Annales Societatis Geologorum Poloniae (2005), vol. 75: 17–25.

OUTLINE OF LITHOSTRATIGRAPHY, SEDIMENTATION AND TECTONICS OF THE TSODILO HILLS GROUP, A NEOPROTEROZOIC–LOWER PALAEOZOIC SILICICLASTIC SUCCESSION IN NW BOTSWANA

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Wendorff, M., 2005. Outline of lithostratigraphy, sedimentation and tectonics of the Tsodilo Hills Group, a Neoproterozoic–Lower Palaeozoic siliciclastic succession in NW Botswana. *Annales Societatis Geologorum Poloniae*, 75: 17–25.

Abstract: The Tsodilo Hills Group is an association of meta-quartzites, meta-conglomerates and quartz-mica schists altered to kyanite metamorphic grade and outcropping in NW Botswana. The unit is a part of the regional Neoproterozoic–Lower Palaeozoic succession deformed during the Pan-African orogenesis and present in the Damara belt of Namibia to the west, in which the main orogenic event occurred at ca. 534–516 Ma, and in the Katangan suite of the Lufilian arc in Zambia and the Democratic Republic of Congo to the north-east.

Sedimentary structures, textures, mineral composition, facies trends and palaeocurrent patterns suggest that the deposition of the Tsodilo Hills Group strata took place on an open continental shelf influenced by tides and supplied with siliciclastic material derived from a source area elevated to the south of the depository. The ongoing sedimentation was punctuated by two regressive stages. The older one is reflected by an association of red mudstone, siltstone and sandstones/quartzites, and incised in them channel-fill sandstone bodies with bimodal-bipolar palaeocurrent patterns, which are interpreted here as deposits of tidal mudflats intersected by tidal creeks. Enrichment of these rocks in phosphorous was probably caused by upwelling of deep ocean waters reflecting sea-level changes. The second regression was related to an increased input of terrigenous material and is indicated by a conglomerate marker bed.

Numerous shear zones, a few small-scale reverse faults and one major thrust, displacing strata towards the south-west, deform the succession. The degree of deformation evolves laterally along the strike of this structure from a prominent thrust in the southern part of the Tsodilo Hills to a thin shear zone in the north.

Key words: siliciclastic shelf, Neoproterozoic, Pan-African, Damara belt, Botswana.

Manuscript received 8 April 2004, accepted 9 February 2005

INTRODUCTION

The Tsodilo Hills occur in the Ngamiland District of NW Botswana. In this region, the Pan-African (Neoproterozoic–Lower Palaeozoic) Damara belt crosses the country extending from Namibia in the SW to Zambia and Congo in the NE, where it is known as the Lufilian arc (Fig. 1). The peak of the Pan-African orogenic movements in the Damara belt, based upon U-Pb zircon and monazite ages, falls within the range of ca. 534–516 Ma (Hanson, 2003 and references therein; Miller, 1983). The Tsodilo Hills succession is exposed ca. 65 km to the south of Shakawe (Fig. 2) in steep slopes and cliffs of three hills traditionally called Nxum Ngxo (Male), Nxum Di (Female) and Picannin (Child) Hills. The hills cover an area approximately 6 by 2 km and rise 420 m above a broad expanse of the surrounding terrain covered by the Cretaceous to Recent Kalahari beds formed by lacustrine, fluvial and aeolian sediments that rest unconformably upon older strata (Carney *et al.*, 1994). Outcrops of the pre-Kalahari beds basement rocks are extremely scarce; therefore, the boundaries of and contacts between the regional units shown on the schematic map (Fig. 2) are tentative and base mainly on interpretations of the geophysical data (Carney *et al.*, 1994; Key & Ayers, 2000; Meixner & Peart, 1984).

This paper presents new observations on the lithology and lithostratigraphy, sedimentary features and tectonic deformation of the succession exposed in the Male and Female

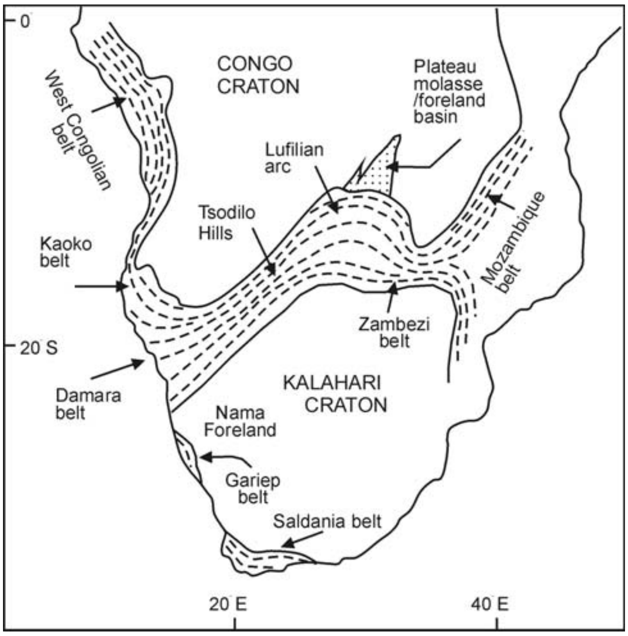

Fig. 1. Position of the Tsodilo Hills Group in the framework of the Neoproterozoic–Lower Palaeozoic Pan-African belts of central and southern Africa (modified from M. Wendorff, 2003)

