 Lithology, Stratigraphic Position and Age

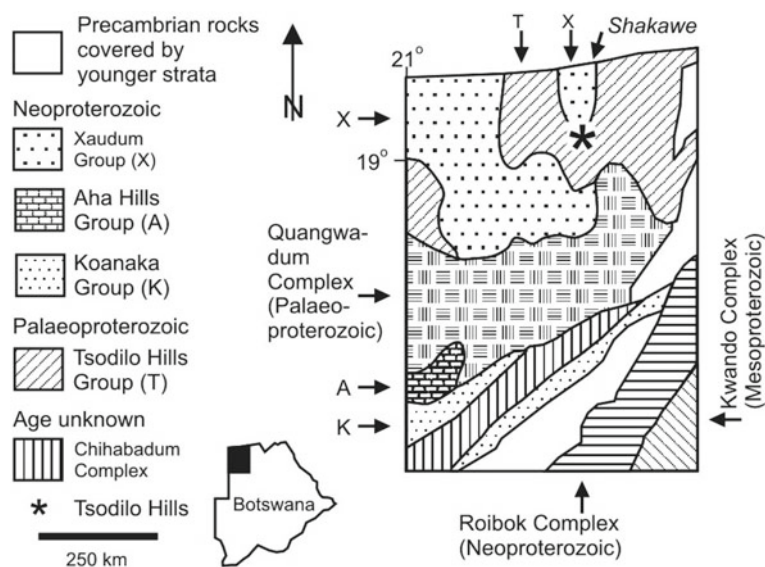
In the earliest, unpublished accounts, the Tsodilo Hills metasedimentary rocks were described as an association of “micaceous schist, quartz-rich layers, grits and pebbly beds” by Wright (1956) and subdivided into four units called “stages” by Vermaak (1962). Both authors noted the occurrences of muscovite, kyanite, hematite, tourmaline and dumortierite as an assemblage of accessory minerals. The succession was named ‘the Tsodilo Hills Group’ by Key and Ayers (2000), who suggested its Mesoproterozoic age. Subsequently, Wendorff (2005) presented preliminary observations on sedimentary features, facies trends, palaeocurrent patterns, mineral composition and metamorphism and suggested a Neoproterozoic age on the basis of regional position and lithological similarities with some Damara units in Namibia. Most recently published accounts presented a map and lithostratigraphic classification of the mappable rock sub-units (Wendorff and Świąder 2019) and age determinations by zircon geochronology (Mapeo et al. 2019).

Stratigraphically, the Tsodilo Hills Group metasedimentary strata rest non-conformably on the Quangwadum Basement Complex (Fig. 20.4) composed of granitoids and

granite-gneisses, which originated between 2031 ± 1 Ma (Singletary et al. 2003) and 2024 ± 3.3 Ma (Mapeo et al. 2019). According to the most recent latter study, the spectrum of ages obtained on detrital zircons from the Tsodilo Hills Group rocks, and their comparison with ages of other rock units in the region, implies that deposition of the Tsodilo sedimentary succession occurred between approximately 1.90 and 1.1 Ga, i.e. during the youngest divisions of the Palaeoproterozoic–Mesoproterozoic. Hence, in spite of their occurrence within the Neoproterozoic Damara orogenic belt, the Tsodilo Hills Group strata are older and represent an exotic element of the unclear tectonic position. These rocks were involved in the Pan-African orogenic movements, which is testified by the $40\text{Ar}/39\text{Ar}$ age of 490 ± 2.3 Ma on metamorphic muscovite from Tsodilo Hills interpreted as the cooling age after regional metamorphism related to the Damara Belt orogeny (Singletary et al. 2003). Therefore, the non-conformable stratigraphic relation with the Quangwadum Complex and spectrum of numerical ages imply that the Tsodilo succession formed as a part of sedimentary cover of the Congo Craton, was first deformed during the Eburnean orogenesis (Mapeo et al. 2019) and then involved with the Neoproterozoic Pan-African orogenic movements. The Late Palaeoproterozoic–Mesoproterozoic depositional age of these rocks also shows that they are age-equivalent to a.o. the Muva Group in the basement of the Neoproterozoic Lufilian Belt succession of Zambia (Mapeo et al. 2019).

The Tsodilo Hills Group rocks are terrigenous detrital sedimentary rocks affected by low-grade metamorphism. The succession is dominated by micaceous and non-micaceous quartzites and contains quartz-mica schists, subordinate layers of meta-sandstones and meta-conglomerates, interbeds of meta-pelites and a red-bed-type association of siltstone, sandstone, mudstone and sedimentary breccia (Wendorff

Fig. 20.4 Precambrian units in NW Botswana (modified from Carney et al. 1994; Key and Mothibi 1999; Key and Ayers 2000; Singletary et al. 2003; Wendorff 2005). Tsodilo strata age updated after Mapeo et al. (2019)



