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The Fish River Subgroup in Namibia: stratigraphy, depositional environments and the Proterozoic–Cambrian boundary problem revisited

G. GEYER*

Institut für Paläontologie, Bayerische Julius-Maximilians-Universität Würzburg, Pleicherwall 1, D-97070 Würzburg, Germany

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Abstract – The Fish River Subgroup of the Nama Group, southern Namibia, is restudied in terms of lithostratigraphy and depositional environment. The study is based on partly fine-scaled sections, particularly of the Nababis and Gross Aub Formation. The results are generally in accordance with earlier studies. However, braided river deposits appear to be less widely distributed in the studied area, and a considerable part of the formations of the middle and upper subgroup apparently were deposited under shallowest marine conditions including upper shore-face. Evidence comes partly from sedimentary features and facies distribution, and partly from trace fossils, particularly *Skolithos* and the characteristic *Trichophycus pedum*. Environmental conditions represented by layers with *T. pedum* suggest that the producer favoured shallow marine habitats and transgressive regimes. The successions represent two deepening-upward sequences, both starting as fluvial (braided river) systems and ending as shallow marine tidally dominated environments. The first sequence includes the traditional Stockdale, Breckhorn and lower Nababis formations (Zamnarib Member). The second sequence includes the upper Nababis (Haribes Member) and Gross Aub formations. As a result, the Nababis and Gross Aub formations require emendation: a new formation including the Haribes and Rosenhof and possibly also the Deurstamp members. In addition, four distinct sequence stratigraphic units are determinable for the Fish River Subgroup in the southern part of the basin. The Proterozoic–Cambrian transition in southern Namibia is most probably located as low as the middle Schwarzrand Subgroup. The environmentally controlled occurrence of *Trichophycus pedum* undermines the local stratigraphic significance of this trace fossil which is eponymous with the lowest Cambrian and Phanerozoic trace fossil assemblage on a global scale. However, occurrences of such trace fossils have to be regarded as positive evidence for Phanerozoic age regardless of co-occurring body fossils. Other suggestions strongly dispute the concept of the formal Proterozoic–Cambrian and Precambrian–Phanerozoic boundary. Carbon isotope excursions and radiometric datings for the Nama Group do not help to calibrate precisely the temporal extent of the Fish River Subgroup. Fossil content, sequence stratigraphy and inferred depositional developments suggest that this subgroup represents only a short period of late orogenic molasse sedimentation during the early sub-trilobitic Early Cambrian.

Keywords: Cambrian, Namibia, chronostratigraphy, biostratigraphy, depositional environment, trace fossils.

1. Introduction

The Nama Group represents a major stratigraphic unit in southern Namibia and adjacent northwestern South Africa, extending generally from the southern rim of the Damara orogen to the Vanrhynsdorp area in the northern Cape province for a distance of more than 1000 km. The area in which the sediments of this unit were deposited covered more than 350 000 km^2 and possess an outcrop area of approximately 125 000 km^2 (Fig. 1).

The group is divided into three more or less distinct lithostratigraphic units, termed the Kuibis, Schwarzrand and Fish River subgroups (SACS, 1980). Whether the three units should be treated as 'subgroups' or as 'groups' is a matter of debate and ultimately depends on conventions. Indeed, the lower two units (Kuibis and Schwarzrand) include numerous unconformities and represent a synorogenic, Damara-time sequence. The age of both subgroups is generally assumed as latest Neoproterozoic because of the presence of numerous Ediacaran-type fossils in various strata of both units. The stratigraphy is known relatively well because of fairly good outcrop situations along the generally N–S-trending Schwarzrand escarpment and recent studies of certain aspects (Germs, 1972*a*, 1983; Saylor, Grotzinger & Germs, 1995, 1998; Saylor & Grotzinger, 1996).

By contrast, the Fish River Subgroup (Fig. 2), generally assigned to the Cambrian, has received little attention. It is bound at the base by angular unconformities and represents largely a late orogenic molasse

* E-mail: gerd.geyer@mail.uni-wuerzburg.de

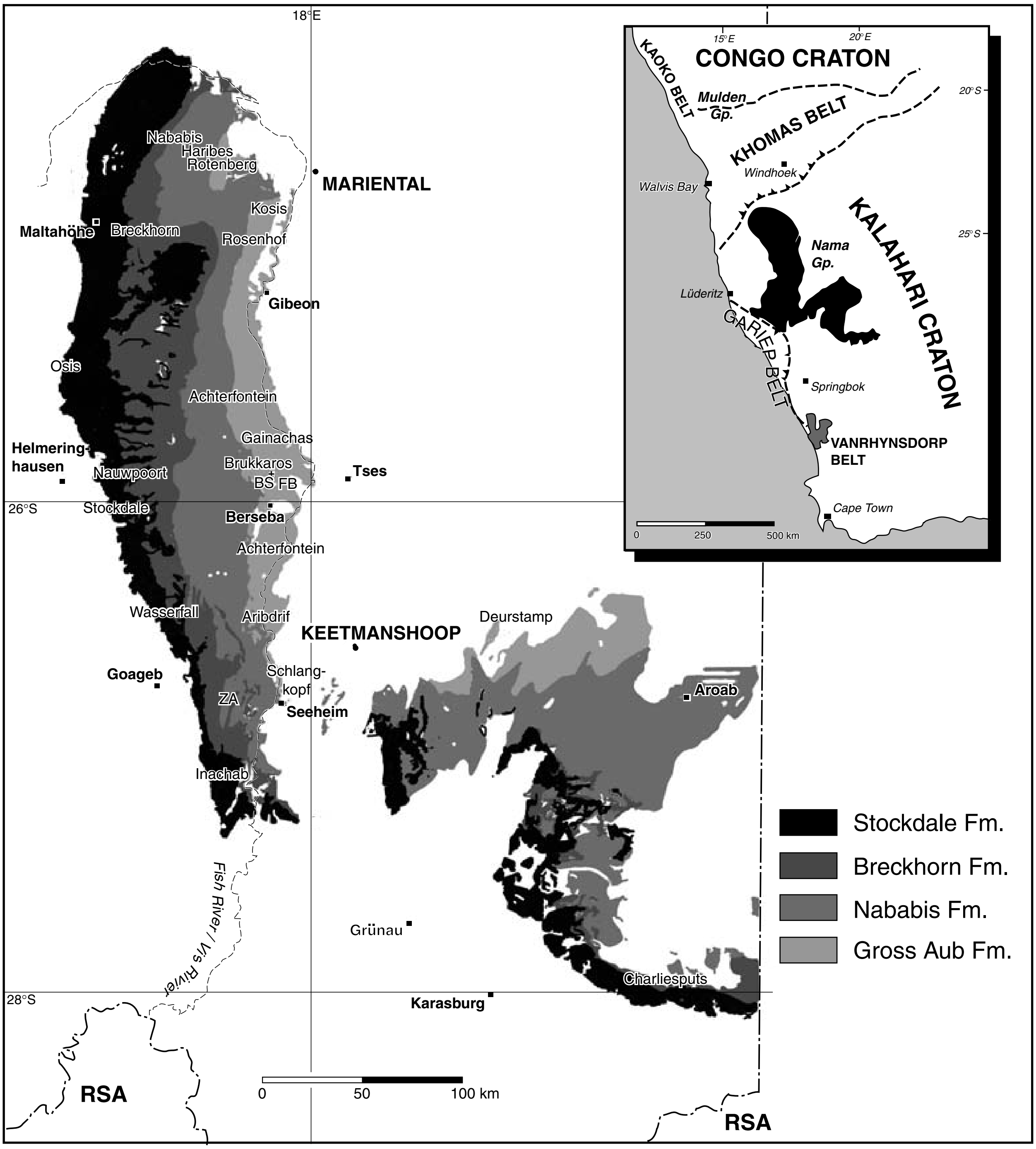

Figure 1. Sketch map of southern Namibia with outcrop area of the Fish River Subgroup (based on the Geological Map of South West Africa/Namibia 1: 1 000 000, 1980) and important localities. Names not in bold type refer to farms. Inset shows position of the outcrop areas of the Nama Group (black) and the adjacent tectonic/tectonostratigraphic units in southwestern Africa.

sequence of the Damara belt. Due to the relatively uniform deposition, the detailed stratigraphy is difficult to evaluate, and despite a huge outcrop area, sections are scarce and difficult to correlate. The major problem in studying the Fish River Subgroup is that the unit presently forms a huge blanket of relatively uniform deposits which gently dip towards the south and east. Due to the geological situation, only some basal parts of the subgroups are exposed at the Schwarzrand escarpment. Most of the subgroup can only be seen in relatively limited outcrops created by river valleys and creeks or along the highway B4 from Keetmanshoop towards Lüderitz in the section from Seeheim to Goageb. Although the area is generally little effected by tectonics, minor faults split the Fish River block into small tectonically bounded units that are extremely difficult to correlate. As a result, no detailed section throughout the Fish River Subgroup has been measured and

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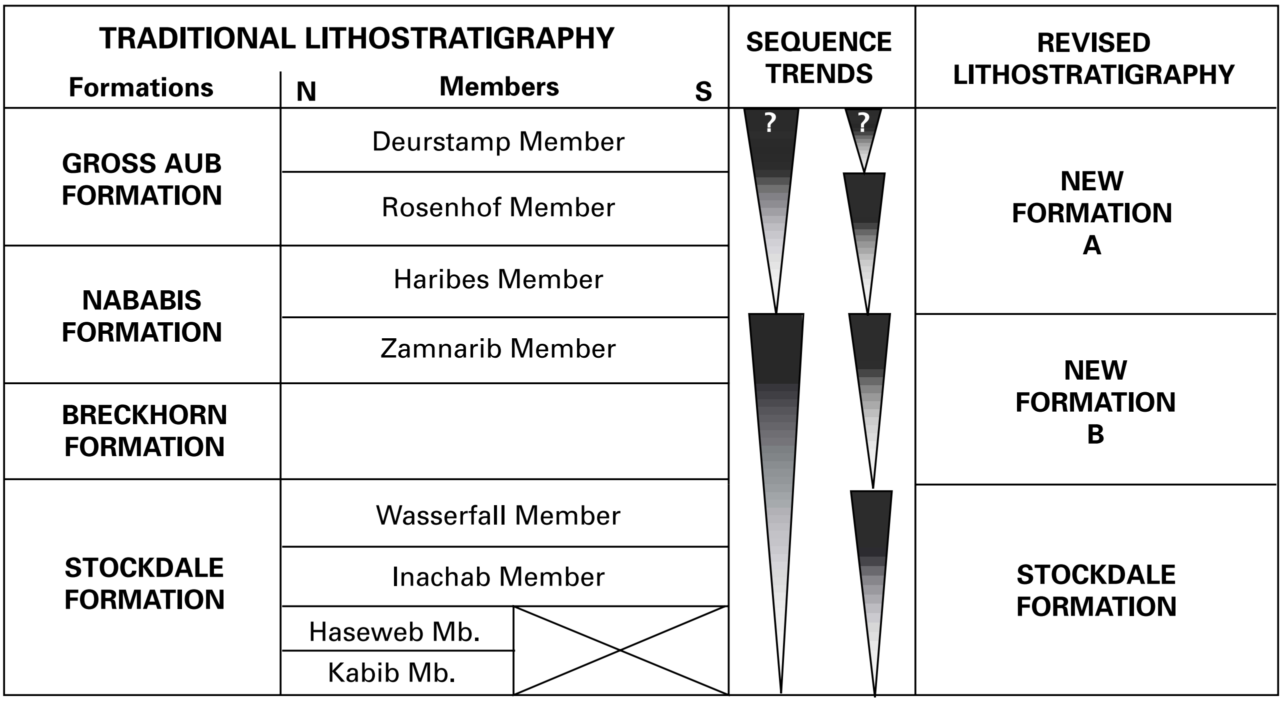

Figure 2. Lithostratigraphy of the Fish River Subgroup (Germs, 1983), with position of deepening-upward cycles in the southern part of the basin and suggested alternative lithostratigraphic classification.

published up to now, and knowledge of this unit has remained scarce. Studies concentrated on a coarse grid of the lithostratigraphy and depositional environment (Germs, 1972*a*, 1974, 1983, 1995) and the trace fossils found so far (Germs 1972*b*; Crimes & Germs, 1982; Geyer & Uchman, 1995).

This study presents some detailed sections, particularly of the upper Nababis and lower Gross Aub formations, with their environmental interpretation, and discusses possibilities for an improved chronostratigraphic interpretation.

2. The Fish River Subgroup – geological setting

The Fish River Subgroup consists in general of red fine- to medium-grained sandstones with frequent intercalations of red to purple shales. A change in the prevalence of sandstones and shales serves as a lithostratigraphic subdivision of the units into members and finally formations. The changes from sandstone-dominated to shale-dominated units can be interpreted as fining-upward cycles (Germs, 1983; Germs, Knoll & Vidal, 1986), best recognized in the northern part of the outcrop area. In terms of sequence stratigraphy, it represents a composite sequence of probably a second-order cyclicity (Gresse & Germs, 1993).

In contrast to the Kuibis and Schwarzrand subgroups, the Fish River Subgroup has a quite uniform pattern of changes in facies and thickness. The total thickness ranges from 600 to 1000 m with increasing thickness towards the south and east (Germs, 1983; Germs, Knoll & Vidal, 1986). It should be noted that this pattern contrasts with those of the Kuibis and Schwarzrand subgroups. These show two distinct bipolar depocentres separated by the so-called Osis ridge (Germs, 1974, 1983), a morphological palaeohigh that created the northern Zaris and southern Witputs subbasins. In addition, both subgroups increase in thickness towards the west.

In contrast, the Fish River Subgroup with its rather uniform facies distribution and thickness and with sediments of fluvial and shallow marine depositional environments is obviously the result of a rapid depositional phase, best interpreted as a molasse-type development. It is therefore understood as decoupled from earlier, synorogenic developments that were responsible for the existence of the Kuibis and Schwarzrand subgroups.

3. Tectonostratigraphic context

The Damara orogeny that produced the Khomas Belt in present-day central Namibia and adjacent Botswana is responsible for the development of the Nama Group (Fig. 1). This tectonic episode was a polyphased event starting in Late Neoproterozoic times with the opening of the Adamastor Ocean and a subsequent rotational opening of the Khomas Sea perpendicular to the Adamastor Ocean (see detailed description by Stanistreet, Kukla & Henry, 1991). The Khomas trough separated a northern Congo Craton from a southern Kalahari Craton. The major development of the enigmatic

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Snowball Earth (Kirschvink, 1992; Evans, Beukes & Kirschvink, 1997; Hoffman, *et al*. 1998) took place during this Khomas Sea development.

In the scenario of the evolution of the Damara (Khomas) and Gariep orogens, the Kuibis and almost the entire Schwarzrand subgroups were deposited during the Late to latest Proterozoic closing of two oceanic arms termed the Adamastor Ocean and the Khomas Sea gulf (Germs & Gresse, 1991). Subsequent convergence of the Congo and Kalahari cratons finally led to a closure of the Khomas Sea with a collision of the cratons. A clockwise rotation of the Kalahari Craton with respect to the Congo Craton created an active Andean-type margin on the Congo Craton, whereas the Kalahari Cration shows a passive margin sedimentation (Stanistreet, Kukla & Henry, 1991). The collision produced a fold-and-thrust belt with parts of the belt being transported southward, resulting in a peripheral foreland basin that represents the early Nama Group sedimentary basin. In particular, the basal Kuibis Subgroup represents a transgressive sequence which flooded the complicated pre-Nama relief. Deposits of the Schwarzrand Subgroup finally levelled the basinal morphology with clear facies changes and differences in sediment accumulation from west to east. During this time, shallow marine, often calcareous units developed in marine environments of the western basin, whereas a fluvial clastic belt with signatures comparable to the present-day Indus and Ganges basins developed along the peripheral margin in the east. The lower and middle parts of the Nama basin were separated by the so-called Osis ridge, a palaeohigh that can be interpreted structurally as a forebulge of the Khomas Belt of the Damara Orogen (Germs & Gresse, 1991).

The end of the Damara orogenic main deformation coincides with the transition from the Schwarzrand to the Fish River Subgroup. The Kuibis and Schwarzrand subgroups, which include numerous unconformities, represent synorogenic sequences. Stacked angular unconformities within the basal part of the Fish River Subgroup (see Section 9.a) are typical of pulsed sedimentation that results from multiple thrust events. Here, orogenic deformation and thrust faults that formed in the Khomas and Gariep belts resulted in angular unconformities within the lower Fish River Stockdale Formation, but no unequivocal angular unconformities are known from younger Fish River units.