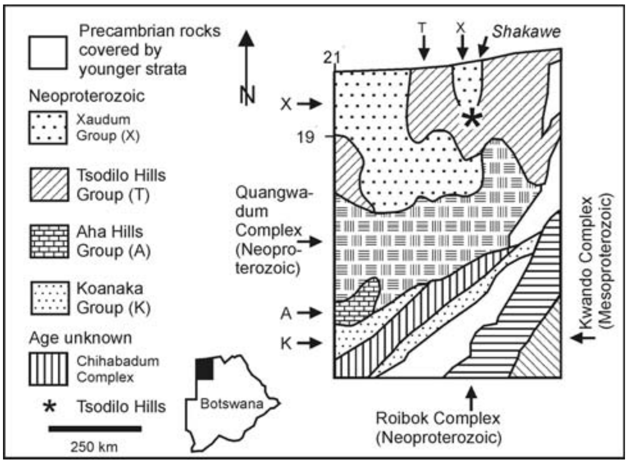

Fig. 2. Precambrian units in NW Botswana (modified from Carney *et al.*, 1994; Key & Mothibi, 1999; Key & Ayers, 2000; Singletary *et al.*, 2003)

Hills. These observations may be important for regional and global reconstructions, and therefore of interest to the European geoscientist.

GEOLOGICAL BACKGROUND

The strata outcropping in the Tsodilo Hills belong to a metasedimentary succession lying to the north of the granitic-gneissic Quangwandum Complex present in the NW part of Ngamiland District (Key & Mothibi, 1999; Key & Ayers, 2000; Fig. 2). The metasedimentary succession is subdivided into two units: the Xaudum Group and the Tsodilo Hills Group (Key & Ayers, 2000). The Xaudum Group is composed of low-grade meta-sandstone, meta-siltstone and carbonate rocks with cherts. Based on detrital zircon ages from sandstone near Shakawe, the Xaudum Group rocks are younger than 1.02 Ga (Mapeo *et al.*, 2000). The Tsodilo Hills Group is an association of "ferruginous and micaceous quartzite, quartz–mica schist, metamorphosed conglomerate, minor shale, phyllite, sandstone and ironstone" (as observed by Key & Mothibi, 1999), which have been altered to kyanite metamorphic grade (Singletary *et al.*, 2003). This unit extends to the Shakawe area, ca. 65 km to the north of the Tsodilo Hills, where it contains interbeds of iron formation. The $^{40}Ar/^{39}Ar$ age of 490±2.3 Ma on metamorphic muscovite from the Tsodilo Hills (Singletary *et al.*, 2003) implies that these rocks were involved in the Pan-African orogenic movements. The two bracketing ages given above imply that the strata exposed in the Tsodilo Hills were deposited during the Neoproterozoic–Early Palaeozoic, prior to the end of the Pan-African orogenesis, and are correlative to a part of the sedimentary successions present in the Pan-African orogenic system extending from the Damara belt in the west to the Lufilian arc in the north-east (Fig. 1). Based upon lithological similarities, the Xaudum Group could be an equivalent to the Nosib Group of the Damara succession in Namibia to the west (Carney *et al.*, 1994; Key & Mothibi, 1999; Singletary *et al.*, 2003). The high content of iron in the Tsodilo Hills Group suggests the possibility of correlating this unit with iron-rich strata in the Damara succession, especially with ferruginous quartzites associated with the Chuos glaciogenic rocks (Singletary *et al.*, 2003 and references therein).

The rocks of the Tsodilo Hills were described by Wright (1956) as an association of "micaceous schist, quartz-rich layers, grits and pebbly beds". This author also noted the occurrences of an accessory mineral assemblage: muscovite-kyanite-haematite-tourmaline-dumortierite. In his mapping report, Vermaak (1961; 1962) subdivided the ca. 420 m thick succession into four units, which he called "stages". Each "stage" is an association of several types and sub-types of terrigenous metasedimentary rocks, and its definition is based on the prevailing and/or characteristic lithology or groups of lithologies. However, neither of these authors recorded the array of sedimentary features and thrust tectonic phenomena documented in the course of this study. A preliminary outline of revised lithostratigraphy and sedimentological aspects of the Tsodilo Hills succession was published by Wendorff (1999; 2000a; 2000b).

LITHOSTRATIGRAPHIC SUCCESSION AND ITS TECTONIC DEFORMATIONS

From the viewpoint of lithostratigraphical classification, each "stage" identified by Vermaak (1961) is an association of lithofacies, and thus represents a lithostratigraphical unit. The lithological content and boundaries proposed by Vermaak are revised below on the basis of the recent field observations by the present author. The identified units are described as lithological complexes numbered I–IV in a stratigraphically ascending order. Their vertical succession is shown in the lithostratigraphic column (Fig. 3) and the lateral relations in the geological map (Fig. 4). Sedimentary features, preserved in spite of metamorphic alterations and locally strong tectonic deformations, and observed by the present author are briefly described and interpreted in the context of the depositional environment in the next section.

1. Unit I is characterised by fine-grained ferruginous and micaceous quartzites. The base of the unit is not exposed and the thickness reaches 65 m. Quartzite beds represent a broad range: hard glassy green, hard green slightly micaceous to strongly micaceous, very fine grained and coarse grained ferruginous quartzite. Some of the ferruginous quartzite beds have lenticular geometry.