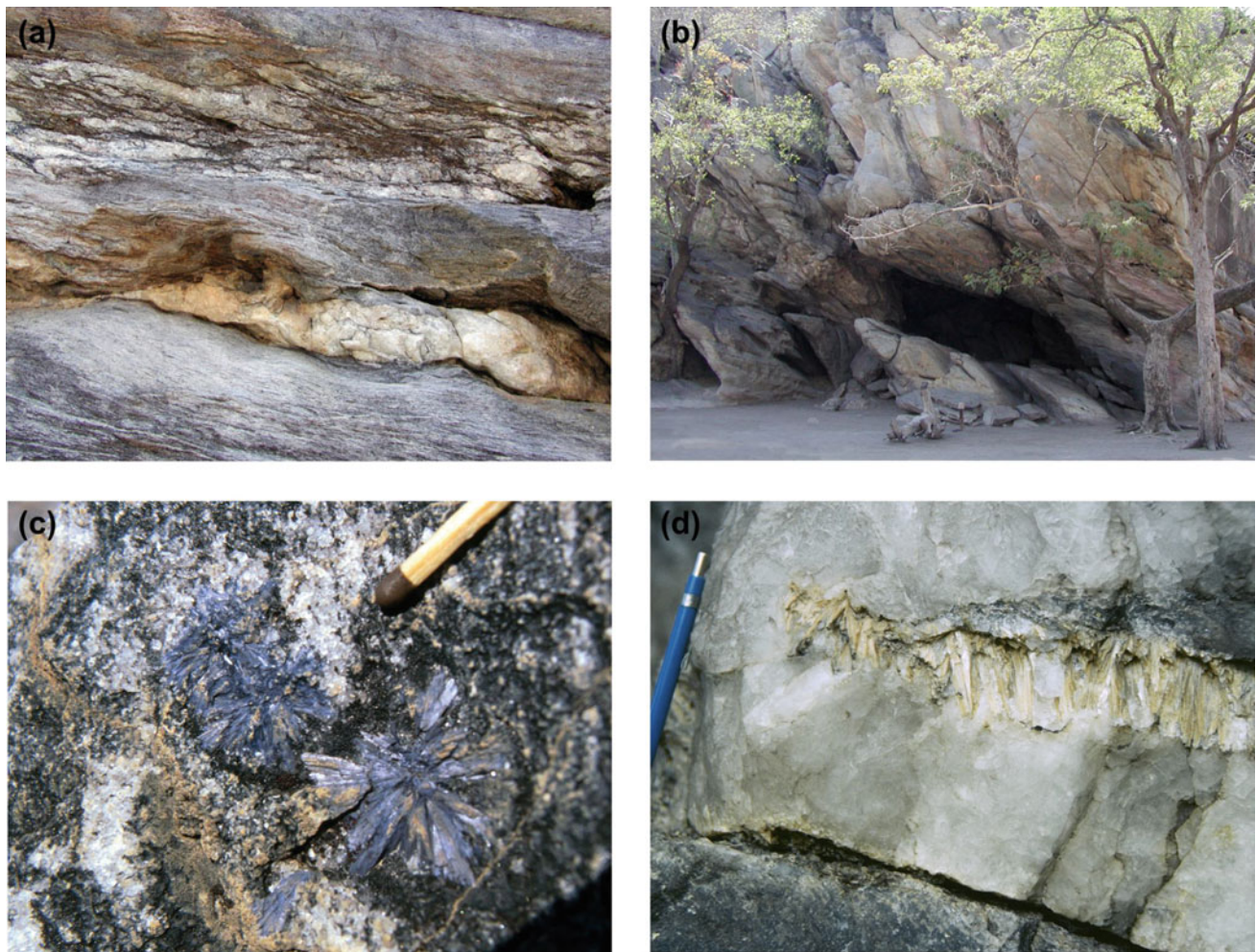


Fig. 20.5 Examples of mineral occurrences in Tsodilo Hills. **a** Quartz vein, ca. 30 cm thick, within sheared micaceous schist; **b** Entrance to Greenstone Mine, S cliff of Female Hill; **c** Two rosettes of dumortierite, tip of matchstick for scale; **d** Kyanite vein in the middle of quartz vein

2005). The succession contains a variety of accessory minerals: disseminated chlorite, ilmenite, titaniferous magnetite, titanite, hematite/specular hematite, tourmaline, biotite and dumortierite. The rock foliation is defined by the metamorphic minerals—muscovite and kyanite and some veins are filled with dumortierite or kyanite (Mapeo et al. 2019; Vermaak 1961, 1962; Wendorff 2005; Wright 1956) (Fig. 20.5).

Tsodilo quartzites/meta-arenites are light to medium grey and composed of usually well-sorted quartz grains cemented with silica. Recrystallisation of the cement ranges from moderate to very intense when the rock attains a glassy appearance and quartz overgrowths observed under polarising microscope show polygonal boundaries. The absence of both clay matrix and clay particles on arenite grains suggests deposition of quartzose sand in highly agitated waters responsible for removal of fine detritus. The mineral composition and very good sorting classify these rocks as super mature meta-arenites. This, coupled with sedimentary facies and bimodal-bipolar (bidirectional) palaeocurrents

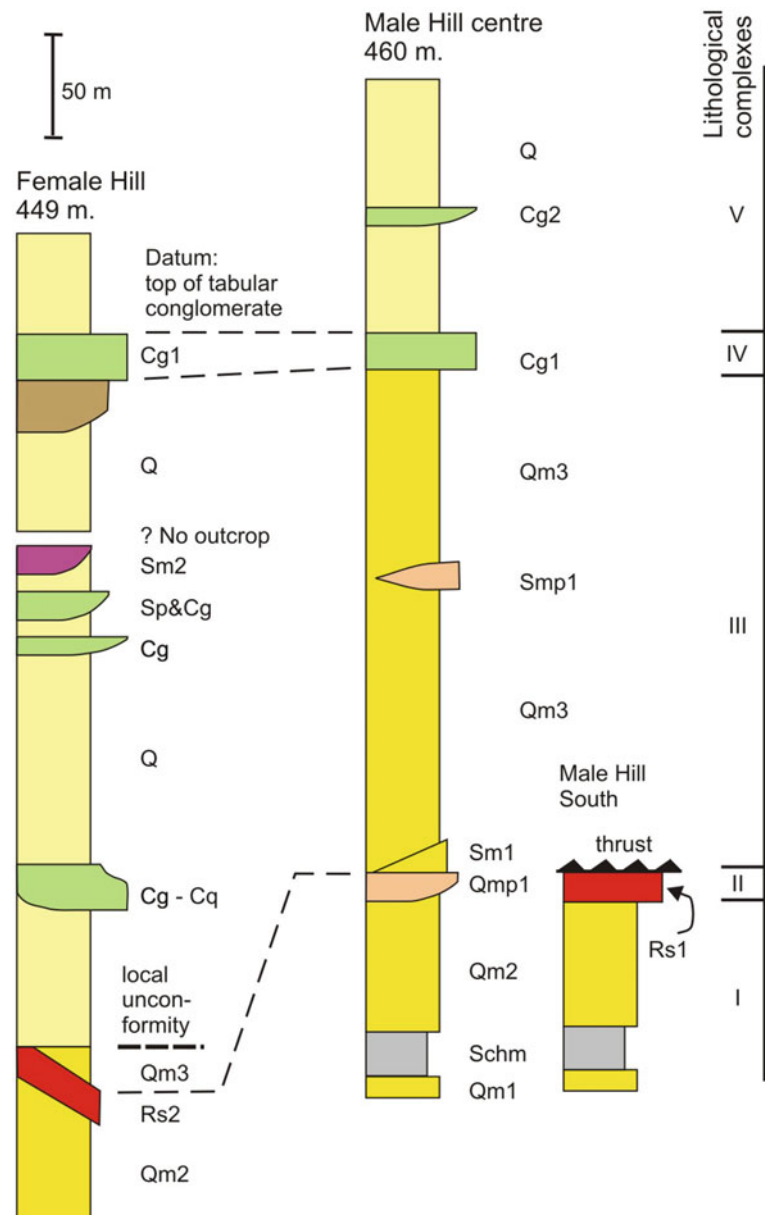
system recorded in the Tsodilo Hills Group suggest deposition and intense reworking and abrasion of arenaceous sediments on an open continental shelf under the combined influence of tidal currents and longshore littoral drift (Wendorff 2005).