The development ultimately gave rise to mature shelves that are characterized by a thick, relatively uniform sequence of fine- to medium-grained, whitish or red to purple siliciclastics. Thus, the Fish River Subgroup was deposited in an extended but quite uniform basin as a relatively monotonous sequence of red clastics of fluvial and shallow marine origin. The deposits are orogen-derived molasse sediments that onlap a basal unconformity and overstep older sequences in a cratonward direction (Germs & Gresse, 1991; Gresse & Germs, 1993). The loss of the Osis Ridge as a major source for facies changes and differential sediment transport led to the development on the Kalahari Craton of a uniform peripheral foreland basin apparently dominated by braided fluvial environments and with sediment transport from northerly and particularly westerly directions (Germs, 1983). However, the westerly transport direction indicates that the development cannot be explained exclusively by the Damara (Khomas) event. The Fish River depositional signature is attributed to a synchronous continent–continent collision, during which the newly assembled unit of Kalahari and Congo cratons collided with the South American São Francisco Craton, closing the Adamastor Ocean. During this Adamastor (or Gariep) Orogeny (see Stanistreet, Kukla & Henry, 1991), clastic sediments of the Fish River Subgroup were partly derived from the newly formed western Gariep (Adamastor) mountain belt, whereas the marine belt moved towards the east and southeast. The slightly increasing marine influence in later Fish River units such as the Zamnarib and Rosenhof members is interpreted herein as a later transgressive stage. Accordingly, Germs (1983) reconstructed a pronounced transport from north to south for late Fish River deposits.

It should be noted that a complementary hinterland basin on the Congo Craton was filled with the sediments that are now known as the Mulden Group.

4. The Tses 1-borehole

The only complete record of the Fish River Subgroup comes from the Tses 1-borehole, a completely cored drilling undertaken in 1971 by Aquitaine SWA and De Beers Oil Holdings in the search for hydrocarbons. The drill cores present the only complete record of a section through the Fish River Subgroup available to date and thus provide a standard of lithostratigraphy, thickness, and facies development for the central part of the Nama Group's present day distribution.

The borehole locality, at 18°04′12″ E and 25°50′30″ S, about 7 km NW of the village of Tses, between Ganigobes and the tarred highway from Windhoek to Keetmanshoop, originated at 924 m above sea level and first penetrated 128 m of late Palaeozoic Karoo deposits (Dwyka Formation).

4.a. Fish River Subgroup

At a depth of 128 m, the basal Dwyka tillites of the Karroo are unconformably underlain by green or purplish, fine-grained siliceous sandstones which form a 15 m thick cap on the Fish River Subgroup (Fig. 3). This unit is the Deurstamp Member of the Gross Aub Formation, which is often difficult to characterize. At Tses 1, the upper half is relatively uniform, consisting of argillaceous to siliceous, resistant fine-grained sandstones, which are grey (and probably decoloured)

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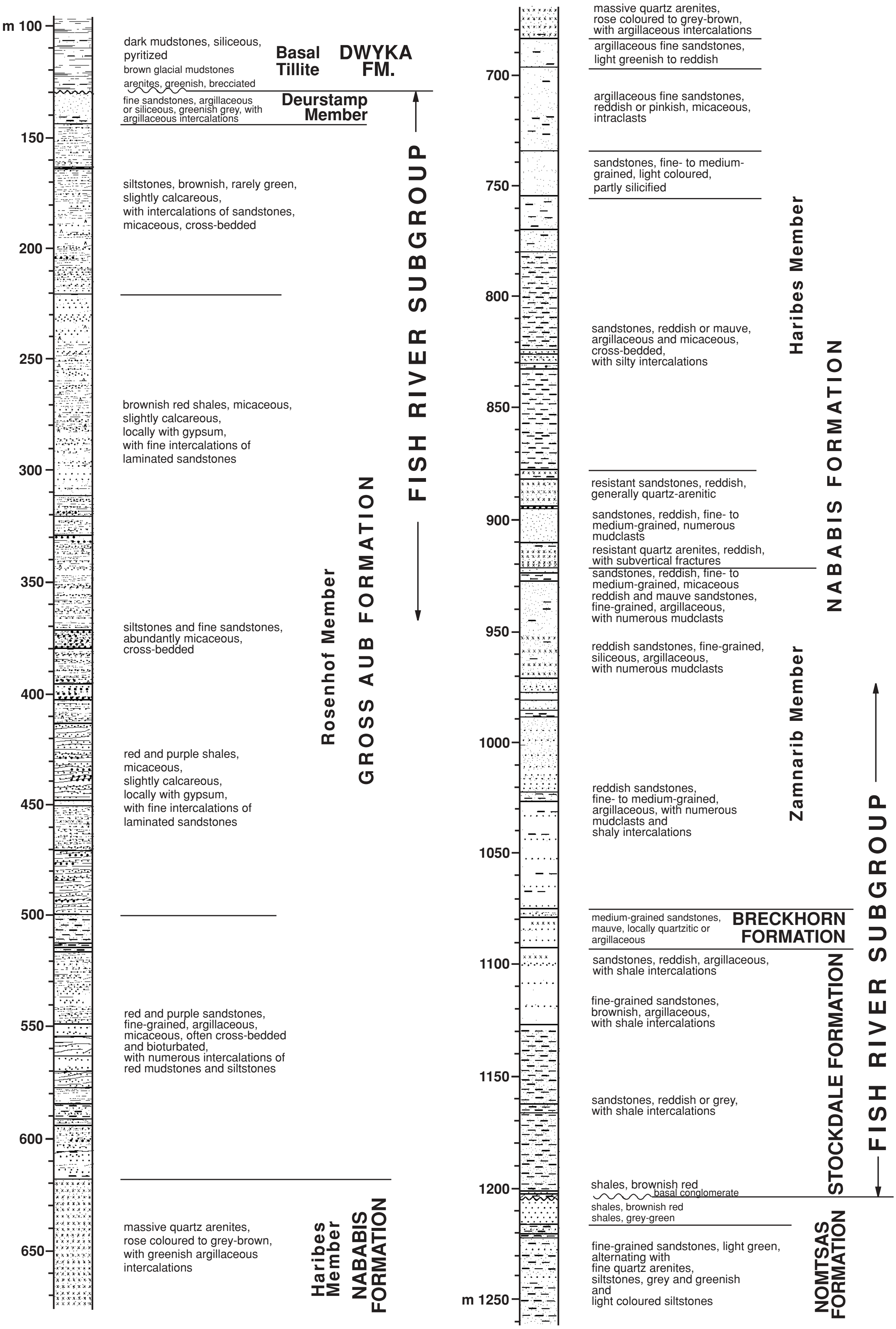

Figure 3. Profile of the Tses 1 borehole log, redrawn, modified and partly reinterpreted after the unpublished open file of Aquitaine SWA & De Beers Oil Holdings, supplied by the Geological Survey of Southwest Africa/Namibia, Windhoek. Depth in metres below surface.

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at the top and progressively reddish to purple downward. The lower part of the member includes brownish to reddish argillaceous and partly quartz-arenitic interbeds.

The Rosenhof Member at Tses 1 is a 474 m thick unit which can be divided into three parts: (1) The upper 227 m are brownish-red silty shale with thin intercalations of purple or grey-green sandstones. They intermittently pass into greenish siltstones and fine-grained sandstones. The shales are highly micaceous, very slightly calcareous, and occasionally contain pyrite. The original core-log reports gypsum from the shales, but it remains unclear how the sulphate is distributed in the rocks. The stratification is generally horizontal but often shows ripples, rarely cross-bedding. Basal lags of the sandstone beds include numerous large flat shale clasts. (2) The middle 118 m are an alternation of brownish-red shale units with purple micaceous siltstones and sandstone. The siltstones are very rich in mica, generally quite homogeneous. Sandstones generally show cross-stratification. (3) The lower 119 m are purple argillaceous and micaceous fine-grained sandstones with some intercalated brownish-red silty shales. The sandstones are quite homogeneous with abundant small mica flakes, but more argillaceous portions show a distinct fine banding. Thick beds are frequently greyish-green. Large flat shale clasts at the base of thicker and cross-bedded beds indicate frequent reworking on already consolidated mud-flats. Shale intercalations may be slightly calcareous.

According to the log, the subdivision of the Rosenhof Member could also be simplified. The upper *c.* 200 m are shale dominated with minor intercalations of sandstones, whereas the lower *c.* 250 m are characterized by prevailing sandstones with progressively more shale intercalations up-section.

The boundary between the Gross Aub Formation/Rosenhof Member and the Nababis Formation/Haribes Member lies at a depth of 617 m in the Tses 1 borehole, where a relatively uniform suite of grey-brown or rose-grey fine-grained quartz arenites ends. This 66 m thick top unit of the Haribes Member consists of relatively thick beds with moderate content of mica flakes and abundant flat shale clasts at their bases. Stratification is generally horizontal to more rarely cross-bedded. This top unit is underlain by 52 m of pinkish and purple argillaceous micaceous sandstones with some gypsum and rare mud clasts. Below are 20 m of beige, porous sandstones which frequently bear the black and brown spots also observed in outcrop deposits of the Haribes Member elsewhere. The major part of the Haribes Member at Tses 1 consists of 122 m of argillaceous and micaceous purple sandstones, with frequent flat shale clasts and generally horizontal stratification but some low-angle cross-bedding. Shale intercalations are quite rare. The basal 44 m of the Haribes Member constitute a very resistant unit. The upper 17 m consist of purple quartz-arenitic sandstones and the lower 12 m of purple and quartz-arenitic sandstones with argillaceous pebbles. Between are purple, pinkish or brownish medium-grained sandstones with numerous shale clasts. These sandstones are generally cross-stratified and occasionally even show a herringbone cross-stratification.

The Zamnarib Member of the Haribes Formation has a total thickness of 153 m at Tses 1. The upper part consists of about 80 m of purple argillaceous sandstones with numerous shale clasts and thin-bedded purple shales. The 3 m are fine- to middle-grained purplish sandstone, very argillaceous, with low mica content and brownish shale clasts. This is underlain by an alternation of purple and brownish argillaceous siltstones with numerous mud clasts and purple to pinkish, often coarse sandstones, which are cross-stratified and immature. They pass into fine-grained and cross-stratified, quartz-arenitic purple to brownish sandstones with thin mudstone intercalations and frequent mud clasts. The rest of the Zamnarib consists of a roughly 75 m thick alternation of purple argillaceous and micaceous fine-grained sandstones and shale interbeds with abundant mica. Flat pebbles of reworked mudstones are abundant.

These are underlain by 17 m of rose-coloured to purple, rarely greenish quartz-arenitic medium-grained sandstones interpreted here as the Breckhorn Formation. The sandstone beds are generally highly micaceous and show considerably increased grain-sizes in some layers. Shale intercalations are rare.

The Stockdale Formation at Tses 1 cannot be divided clearly into members. With a total thickness of only 108 m, it is dominated by fine-grained sandstones with minor shale interbeds. The top 14 m consist of purple, argillaceous medium-grained sandstones, some of which are slightly quartz-arenitic, and with rare intercalations of brownish-red mudstones and siltstones. Calcareous nodules are reported in the original drill log. The lower 88 m are made up of the typical mauve argillaceous micaceous, fine-grained sandstones with rare brownish shaly interbeds. The top unit is underlain by roughly 20 m of fine-grained, rarely coarser sandstones which are argillaceous and abundantly micaceous. Again, intercalations of brownish-red or even greenish shales occur rarely. Below is a thick (*c.* 75 m) unit of homogeneous sandstones, which changes colour from purple to greyish-mauve. Argillaceous intercalations are rare. The base of the formation consists of brownish-red shales which overlie a coarse sandstone layer with coarse angular clasts and reworked mud flakes at a depth of 1203 m.

4.b. Schwarzrand Subgroup

The Schwarzrand Subgroup at Tses 1 consists of only 345 m of rocks and is thus clearly thinner than the Fish River Subgroup, although it is usually the thickest unit of the Nama Group in the southwestern outcrop areas.

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It is almost devoid of carbonates and thus represents the facies known from the Zaris Subbasin.

The top 12 m consist of red and green shales that probably represent the Vergesig Formation (or Member). The topmost 5.5 m are brownish-red silty mudstones; below are greyish-green to dark grey silty mudstones.

A suite that can be identified as the Niep Member of the Nomtsas Formation underlies this shale unit, but it is difficult to define its base. These *c.* 60 m consist mainly of green fine-grained micaceous and siliceous sandstones with frequent thin shale seams. Oblique stratification can be frequently observed. Occasional pyrite and carbonate nodules are present. Some strata consist of quartz-arenitic, finely pyritic sandstones. Intercalations of purple or green siltstones and mudstones may also include calcareous nodules.

This unit is underlain by about 12 m of brownish-red or green silty shales with some sandy intercalations and rare pyrite content. The strata appear to represent the lower Kreyrivier Member of the Nomtsas Formation. Below are again purple, rarely greyish-green argillaceous fine- to medium-grained sandstones (about 15 m), underlain by a single calcareous thin (0.5 m) unit of light grey limestone within black, greenish speckled shales, which appears to represent the Spitskop Member of the upper Urusis Formation. The *c.* 25 m of purple, fine-grained sandstones below include quartz-arenitic intercalations and have an essentially calcareous matrix. This unit passes into roughly 50 m of greyish-green, sometimes pinkish micaceous sandstones with brownish shale intercalations, which are herein interpreted as the lower Urusis Formation in its proximal facies development.

Strata of the Schwarzrand Formation below include some 155 m of generally siliciclastic deposits which are not discussed in detail here.

4.c. Biostratigraphic information

Biostratigraphic information from the Tses 1 borehole is based on a few organic remains described by Germs, Knoll & Vidal (1986). These authors analysed microfossils in a number of samples taken from the cores of the Schwarzrand Subgroup. Most productive were samples from the upper Urusis Formation at a depth of 4533 feet (= 1284 m) that included organic microfossils such as *Leiosphaeridia* spp., *Chuaria circularis* Walcott, *Bavlinella faveolata* (Shepeleva) Vidal, and probably oscillatorian cyanobacteria, but also fragments attributed to the problematic algal-type *Vendotaenia*, best known from the terminal Proterozoic of the East European Platform. These vendotaenids are most abundant in some of the samples taken from the upper Urusis Formation.

Filamentous sheaths that could represent considerably altered remains of vendotaenids also occur in younger samples such as at a depth of 3973 feet (=1212 m) (Germs, Knoll & Vidal, 1986, fig. 5d), which come from the greenish shale unit interpreted herein as the lower Vergesig Formation.

5. Sections of the Stockdale Formation

The Stockdale Formation with its three members was studied on Farm Stockdale, *c.* 25°59′35″ S, 17°02′30″ E and the adjacent farms Rotterdam, Nauwpoort and Bremen (Fig. 1). The Stockdale farm is the eponymous locality for the formation and exposes much of the rock succession in a low ‘rivier’ (dry river valley). However, the lithologies are not favourable for recognition of details. Because of weathering, only medium- and coarse-grained sandstones present measurable beds, whereas finer-grained clastic rocks and their sedimentary structures are difficult to identify precisely. Fine clastics are generally deeply weathered between coarser rocks and now serve as homes or hideouts for dassies (hyraxes).

Our measurements included just a few sections of up to 20 m in thickness that cannot be tied to a continuous section throughout the formation. The total thickness is estimated here as roughly 140 metres. Along the road from Seeheim to Goageb, roughly 13 km west of the Fish River bridge, the formation is dissected by several faults so that no complete succession can be examined.

The base of the formation (the Inachab Member) is exposed for several metres at 25°59′37″ S, 17°02′29″ E, close to the upper edge of the Schwarzrand Escarpment. The outcrops exhibit multiple erosional contacts on top of the Nomtsas Formation. The Stockdale Formation commences at an erosive contact overlain by pebble conglomerates grading upward into coarse sands. The basal pebbles are here generally fairly well rounded and consist almost exclusively of pure quartz. The lithology changes upward into coarse- and medium-grained and also fine-grained sandstones with frequent brownish mudclasts at the bases of the beds. Basal surfaces of medium- to coarse-grained sandstones may also show large and complex load casts (Fig. 4b), occasionally on a thin drape of mica, or even convolute lamination.

These lowermost beds of the Stockdale Formation display a distinct framework of closely spaced conglomeratic units divided by erosional surfaces which are characterized by angular contacts. The changes in the dipping of overlying strata can be traced over distances of several kilometres. Thus, the erosional contacts have the character of angular unconformities. Characters and granulometry of the clasts of the conglomeratic beds (well-roundedness and sorting of coarse fraction with bash marks, but mixing with finer grains and less well-rounded fine- to medium-sized grains) appear to indicate that coastal gravel beds were subsequently reworked by fluvial activities.