2. Following in the succession is an 80 m thick unit II composed of mica schist and mica-quartz schist with intercalated quartzite layers. By comparison with the underlying unit I, several parts of unit II show a lower content of silica cement. The thickness and proportion of quartzite intercalations decrease northward, which accounts for a general lateral trend of grain size decrease within the complex towards the north. The quartzites are fine to coarse grained greenish, medium grained grey and medium grained micaceous green; some are ferrugineous. Some beds have a lenticular geometry. Unit II wedges out towards the north between units I and III (Fig. 4).

3. Unit III is a 150 m thick complex of quartzite containing intercalations of sandstone. Beds of green, micaceous quartzite occur often in this unit. Quartzites range from coarse to fine grained and from micaceous to non-micaceous. Rock colour varies from grey to green to red and bed geometry from tabular to lenticular. Sandstone occurs as subordinate sugary, quartzitic beds with silica cement incompletely recrystallised.

4. The base of ca. 140 m thick Unit IV is marked by a laterally extensive polymictic conglomerate, which contains pebbles set in a poorly sorted matrix of micaceous quartzite. The conglomerate thickness varies laterally from 10 m on the south side of the Male Hill to ca. 5 m in the Female Hill. Unit IV can be distinguished from the underlying units by the presence of ferruginous quartzites, often cross bedded, with subordinate intercalations of micaceous and pebbly quartzite layers. Quartzites are fine to coarse grained and sometimes pebbly, glassy, cross bedded, coarse grained, sometimes brownish with green banding, micaceous, micaceous dark brown rich in haematite/specularite and pinkish-white ranging from coarse grained to pebbly. Pebbly strata range from tabular pebbly quartzite to lenticular conglomerate beds to layers one pebble thick. Mica schists appear as subordinate interbeds in unit IV.

Under the microscope, the quartzite and sandstone beds are composed entirely of quartz grains, and are locally enriched in heavy minerals. The pebbles in the conglomerates are composed mostly of vein quartz associated with a subordinate proportion of quartzite and solitary clasts of reddish, hematite-enriched quartz arenites. This mineral composition classifies the protoliths of the quartzites as quartz arenites, i.e. mature sandstones. Considering the abundance of metamorphic muscovite (Singletary *et al.*, 2003 in press), the protoliths of the micaceous strata are interpreted as follows: micaceous qaurtzites as impure quartz arenites, mica-

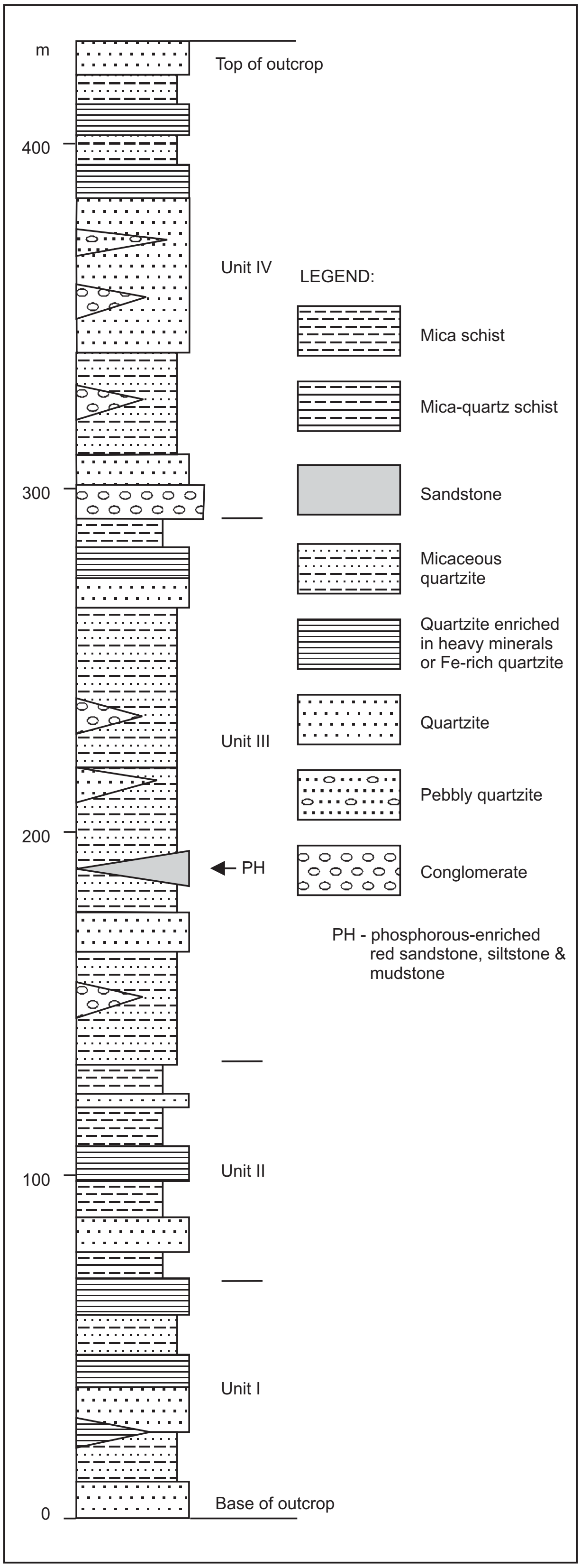

Fig. 3. Lithostratigraphic column of the Tsodilo Hills Group succession exposed in the Tsodilo Hills, the Male Hill