The Tsodilo rock succession is deformed by several thrust faults and many shear zones, locally several metres thick, commonly indicating the direction of thrusting towards the southwest. Importantly, the deformations that would totally obliterate the primary features of meta-sandstones are not ubiquitous, and therefore intact primary sedimentary structures occur in abundance recording the sedimentary processes that shaped the Tsodilo Group strata.

20.3.2 Rock Complexes of the Tsodilo Hills

Lithostratigraphy, geographical distribution and correlation of the rock successions outcropping in the Male and Female

Fig. 20.6 Lithostratigraphic columns of the Tsodilo Hills Group strata exposed in Tsodilo Hills constructed along cross-section lines A-B for Male Hill and C-D for Female Hill shown in the geological map (Fig. 20.7)



Hills (Wendorff 2005; Wendorff and Świąder 2019) has been re-examined most recently and is presented here in a generalised form. The sequence is subdivided into five major, lithologically distinct complexes labelled I-V (Fig. 20.6). Their extent can be traced, or outcrops correlated, through the whole area of the Male and Female Hills (Fig. 20.7). Each complex is characterised by the predominant lithology or lithological association, as well as sedimentary structures and stratigraphic position in the succession. The features of some complexes show lateral variations and the prominent units contain mappable lenticular or wedge-shaped interlayers of different rock types. Some non-mappable occurrences are mentioned in the descriptions that follow, which

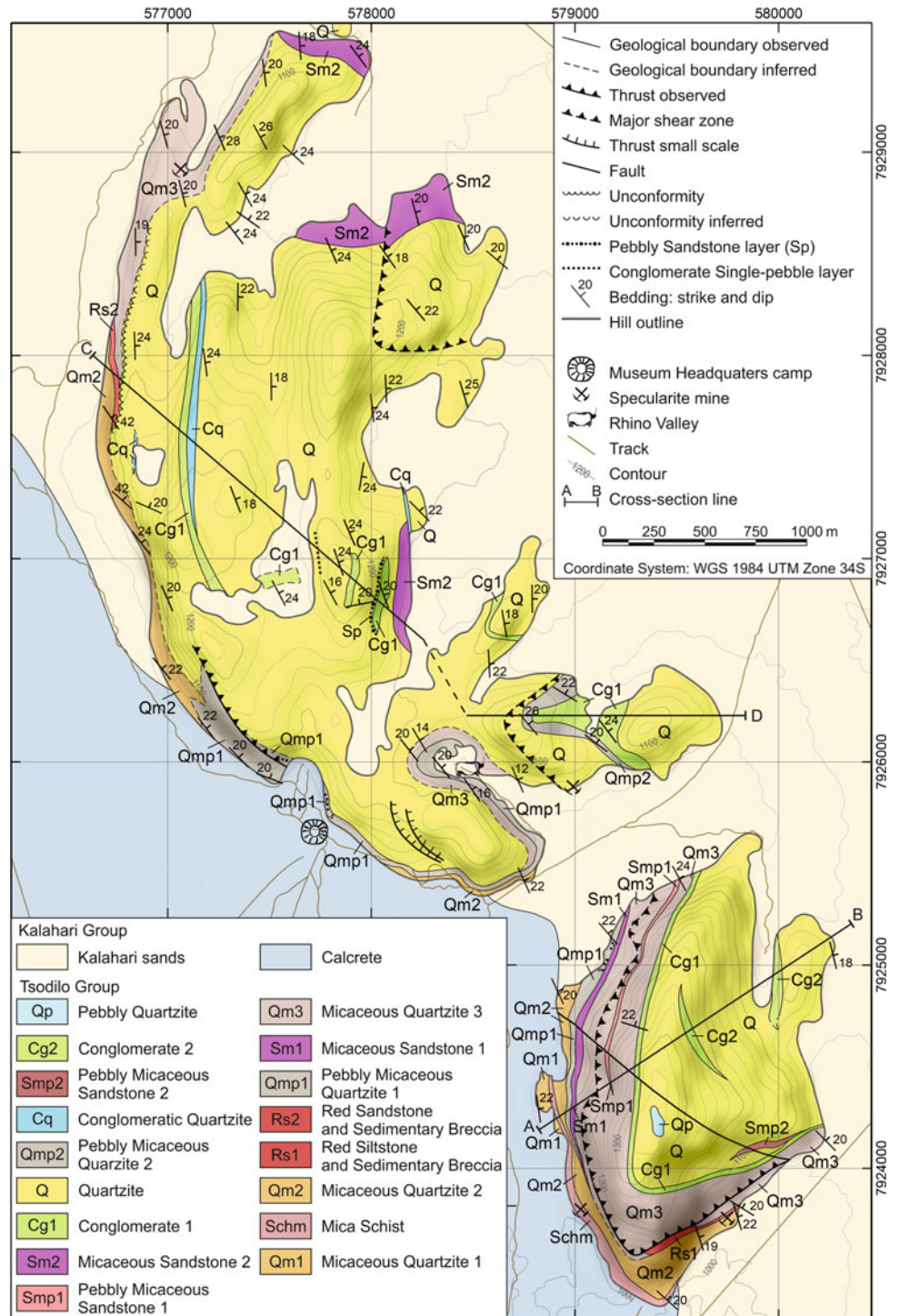
summarise the features observed on both hills and outline their lateral variations with reference to Figs. 20.5 and 20.6.

Lithological complex I

Emerging from underneath the Kalahari Beds is ca. 90-m-thick oldest part (I) of the Tsodilo Hills Group succession. It is exposed in the lowermost slopes of the Male and Female Hills and consists of micaceous quartzite units Qm1 and Qm2 separated by an interlayer of micaceous schists Schm and terminating with pebbly micaceous quartzite.