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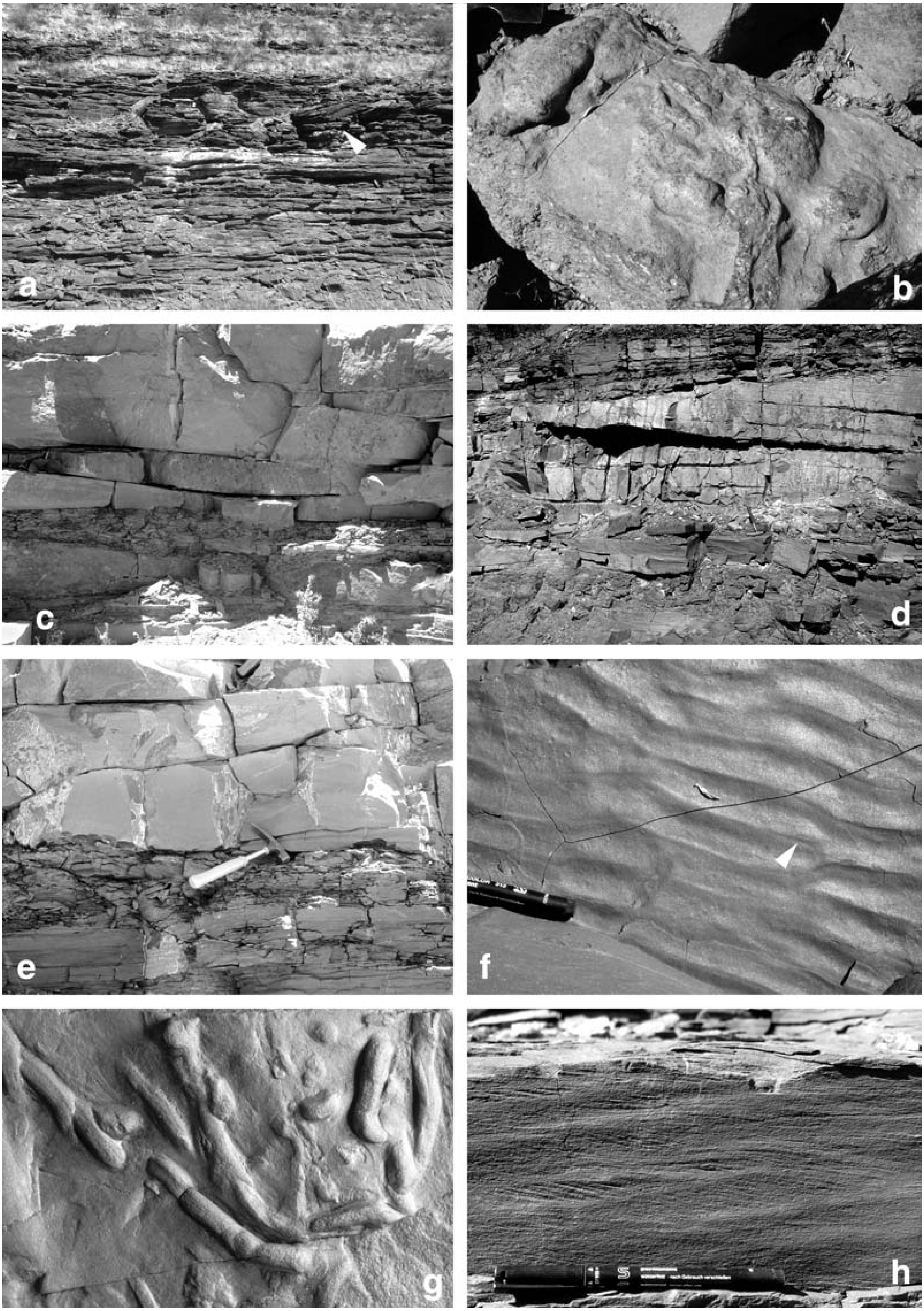

Figure 4. For legend see facing page.

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The lower part of the formation (estimated thickness at least 90 m) on Farm Stockdale consists of a relatively uniform succession of medium-grained sandstones with subordinated thin layers of coarse-grained sandstones and thicker beds of fine-grained sandstones. The generally feldspathic sandstones have an argillaceous matrix and are often richly micaceous. They are typically developed as comparatively thin and laterally small (several metres) trough cross-beds. Fine-grained sandstone layers show various sedimentary structures such as atypical load structures figured by Geyer & Uchman (1995, fig. 10.4). The dense pattern of the sandstone lenses with the trough shapes, partly crude bedding and imbrication of clasts, occasional planar–tabular cross-sets, and ladderback ripples are architectural elements typical of a fluvial regime that includes braided rivers and occasional floodplains. Transport directions are generally from NW to SE but appear to fluctuate greatly for the different beds.

Fresh rocks are rarely observed on the Stockdale, Rotterdam and Nauwpoort farms, and the usually brownish to reddish colours of the sandstones partly result from weathering. Rare thin shale intercalations are brownish-red or purple. The exposures on the Nauwpoort and, to a lesser extent, Bremen farms have a similar pattern of comparatively thin (*c.* 40 to 60 cm, occasionally up to more than 1 m) and laterally small (*c.* 2–4 m) trough cross-beds (Fig. 4a) of generally medium-grained feldspathic sandstones with frequent basal lags of reworked mudclasts, a facies distinguished by Germs (1983) as the Wasserfall Member. Flat-bedded and laminated sandstones remain subordinated but the bed tops of such rocks may be covered with ripples. Shale intercalations are thin.

The exposures along the highway from Seeheim to Goageb show for the middle to upper part of the section lenticular fine-grained, often feldspathic, sandstone beds with only low convex channel bases (Fig. 4c). The conspicuous internal lamination with low-angle cross-stratification and thin interbeds of shaly sandstones indicates a less energetic fluvial regime with numerous, relatively small channels. In total, the transport direction was easterly, as previously illustrated by Germs (1983).

The uppermost part of the formation on the Nauwpoort and Bremen farms consists of fine- to less frequently medium-grained, often quartz-arenitic sandstones, which are reddish to purple but also light-coloured. They are typically developed as tabular bodies without obvious erosive bases. They weather into platy slabs without conspicuous sedimentary structures. Fine-grained sandstones with low to very low cross-sets occur and suggest a tidally influenced, upper shoreface deposition of those beds. A similar succession is exposed along the Seeheim–Goageb highway showing primarily light-coloured, whitish to pinkish cross-laminated fine-grained sandstones with reddish or purplish intercalations of sandy shales. It should be noted that fine detritic feldspars have been observed at several horizons.

Germs (1983) reports greyish fine- to medium-grained quartzitic sandstones and thin mudstones intercalated in the Wasserfall Member (upper Stockdale Formation), with mudcracks, runzelmarks, interference ripples and raindrop imprints and interpreted those layers as tidally reworked fluvial deposits.

6. Sections of the Breckhorn Formation

The Breckhorn Formation (Germs, 1983) takes its name from Farm Breckhorn in the northernmost part of the Fish River outcrop area with the best sections along a river valley on the farm south of the the main road C34 from Maltahöhe to Mariental. The road passes this farm and also the Breckhorn Formation roughly 20 km east of Maltahöhe. However, the low exposures along the road do not present a detailed and complete picture of the rock succession. Visible are fine- and less frequently medium-grained, laminated or slightly cross-stratified sandstone beds arranged partly as trough-shaped bodies with very minor purplish shale intercalations. Some beds include coarse sandstones. Where the exposures are favourable, the beds may reach considerable thicknesses of more than 1.2 m, and

Figure 4. Outcrop pictures of the lower Fish River Subgroup. (a) Stockdale Formation, Wasserfall Member. Cross-bedded medium-grained sandstones with typical weathered appearance. Arrow points to base of trough. Farm Nauwpoort (east of Helmeringhausen). Picture shows *c.* 8 m of section. (b) Stockdale Formation, lowest part of Inachab Member. Oblique view of large load structures on lower surface of conglomeratic layer. Farm Nauwpoort (east of Helmeringhausen). Slab is *c.* 50 cm in diameter. (c) Stockdale Formation, middle(?) part. Trough cross-bedded sandstones. Highway between Seeheim and Goageb. Picture shows *c.* 1.5 m of section. (d) Breckhorn Formation. Large sandstone wedge with shallowly dipping planar foresets. Highway between Seeheim and Goageb. Picture shows *c.* 2 m of section. (e) Nababis Formation, middle part of Zamnarib Member showing conspicuous change from purple, laminated and partly flaser-bedded shales to light-coloured, cross-bedded fine-grained sandstones with internal low-angle cross-bedding. Note large reworked mudclasts at contact. Highway between Seeheim and Goageb. Hammer (length 30 cm) for scale. (f) Nababis Formation, Zamnarib Member. Surface with symmetrical ripples branching in 'tuning-fork' fashion and with collapse structures on ripple crests (arrow). Highway between Seeheim and Goageb. Pen (9 mm in diameter) for scale. (g) Nababis Formation, Zamnarib Member. Trace fossil *Trichophycus tripleurum* Geyer & Uchman, 1995; holotype (PIW 94X45) in upper left corner with clear longitudinal tripartition. Hyporeliefs on lower surface of fine-grained sandstone bed. Highway between Seeheim and Goageb. Natural size. (h) Nababis Formation, Zamnarib Member. Vertical section of fine-grained purple sandstone bed showing climbing ripples with low angles of the stoss and lee surfaces. Highway between Seeheim and Goageb. Pen (14 cm in length) for scale.

cross-bedding may be developed as relatively thick sets. The beds may include basal lags of mud clasts. Shale intercalations are from a few centimetres to more than 20 cm thick.

The formation has been examined in detail for this study along the road between Seeheim and Goageb close to the district boundary between Keetmanshoop and Bethanie, about 17 to 18 km west of the bridge over the Fish River. The contact with the Stockdale Formation is at a vertical fault so that the base cannot be studied. (Another, probably complete, succession of the Breckhorn Formation along the same highway several kilometres to the west on Farm Uitkoms does not offer informative outcrops.)

A *c.* 35 m thick succession of violet and mauve-coloured, rarely purple sandstones is exposed. This indicates that the thickness of the formation is clearly greater than the unit in the Tses 1 borehole. Bed sizes vary considerably but are generally in the order of 30 to 60 cm. Most of the sandstones are well-sorted, fine-grained and quite uniform, but medium-grained sandstones may also occur. Sometimes a slight fining-upward can be observed, with rare layers of coarse quartz grains. Relatively fine-grained and thinner sandstone beds occasionally have a greenish colour. The generally high content of mica on bedding planes is conspicuous.

Shale intercalations were generally described as thin and negligible. However, the examined outcrops along the road between Seeheim and Goageb include packages of purple siltstone that may attain a prominent thickness of up to about 25 cm. The shale units separate the sandstone beds but also develop from sandy bed tops as coalescing mud flakes.

The sandstone beds are very variable in shape. Usually they form lenticular bodies with shallow erosive channel bases and appear to be amalgamated from two to four layers separated by thin joints. Conspicuous wedges may occur, representing distinct foresets with parallel lamination at an extremely low angle (Fig. 4d). The transport in these sandstones took place in easterly directions (65 to 95°), which is in accordance with the transport direction suggested by Germs (1983). By contrast, channels have a preferred NNE–SSW to NE–SW orientation. Horizontal sandstone layers are developed as medium-thick, tabular bodies and have a fairly wide lateral extension that may rhythmically alternate with thin shale layers.

An analysis of the depositional environment is relatively difficult. The wide spectrum of sedimentary structures appears to indicate both a deposition under a distal fluvial and very shallow, tidally influenced marine regime. Particularly interesting are large sandstone wedges with shallowly dipping planar foresets. The angles of these foresets are generally too low for a fluvial regime under recent conditions on earth (e.g. Miall, 1996; Best *et al*. 2003). Although the terrestrial condition during Early Cambrian times may have been dramatically different due to the absence of vegetation on land and resulting different conditions for a flow regime, the sedimentary structures are better interpreted as formed in the upper shoreface. The sediment bodies indicate that lateral transport was very modest. Parallel lamination of the bodies without bars indicates high velocities of streaming water. Frequent intercalations of muddy shales between the cross-bedded or laminated fine-grained sandstones excludes the interpretation of formation by a braided river system (although some localities possibly show a fluvial component: G. Germs, pers. comm. 2003). Instead, the sedimentary structures and fabrics suggest a sequence formed under shallowest marine conditions, mostly along a tidally dominated coastline.

7. Sections of the Nababis Formation

The Nababis Formation as in current use of the term was introduced by Germs (1983) and subdivided into two members, termed the Zamnarib and the Haribes Member. Although the Zamnarib and Haribes members constitute a major part of the Fish River Subgroup and represent a considerable part of the outcrop area, helpful exposures are rare, particularly for the Zamnarib Member.

7.a. The Zamnarib Member

Like the Breckhorn Formation, the Zamnarib Member has been examined along the Lüderitz road B4 between Seeheim and Goageb, close to the district boundary between Keetmanshoop and Bethanie, *c.* 10.5 km west of the bridge over the Fish River.

A relatively thick and variable succession of purple sandstones and shales is exposed. Several faults cut the outcrops so that an exact measurement of the thickness is not possible. The supposed basal part of the Nababis Formation and Zamnarib Member in the western part of the exposure is truncated by such a fault, which obviously brought down the eastern block so that part of the lower Zamnarib Member is missing.

The lower Zamnarib Member at the Lüderitz road is generally an alternation of fine-grained sandstones with minor shale intercalations. This part of the succession resembles in general the Rosenhof Member of the Gross Aub Formation but shows a higher content of sand with a less mature composition. This part and a structurally limited block to the east include at least 50 metres of thickness with similar lithologies and sedimentary structures. The bed thickness of the sandstones generally ranges between 20 and 70 cm. The sandstones are usually fine-grained and often abundantly micaceous. Their top surfaces are frequently covered with wave ripples (Fig. 4f) and may also show syneresis cracks. The beds may also show flame structures and internal truncation scours. Basal lag deposits are often developed with numerous purple mudclasts with a lithology that matches that of the shales below. The clasts are up to several centimetres in size and are usually flat with a subcircular shape.

No trace fossils have been found as epichnia on the bed tops. However, *Skolithos*-type vertical tubes were observed in two beds, and the studied section is the type locality of the complex ichnofossil *Trichophycus tripleurum* Geyer & Uchman, 1995. It is a winding burrow system consisting of 3 to 4 mm wide subangular segments which are horizontally arranged proximally and curve upward distally, with a delicately trilobate lower side. The trace occurs as hypichnia on the lower side of sandstone beds (Geyer & Uchman, 1995; Fig. 4g). Apparently, the same ichnofossil was informally described as 'trails with three parallel ridges' by Germs (1972*a*,*b*) from the Nasep Member of the Schwarzrand Subgroup.

The shales in this lower part of the formation change between brownish-purple mudstones and siltstones with frequent horizontal lamination. The middle and upper parts of the Zamnarib Member are generally similar but include conspicuous amounts of whitish to pinkish sandstones. These sandstones are fine-grained and have an internal cross-stratification or a clear horizontal lamination due to slight differences in grain sizes. The beds are generally between 20 and 40 cm thick and form extended lenses, typically arranged laterally in alternating wedge-shaped bed complexes (Fig. 4e). The complexes usually show large reworked mudclasts at the base, irregularly resting on generally flaser-bedded units of brownish-purple siltstones and finest-grained sandstones (Fig. 4e). Measurements on the foresets indicate transport directions from the north and northwest.

A slight change in facies is marked by less frequent mudclasts in the middle part of the member and a slight increase in grain size up-section. However, the amount of light-coloured sandstones decreases up-section, where reddish to purplish fine-grained sandstones as well as relatively thin units of purple shales attain again a greater amount of the succession. The fine-grained argillaceous sandstones often show climbing ripples with a relatively low angle of the stoss as well as the lee surfaces (Fig. 4h). The bases may have abundant shale clasts.

Again, faults cut the exposures in the upper part of the Zamnarib Member so that an exact measurement of the thickness is not possible.

7.b. Sections of the Haribes Member

Apart from the Stockdale Formation, the Haribes Member is geomorphologically the principal and governing element of the Fish River Subgroup. Much of the immense plain east of the Schwarzrand escarpment is caused by the resistant quartz-arenitic sandstones of the member. The relatively thin blanket of Rosenhof 'shales' on top barely veils the easterly dipping Haribes platform. Structural deformations such as subtle flexural bulgings of the unit in response to tectonic and sedimentary loading inflections are even depicted by the surface topography.

Nevertheless, outcrops that show a considerable part of the Haribes Member are scarce. Our field investigations included partial sections on Farm Landshut (*c.* 45 km WSW of Berseba) and along the highway from Seeheim to Lüderitz, a short distance west of the Fish River bridge, and a major section on the southern slope of the Gross Brukkaros mountain near Berseba.