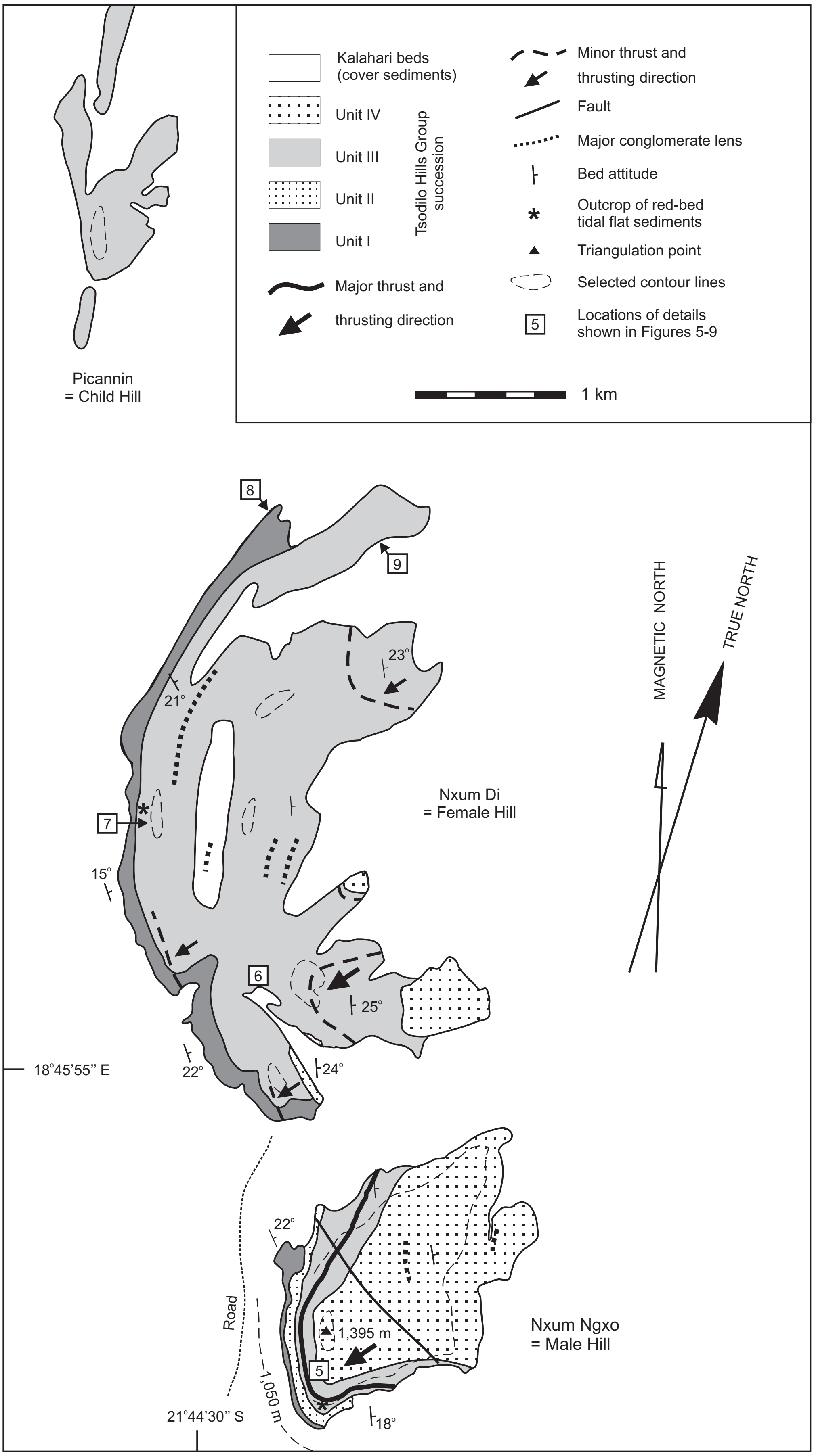

Fig. 4. Schematic geological map of the Tsodilo Hills. Lithological units I–IV are shown in Figure 3 and described in the text