The quartzites are coarse- to fine-grained and enriched in dark heavy minerals; high content of muscovite in the Male

Fig. 20.7 Geological map of the Tsodilo Hills (from Wendorff and Świąder 2019)

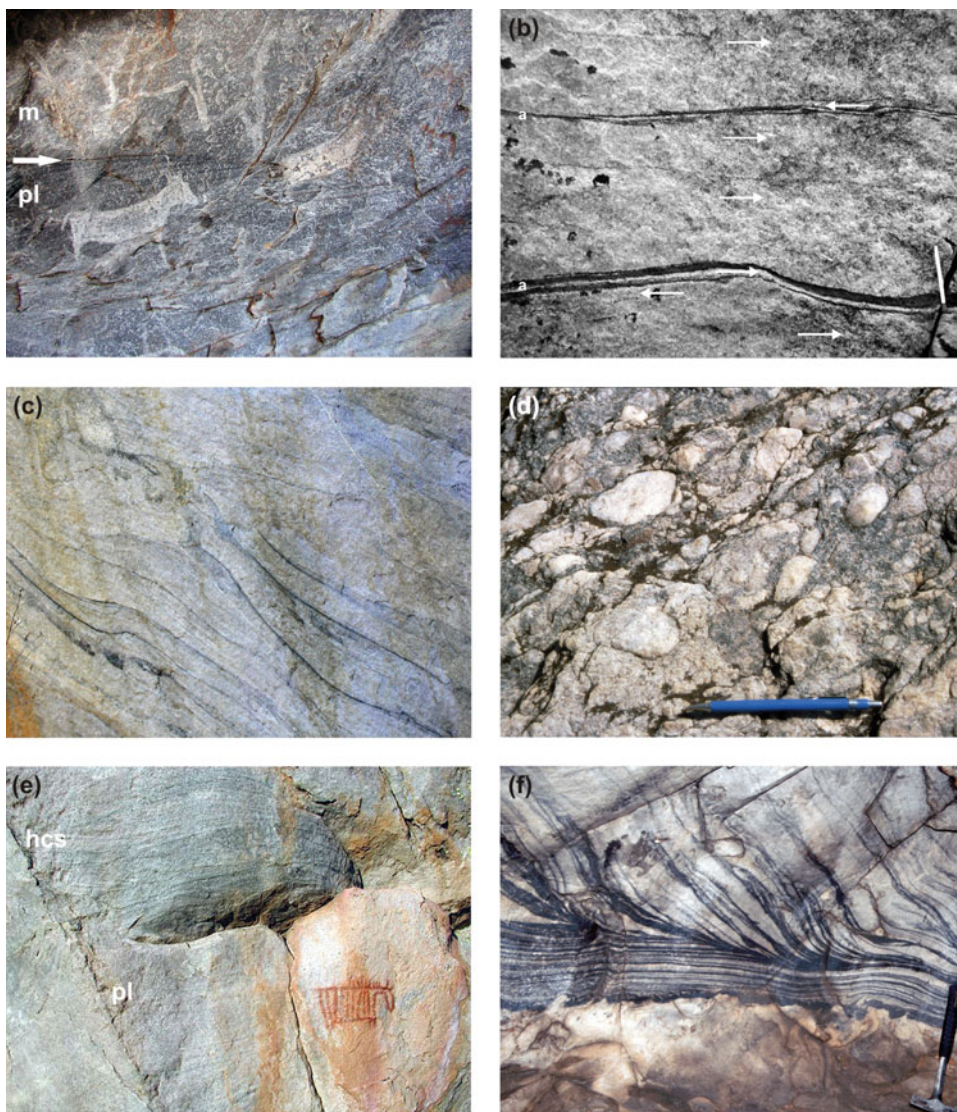


Hill decreases northwards through the Female Hill. Sedimentary structures are dominated by various types of cross-bedding occasionally associated with subordinate parallel-bedded layers (Fig. 20.8a). The cross-bedding is represented by low angle, swash-type and small to medium-scale tabular and trough cross-bedded sets, which often show alternating palaeocurrent directions towards the

NW and the SE, contain reactivation surfaces and mud drapes (Fig. 20.8b). Large-scale cross-bedded units exceed 2 m in thickness, often contain normally graded foreset layers terminating with mud-drapes, and are occasionally deformed by slumping (Fig. 20.8c). The micaceous schist Schm forms a flat elongated lens maximum 20 m thick, present only in the Male Hill slopes between Qm1 and Qm2.

Fig. 20.8 Examples of sedimentary features of quartzites, meta-sandstones/arenites and meta-conglomerates exposed in Tsodilo Hills.

a Parallel-lamination truncated by an erosional incision (arrowed) filled with massive quartzite (m); white paintings adorn the rock face (Snake Mine, Female Hill); **b** Small current ripplemarks showing two opposite current directions (arrowed) and interlayered with two couplets of mud drapes (black) typical for tidally-influenced environment (matchstick for scale); **c** Circa 2 m thick set of very large-scale cross-bedding composed of meta-arenite beds about 10 cm thick separated by black mudstone drapes and deformed by small slumps; **d** Massive conglomerate with cobbles and pebbles embedded in quartz arenite/quartzite matrix. **e** Hummocky cross stratification (hcs) overlying parallel and low angle cross-bedded set (pl) with red rock painting of zebra ca. 20 cm high; **f** Parallel lamination followed by large-scale cross bedding of quartz arenite/ quartzite containing dark laminae of specularite



The rock is grey in colour, contains a high proportion of muscovite and shows well-developed foliation. This layer is absent in the Female Hill outcrop probably due to facies pinch-out.

The pebbly micaceous quartzite Qmp1 has a limited lateral continuity. It wedges out southward along the western slope of the Male Hill, whereas in the south-western part of the Female Hill passes towards the north into quartzite Qm2. The unit displays significant lateral variations in the textural composition. In the Male Hill outcrops, the rocks range from micaceous quartzite containing several thin, discontinuous pebble layers to quartzite with scattered pebbles and cobbles. The coarse clasts size increases northwards from 0.5–3 cm in the south to 5–7 cm across in the Female Hill outcrops, and this trend is associated with an increase in the proportion of pebbles and cobbles, which are rounded- to well-rounded,

of very low sphericity and represent vein quartz, red jasper and mudstone (Fig. 20.8d).