The section on Farm Landshut is a deep canyon that exposes a typical part of the lower Haribes Member with a total measurable thickness of about 40 m. The succession is monotonous, showing up to 1.2 m beds of pinkish to purple quartz arenites, which are now largely covered with dark grey desert varnish. The lowermost parts of the beds often include medium-sized to very large (up to more than 10 cm) intraclasts, which are usually subcircular in shape and indicate reworked purple shales. Internal sedimentary structures include lamination with very minor changes in grain-sizes and low-angle cross-stratification. The architecture usually shows beds with a moderate change from maximum to minimum thickness over one to several decametres so that a close view of the succession appears to show nearly constant thicknesses of the beds. Due to exposure in an arid climate, thin shale intercalations are extremely difficult to characterize with confidence. Thicker shale intercalations are recognizable as scoured horizons.

7.b.1. Brukkaros section MV

The Gross Brukkaros section MV (Fig. 5) stretches along the lower course of the subradial main valley that drains the crater-like central depression of the Brukkaros mountain (Fig. 1) in a southerly direction. The exact location and position in relation to the stratigraphically younger sections of the Gross Brukkaros area are described below in Section 8.a.

The strata of the Haribes Member in the lower and middle part of the slope generally dip at *c.* 15 to 20° towards the periphery. The outcrops on the valley's flanks expose a succession of 91 m which represents the middle and upper part of the member.

The succession (Fig. 5) is relatively uniform throughout, mainly consisting of very resistant siliceous fine- and medium-grained sandstones and minor intercalated shale units (generally only up to 20 cm thick). The sandstone beds are usually 0.5 to 0.8 m thick although the bed thickness varies considerably. Comparatively thick beds usually include a basal lag of shale clasts that forms 'conglomeratic' layers. The shale clasts have a characteristic subcircular outline but are relatively thin. The size varies enormously. The largest clasts observed in the MV section were 14 cm in diameter with a thickness of about 2.5 cm. Upper and lower

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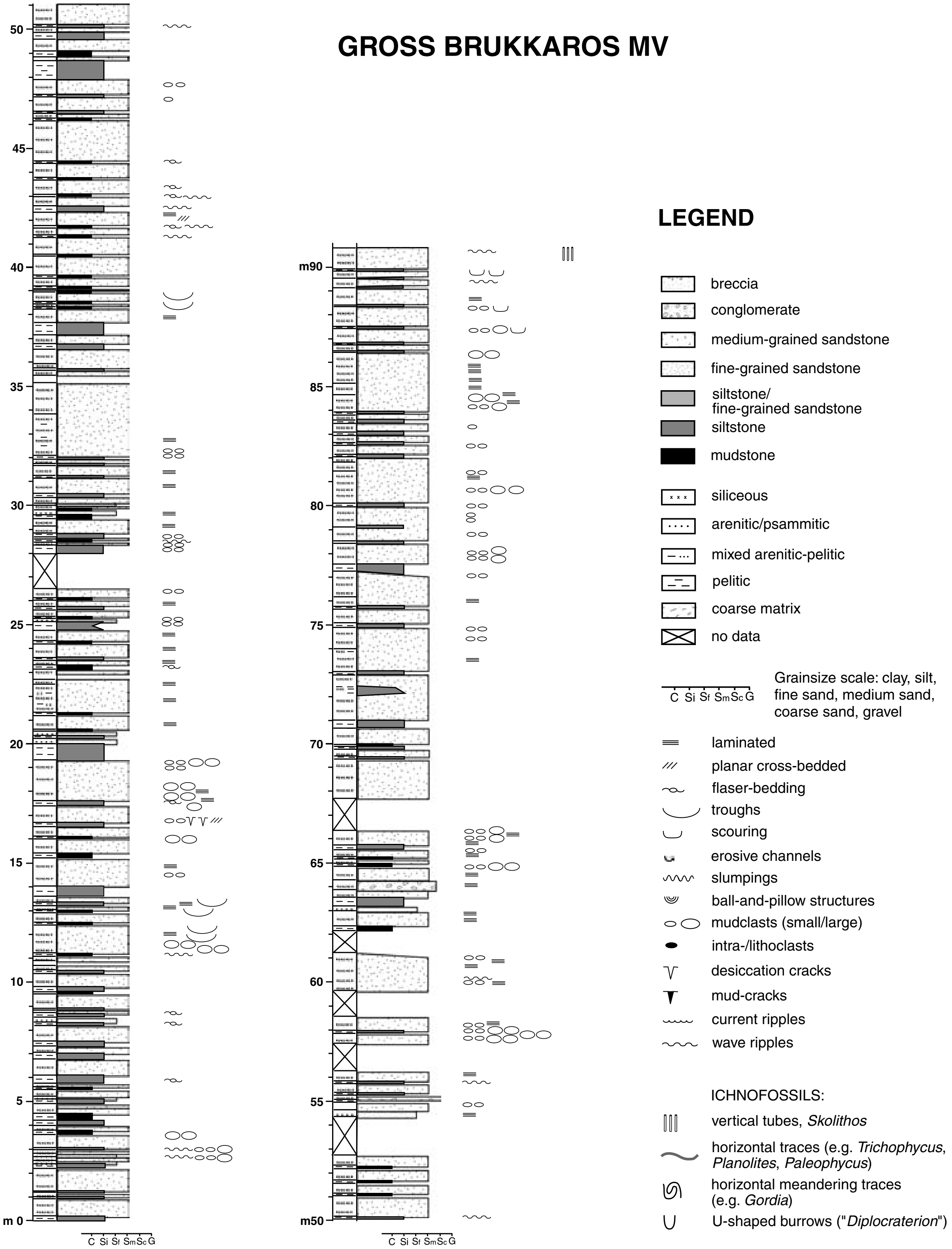

Figure 5. Profile of the Gross Brukkaros MV section, displaying lithologies and grain sizes of the middle and upper Haribes Member of the Nababis Formation.

surfaces are roughly even but may show some wavy subconcave habit due to post-sedimentary compaction. The shape and lithology suggest that the clasts were regularly eroded from strata underlying the sandstone beds with the shales having undergone early diagenesis before being reworked.

The lower part of the MV section (*c.* 11 m) consists of relatively thin sandstone units which are usually

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amalgamated from single, *c.* 20 to 30 cm thick beds of quartz-arenitic, medium-grained sandstone. Shale clasts are relatively scarce in that part of the section, but several ripple surfaces can be seen. Intercalations of reddish to purple siltstones and mudstones are thicker than in the stratigraphically higher parts of the section and reach up to 0.5 m. Siltstones at 6, 8 and 9 m show flaser bedding.

Between 11 and *c.* 20 m is a first unit dominated by thick medium-grained quartz arenites. The bed complexes are clearly composed of series of platy, 20 to 30 cm thick beds with large to very large shale clasts in the basal centimetres and attain thicknesses of up to 1.4 m. Internal sedimentary features are scarce, but tabular cross-stratification is visible in a few beds, and large-scale fining-upward successions are recognizable. Beds tops may show syneresis cracks. The sediment transport in these beds indicates flow directions to the south and southeast. A more shaly unit follows above (20 to 32 m). The succession is quite variable with a steady fluctuation from laminated mudstones and siltstones to platy quartz arenites with only relatively small reworked shale clasts at their bases.

A second unit dominated by thick medium-grained quartz arenites makes up the section between 32 and 48 m. Shale clasts in this stratigraphic interval are comparatively rare, whereas the bed tops are regularly covered by ripples. Thinly laminated sandstones occur at *c.* 33 and 38 m, tabular cross-stratification at 43 m, and shale intercalations as well as sandstones show a slight flaser-bedding between 41 and 44 m. The beds with tabular cross-stratification appear to show sediment transport in easterly or northeasterly directions. The shale units remain thin (up to about 15 cm), but a *c.* 55 cm thick unit of purple siltstones is developed at 37 m, and another relatively thick unit at 42 m.

The dominance of quartz arenites is interrupted by a *c.* 75 cm thick siltstone package at 48 m, followed up-section by a quite variable succession of platy quartz arenites, thin to moderately thick siltstone horizons and thin mudstone layers (between 48 and 68 m). In this interval, the number of beds with reworked shale clasts increases dramatically, with a succession of relatively thin multiple intraclast beds between 57 and 68 m. The sandstone units are often composed of thin to very thin sandstone layers attaining even a shaly appearance and are often interrupted by relatively thick siltstone units. At 68 m another unit dominated by thick medium-grained quartz arenites starts with a 1.6 m thick homogeneous bed of medium-grained sandstone. Up to the top of the formation, amalgamated sandstone beds form roughly 1 to 1.5 m thick bed complexes which are usually separated into roughly 20 cm thick individual beds each with small- to medium-sized, occasionally very large, shale clasts in a basal layer. Bed thickness of the sandstones decreases between 81 and 86 m with the sandstones at 84 to 86 m being thinly to very thinly bedded. The sandstone units in this interval intermittently show lateral swelling that creates a trough-shaped base of the beds and also accounts for a reworking of shales during an initial erosional phase. The sediment transport in these beds again indicates flow directions to the south and southeast. Shale layers are usually thin (up to 20 cm) in this interval but in response to the sandstone lenses may show variable thicknesses of up to 40 cm.

The sandstones of this top unit of the Haribes Member particularly contradict the orthodox view of an almost entirely fluvial origin of the member. The thick beds consist of well-rounded grains. They are well-sorted and mature and may be termed 'orthoquartzites' *sensu* Pettijohn, and they include several horizons with *Skolithos* tubes (above 88 m) (Fig. 6e). Therefore, they are quite clearly recognizable as coastal sands.

7.b.2. Seeheim section

The outcrops in the area of Farm Naiams along the highway west of Seeheim expose the lower, middle and part of the upper unit of the member in a fresh condition so that details of the sedimentary structures can be studied. However, the succession is cut by a number of small faults so that the section is not continuous. In addition, the uppermost part is covered and cannot be examined.

The lower part of the member is made up primarily of a comparatively uniform succession of fine-grained well-sorted sandstones with rhythmic fluctuations into shaly intervals. Fresh outcrops indicate that the sandstones are primarily greyish-green but tend to grade secondarily into reddish and purple horizons (Fig. 6b). The beds have thicknesses between 10 and 40 cm and are actually thin troughs that may extend over distances of some decametres. The internal fabric consists of fine lamination and cross-stratification (Fig. 6b). Bed tops of trough sets occasionally show asymmetric ripple marks.

Shaly intervals are composed of purple siltstones with thin stratiform sandstone layers and frequently include beds of fine-grained sandstones that show a more or less constant thickness over observable distances. There is a tendency up-section for an increase of oblique joints and resulting sigmoidal sediment bodies, often forming conspicuous channels. Such channels occasionally cut vertically and laterally into units of purple shales (Fig. 6a). Also found are rare lateral accretional surfaces with relatively steep angles.

The middle part of the member consists of pinkish, brownish or mostly purplish sandstones, which are less siliceous and generally possess an argillaceous matrix. The fine-grained sandstones form composite suites of beds with a general thickness of 0.8 to 1.2 m. Such subunits are composed of beds with fine lamination and cross-stratification at very low angles. The beds are lenticular over some distance but do not show drastic changes in thickness. The bed complexes

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Figure 6. Outcrop photographs of the Haribes Member, Nababis Formation. (a) Fine-grained, slightly cross-stratified sandstones with oblique joints and resulting sigmoidal sediment bodies. Note abrupt, erosive contact of channel on lower left with thick unit of purple mudstones and siltstones. Highway between Seeheim and Goageb. Picture shows *c.* 1.7 m of section. (b) Fine-grained sandstones changing in colour from green to reddish and purple. Note cross-stratification in upper third and planar bedding in the lower part of the outcrop. Highway between Seeheim and Goageb. Picture shows *c.* 3 m of section. (c) Laminated quartz-arenitic sandstone beds, separated by shaly layers. Note swaly bed architecture. Gross Brukkaros, section MV. Picture shows *c.* 0.9 m of section. (d) Cross-stratified fine- and medium-grained sandstones with numerous oblique joints, forming large channels. Gross Brukkaros, section MV. Hammer (length 30 cm) for scale. (e) Surface of massive quartz-arenitic bed close to the top of the Haribes Member, showing slight load structures and tops of *Skolithos* tubes (right). Gross Brukkaros, section MV, at 91 m. Hammer (length 30 cm) for scale. (f) Flute casts on lower surfaces of quartz-arenitic beds. Gross Brukkaros, section MV, at 39 m. Hammer (length 30 cm) for scale.

are rhythmically interrupted by roughly 0.3 to 0.5 m thick thinly laminated purple shaly units, which are formed by alternations of siltstones and fine-grained sandstones. Hummocky cross-stratifications appear to be present occasionally in this stratigraphic interval of the Haribes Member.

8. Sections of the Gross Aub Formation

A main objective of this study was the stratigraphy and depositional environment of the Rosenhof Member, lower Gross Aub Formation. The member was examined in a number of sections stretching over a distance of more than 200 km. Due to the location on the platform-like area, the sections usually are relatively thin, and the base and top of the formation were mostly not exposed. The Gross Brukkaros section is used herein as a standard to which other sections and the Tses 1-borehole are calibrated.

Not discussed are a few relatively thin sections that could not be correlated with the Gross Brukkaros section, such as the southernmost section along the Fish River on Farm Schlangkopf, roughly 12 km north of Seeheim, which presents low outcrops of the lower Rosenhof Member.

On Farm Kosis the lower part of the Rosenhof Member is exposed on shallow slopes close to the farmhouse. The succession cannot be measured at this locality, but the slopes deliver large slabs of platy sandstones with excellently preserved trace fossils. Specimens of *Trichophycus pedum* from this area were described and figured by Geyer & Uchman (1995).

8.a. The Gross Brukkaros sections

The Gross Brukkaros is a huge inselberg 16 km northeast of the village of Berseba and about 100 km northwest of Keetmanshoop (25°52′ S, 17°50′ E) (Fig. 1). It rises 600 m from the vast, *c.* 980 m high Namaland plain formed by strata of the Fish River. The summit of the Gross Brukkaros is at 1586 m. The mountain has a volcano-type morphology with a central basin surrounded by a ring-shaped saddle structure formed by strata of the Haribes Member of the Nababis Formation and strata of the Rosenhof Member of the Gross Aub Formation. A canyon on the southern slope provides good outcrops of the rocks. The composite section from the southern flank of the Gross Brukkaros provides the only possibility of measuring a fine-scaled succession with a transition of the members in the northern and central area of the Fish River outcrop area.

Except for the Scolo Canyon section, auxiliary sections were measured but are not discussed herein. An additional section was studied on the northwestern flank of the Gross Brukkaros mountain, at a semicircular structure commonly termed the ‘balcony structure’, but it is not discussed here. Parts of the Rosenhof Member in that area are very rich in trace fossils such as a peculiar *Gordia* isp. (figured in Geyer & Uchman, 1995, fig. 3).

It should be noted, however, that the Fish River strata on the flanks of Gross Brukkaros form a ring-shaped anticline, whereas strata in the plain around the mountain gently dip towards the east. Nevertheless, the volcano-type morphology is mainly a result of exogenous processes (Stachel, Lorenz & Stanistreet, 1994).

The strata of the Haribes Member in the lower and middle part of the slope generally dip at about 15 to 20° towards the periphery of the Gross Brukkaros. By contrast, the overlying shales of the Rosenhof Member lie almost flat in the lower part and dip progressively toward the central depression up-section. The Cambrian rocks are limited by (sub)recent erosion, by a contact against the volcanic Brukkaros complex in the central depression, and/or by overlying Cretaceous or Palaeogene lake beds (Stachel, Lorenz & Stanistreet, 1994).

The lower part of the Fish River sequences at Gross Brukkaros exposes the Haribes Member of the Nababis Formation (see Section 7.b.1, above). The measured section (section MV) includes 90.8 m of quartz arenites with intercalated minor shale horizons. The top of the MV section overlaps with the base of the BS section on the higher slope of the Gross Brukkaros. This section covers the top of the Haribes Member and the lower and middle part of the Rosenhof Member of the Gross Aub Formation with a total thickness of the strata of 225.5 m.

8.a.1. *Section BS*

Section BS (Fig. 7) exposes the Rosenhof Member of the Gross Aub Formation with a thickness of 266 m. Comparison with the Tses-1 borehole log, where the member is 474 m thick, suggests that the lower and middle part of the member are represented in the section.

The lithological sequence seems relatively uniform at first glance but shows rhythmic alternations of clastic rocks in a high frequency pattern (Fig. 8a, b). The base (*c.* 6 m) consists of quartz-arenitic medium-grained sandstones interrupted by thin siltstone beds, followed by a rhythmic alternation of fine-grained sandstones and siltstones (*c.* 15 m), then another 6 m of quartz-arenitic medium-grained sandstones dominate. Large flakes of white mica are usually secondary muscovite crystals, but small muscovites in the shaly units appear to have a detritic origin. The siltstones contain simple but frequently occurring trace fossils, the assemblages of which differ from those of the Haribes Member, whereas the quartz arenite beds still include numerous large intraclasts at their bases.