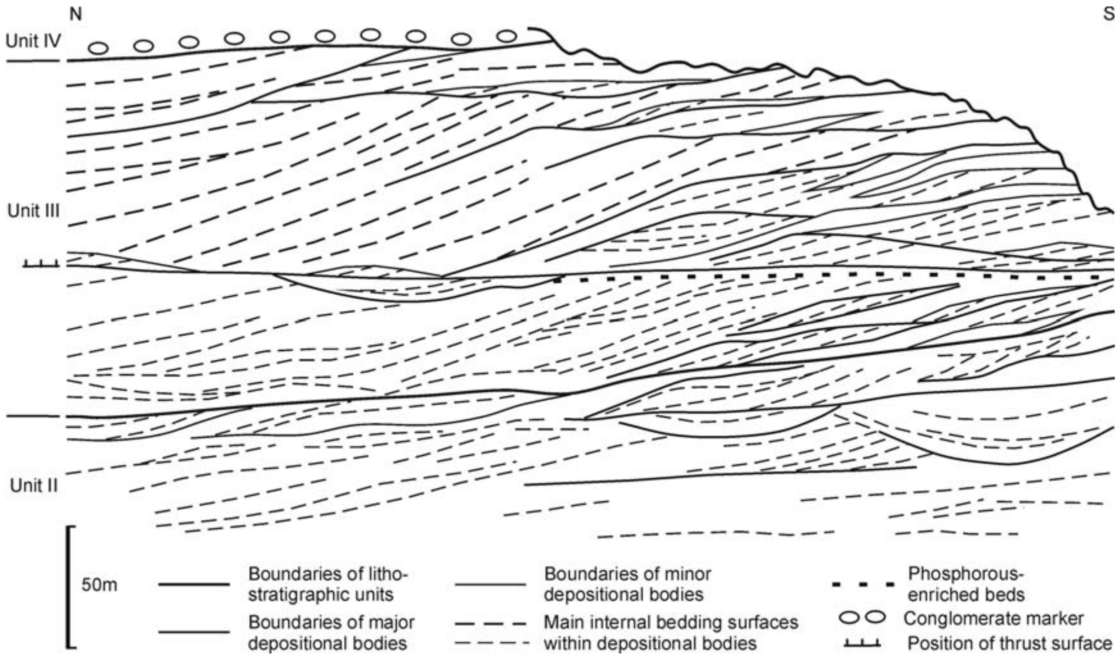

Fig. 5. Quartz-mica schists with lenticular channel-fill and megaripple quartzites of Unit II are overlain by two cosets of giant cross stratification of Unit III interpreted as two stages of Gilbert-type delta progradation. The lower coset, overlain/truncated by phosphorous-enriched beds is regarded as shallowng-upwards distal part of prograding delta, and the upper coset as proximal part of prograding and intensely aggrading delta truncated by regressive conglomerate defining base of Unit IV. The Male Hill cliff, locality 5

quartz schists as sandy mudstones and micaceous schists as silty mudstones (Levell, 1980).

The succession in the Tsodilo Hills is gently dipping to the east and NE at an angle ranging from 15 to 25 degrees (Fig. 4). The rock is often sheared and several of the major shear zones contain thick quartz veins. A major thrust developed within the succession of lithological unit III is the most prominent tectonic feature. The degree of deformation decreases northward, so that only a narrow shear zone represents the thrust on the southern slope of the Female Hill. Slickensides, striations, small-scale recumbent folds and thrust faults in the strata underlying the thrust complex in the southern slope of the Male Hill indicate thrusting to the SW. A few small-scale reverse faults (thrust faults) exposed in the Male and Female Hills, in the succession underlying the major thrust, show the same SW-orientated direction of thrusting. Similarly with the major thrust above, the degree of deformation in these faults decreases northwards as well. This lateral trend, similar in both major thrust and minor reverse faults below, suggests thrusting associated with dextral rotation of the thrust slab.

SEDIMENTARY FEATURES, PALAEOCURRENT DIRECTIONS AND DEPOSITIONAL ENVIRONMENT

Sedimentary structures present in the quartzites range from giant-scale cross bedding, large- to medium-scale tabular planar and tangential cross bedding with common reactivation surfaces, herringbone cross bedding, current ripple cross lamination, current and wave ripples, parallel bedding, swash cross lamination, and occasional trough and hummocky cross stratification (Figs 5–9). Mudstones occur as either single mud drapes or mud-drape couplets (Fig. 6). Trough cross bedding is rare and always of small to medium scale only. Shallowing-upwards sequences of varying thickness, with or without conglomerates are characteristic of the Tsodilo Hills succession.

Pebbly deposits, whether massive, cross-bedded, normally or inversely graded, usually occur as topmost components of sequences coarsening upwards from quartzite to pebbly quartzite to conglomerate. The sequences composed solely of quartzites begin with sedimentary structures pro-

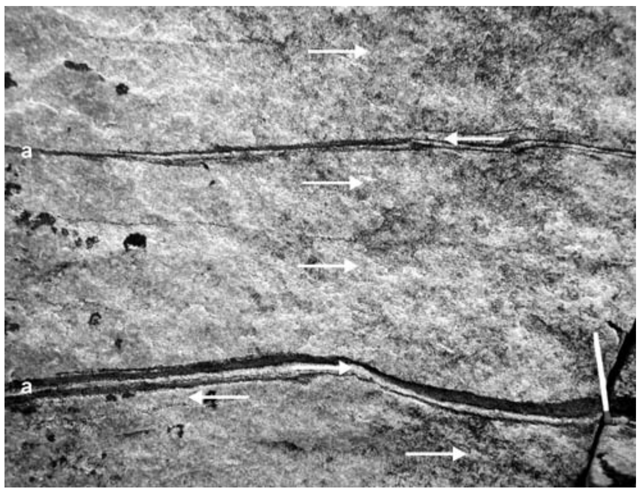

Fig. 6. Two couplets of tidal mud drapes (black) interbedded with current ripplemarks. Note higher frequency of ripplemarks related to offshore- than onshore-oriented currents. Matchstick for scale is 4 cm long; view azimuth 310°. The Female Hill, locality 6