The most common sedimentary structures in Qm2 are: tabular planar and tangential cross-bedding, current ripples, mud drapes, tidal bundles and swash cross-stratification. The cross-bedded sets reach a thickness of 40 cm and are bounded by 1–2 cm-thick mudstone beds. Dip directions of cross-bedded layers indicate NW- and SE-directed alternating palaeocurrents.

Lithological complex II

Complex II is represented by red-bed facies (Rs). It is maximum 20 m thick, therefore thin by comparison with other rock complexes, but composed of distinctly different lithological associations. On the other hand, the internal

organisation and specific characteristics of this unit vary between the Male and Female Hill outcrops.

The south-eastern part of the Male Hill, complex II (Rs 1) consists of red siltstone containing intercalation of sedimentary breccia, which extends over 3 m along outcrop face, and about 20-cm-thick interlayer of dark red to brownish silty mudstone hosting scattered phosphorite nodules. Sedimentary structures in the siltstone vary from parallel lamination to lenticular bedding expressed by isolated, small current ripplemarks composed of very fine-grained sandstone. The sedimentary breccia consists of randomly oriented angular to subrounded clasts of red siltstone embedded in reddish-brown, occasionally yellowish, silty matrix. The breccia is massive, but in places shows high porosity caused by leaching of clasts not resistant to weathering.

By contrast, the red bed facies exposed in the western slopes of the Female Hill (Rs2) are much coarser-grained. Here, the unit consists of ferruginous sandstone, which includes two broad lenses of sedimentary breccia in the lower part and a wedge of quartzite in the middle. The predominant ferruginous sandstone is coarse- to fine-grained, tabular cross-bedded and contains small subangular to rounded intraclasts of red siltstone. Each of the two sedimentary breccia lenses is maximum of 1–1.5 m thick and ca. 60 m long at the outcrop face. The breccia clasts represent three rock types: well-rounded fragments of ferruginous silty mudstone, subangular tabular fragments of reddish-brown mudstone, and whitish argillaceous flakes, 1–2 mm thick and up to 2 cm across, rich in phosphorous minerals (Wendorff 2005). The breccia matrix varies from light-grey sandstone to yellow siltstone. The quartzite wedge embedded in the ferruginous sandstone above the breccia lenses attains a maximum thickness of 6 m and consists of stacked tabular cross-bedded sets and mega ripplemarks up to 35 cm high. The upper part of the Rs facies unit contains a few shallow (≤ 2 m) erosional incisions filled with thin ripple cross-laminated sandstone and siltstone beds with forests indicating bipolar palaeocurrents oriented about the SW-NE axis (Wendorff 2005). The upper boundary of the Rs unit is conformable in the Male Hill outcrop but in the Female Hill occurs as an angular unconformity of 5° – 10° below an erosional base of the overlying, large-scale cross-bedded quartzite Q of the succeeding lithological complex III.

Lithological complex III

Lithological complex III is dominated by meta-arenites, the composition of which grades laterally between the two hills. About 220-m-thick succession of mainly micaceous facies outcropping in the Male Hill (Qm3) evolves laterally to ca 305 m thick mainly non-micaceous strata in the Female Hill (Q) section. Subordinate are lenses of sandstone and pebble-

bearing strata. The proportion of muscovite decreases laterally in the northern direction generally in the succession and within individual subunits. Relatively frequent are beds, or thick laminae, enriched in dark grains of heavy minerals.

Micaceous quartzite Qm3 exposed in the Male Hill slopes is medium- and fine-grained. The lower part contains stacked cosets of trough cross-bedding succeeded by a discontinuous layer of imbricated pebbles followed by a succession with current ripplemarks that show bidirectional/bipolar SE-NW palaeocurrent directions. The upper part is dominated by low-angle tabular planar cross-bedding alternating with swash-type cross-bedding. The Qm3 unit continues along the north-western slopes of the Female Hill where it displays hummocky cross-stratification (Fig. 20.8e), mud drapes, large-scale trough cross-beds and tabular planar cross-beds with reactivation surfaces. Parallel-laminated and large scale cross-bedded sets are sometimes enriched in specularite (Fig. 20.8f).

Up the Female Hill succession, Qm3 evolves into occasionally muscovite-bearing, coarse- to fine-grained quartzite Q containing some interbeds of weakly cemented sandstone; the boundary between these lithological varieties changes laterally from conformable to locally erosional associated with an angular unconformity (Fig. 20.7). Sedimentary structures are well-preserved, and the most common are: medium-scale current ripples, climbing ripples, a variety of cross-bedding (trough, tabular planar, swash, bi-directional/herringbone, hummocky), reactivation surfaces, mud drapes, double mudstone layers called tidal bundles and rare symmetrical wave ripplemarks. Completely preserved depositional bedforms range in size from large current ripplemarks, through subaqueous dunes, to sand waves from 2 to 10 m thick with composite internal structure and giant-scale cross-bedding.

Two laterally discontinuous rock units crop out at the western slopes of Male Hill. Micaceous sandstone Sm1 forms a wedge overlying the Qmp1 conglomerate, attaining a maximum thickness of 15 m, and pinching out below Qm3 in the western slopes of the Male Hill. The rock is massive ('structureless'), coarse- to very coarse-grained arenite, which weathers relatively easily because of a much lower proportion of silica cement than the quartzite facies present in other units. A lens of pebbly micaceous sandstone (Smp1), about 1200 m in length along strike and up to 15 m thick, crops out on the western slope of the Male Hill in the middle of the Qm3 unit. It is medium- to coarse-grained, and contains a subordinate proportion of well-rounded vein quartz pebbles 0.5–4 cm in diameter.

In the Female Hill slopes, a few single-pebble conglomerate layers and several thin and laterally discontinuous, non-mappable conglomerate beds, are intercalated within the non-micaceous Q unit. They contain pebbles up to 6 cm across composed of vein quartz, accessory red jasper and rare mudstone intraclasts set in a matrix of arenite enriched

in heavy minerals. Sedimentary structures range from massive to cross-bedded with pebbles dipping to the N, to quartzite normally graded from pebbly to medium- to fine-grained.

In the western part of the Female Hill, a broad lens ca. 25 m thick and extending over ca. 1600 m along strike is formed by very thick beds of conglomerate (Cg1) overlain by pebbly quartzite (Cq) (Fig. 20.8d). The lenticular form and sharp erosional lower boundary of this association suggest that it fills a shallow, broad erosional feature. Sedimentary structures preserved in the pebbly quartzite range from tabular to trough cross-bedding to ripplemarks.