The first determinable specimens of the characteristic trace fossil *Trichophycus pedum* (Seilacher, 1955) were found at 10 m. Supposed trace fossils at 26.2 m are preserved on the lee-sides of ripples on a bedding plane with relatively large interference ripples. The specimens consist of concave epichnial nets with irregular pattern (Geyer & Uchman, 1995, fig. 10.6). The string of the net equals 0.5 mm in diameter. The meshes vary broadly in shape and size. The specimens represent most probably an unexpectedly

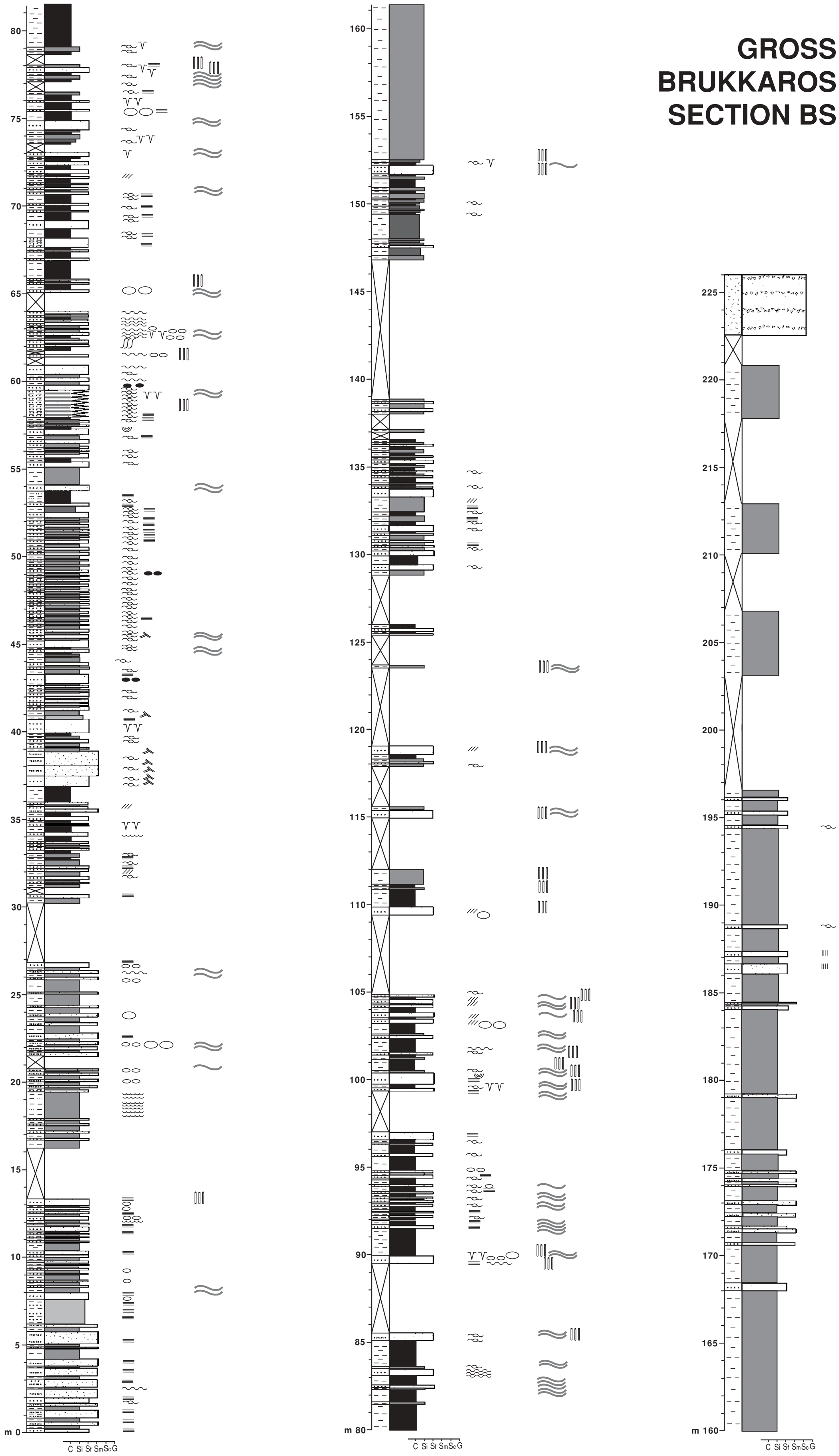

Figure 7. Profile of the Gross Brukkaros BS section, displaying lithologies, grain sizes, and trace fossil occurrences of the lower and middle Rosenhof Member of the Gross Aub Formation. Numbers refer to thickness in metres. See Figure 5 for legend.

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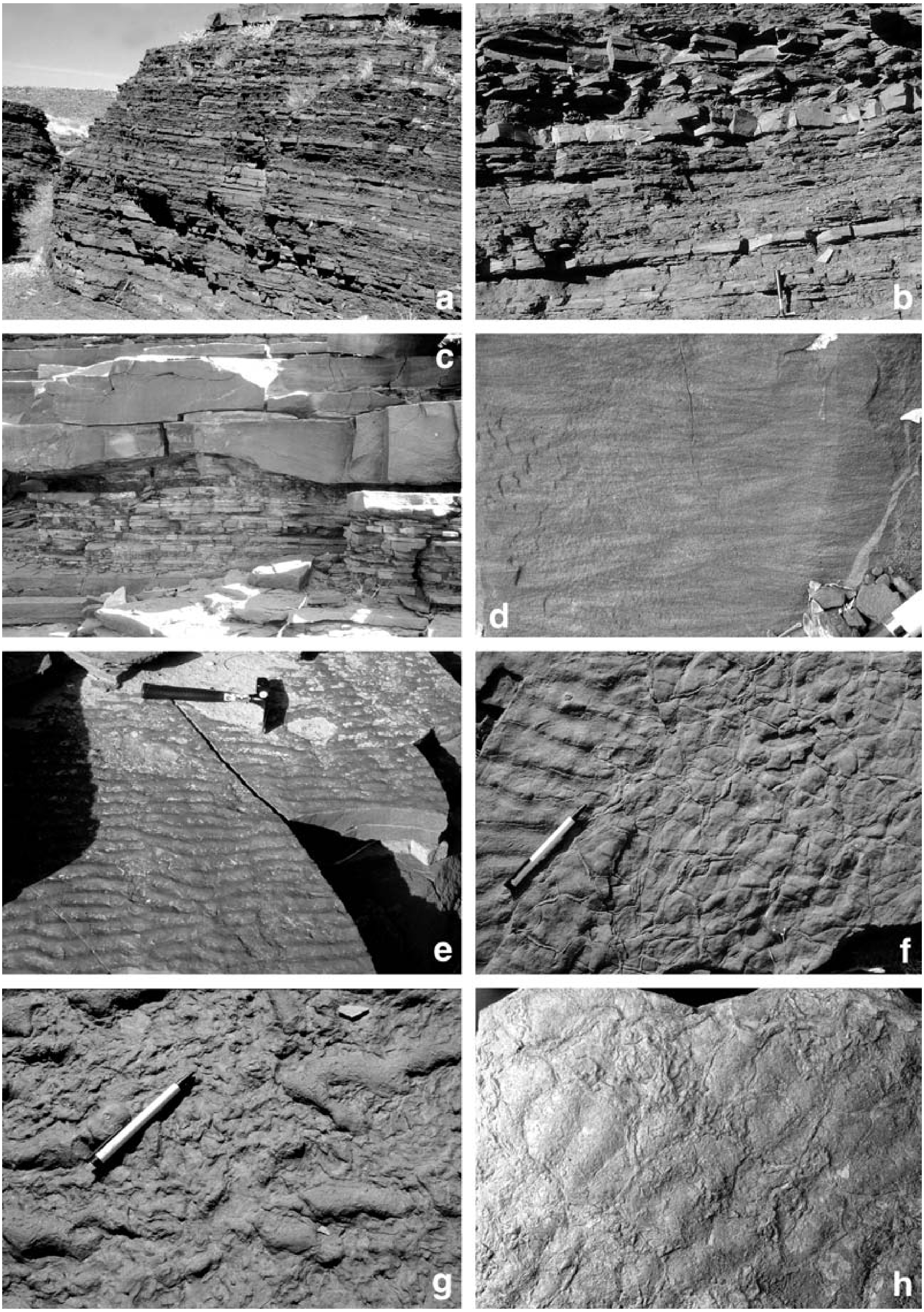

Figure 8. For legend see next page.

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early occurrence of this type of trace fossils although an abiotic origin as compactional structures cannot be ruled out.

A change in wave action is indicated at about 30 m when flaser-bedded siltstones and sandstones as well as beds with planar cross-beddings appear. A thick complex (about 2 m) of cross-bedded quartz-arenitic medium-grained sandstones marks the last occurrence of relatively coarse clastics in the member. Above are about 20 m of thin beds of fine-grained sandstones rhythmically interrupted by equally thin, flaser-bedded siltstones, grading into thin ripple-topped sandstone beds and finally a normal, irregular sequence of thin fine-grained sandstone beds, thicker flaser-bedded mudstones and siltstones, thin sandstones with syneresis cracks and frequent sandstones with burrow-churned tops (from *c.* 65 to 100 m). Surfaces with sinuous or linguloid wave-ripples can be seen in this unit, indicating a (at least temporary) position in a shoreface environment. *Trichophycus pedum* is the most frequent determinable trace fossil in the association with particularly well-preserved specimens found at 62.5, 73.5, 90 and 105 m and numerous slabs in the float. Burrows are particularly abundant between 100 m and 105 m, where vertical, *Skolithos*-type burrows are also frequent. At 100 m, a thick sandstone ledge shows ball-and-pillow structures in the topmost part. Planar cross-bedding persists from 103 m to 120 m.

Well-preserved trace fossils occur frequently in this part of the section. Interestingly, *Treptichnus pollardi* Buatois & Mángano, 1993 was discovered at 110 m. This delicate burrow consists of bedding surfaces of small and nearly straight to slightly curved segments which join at small circular pits (about 0.5 mm in diameter) that indicate the vertical shafts of the burrow system. The segments are 5 to 8 mm long. The burrows are covered by thin shaly laminae and form distinct ridges.

Float of debris makes it difficult to record a fine-scale lithological log. Nevertheless, the sequence is similar to that below the fine-grained sandstones with planar cross-bedding. Again, flaser-bedded siltstones and fine-grained sandstones alternate rhythmically. Intercalated are thin units of mudstones and mixed silty to sandy layers.

A conspicuous change is visible at 153 m. At that point of the section, a thick pile of very uniform siltstones (15 m in total) marks a distinct change to finer-grained deposits. Siltstones apparently became dominant some 10 m below, but the homogeneous 15 m unit is unique in the section. Siltstones persist as the dominating lithology almost to the end of the section but are divided by usually thin (*c.* 20 cm) beds of fine- and medium-grained sandstones that do not show obvious sedimentary structures or biotic activities. The result is a > 80 m thick unit dominated by uniform burgundy-coloured siltstones, which appears to be a correlatable lithostratigraphic unit.

The top of the succession is truncated by a contact against the post-Palaeozoic volcanic Brukkaros complex (Stachel, Lorenz & Stanistreet, 1994).

8.a.2. *Scolo Canyon section*

An auxiliary section (SC) in the Gross Brukkaros area was measured along a small but steep creek connected with the main valley on the southern slope of Brukkaros mountain. The *c.* 18 m of strata of the Rosenhof Member are very well exposed and allow a detailed recognition of sedimentary structures and burrowing activities in the deposits (Fig. 9, centre).

The lower 6 m are dominated by fine-grained sandstones, although a change in the style of deposition is recognizable. The basal 2.5 m are mainly sandstones with tabular cross-sets and occasional ball-and-pillow structures, occasionally interrupted by flaser-bedded siltstones. Above are *c.* 4 m of flaser-bedded sandstones and siltstones. The sandstones at 2.5 and 3 m include numerous mudclasts and several ripple tops.

The strata above the 6 m point of the section are markedly finer-grained. Numerous thin sandstone beds (in general about 10 cm thick) are separated by thicker units of flaser-bedded siltstones and mudstones. The rocks of this interval are among the finest-grained deposits found in the Rosenhof Member, although the sandstones still make up a considerable portion of the rocks (roughly 30 %). It is also unusual that almost all of the exposed beds show distinctive flaser-bedding. Several horizons include reworked small mudclasts. Trace fossils (mostly horizontal traces)

Figure 8. Outcrop photographs of the Rosenhof Member, Gross Aub Formation. (a, b) Rhythmic alternation of flat-bedded shales and thin sandstone beds typical for most of the Rosenhof Member. (a) Gross Brukkaros, SC section. (b) Gross Brukkaros, BS section. Hammer (length 30 cm) for scale. (c) Cross-bedded sandstone erosively incised into a flat-bedded shaly unit, overlain by low-angle hummocky cross-stratified beds. Aribdrif, section FA, at 13 m. Thickness of depicted succession *c.* 1.2 m. (d) Flaser-bedded argillaceous fine-grained sandstone. Gross Brukkaros, section BS, at *c.* 49 m. Pen (12 mm diameter) for scale on lower right. (e) Ripple-topped surface. Gainachas section, at *c.* 3 m. Hammer for scale. (f) Large-scale syneresis cracks on a bedding plane formerly covered by shallow ripples. Simple syneresis cracks are also seen on the underlying bedding plane (left) concentrated as semi-linear cracks in ripple valleys. Gross Brukkaros, section BS, at *c.* 59 m. Pen (*c.* 15 cm long) for scale. (g) Lower surface of burrow churned sandstone bed. Recognizable are *Paleophycus* isp., *Planolites* isp. and cf. *Trichophycus pedum*. Gross Brukkaros, section BS. Pen (*c.* 15 cm long) for scale. (h) Lower surface of sandstone bed showing oscillation ripples overprinted by widely spaced syneresis cracks and various trace fossils. The majority of the ichnofossils are different preservational stages of *Trichophycus pedum* (recognizable by the irregular garlands). Gibeon, section GW, sample horizon GW-58.6. × 0.7.

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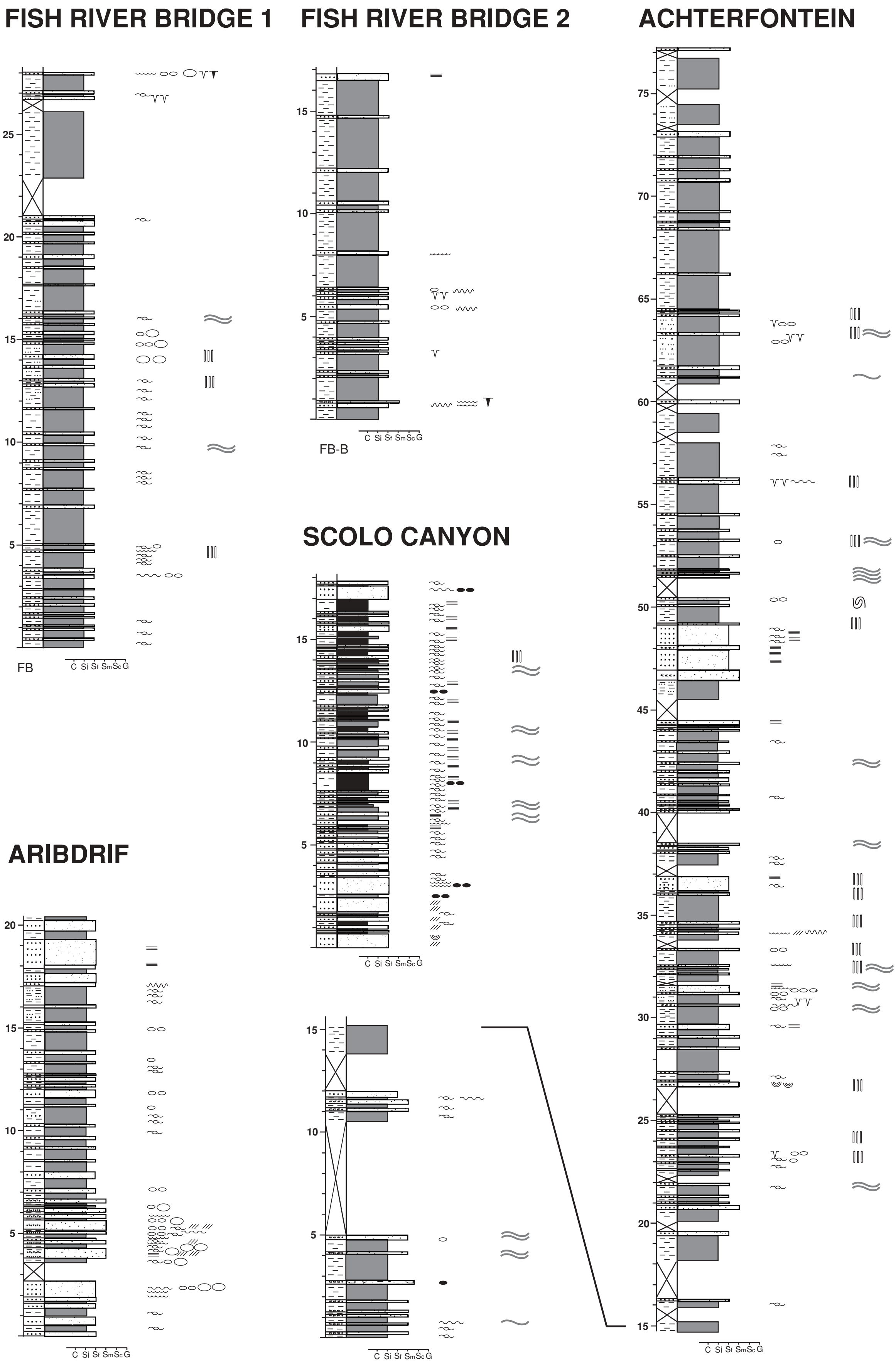

Figure 9. Profiles of the Fish River bridge (FB-1 and FB-2), Scolo Canyon, at Brukkaros mountain, Aribdrif and Achterfontein sections, central and southern study area. The simplified columns display lithologies, grain sizes and trace fossil occurrences of the lower and middle Rosenhof Member of the Gross Aub Formation. Numbers refer to thickness in metres. See Figure 5 for legend.