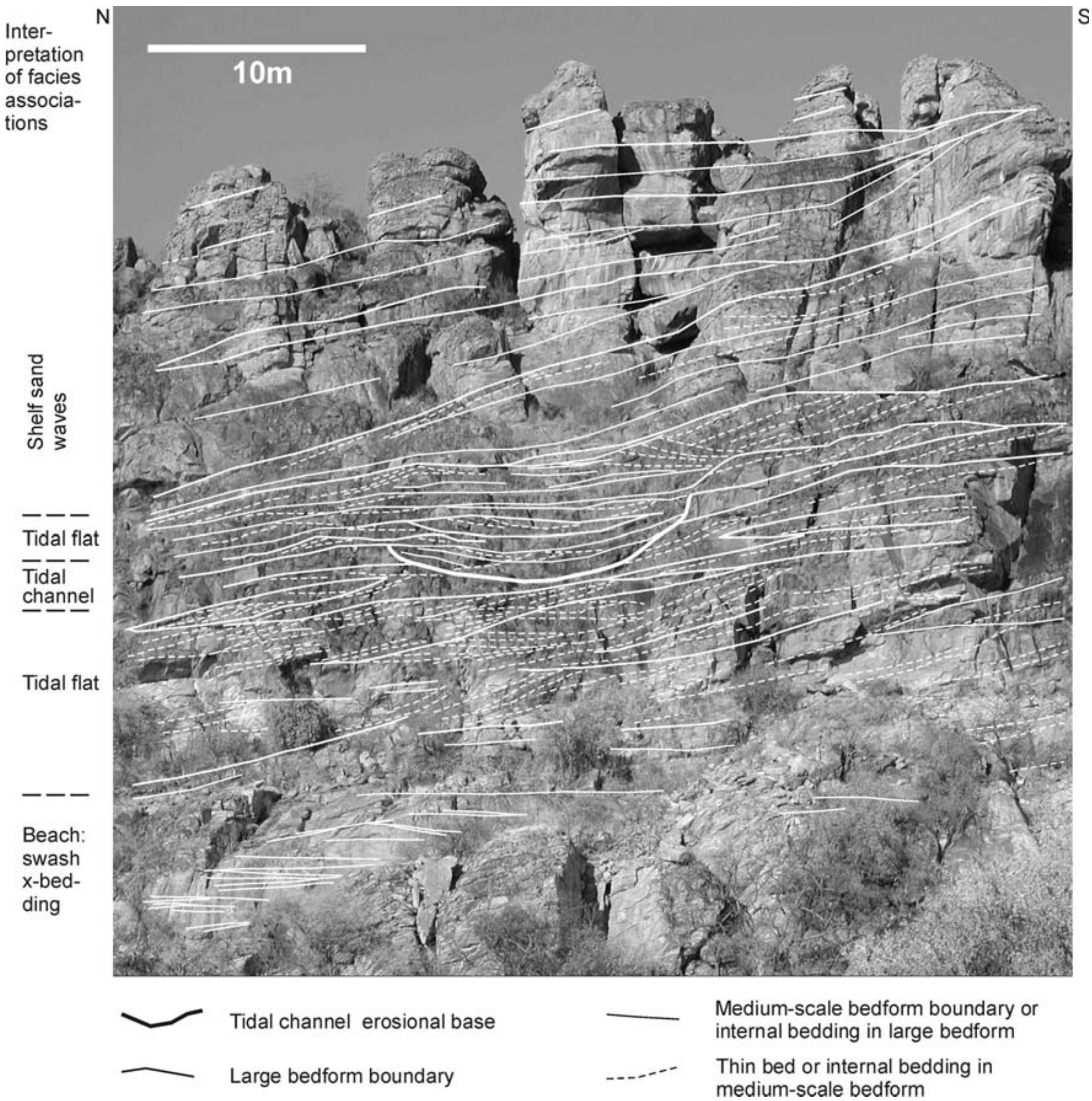

Fig. 7. Quartzites of beach facies succeeded by quartzites, siltstone and mudstone of tidal flat with incised tidal channel are overlain by transgression-related quartzites interpreted as open shelf sand waves. The Female Hill, locality 7

Fig. 8. Hummocky cross stratification (a) overlying swash cross bedded set (b); *ca.* 1,000 years old rock painting depicting zebra is 17 cm high. The Female Hill, locality 8

duced below wave base and often end with wave-rippled sets in the upper part. Both quartzite and pebble-bearing sequences frequently terminate with swash cross stratification.

Two occurrences of red sandstone, siltstone and mudstone up to 8 m thick are exposed in the litological association of unit III and contain small bodies of sedimentary/intraformational breccia. The outcrop on the southern and western slopes of the Male Hill (Fig. 5) also contains a 25 cm thick layer of phosphorite nodules deposited in a dark red silty mudstone. A similar facies outcropping in the Female Hill cliff below the waterhole (marked with an asterisk on the map Fig. 4 and shown in Fig. 7) contains phosphorous-enriched siltstone flakes embedded in a matrix of red sandy-mudstone. At both localities, the red-coloured rock is enriched in phosphorous minerals, which also occur in the underlying and overlying quartzite (XRD identification by B. Vink, pers. commun., 2000). The red-bed complex in the