In the eastern part of the Female Hill, there is another lens, ca. 400 m wide, composed of a 18-m-thick succession of pebbly sandstone (Sp) coarsening upwards to conglomerate (Cg1). The sandstone is poorly sorted, contains scattered pebbles up to 6 cm across. Tabular planar cross-bedded sets ca. 40-cm-thick overlain by current ripplemarks and 1-cm-thick mud drapes are the characteristic sedimentary structures.

At three localities, micaceous sandstone Sm2 overlies non-micaceous quartzite Q in the north and east of the Female Hill (Fig. 20.7). The sandstone is fine- to medium-grained with an occasional admixture of fine pebbles of vein quartz, jasper and mudstone. Medium-scale tabular planar cross-bedding sets, about 50 cm thick, and current ripplemarks are the main sedimentary structures.

Lithological complex IV

Complex IV consists of a tabular conglomerate body (Cg1) ranging from 11 to 20 m thick forming a marker bed between the Male and Female Hills, and underlain in the southeastern part of the Female Hill by a lens of pebbly micaceous quartzite (Qmp2). The quartzite is a medium- and coarse-grained meta-arenite containing randomly scattered, well-rounded pebbles of vein quartz and brown mudstone. The overlying tabular conglomerate unit consists of conglomerate beds associated with subordinate layers of quartzite and sandstone. The conglomerate beds range in thickness from 10 to over 200 cm, contain well-rounded pebbles of vein quartz, jasper and mudstone, and vary in sorting from clast- to matrix-supported. Structurally, the Cg1 unit is dominated by tabular cross-stratified sets ranging in thickness from 20 to 80 cm, whereas subordinate massive beds are 20–50 cm thick.

Lithological complex V

Complex V is maximum 120 m thick, dominated by medium- to coarse-grained, non-micaceous quartzite (Q), mostly grey but pinkish in places. Well-preserved sedimentary structures comprise current ripplemarks, hummocky cross-

stratification (Fig. 20.8e) and a variety of cross-bedding: swash, tabular and trough, ranging from small to large scale.

A lens (Cg2) of pebbly conglomerates interbedded with quartzite layers crops out within the micaceous quartzite of complex V at the eastern slope of the Male Hill. Due to the slope undulations, it is exposed in both the upper and lower reaches of the slope. The geometry of the outcrops implies that sediments forming the lens fill an erosional channel ca. 500 m wide, maximum 12 m deep and minimum 700 m long. The infilling conglomerate beds are usually clast-supported, whereas some of the quartzite interbeds contain a varying admixture of pebbles. Tabular cross-bedded sets and massive bedding occur in both conglomerate and quartzite facies.

Tectonic structures

The succession is deformed by several thrust faults and many shear zones of various scale, commonly indicating the direction of dislocation towards the southwest. An impressive exposure of a prominent thrust occurs in the southern slopes of the Male Hill where it affects the upper part of the red bed complex (Rs) resulting in brecciation and south-west verging drag folds. Thrusting direction towards the south-west is also indicated by slickensides, striations, small drag folds and reverse faults that affect the underlying strata. Laterally, the thrust-related deformation decreases along strike across the western slope of the Male Hill, evolving towards the north into a thin shear zone extending into the south-eastern part of the Female Hill (Fig. 20.7).

At several other points, locally developed thrust zones of limited lateral extent, and small-scale reverse faults pass laterally into shear zones, which often contain lenticular quartz veins (Fig. 20.5a). The southwest-oriented direction of tectonic deformation is also indicated by occasionally observed slightly stretched pebbles, sigmoidal structures and deformed, or sheared, primary sedimentary structures. The micaceous units show a well-developed schistose fabric. Several joint systems cross the Tsodilo Group succession. Vertical joints with orientation changing between W-E and WNW-ESE and dipping up to 50° to NE occur in the Male Hill. The Female Hill contains a prominent NNW-SSE system and subordinate N-S sets of joints, both vertical to subvertical.

20.4 Geomorphic Relations in the Tsodilo Hills

20.4.1 Wind-Blown Sands

In the direct vicinity of the Hills, wind-blown sand is piled up at the foot of the topographic barrier of the Male and Female Hill, forming ramps adjacent to their E slopes. This

is especially prominent at the foot of the eastern slope of Female Hill where such a ramp (Fig. 20.9) has been interpreted as an access route used by the ancient inhabitants of a settlement located at the Nqoma plateau (Denbow 2011). On the other hand, a zone devoid of dune sands (Fig. 20.2) that extends ca. 50 km to the W of the Hills is interpreted as ‘wind shadow’ (Campbell et al. 2010). These two features combined and associated with the E-W extension of the linear dune ridges in the region, suggest that prevailing easterly winds transported Kalahari sands over a geomorphologically significant period.

20.4.2 Upper Depressions

Two shallow sand-filled internal depressions in the upper part of the Female Hill provided important archaeological documentation of the times when the area was inhabited in the environmentally hospitable periods, before ca. AD 800 (Robbins et al. 2010; Denbow 2011). Smaller of the two, the Nqoma plateau is located in the S part of the hill, ca. 90 m above the Kalahari plain. Adjacent to the north, and 70 m higher, there extends a much larger plateau, the Divuyu that occupies the south-central part of the Female Hill (Fig. 20.9).

20.4.3 Palaeolake

Sedimentary and fossil records enabled the interpretation of a palaeolake that existed to the SW of the mouth of the valley, which separates Male and Female Hills (Figs. 20.2 and 20.9). The sediments and fossils of diatoms, molluscs and freshwater algae preserved in calcrete show that the lake was permanent, with a maximum radius of ca 4 km, up to 7 m in depth and laterally oscillating shoreline indicating variations in water levels. Radiocarbon dating on mollusc shells suggests a predominance of the lacustrine conditions during two stages, namely 27,000–22,000 and 19,000–12,000 years ago (Brook et al. 1992; Thomas et al. 2003). The lake was adjacent to the Female and Male Hills cliffs in the NE and its outer margin is marked by an abrupt termination of the linear dunes to the south and west against the lacustrine sediments; four palaeoshorelines identified by Geppert et al. (2021) document climatic variations. As there are no traces of any palaeostreams entering the area, seepage of groundwater hosted in the Kalahari beds is inferred as the main source of supply in addition to the runoff down the slopes of the adjacent hills during rainy periods. Even today, the groundwater table is very shallow remaining at ca 2 m depth, which results in springs, seeps and even long-lived ponds within the Hills. Of these, the most important source



Fig. 20.9 View to N of Female Hill from the top of Male Hill showing position of two ancient settlements accessible via sandy access ramp and palaeolake sediments adjacent to cliffs of both hills

of permanent spring water is known as the Water Hole Mine, at the foot of the western cliff of the Female Hill (Brook 2010; Campbell et al. 2010). Interestingly, the palaeolake area shows high uranium concentrations ascribed to the past surface runoff down the adjacent hill slopes (Bezuidenhout 2019).