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are found at several horizons (e.g. at 6.2, 6.9, 9.3, 10.7 and 13.6 m). They may be so abundant that the entire bedding plains are covered. *Skolithos* tubes are found at 14.1 m. The top of the section is made up by a resistant cap of a thick (*c.* 0.7 m) bed of fine sandstone with erosional contacts and reworked mud-clasts.

8.b. Fish River bridge sections FB-1 and FB-2

A section in the Fish River valley close to the bridge between Tses and Berseba (Fig. 1) exposes a minor part of the Rosenhof Member of the Gross Aub Formation. It shows 28 m of a succession dominated by siltstones with frequent thin (10 to 20 cm) beds of fine-grained sandstone occasionally with mudclasts at their base (Fig. 9).

Several beds show ripple-tops that occasionally include current ripples with crests rounded by backflow and mud-draped wave ripples. However, the lower part of the sequence is particularly rich in flaser-bedded siltstones (between 0 and 1.5 m, between 4 and 5 m, and between 8 and 13 m). Noteworthy are two beds with the trace fossil *Trichophycus pedum* (at 9.8 m and at 11.2 m) and several sandstones with vertical *Skolithos*-type traces. The top of the section includes somewhat thicker sandstone beds with syneresis cracks and ferric mineralizations (at 26.6 and 27.9 m).

About 17 metres of section FB-2 supplementary to the main section were measured on the opposite side of the valley, with the bed at 0.8 m situated slightly above (estimated between 0.5 and 1 m) the bed at 27.8 m of the main section. This reference bed in Section FB-2 developed as a medium-grained, siliceous sandstone underlain by conspicuously slumped fine-grained argillaceous sands, both beds covered with high-frequency oscillatory ripples and syneresis cracks. Syneresis structures and ripples are found in the sandstone beds between 0.8 and 8 m. Intraclast-bearing sandstones and ferric mineralizations are present in the beds around 6 m, where slump structures can be seen as well. The upper part of this supplementary section is relatively poorly exposed and consists of apparently homogeneous siltstone units interrupted by thin beds of fine-grained sandstones. The top is made up of a comparatively thick (*c.* 30 cm) bed of platy, laminated sandstones.

The topographic position of the section with respect to Brukkaros mountain and the Dwyka deposits to the east suggests that this succession represents part of the upper Rosenhof Member, which is not represented in the Brukkaros sections.

8.c. Gainachas section

A distinctive bend in the ‘rivier’ northeast of Gainachas, Berseba District (Fig. 1), exposes a section of 105 m of measurable strata of the Rosenhof Member (Fig. 10).

The lower part of the section (22 m) has a comparatively high content of sandstones (about one-fourth) with particularly thick units of platy or cross-bedded fine sandstones in the basal 8 m of the section. The sandstones between 3 and 8 m show several ripple-tops and numerous trace fossils, preferably simple or conspicuously winding *Planolites*-type traces on the bedding planes. Noteworthy is a lowest occurrence of the endemic trace fossil *Enigmatichnus africani* Crimes & Germs, 1982 at 4 m in the section and a second at 12 m. Indeed, this section is more or less identical with the type locality of the trace *Enigmatichnus africani* Crimes & Germs, 1982, characterized by a pair of semicircular impressions, often showing these impressions with one side steeper than the other and tending to exhibit asymmetrical median furrows between the two bumps. A few specimens are conspicuously asymmetrical (Geyer & Uchman, 1995, fig. 4.1). These facts suggest that the trace was formed as scratch marks with the shallower flank marking the beginning of the excavation of sediment. If the impressions portray the producer, the trace was probably formed by a bilateral organism or a part thereof, with a convexity towards the substrate and without strongly differing anterior and posterior sides.

Siltstone units between 8 and 18 m show flaser-bedding, and this interval shows several beds of quartz-arenitic medium-grained sandstones, often with abundant reworked clasts at their bases. Vertical, *Skolithos*-type tubes can be seen at 11.3, 17.1 and 19.8 m.

The middle part of the Gainachas section (between 22 and 67 m) is dominated by fairly thick (3–5 m) units of burgundy-coloured siltstones. Flaser-bedding of these siltstones occurs between 22 and 25 m and between 47 and 56 m. An increase of grain-size is noted for the intervals between 32 and 35 m and between 48 and 53 m. The siltstone units are rhythmically divided by thin complexes of sandstones which consist generally of two to five thin beds that obviously mark times of pronounced coarser clastic input. The rhythmic fluctuation is typically shown by a middle bed of medium-grained quartz arenites framed by thinner, often platy fine-grained sandstone beds. The coarser sandstone beds again show frequent reworked mudclasts and occasionally oscillation ripples on top. Slump structures, horizontal and vertical trace fossils are also observed (with *Enigmatichnus africani* at 46 m). Such complexes reach a maximum thickness of about 3 m but are generally around 1.5 m.

The upper part of the Gainachas section (67 m to 105 m) is dominated by very uniform, thick siltstone units (up to more than 10 m thick). Intercalated are sandstone beds which usually occur as twins, with a platy, multiple fine-grained sandstone bed below and a slightly thinner quartz-arenitic medium-grained

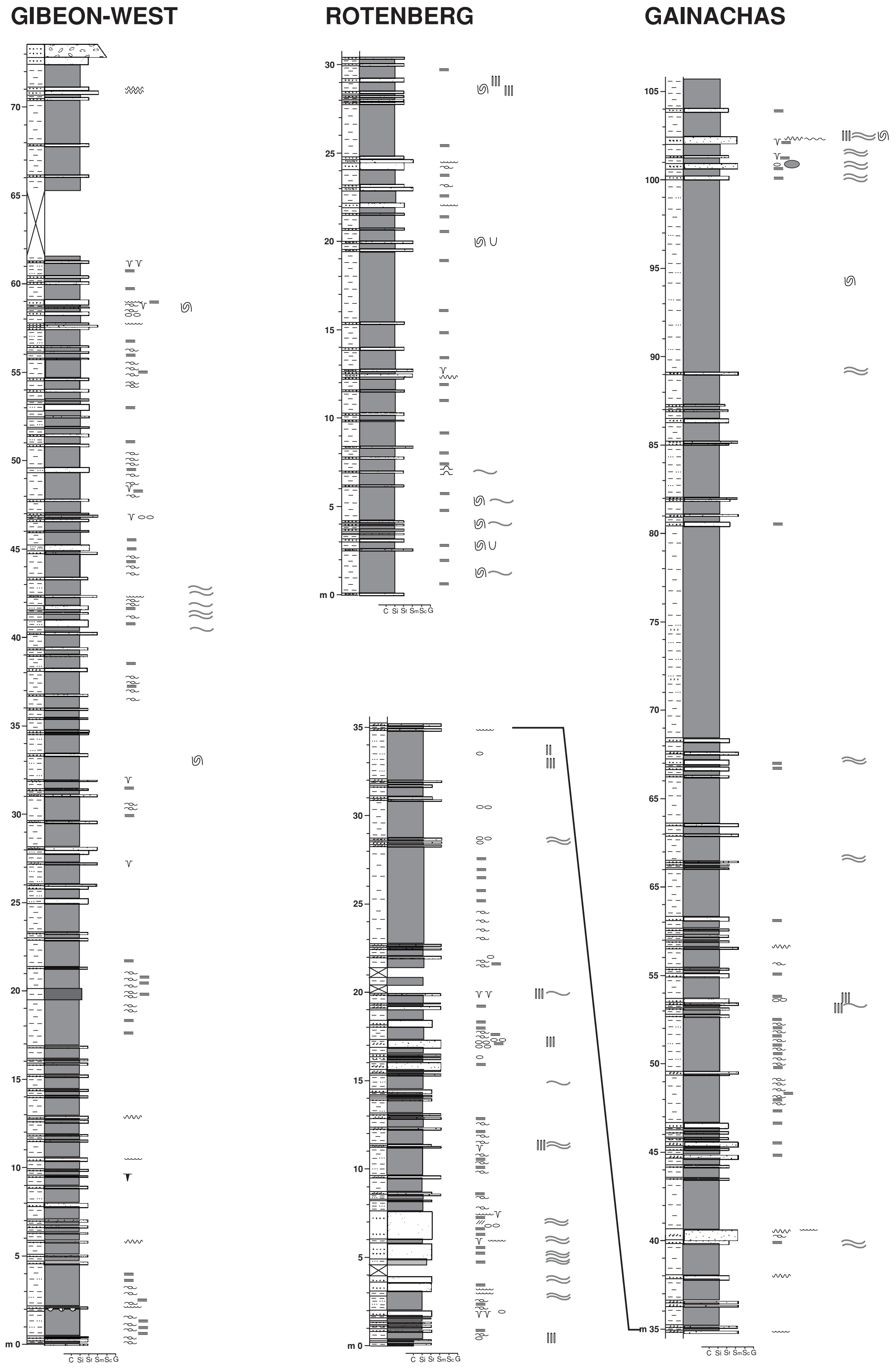

Figure 10. Profile of the Gibeon-West, Rotenberg and Gainachas sections, northern study area. The simplified columns display lithologies, grain sizes, and trace fossil occurrences for the lower and middle Rosenhof Member of the Gross Aub Formation. Numbers refer to thickness in metres. See Figure 5 for legend.

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sandstone above. However, the precise pattern varies considerably. Particularly thick sandstones are found between 99.5 and 103.5 m. The surfaces of these beds are covered by numerous trace fossils and syneresis cracks, occasionally with oscillation or interference ripples. Additional traces are seen at 88.6 and 94 m. The level at 94 m showed the stratigraphically highest specimens of *Enigmatichnus africani*, but also typical specimens of *Trichophycus pedum*.

The Gainachas section is difficult to correlate with the Gross Brukkaros sections, which serve here as a standard for the lithostratigraphy of the Rosenhof Member. It is assumed that the change from the lower to the middle part of the Gainachas section, with a pronounced decrease of sandstones and a disappearence of planar cross-bedding, portrays the change to the siltstone-dominated third unit in section BS. If this correlation is correct, the succession of the Gainachas section corresponds to about the upper 100 m of strata of the Brukkaros section with the top probably slightly above the uppermost strata of section BS.

8.d. Achterfontein section

A section along the Fish River in the vicinity of Achterfontein, south of Berseba (Fig. 1) exposes 77 m of the Rosenhof Member of the Gross Aub Formation. Loose blocks on the relatively shallow slopes hinder the recognition of details where fine-grained clastics are exposed. Most of the rocks indicated as missing section in Figure 9 therefore most probably represent uniform siltstones.

The section can be divided into three parts. The lower *c.* 20 m obviously show a dominating sequence of siltstones that are occasionally flaser-bedded. Intercalated are thin, often multiple beds of fine- to medium-grained, often quartz-arenitic sandstones, sometimes with ripple tops. Trace fossils (including *Trichophycus pedum*) occur at various levels.

Sandstones become much more frequent in the middle part (from 20 m to *c.* 50 m), where they make up about one-fourth of the succession. Although the medium-grained quartz arenites are similar to those in the lower part of the section, their particular facies includes: trough cross-beds (at 26.6 m); tabular cross-sets (at 34 m); serpent-shaped slumping structures (at 23.1 and 34.0 m); numerous beds with smaller reworked clasts; oscillation and interference ripples, rarely even ladderback ripples; syneresis cracks; horizontal trace fossils often enriched on surfaces, but also *Trichophycus pedum* and *Skolithos* tubes. Particularly instructive material of *Trichophycus pedum* occurs at 50 m (figured by Geyer & Uchman, 1995). The top of this middle part is formed by a relatively massive sequence of fine- and medium-grained sandstones (46 to 50.5 m) with platy, partly flaser-bedded fine-grained sandstones.

The upper part of the Achterfontein section (*c.* 50 to 77 m) consists of on average 1 m thick siltstone packages interrupted by thin sandstone beds. In contrast to the lower part, the siltstones tend to contain a notable amount of sand, which often creates relatively quartz-arenitic and resistant slabs. Flaser-bedding occurs only in the basal metres. Horizontal and vertical trace fossils can be observed in the interval between 61 and 65 m.

The clear tripartite section is correlatable with the Gross Brukkaros sections by means of the recognizable complex of medium-grained, relatively variable sandstones with different sedimentary structures and the overlying shale-dominated succession. It is therefore a lateral equivalent of approximately metres 85 to 160 of Brukkaros section BS, thus representing the upper lower and lower middle part of the Rosenhof Member.

8.e. Gibeon section

The road about 11 km west of Gibeon (Fig. 1) exposes 73 m of measurable strata of the Rosenhof Member, Gross Aub Formation. The succession (Fig. 10) is remarkably uniform, generally consisting of about 1 m of brownish-burgundy coloured siltstones and thin (5 to 20 cm thick) beds of fine-grained sandstones. Flaser-bedding of the siltstones occurs between 1 and 3.5 m, between 19.5 and 21 m, between 30 and 31 m, between 36 and 38 m, between 41 and 45 m, between 47 and 51 m, and between 53 and 59 m. Trough cross-beds are found at 1.9 m, with syneresis cracks in several beds, mostly between 17 and 49 m. A number of sandstone beds throughout the section show ripple tops. A certain change in clastic input is shown by quartz-arenitic medium-grained sandstone concentrated between 26 and 47 m, where sandstones are in general somewhat more frequent than in the parts of the section below and above.

Trace fossils are relatively scarce. However, *Trichophycus pedum* occurs in several beds, with particularly typical specimens associated with oscillatory ripples at 33.5 and 58.6 m. Additional material of *Trichophycus pedum* was found in the cores of the Gibeon drill hole which were left at the location after completion of the drilling. It should also be noted that hypichnial, densely crowded subcylindrical burrows were found at 40.5 m. These irregularly meandering horizontal loops are tentatively assigned to the ichnogenus *Gordia* (Geyer & Uchman, 1995).

A unit of fine- and medium-grained sandstones between 70 and 71 m shows spectacular slumping, or deformational structures. About 1.2 m above is a roughly 40 m thick bed of fine sands overlain by a *c.* 80 cm thick coarse sandstone. This bed shows a fining-upward from a coarse- to a medium-grained sandstone without other recognizable internal sedimentary features.

The section cannot be correlated readily with the section BS at Brukkaros Mountain. Lateral variation and possibly a more proximal position in respect to the proposed source area in the west may account for a larger amount of sandstones. The general depositional regime appears to match that recognized for the upper part of the BS section. However, a counterpart of the conspicuous uppermost part of the GW section has not been observed in other measured sections.

8.f. Rotenberg section

The northern regions of the Fish River Subgroup are notoriously poor in outcrops. The northernmost possibility of measuring a section is at an outlier termed Rotenberg on Farm Friedabrunn (24°41′51″ S, 17°33′26″ E; Fig. 1). The name Rotenberg (German for 'red mountain') is most probably derived from the conspicuous red colour created by the red shales of the Rosenhof Member of the Gross Aub Formation, which form the hill.