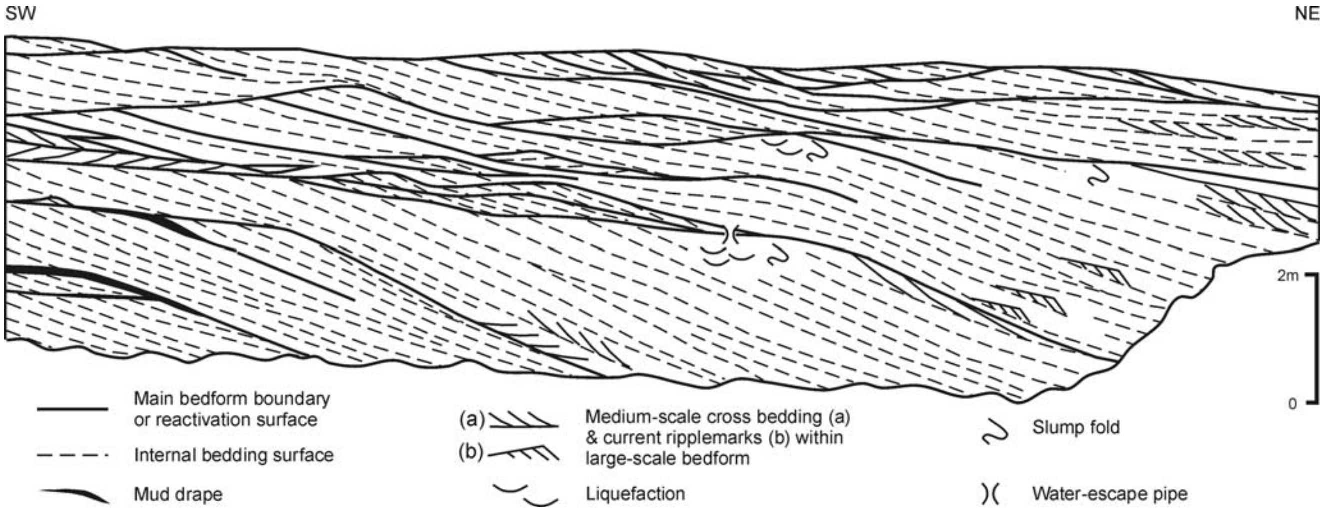

Fig. 9. Composite structure of prograding and aggrading tidal sand wave deposited by unidirectional and reversing currents (bedform Class IV of Allen, 1980). Note tidal influences recorded by predominant offshore currents towards NE, subordinate influence of shoreward currents towards SW, herringbone cross stratification, reactivation surfaces and mud drapes. Synsedimentary deformations – liquefaction (dish structures and a water-escape pipe) and related small-scale slump folds – indicate occasionally rapid deposition and instability of foresets. The Female Hill, locality 9

Female Hill is dissected by small-scale channels (Fig. 7) filled with sandstone and siltstone beds showing bipolar cross bedding. Some channels contain irregular layers of sedimentary breccia adjacent to the channel margin and composed of red mudstone clasts embedded in matrix of yellowish siltstone and sandstone. Some of the channel-fill sandstone beds are cross laminated with foresets showing bipolar palaeocurrents of NE–SW orientation. It is not certain at this stage of work whether the two occurrences of red bed strata, the one in the Male Hill and the other in the Female Hill cliff, represent an isochronous marker, the continuity of which was disrupted by erosion prior to the deposition of the overlying strata, or whether they occur at two different stratigraphic levels within unit III.

A laterally extensive conglomerate marker separates unit III from unit IV (Figs 3–5) and its thickness decreases northward, from ca. 10 m on the SW side of the Male Hill, through 5 m to <2 m in the Female Hill. Some minor conglomerate intercalations show a similar thinning tendency. The lateral trend of grain size decrease towards the north is a general feature of most complexes in the succession.

Indicators of palaeocurrent direction form two populations (Fig. 10) – a bimodal-bipolar pattern (A1-A2) and a unidirectional component of eastward-orientated currents (B). The cluster/modal class I (labelled A1), represents one giant cross stratification set outcropping in Unit III in the S cliff of the Male Hill and includes mainly large- to small-scale cross bedded sets in other lithostratigraphic units, at other localities. An unidirectional set of eastward-orientated currents (B) is recorded by small-scale cross bedding and current ripple marks.

DISCUSSION AND CONCLUSIONS

The lithological development of the Tsodilo Hills Group suggests that the deposition took place on a marine shelf supplied with mature siliciclastic material and influenced by tidal and littoral long shore currents. The lateral trends of grain-size, fining towards the north in both quartzite/sandstone and conglomerate intervals, coupled with the bipolar palaeocurrent pattern imply that the source zone of the clastic material was located in the south. The ongoing deposition was interrupted by three regressive events. The two complexes of phosphorous-enriched red mudstone and siltstone associated with quartzite, sandstone, sedimentary breccias and accompanying small channels filled with sand-

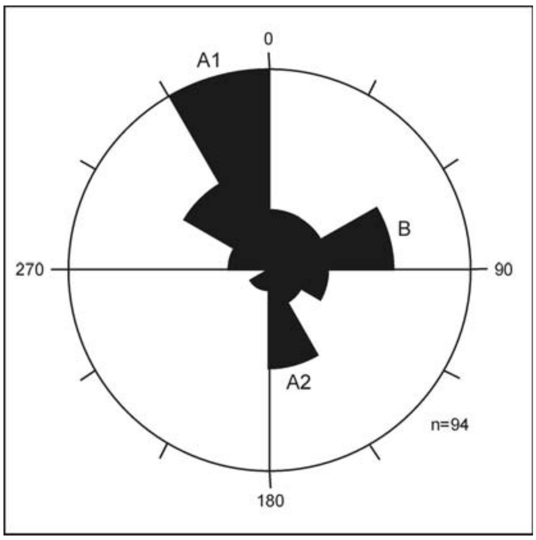

Fig. 10. Rose diagram of cross bedding and cross lamination in quartzites of the Tsodilo Hills Group. Modal classes A1-A2 define bimodal-bipolar pattern recorded by cross bedding ranging from giant- to small-scale, with offshore component predominant (A1 – giant- to mainly medium-scale); class B is represented by mainly small-scale cross bedding, ripple cross lamination and current ripplemarks interpreted as products of deposition by littoral long-shore currents