20.4.4 Weathering and erosion of the Tsodilo Hills rocks

Geomorphic features of the Tsodilo Hills document processes of physical and chemical modifications of the rock succession. The character of angular, loose rock debris is influenced by lithology of the parent rock—boulders are derived from massive quartzite complexes and finer fragments result from disintegration of micaceous schist, meta-siltstone and mudstone. Some generally very steep slopes have stepped appearance; namely, cliffs formed on quartzite complexes are separated by benches of lower inclination underlain by micaceous schists, meta-siltstone or mudstone and vegetated by grasses and small bushes (e.g. Fig. 20.10a and b). Some of the cliffs rising above the surrounding Kalahari sediments surface have flared sides. The scale of this feature ranges from small, with overhangs occurring ca. 1.5–3 m above the adjacent ground level, to large, up to ca. 15–20 m in height (Fig. 20.10b). Some of the former occurrences are called ‘shelters’ (Campbell et al. 2010), in which the overhang protects paintings on the recessed lower face of the outcrop from the destructive elements.

Karst-like features suggestive of palaeokarstification and signs of recent dissolution of silica are infrequent and locally subtle. The ‘Water Hole Mine’ (also called “Python

Spring”), holding water throughout the year and overflowing during rainy periods, occurs in the lower part of the Female Hill westernmost cliff. This feature is considered in the literature as one of the ancient specularite mines (Campbell et al. 2010). However, it appears to be a smooth-surfaced shaft inclined over 45 degrees into the rock face, elliptical in cross section and measuring 2.5×2 m across. These features suggest against its formation exclusively by ancient mining, which used to involve spalling and rock breakup that would have resulted in sharp-edged surfaces of the mine workings (Murphy et al. 1994). Instead, it is proposed here to be a karst feature—the epiphreatic oblique tube functioning as a subartesian well. Vadose zone-related features occur high up the western ridge of Female Hill, above the red bed (Fig. 20.7). The walls of ca. 12 m deep vertical shaft with some collapsed blocks of breakdown breccia at the Kalahari sand-covered bottom shows subhorizontal layer-parallel solution features at bed boundaries, and an array of small karren in the upper part (Fig. 20.11). In the eastern slope of this ridge, entrance to a horizontal tube occurs high up in the cliff face. The tube, or passage, is about 50 m long, roundish in cross-section, ca. 1–1.5 m in diameter, and with smooth walls; mirroring similar karst features known in the carbonate rock complexes. The floor of the passage is covered with the Kalahari sand.

Other effects of chemical weathering are reflected by the variations in quartzite hardness and rock-surface colouration. Laterally restricted zones of weakly cemented, crumbling parts of otherwise resistant to weathering, extremely hard, quartzite beds occur sometimes in recessed parts of cliffs and steep slopes. Such cases are interpreted here as a reflection of arenisation (Wray and Sauro 2017), i.e. preferential dissolution along crystal boundaries of quartz overgrowths by



Fig. 20.10 Examples of stepped appearance of the Tsodilo Hills steep slopes. **a** NW slope of Male Hill (height 410 m); **b** western slope of Female Hill with flared cliff side on the left (ca. 20 m high) and

contrasting rock debris types: angular boulders beneath cliff-forming massive quartzite and finer fragments overlying benches on thinner beds of meta-siltstone, mudstone and schist



Fig. 20.11 Vertical shaft with two karst-like solution features parallel to bedding in the lower part and an array of karren in the upper part, on the right

seeping groundwater. On the other hand, deposition of iron oxides resulting from specularite weathering results in frequently occurring multi-coloured staining of rock faces.

20.5 Ancient Human Activity: Mining and Rock Art

Human activity and cultural evolution through millennia are documented by a world-class treasure of over 4,000 rock paintings and other items of rock art and mine workings bearing witness to prehistoric mining of specularite. Several archaeological sites provided evidence for the arrival of the earliest settlers about 100,000 years ago, in the Middle Stone Age, the use of pigments minimum 40,000 years ago, use of pottery, metal implements, fishing tools and other artefacts (Robbins et al. 2000). The paint was made from locally available minerals—red ochre in case of red

paintings and chalk-like calcrete for white paintings (Kiehn et al. 2007).

Specularite was mined in the Tsodilo Hills and ground to produce hematite flakes of deep red shine traded for copper and iron implements as well as jewellery. Specular hematite, briefly called specularite, is a rock composed of light-reflecting tiny hematite crystals (Fe_2O_3) with metallic lustre, and reddish streak, which break up to form shining flakes when scratched or ground. The term is derived from specular reflection, i.e. mirror-like, as opposed to diffuse reflection in all directions from, e.g. a matte surface (Fox 2001). The mineral occurs in the Tsodilo schists, quartz veins and quartzites as disseminated crystals and specularite-enriched laminae, lenses and thin beds black in colour and often emphasising the primary structures, e.g. cross-bedding in meta-arenites.

Nineteen ancient mining sites of specularite are known, five of which in the Male Hill, thirteen in Female and one in Child (Murphy et al. 1994; Fig. 6.1 in Murphy et al. 2010). The earliest, occasional mining has been dated at 5300 ± 160 yr. B.P., and the radiocarbon dating of charcoal excavated from the floors of the mining sites provided dates in the range AD 850–1025 (Kiehn et al. 2007). However, a suggestion that the efficient mining activity might have had started even a few thousand years earlier is supported by the size of some of the mine excavations compared to the laborious mining method utilising fire spalling and stone tools to crush the ore-hosting rock (Murphy et al. 1994, 2010; Robbins et al. 1998). Nevertheless, the available data and historical accounts indicate that the specularite mining in Tsodilo started sometime before A.D. 850 and the last traces of this industry date back to the nineteenth century. It was traded throughout Southern Africa through the Late Stone Age and Iron Age up to the nineteenth century as a cosmetic since a mixture of ground specularite and grease applied to the hair and body gave the wearer a glittering appearance (Kiehn et al. 2007).