A huge blanket of talus covers the lower slopes so that only about 30 m of strata can be observed. The visible part of the succession is dominated by the typical reddish to burgundy-coloured argillaceous siltstones which are rhythmically interrupted by thin (generally 8 to 20 cm-thick) fine-grained sandstone beds (Fig. 10). Exceptions are medium-grained, siliceous sandstones at 3.5, 8.3, 12.3 (with conspicuous plastic deformation structures) and 12.7 m (with syneresis cracks), 19.4 and 19.9 m, 22.8 and 24.4 m (with oscillation ripples on top). Thicker sandstone beds at 24.0 and 24.6 m are flaser-bedded as are the siltstones between 2.5 and 3.0 m. Noteworthy are the current lineation observed at 20.7 and 21.6 m and the asymmetric ripples at 23.1 and 24.5 m, which apparently indicate distal fluvial episodes. Also remarkable are a number of well-preserved trace fossils. At 7 m and 28 m, the rocks yielded *Skolithos* tubes with a precisely determinable morphology. These vertical to subvertical, thinly lined, sand-filled tubes have a diameter of 2.5 to 6 mm. The form is generally represented as convex knobs of circular to elliptical cross-sections on lower bedding surfaces and as concave pits on upper surfaces. The tubes are randomly distributed; their density varies between 10 and 30 burrows per square metre in the material studied. *Trichophycus pedum* occurs in several horizons, particularly in the sandstone bed at 20 m and on loose slabs that originate from between 1 and 6 m. *Gordia*-type loops have been observed at 6.9 m.

The Rotenberg section, too, is difficult to correlate with other sections. In terms of the alternation of siltstone units and fine- and medium-grained sandstones as well as sedimentary structures, much similarity is found with the middle part of the Gibeon section.

8.g. Aribdrif section

A section along the Fish River in the vicinity of Aribdrif, southern Berseba District (Fig. 1), exposes roughly 30 m of the Rosenhof Member of the Gross Aub Formation. The upper slopes are densely covered by loose blocks so that only *c.* 20 m of strata can be examined in detail.

The succession (Fig. 9) starts with relatively massive fine-grained sandstones (*c.* 4 m) each interrupted by about 30 cm of flaser-bedded siltstones. The interval from 4 to *c.* 7 m exhibits quartz-arenitic medium-grained sandstone beds with planar cross-bedding, abundant large intraclast layers as well as many bedding planes covered with oscillation ripples. The interval between 7 and 17 m is mainly composed of the typical reddish siltstones, which are flaser-bedded between 9.5 and 13.5 m and often tend to include a certain amount of sand. Intercalated are numerous fine-grained sandstone beds with frequent small mudclasts (particularly between 11 and 15 m). The top of the measured section is dominated by thick fine-grained sandstones without conspicuous sedimentary structures (except for slumpings at the base at 17.1 m). Although trace fossils appear to be absent in the outcrop, *Trichophycus pedum* and other horizontal trace fossils can be found on numerous loose blocks.

Precise comparison of the measured interval with the Brukkaros section is difficult. However, it probably corresponds to a low but not the lowest part of the Rosenhof Member.

9. Lithostratigraphy and depositional environments revisited

The classical lithostratigraphic subdivision by Germs (1972*a* and particularly 1983) distinguishes four formations termed the Stockdale, Breckhorn, Nababis and Gross Aub formations, respectively. Except for the Breckhorn Formation, all have two or more distinct members.

9.a. Stockdale Formation

The Stockdale Formation has been subdivided by Germs (1983) into a maximum of four members (Kabib, Haseweb, Inachab and Wasserfall members), which are best recognizable in the north. Although all have a very similar lithology of trough cross-bedded medium- and also coarse-grained sandstones, their separation is justified due to distinct unconformities which separate these units. Towards the south, the basal members decrease in thickness so that finally only the Inachab and Wasserfall members can be identified (Fig. 2).

The basal portion has stacked erosional contacts with coarse gravel beds overlain by cross-bedded medium- and coarse-grained sandstones rich in load structures.

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Granulometry of the conglomeratic layers appears to indicate that coastal gravel beds were subsequently reworked by fluvial activities. The major part of the Stockdale Formation was interpreted as having been deposited in a braided river system (Germs, 1983). Indeed, this reconstruction of the depositional environment is consistent with the data for the lower part of the formation where medium- to coarse-grained sandstones usually form significant channels. This typical 'Stockdale facies' marks the transition from syn-orogenic depositional environments of Fish River Subgroup to the late orogenic molasses sedimentation that characterizes the rest of the Fish River Subgroup.

In the middle to upper half, however, the sandstones are generally fine- to medium-grained and show sandbeds with only low convex channel bases (Fig. 4a). This indicates a less energetic fluvial regime, probably on an extended flood plain with a low to very low relief gradient with numerous, relatively small channels.

Shale intercalations are comparatively rare and only found in the Wasserfall Member in the more southern part of the outcrop area. Particularly a unit with shales and fine-grained sandstones at the base of the Wasserfall Member can be interpreted as deposited under shallowest marine, probably tidally influenced (Germs, 1983) conditions.

Previous reports on trace fossils from the Stockdale Formation were most probably erroneous. Such samples from this formation consist of fine-grained sandstones which locally contain numerous sedimentary structures that could be mistaken for traces. These layers are usually intercalated in medium-grained sandstones with cross-sets that indicate deposition in fluvial environment.

Special reference should be made to tool marks from the Stockdale Formation (see Geyer & Uchman, 1995, fig. 10.4) which resemble arthropod trails in soft sediment, especially *Multipodichnus*. (see also Walter, 1996). Similar tool marks have been obtained experimentally and observed in rocks (Dzulynski & Walton, 1965).

9.b. Breckhorn Formation

A relatively thin (*c.* 20 m) pile of cross-bedded sandstones and silty shales has been defined as the Breckhorn Formation (Germs, 1983). This formation, according to Germs (1983), records a facies change from partly trough cross-bedded sands formed under braided river conditions in the western part of the outcrop area to siltstones of a distal fluvial regime in the east. Our investigations, centred in the area between Seeheim and Goageb, showed a prevalence of well-sorted fine-grained sandstones with quite uniform, shallowly dipping planar foresets. The sediment bodies and sedimentary structures indicate that the lateral transport was moderate but high velocities of streaming water occurred. Frequent intercalations of muddy shales between the cross-bedded or laminated fine-grained sandstones exclude the interpretation of formation by a braided river system for this part of the basin. Instead, the sequence was most probably formed under shallowest marine conditions, mostly along a tidally dominated coastline.

Distinguishing between the Breckhorn Formation and the overlying Zamnarib Member of the Nababis Formation is difficult. The Breckhorn generally consists of sandstones similar to those of the 'ordinary' cross-bedded lower Zamnarib Member. A distinction is only possible if the lower part of the Zamnarib is shale-dominated. The Breckhorn Formation and Zamnarib Member represent a depositional sequence reflecting a deepening-upward cycle with a development from braided fluvial to shallow marine environments.

9.c. Nababis Formation

Analysis of the depositional environments indicates that two members of this formation (the Zamnarib and the overlying Haribes Member) would be better coupled with the Breckhorn Formation below and the Rosenhof Member of the Gross Aub Formation above, respectively, so that new formation names would be required (Fig. 2). It is suggested herein that two (instead of three) formations above the Stockdale Formation best comply with these conditions. However, these formations are not formally introduced herein because potential stratotype sections are not yet known in enough detail to fulfil the formal requirements.

The Zamnarib Member consists of cross-bedded fine- to medium-grained sandstones in its lower part and more typically an alternation of shales and fine-grained sandstones in the upper part. The lower part of the formation was interpreted as having been formed partly by braided rivers, whereas the middle and upper part are shallow marine deposits (Germs, 1983). The member was deposited more proximally north of Maltahöhe, which results in a more sandy development and the presence of numerous trough-crossbeds (Germs, 1983 and pers. comm. 2003). A fining of the deposits can be recognized towards the south and east, in accordance with growing thickness and obvious change in depositional environment. Our observations in the southern part of the basin do not confirm the presence of trough cross-sets in the lower part of the member that would indicate deposition in braided rivers. Apparently, distal fluvial low-angle cross-bedded sandstones are replaced by shallow to shallowest marine shaly deposits. Typical sedimentary structures include symmetrical, frequently bifurcating ripples with often truncated ripple tops that indicate tidal conditions with temporal subaerial exposure. Associated with these structures are low-angle climbing ripples, extended beds with oblique but shallowly dipping basal and top surfaces and occasionally even slight flaser-bedding. This set of sediment structures points to deposition in a tidal flat-type environment. Other structures that corroborate the tidal interpretation include: (1) current ripples with crests rounded by backflow, (2) clay-draped reactivation surfaces, and (3) mud-draped wave ripples.

Very diverse mudclast accumulations at the bases of well-sorted, laminated sandstone beds suggest reworking and extremely short transport of unconsolidated mud flakes and appear to indicate occasional storm events.

The Haribes Member of the Nababis Formation is again a sandstone dominated unit, generally consisting of cross-bedded sandstones with minor shale intercalations. It is assumed that the unit was generally deposited under a fluvial regime in braided river systems (Germs, 1983). Due to the often siliceous cementation, the thick sedimentary pile of the Haribes sandstones often forms resistant units that shape a considerable part of the huge plain in the middle part of the outcrop area.

Germs (1983) outlined a variable picture of the facies relationships in the upper Fish River Subgroup, particularly for the Haribes Member and for the Rosenhof Member. A facies map (Germs, 1983, fig. 13D) shows four different facies distributed over the outcrop area. The northern area from the Berseba District and northwards is made up of cross-bedded sandstones of a braided fluvial environment. A central belt stretching eastward from Aus via the Goageb and Seeheim region has, according to Germs (1983), a western area of flat-bedded sandstones of a distal fluvial environment which grades laterally into cross-bedded sandstones and mudstones deposited by braided rivers but including a considerable amount of over-bank deposits. The southern area is characterized by alternating mudstones and sandstones of a muddy tidal environment with minor amounts of distal fluvial deposits. This area represents the facies of the Rosenhof Member so that the Haribes Member would pass laterally and southward into the Rosenhof Member.

This interpretation poses two problems that need to be discussed. Firstly, the facies distribution suggests the existence at that period of a fluvial system that drained the area in a southerly direction with a coastline roughly south of the present line from Lüderitz to Keetmanshoop and Aroab. The resulting flow directions should therefore indicate a unidirectional transport towards the south. This is only partly corroborated. Our investigations in the Gross Brukkaros area indicate flow direction to the south and southeast in the lower and upper parts of the member. Other parts, however, indicate sediment transport in easterly directions (as reconstructed by Germs, 1983, fig. 14C).

Secondly, the supposed facies change from the ‘Haribes quartzites’ to the ‘Rosenhof shales’ is primarily indicated lithstratigraphically by the boundary between the Haribes Member and the overlying Rosenhof Member. This means that the shallow marine facies prograded over the supposedly fluvial facies and would suggest a marine transgression. Such a transgressional event, however, usually leaves a characteristic lithological signature that should be recognizable in the sections. This problem will be discussed in detail below under the Rosenhof Member (see Section 9.d).

The Haribes Member was one of the major targets of our investigations. Several sections were examined in detail, with fine stratigraphic sections measured at the Gross Brukkaros mountain and along the highway from Seeheim to Goageb. These analyses indicate a slight modification of the depositional environment. The majority of the unit consists of fluvial deposits. However, trough cross-sets are rare even in the Gross Brukkaros sections. Instead, the member is dominated by well-sorted sands that form beds with thicknesses between *c.* 10 cm and *c.* 40 cm with a tendency to swell slightly over distances of some decametres. The internal fabric consists of fine lamination or, more rarely, low-angle cross-stratification. Bed tops occasionally show asymmetric ripples that indicate unidirectional water flow.

Sole marks that point to deformation of unconsolidated, highly liquid sediments at the base of sand layers are particularly frequent in the upper part of the formation. Thick sandstone beds often include reworked shale clasts as a basal lag deposit. Typically, the shale clasts are large (often up to 8 cm in diameter and occasionally larger) and with an almost perfectly rounded shape but with somewhat sculptured top and bottom surfaces. Although a fluvial origin of the deposits is obvious, it is difficult to infer an environmental model that is consistently able to explain all of the observed characters.

The sections indicate an increase of finer-grained clastics towards the south with more reddish siltstones present in the area west of Seeheim. In this area, the presence of numerous oblique joints and resulting sigmoidal sediment bodies points to high-energy conditions during deposition. Locally, distinct channels cut vertically and laterally into relatively thick purple shale units. These are best explained by a deposition on a very shallow-dipping coastal area with significant portions of beach and tidal plain deposits. In addition, lateral accretional surfaces with relatively steep angles are present which could be interpreted as vestiges of tidal channels. However, hummocky cross-stratifications also appear to be present occasionally in the sections west of Seeheim.

The top subunit of the Haribes Member differs from the underlying sediments in being better sorted, light coloured and composed of fine- to medium-grained sands. This subunit (roughly 7 m thick in the Brukkaros section) is regularly silicified and shows vertical burrows (*Skolithos* isp.) and (rarely) horizontal, looped trace fossils on the slightly wavy, vaguely rippled top surfaces of the beds. This rocks are interpreted herein as foreshore to shoreface deposits.

9.d. Gross Aub Formation

The Gross Aub Formation consists traditionally of the Rosenhof and the Deurstamp members. The Rosenhof Member is a unit consisting of thin (centimetre-thick) layers of fine-grained sandstones regularly alternating with shales so that a generally shaly habitus is created. Sedimentary structures such as asymmetric ripples and current lineation in some of the northernmost outcrops appear to indicate that those parts of the member were deposited in a distal fluvial environment, whereas the majority of rocks in the member are products of shallow to shallowest marine environments (Germs, 1983). Laminated shales with heterolithic rhythmites appear to indicate subtidal deposition in tidal channels.

This member is the major source of trace fossils in the Fish River Subgroup, including *Trichophycus pedum*, *Enigmatichnus africani*, *Treptichnus pollardi*, *Gordia* isp., *Planolites* isp. and *Paleophycus* isp. (see Geyer & Uchman, 1995, for details). The diverse ichnoassemblages consist of traces of deposit feeders, as well as others which were probably created by suspension feeders and agrichnial farmers. Most of the trace fossils occur on sediment interfaces as monospecific assemblages with abundant individuals, especially of *Trichophycus pedum*. *Trichophycus pedum* exemplifies an opportunistic strategy. The producer of *T. pedum* favoured shallow marine habitats under conditions which offer open niches. Although a small majority of the deposits from which *T. pedum* is known to occur appear to be formed under transgressive conditions, *T. pedum* is also found in sequences which represent regressive conditions. However, most habitats of *T. pedum* suggest a typical r-selected strategy of colonization by opportunistic forms under stressful environmental conditions. As a result, population density as well as preservation varies considerably due to rapidly varying depositional and taphonomic conditions. Locally, *Trichophycus pedum* occurs on surfaces cut by desiccation cracks. Hence, the inferred opportunism is easily explained as a response to unstable conditions in the tidal environment including a temporal exposure of the sea-floor and notable changes in salinity. Local semi-aggregational distributions of *T. pedum* and *Planolites*-type ichnofossils are not readily explained as a result of inhomogeneities of the substrate or differing water currents. However, associations with unusual densities of burrows appear to reflect favourable conditions which may result from a higher content of organic matter in the deposits.

The densely crowded specimens of *Gordia* reflect a typical behaviour of mobile infaunal deposit feeders, which reworked certain horizons that apparently mark nutrient-enriched zones within the substrate.

The Rosenhof Member shows a large range of sedimentary structures and characters that permit reconstruction of depositional environments. Primary indicators are numerous trace fossils, which generally occur at parting surfaces of the fine-grained sandstones and shales. Occasionally, old ripple faces with symmetrical oscillation ripples are overprinted by plentiful traces. Intermittently, at least two different generations of traces can be identified superimposing older sediment surfaces.

Diagnostic features for tidal interpretation also include current ripples with crests rounded by backflow and mud-draped wave ripples. Surfaces with sinuous wave-ripples indicate a position in a shoreface environment. Associated with ripple surfaces may be syneresis cracks which may align to ripple crests or form a polygonal network on sandstone beds. These cracks in shales are much smaller and usually have a crowfoot-like shape. Layers with numerous syneresis cracks at changing lithologies indicate fluctuating salinities in marginal marine settings. In accordance, cross-bed sets may show single and double mud drapes.

Accumulations of mudclasts (up to 4 cm in diameter) as basal lags of fine-grained sandstones are a frequent feature. The mud clasts are sometimes distinctly deformed and the argillaceous material was thus not lithified before being reworked.

The development from the Haribes Member of the Nababis Formation to the Rosenhof Member of the Gross Aub Formation again can be interpreted as a deepening-upward cycle with development from fluvial to shallow marine environments. This development is in accordance with the reconstruction of the facies development sketched by Germs (1983, fig. 13D). However, we were not able to recognize striking lateral facies changes during our field investigations. Typical sedimentary features of a transgressive event (e.g. transgressive conglomerate, black pebbles, typical erosive contacts) have not been identified. The boundary between the Haribes Member and the Rosenhof Member is marked by a considerable change from reddish fine-grained argillaceous sandstones to purple siltstones. The lower boundary of the Rosenhof Member is drawn at the base of siltstones that rest on a thick bed of pale quartz-arenitic middle-grained sandstone.