stone beds that show bipolar palaeocurrent pattern are interpreted as regression-related deposits of tidal mudflats and sandflats intersected by tidal channels (Figs 5 and 7). The occurrences at the channel margins of the sedimentary breccia composed of red-bed mudstone and siltstone clasts embedded in poorly sorted channel-fill sandstone are interpreted as resulting from collapse of the undercut tidal channel banks. The enrichment in phosphorous is here considered to be the result of upwelling of deep marine waters related to the eustatic sea-level changes. The next regression was associated with deposition of the widespread conglomeratic complex at the top of unit III caused by an increased supply of the terrigenous material from the south (Fig. 5).

The sedimentary features and the palaeocurrent patterns are consistent with the palaeoenvironmental interpretation suggested above, and provide some more details. The giant-scale cross stratification in Unit III (Fig. 5) is interpreted as the deposit of Gilbert-type delta. The bimodal pattern A1-A2 is considered to be the result of deposition on open shelf influenced by the NNW–SSE oriented tidal currents. Generally the same orientation of the modal class I (A1), dip direction of foresets in the giant-scale cross stratification complex and pinching-out of the conglomerate marker towards the north confirm the position of the source elevated to the south of the depository. Class proportions between A1 and A2 suggest that, in the process of redistribution of the terrigenous material brought to shelf from the source area, offshore-orientated flows prevailed over the landward component of the tidal currents. A unidirectional set of eastward-oriented currents (B) is proposed to result from reworking of shelf sediments by the long shore littoral currents.

Acknowledgements

I thank Bernard Vink for XRD identification of phosphorous minerals and acknowledge the help offered in the field by my B.Sc. students – R. Lasarwe, C. Mashabila and S. Lekula. J. Golonka and the referees A. Ślączka and S. Mazur are sincerely thanked for constructive criticism and suggestions. This work was supported by the University of Botswana Research Grant No. R270.

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Streszczenie

LITOSTRATYGRAFIA, SEDYMENTACJA I TEKTONIKA GRUPY TSODILO HILLS, NEOPROTEROZOICZNO-DOLNOPALEOZOICZNEJ SUKCESJI SILIKOKLASTYCZNEJ W NW BOTSWANIE

Marek Wendorff

Praca prezentuje w zarysie nowe wyniki badań nad grupą Tsodilo Hills, odsłaniającą się w północno-zachodniej części Botswany. Jednostka ta reprezentowana jest przez zmetamorfizowane skały terrygeniczne: kwarcyty, piaskowce, zlepieńce i łupki muskowitowe będące cześcią sukcesji deponowanych od neoproterozoiku, a następnie zdeformowanych we wczesnym paleozoiku podczas orogenezy panafrykańskiej, której maksimum w orogenie Damara w Namibii, bezposrednio na zachód od dyskutowanego obszaru, przypada na okres ok. 534–516 Ma. Skały te reprezentują kyanitową fację metamorficzną. Grupa Tsodilo Hills leży w obrę-

bie pasma orogenicznego Damara, które ciągnie się z Namibii poprzez Botswanę. Jego przedłużenie ku pólnocnemu wschodowi znane jest jako orogeniczny łuk lufilianski ("Lufilian arc") rozciągający się pomiędzy Zambią na południu a Demokratyczną Republika Konga (DRC) na północy.

Struktury i tekstury sedymentacyjne, systemy paleoprądów oraz kierunkowe zmiany facjalne sugerują iż depozycja grupy Tsodilo Hills przebiegała na obszarze otwartego szelfu pozostającego pod wpływami pływów i zaopatrywanego w materiał terrygeniczny dostarczany ze strefy źródlowej położonej na południe od obszaru sedymentacji. Postępująca depozycja została przerwana przez dwa epizody regresywne. Świadectwem pierwszej regresji jest kompleks czerwonych mułowców, pyłowców i piaskowców/kwarcytów erozyjnie rozciętych przez kanały wypełnione piaskowcami o dwukierunkowym warstwowaniu skośnym, interpretowane tutaj jako osady równi pływowych. Wzbogacenie tych skał w fosfor spowodowane było prawdopodobnie przez 'upwelling' głębinowych wód oceanicznych wywołany eustatycznymi zmianami poziomu morza. Druga regresja, której odbiciem jest poziom zlepieńcowy, wywołana była wzrostem intensywności dostawy materiału klastycznego.

Sukcesja osadowa jest zdeformowana przez liczne fałdki ciągnione, małoskalowe uskoki wsteczne oraz jedno nasunięcie. Stopień deformacji zmienia się stopniowo wzdłuż biegu tej struktury tak, że wyraźna strefa nasunięcia w południowym sektorze Tsodilo Hills ewoluuje lateralnie w cienką strefę skał nieznacznie zdeformowanych przez ścinanie w obszarze północnym. Kierunkowe struktury tektoniczne wskazują, iż lokalne ruchy nasuwcze skierowane były ku południowemu zachodowi.