20.6 Summary

The age dating obtained most recently (Mapeo et al. 2019) sheds new light on the geological evolution of the Damara Belt in NW Botswana and highlights a special role of the Tsodilo Hills Group succession as a unit that may help to refine palaeogeographical reconstructions of the Late Paleoproterozoic–Mesoproterozoic continental masses, the remnants of which are now scattered and incorporated as parts of African and South American cratons. Marine siliciclastic strata deposited at continental margins hold information important for broad tectonostratigraphic reconstructions because they reflect the evolution of shallow marine

depositional basins and elevated source areas. Therefore, detailed knowledge of the Tsodilo Hills rocks may support future mapping of age-equivalent, lithologically similar regions and their interregional correlation.

The Neoproterozoic-Lower Palaeozoic age of the last tectonic deformation suggests that during the Pan-African orogenesis a part of the older Quanguwadum granitoid basement (Palaeoproterozoic) could have been sheared off the Congo craton together with the overlying sedimentary rocks of the Tsodilo Hills Group and emplaced as a tectonic unit lodged within the Damara Belt fold-and-thrust structure. Such tectonic position would be similar to the huge fragments of basement rocks known in the Domes Region of the Lufilian Belt in Zambia (Cosi et al. 1992).

The sedimentary features and regional position of the Tsodilo Hills succession suggest deposition in the open shelf environment at the Congo Craton margin. Male Hill was located closer to the source area as suggested by the deposits interpreted as Gilbert-type delta (Fig. 20.12a), and Female Hill facies suggest a more distal location. The shelf was influenced by tidal currents, littoral longshore currents, occasional storms and variations in sea level resulting in

alternating regressive and transgressive trends within the Tsodilo suite. Of two regressions, the first one resulted in a tidal flat (Rs1 in Fig. 20.12a) incised by tidal creeks (Rs2 in Fig. 20.12b) and a break in the deposition of the Gilbert-type delta sequence, resulting in two stages of its evolution (Fig. 20.12a). The second regression is reflected by the tabular conglomeratic body truncating the Gilbert-type delta top in the uppermost reaches of the Male Hill (Fig. 20.12a), which records a substantial increase in the sediment supply, probably caused by uplift of the source area to the south. This conglomerate layer is succeeded by a fining-upwards succession of another transgressive event. Farther to the north, during submergence periods related to transgressive stages, giant cross-bedded sand waves were formed (Fig. 20.12b), migrated northward, away from a coastal zone, and accumulated to form the aggrading succession of the Female Hill.

In the context of regional stratigraphy, the relations observed in the Tsodilo Hills area suggest large-scale landscape-sculpting processes that resulted in two erosional cycles since the turn of Neoproterozoic and Palaeozoic when the Damara orogenic belt was elevated.



Fig. 20.12 Interpretation of depositional complexes. **a** Male Hill, W face: Gd1—Gilbert-type delta stage 1, Rs1—red siltstone unit, Gd2—Gilbert-type delta stage 2, Cg1—tabular conglomerate; **b** Female Hill, W cliff: bsc—beach facies swash cross-bedded interval, Rs2—red

siltstone, quartzite and mudstone of tidal flat (tf) with incised tidal channel (tfc), swg—shelf sand waves of giant-scale cross-bedded quartzite (cliff height ca. 60 m)

Weathering and erosion of the Damara mountains continued to the Carboniferous-Permian glaciation of Gondwanaland. It is suggested here that the Tsodilo Hills Group rocks formed nunataks within the Dwyka continental glacial cover. The glacially scoured landscape was covered by a succession of syn- and post-glacial deposits of the Karoo Super-group. These were subsequently eroded in hot and humid late Cretaceous climate to form a regional peneplanation surface called the “African Surface” (Key and Ayers 2000; Miller 2008), which is an unconformity at the base of the succeeding Kalahari sediments.

Flared sides of some cliffs suggest prolonged evolution of the boundary between rock and regolith associated with topographic surface stability in the geological past, followed by regolith denudation. Karst-like features result from silica dissolution at a large scale, whereas this process progressing at a microscopic scale is reflected by the localised arenisation of some quartzite beds. Ongoing, recent fragmentation of the Tsodilo rocks produces debris ranging from fine clasts of micaceous schists, siltstone and mudstone to angular boulders of quartzite.

Frequent, strong easterly winds result not only in the wind shadow (mentioned earlier) but also carry abrasive quartz sand grains. No direct effects of the resulting erosion were studied in the Tsodilo Hills, but it is suggested here that especially the eastern rock faces, exposed to sand blasting, should be expected to act as a ‘factory’ enriching the Kalahari environment in detritus of quartz, muscovite and other minerals.

A limited selection of geomorphological features outlined here indicates that systematic research into the geomorphic characteristics and history of Tsodilo Hills is very much needed. The few karst-like features mentioned above suggest that several caves archaeologically investigated in the past (Campbell et al. 2010 and references therein) may represent karst features formed in quartzite, similar to the phenomena documented in Brazil, for example (Wray and Sauro 2017 and references therein). These should be studied in Tsodilo as well.

Considering the interesting geological and geomorphological features intertwined at Tsodilo with the record of ancient human activities and with the recently continuing religious and symbolic significance for the local communities, we may summarise by quoting a fragment of geological documentation by the present author and included in the Tsodilo Dossier prepared for UNESCO (Botswana National Museum 2000): ‘The Tsodilo Hills have multifaceted values that combine uniquely, and in a fascinating way, several aspects of Earth’s history with the cultural history of humankind. The area shows a most interesting interplay between a broad variety of geological processes spanning over a billion years of the Earth’s history. At the same time, the Hills demonstrate how the minerals, products of slow natural processes, reflected on the cultural activity of our

ancestors who fashioned the foundations of our history. Thus, the history of nature acting over many millions of years is intertwined with the history of people active in the Hills about a thousand years ago, and both are now being unravelled by modern science. These three elements can be perceived as a symbolic bridge between the past and present and make the Tsodilo Hills worthy of consideration for World Heritage Status’. This status was granted in 2001 by the World Heritage Committee.

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