It should be emphasized that both the Haribes and the Rosenhof members apparently represent only a short to very short period. As a consequence, a prograding of facies with lateral intertonguing would be difficult to prove even if a fine-scaled chronostratigraphic scheme could be applied. In addition, a lateral facies change, whether or not chronostratigraphically resolvable according to international stratigraphic conventions, suggests that both facies units and members belong to the same formation. It is therefore suggested that the lithostratigraphic scheme of the Fish River Subgroup should be revised to include both members in one formation.

The Deurstamp Member is restricted in its outcrop area but well known from the eponymous Farm Deurstamp, from near Garuchab, Farm Naute, and from the Tses 1 borehole. A rapid investigation during the field work for this article was insufficient to reveal distinct features for an accurate interpretation. Germs (1983 and pers. comm. 2004) indicated that the member consists of cross-trough bedded sandstones at the base, overlain by shaly deposits and a change from braided fluvial to distal fluvial and muddy tidal depositional environments so that it could be interpreted as another depositional sequence.

9.e. Conclusions

The Fish River Subgroup can be divided into deepening-upward cycles, or transgressional sequences. Deepening-upward cycles are often regarded as unusual for basinal areas. Because sedimentary cycles often can be interpreted alternatively, basinal fill usually suggests that the amount of deposited sediments finally terminate a cycle. However, as the name 'cycle' suggests, deposition varies between the extreme environmental conditions that occur in the specific setting. Which half-cycle is finally expressed in the sedimentary record depends primarily on the relative rate of subsidence. Shallowing-upward cycles are usually developed under high subsidence conditions whereas low to moderate rates of deposition may create deepening-upward cycles.

In this context, four sequence stratigraphic units are determinable for the Fish River Subgroup in the southern part of the basin. Sequence 1 is represented by the Stockdale Formation, with a clear deepening trend towards the top of the Wasserfall Member. Sequence 2 is represented by the Breckhorn Formation and the Zamnarib Member of the Nababis Formation, with a deepening towards the top of the Zamnarib. Sequence 3 is represented by Haribes Member of the Nababis Formation and the Rosenhof Member of the Gross Aub Formation. This sequence has the greatest thickness of all the sequences of the Fish River Subgroup. Sequence 4 is apparently represented by the Deurstamp Member alone, although more data are needed to confirm its status. Each of these sequences is interpreted to represent third-order composite sequences.

The multiple unconformities in the Stockdale Formation enclose progressively thicker rock units towards the north and indicate a more complex sequence stratigraphy. Each of the unconformities can be interpreted as a sequence boundary so that more sequences are recognizable towards the Damara belt. Germs (1983, fig. 3) reconstructed two sequences for the Stockdale Formation (the second sequence commencing at the base of the Inachab Member) so that he showed five sequences for the basin north of Bethanie.

10. Chronostratigraphic significance

Due to the absence of faunas with hard parts and high biostratigraphic significance, the age of the Fish River Subgroup and the position of the Proterozoic–Cambrian boundary in Namibia have been open to speculation.

Radiometric datings which appeared to shed some light on the age of the Fish River Subgroup are mostly of little value in the light of the present state of knowledge. According to radiometric datings, white micas from the higher Nama Group range from 547 Ma to 443 Ma (see compilation in Miller & Grote, 1988). These had been interpreted primarily as cooling ages. However, similar $^{40}Ar/^{39}Ar$ metamorphic ages (552 Ma to 476 Ma: Gresse, Fitch & Miller, 1988) from the Vanrhynsdorp Group in Namaqualand, South Africa, a correlative of the Nama Group, indicate the influence of a metamorphic event. In accordance, K/Ar datings by Horstmann (1987) and Horstmann *et al*. (1990, 1992) suggest a low-grade metamorphic alteration of Fish River rocks between 530 and 500 Ma. Data by Ahrendt, Hunziker & Weber (1977) and Ahrendt *et al*. (1983) further indicated that the Nama Group was affected by a low-grade metamorphism at about 530 Ma. The problem is further enhanced by the fact that systematic errors in some classical radiometric dating methods indicate significantly overly high ages for rocks older than Middle Ordovician (e.g. Compston *et al*. 1992), so that the extended Cambrian now has its base at about 545 Ma according to IDTIMS (isotope dilution thermal mass spectrometry) zircon datings. Therefore, a precise determination of the thermal event that would also bracket the uplifts of the Damara (Khomas) and Adamastor (Gariep) orogenic belts with the deposition of the Fish River Subgroup is not possible at present.

Chronostratigraphy has to be based on the occurrence of (1) Ediacaran-type fossils, the so-called 'petalo-organisms' or Petalonamae (Gürich, 1930; Pflug, 1966, 1974; Germs, 1973*a*,*b*, 1983); (2) the enigmatic genus *Cloudina* and similar forms (Germs, 1972*b*; Grant, 1990; Grotzinger, Watters & Knoll, 2000; Wood, Grotzinger & Dickson, 2002); (3) carbon-isotopic data (Kaufman *et al*. 1991; Corsetti & Kaufman, 1994); (4) reconstruction of polar wander paths (Meert, Eide & Torsvik, 1997); (5) the occurrence of trace fossils (Crimes & Germs, 1982; Germs, 1983; Geyer & Uchman, 1995); and (6) the occurrence of vendotaenids (Germs, Knoll & Germs, 1986; Geyer, 1993; Geyer & Uchman, 1995). Although the scenario recognizable from the Nama Group does not readily match the global composite sub-trilobitic stratigraphy as sketched by Knoll & Walter (1992), the stacked occurrence of fossil groups in the Nama Group as described by Geyer & Uchman (1995) permits identification of the general zonation of the Proterozoic–earliest Cambrian recognized on a global scale (e.g. Geyer, 1998).

The occurrence of the Ediacaran-type Petalonamae (or 'Vendobionta' *sensu* Seilacher, 1989 and Buss & Seilacher, 1994) in the Kuibis Subgroup and the lower and middle part of the Schwarzrand Subgroup appears to suggest an Ediacaran ('Vendian' of many authors) age of these units. Trace fossils reported from the Nomtsas Formation (Germs, 1974, 1983) and the Fish River Subgroup (Crimes & Germs, 1983; Geyer & Uchman, 1995) are of Phanerozoic aspect and hence suggest a Cambrian rather than a Proterozoic age. As a result, the age of the Nomtsas Formation seemingly played a key role in the identification of the Proterozoic–Cambrian boundary; Germs (1974, 1983) reported the presence of the trace fossils *Trichophycus pedum* (as '*Phycodes pedum*') and *Diplichnites* isp. from immediately above the base of the Nomtsas Formation. Both are regarded as index fossils for a Phanerozoic age, and particularly *Trichophycus pedum* is the eponymous fossil of *Trichophycus pedum* assemblage which indicates the lowermost Lower Cambrian 'biozone' used to define the Proterozoic–Cambrian boundary in the GSSP at Fortune Head, southeastern Newfoundland, and on a global scale (Narbonne *et al*. 1987; Narbonne & Myrow, 1988; Landing, 1994). Other trace fossils from the Nomtsas Formation include *Neonereites uniserialis* and *N. biserialis* (Germs, 1983). This has led to the assumption that the Proterozoic–Cambrian boundary is represented within the apparently profound unconformity below the Nomtsas Formation (Daily, 1972; Germs, 1983).

In contrast to these indications of probable Cambrian age of the uppermost Schwarzrand and the Fish River subgroups, Petalonamae have been found in the Nudaus and upper Urusis formations of the lower and middle Schwarzrand Subgroup and in the Kuibis Subgroup. *Cloudina*, assumed to indicate a latest Neoproterozoic age, occurs up to the upper Urusis Formation (Germs, 1983; Saylor, Grotzinger & Germs, 1995). As a result, the occurrence of apparent *Trichophycus* specimens in the Nasep Member of the Urusis Formation (Geyer & Uchman, 1995) in the same strata as Petalonamae appears to indicate a serious problem not only for the position of the Proterozoic–Cambrian boundary in Namibia but for the stratigraphic utility of *Trichophycus pedum* and early associated traces in general.

Before going into more detail, it should be mentioned that there is a disagreement about the precise taxonomy of *Trichophycus pedum* and similar ichnospecies. The species *pedum* was transferred from *Phycodes* to the ichnogenus *Trichophycus* by Geyer & Uchman (1995) because of the behaviour exemplified by the type species, *T. lanosum* Miller & Dyer, from the Cincinnati Group, which resulted in a relatively random pattern of serial upward-directed teichichnoid probes that often led to bent chains of probes, all originating on the same (left or right) side of the burrow. By contrast, the very similar trace fossil genus *Treptichnus* was defined (according to the orthodox ichnogeneric concept) by regularly zigzagging probes. Following a revision by Maples & Archer (1987), Jensen (1997) preferred to place the ichnospecies under *Treptichnus* without discussing the differences from *Trichophycus*. Although both genera may be regarded to be synonymous, the species should be retained under *Trichophycus* unless better evidence for transitional forms and behaviour is found.

Further investigations by the author in the Schwarzrand Subgroup showed that *Trichophycus* isp. (and *Neonereites* cf. *N. uniserialis*) can be found in the Spitskop Member of the Urusis Formation, where it even co-occurs with Ediacaran-type fossil remains and *Cloudina*-type calcareous fossils.

Jensen *et al*. (2000) discussed a form similar to *Treptichnus tripleurum* Geyer & Uchman (assigned as '*Treptichnus* isp.') in the lower Huns Member of the Urusis Formation even below the Spitskop Member, at a stratigraphic position which clearly pre-dates some of the late occurrences of the Ediacaran-type fossils such as *Swartpuntia* and *Pteridinium*. They concluded that these traces (previously described by Germs, 1972*b*, as 'three lobed traces') provide 'strong evidence for advanced latest Proterozoic bilaterians' (Jensen *et al*. 2000, p. 143). Indeed, this shows a total misconception of the Proterozoic–Cambrian (and Precambrian–Phanerozoic) boundary concept developed by the International Subcommission on Cambrian Stratigraphy (ISCS) and turns a biostratigraphic rule upside down. To follow the historical concept, the ISCS attempted to place this boundary as closely as possible at the earliest occurrence date of bilaterian animals on a global scale. Because body fossils were not suitable to prove an earliest occurrence of bilaterians, complex trace fossils that apparently indicate a somewhat complex behaviour and therefore require a body plan that has bilaterian grade provided the best approximation for this earliest occurrence of bilaterians. In several areas, there is a more or less clear evolution of trace fossil assemblages from (1) very simple, unbranched traces to (2) assemblages with branched and somewhat sophisticated trace fossils (that usually include *Trichophycus pedum*), and finally to (3) trace fossil assemblages which include undoubtedly arthopod traces (such as *Rusophycus*). Trace fossil assemblage (2), termed the *Trichophycus pedum* (formerly *Phycodes pedum*) assemblage, is the first association with unquestionable trace fossils produced by bilaterians. According to the rules of the International Commission on Stratigraphy, the ISCS elected a Global Stratotype Section and Point (GSSP) in southeastern Newfoundland because it fulfilled all requirements (Landing, 1994). One of the major requirements is a largely monofacial development of the succession (the Chapel Island Formation) so that an environmentally controlled occurrence can be largely excluded. This 'Golden Spike' was placed at the lowest known specimen (= earliest occurrence) of *Trichophycus pedum* in the Chapel Island section.

The idea behind this GSSP concept is that it equally reflects the earliest occurrence of the relevant fossil on a global scale. It should also be emphasized once again that *Trichophycus pedum* is not *the* index fossil for the zone but stands *pars pro toto* for the onset of a global benthic community. Wherever *Trichophycus pedum* is lacking in coeval sections, the onset of complex trace fossils is able to indicate tentatively the base of the Phanerozoic.

Gehling *et al*. (2001) reported specimens of *Trichophycus pedum* in the Chapel Island section a short distance (4 m) stratigraphically below the GSSP and closer to a supposedly fluvially influenced part of the succession. These authors thus challenged the validity of the ISCS decision and emphasized a gradational onset of burrowing 'across the Proterozoic–Cambrian boundary'. However, whether a specimen can be discovered by chance a short distance below the Golden Spike is not of great relevance for the global concept (1) because the presence of such critical ichnofossils below the GSSP only illustrates minor deficiencies of fieldwork at this place, and (2) because of the immense thickness of the Chapel Island Formation which suggests that the small time interval illustrated by these different occurrences cannot currently be resolved by either biostratigraphic and chronometric methods.

The specimens of *Trichophycus* (or *Treptichnus*) in the Urusis Formation of the Schwarzrand Subgroup thus indicate that these strata are of Cambrian (and Phanerozoic) age so that the co-occurring and later Ediacaran- and *Cloudina*-type fossils are Cambrian in age, and that the Precambrian–Phanerzoic boundary is at least as low as the lower Urusis Formation and middle Schwarzrand Subgroup. The problem of an environmentally/facies-controlled occurrence addressed by Jensen *et al*. (2000) for the trace fossils is equally valid for Ediacaran-type fossils as already illustrated by Mount (1989) and McIlroy, Jenkins & Walter (1997). In addition, it has been shown that Ediacaran-type fossils range well into the Cambrian (Conway Morris, 1993; Jensen, Gehling & Droser, 1998) so that they cannot be used as index fossils for an Ediacaran age without severe restrictions.

Those problems are neither a novelty nor restricted to the Namibian sequences (compare data in Brasier, 1979; Liñán, Palacios & Perejón, 1984; and Palacios Medrano, 1989) and were readdressed based on data from the Siberian Platform (Vidal, Moczydlowska & Rudavskaya, 1995). Nonetheless, the situation appeared to be complicated further by findings of vendotaenid 'algae' in the Nomtsas Formation (Geyer, 1993). Although vendotaenid fragments have been reported earlier from a core of the Tses-1 borehole (Germs, Knoll & Vidal, 1986), the precise stratigraphic position and significance presented difficulties. *Vendotaenia*-type fossils had previously been regarded as indicators of late Neoproterozoic age because of their stratigraphic occurrence on the East European Platform and in other regions (Gnilovskaya, 1971, 1979, 1990; Hofmann, 1985; Steiner, 1994). Nevertheless, even the stratigraphic significance of vendotaenids has been challenged by recent examinations of the Proterozoic–Cambrian transition in regions such as Spain (Palacios Medrano, 1989; Vidal, Jensen & Palacios, 1994) and Finnmark (G. Vidal, pers. comm. 1994; Vidal & Mozcydlowska, 1995), and they have now been found in Ukrainian sections, in rocks of Cambrian age (M. Steiner, pers. comm. 2002). It should also be noted that the Chapel Island Formation in the global stratotype section at Fortune Head, Newfoundland, yields *Tyrasotaenia*-type vendotaenids in the earliest Cambrian *Trichophycus pedum* and *Rusophycus avalonensis* assemblage zones (Narbonne & Myrow, 1988). Moreover, the material from the Nomtsas Formation has recently been studied and identified as *Vendotaenia antiqua* and *Sabellidites cambriensis* (Steiner, 1994; A. Hoppe, unpub. thesis, Technische Univ. Berlin, 1995). Hoppe interpreted the taxonomic disparity between *Vendotaenia* and *Sabellidites* as a result of preservation and suggested both to be synonymous. In addition, Steiner (1994) and Hoppe (A. Hoppe, unpub. thesis, Technische Univ. Berlin, 1995) both regard *Tyrasotaenia* as a synonym of *Vendotaenia*. These results undermine considerably the stratigraphic potential of this fossil group, and in turn require reconsideration of the stratigraphic value of *Sabellidites*.

Non-conventional stratigraphic data from the critical interval of the Namibian sequence are presently of little help for fine-tuning the Proterozoic–Cambrian boundary. Kröner *et al*. (1980) presented palaeomagnetic data from various formations of the Nama Group including the Nomtsas Formation. According to these results, magnetization of the Nomtsas Formation does not differ significantly from the component of the underlying formations for which a primary remanence of a magnetization age of about 630 to 650 Ma has been determined (Kröner *et al*. 1980). In contrast, for the overlying formations of the Fish River Subgroup, magnetic data present a pole position which is interpreted to be of Cambrian age (Horstmann *et al*. 1990). Hence, Kröner *et al*. (1980) suggested a major break between the Schwarzrand Subgroup and the Fish River Subgroup that is above the Nomtsas Formation, and interpreted this gap as the position of the Proterozoic–Cambrian boundary.

These interpretations contrast with those based on carbon-isotopic investigations by Kaufman *et al*. (1991) and Corsetti & Kaufman (1994). An isotopic maximum was found in the Zaris Formation of the upper Kuibis Subgroup, which suggests a late Neoproterozoic peak (Kaufman *et al*. 1991). The Zaris Formation has the type stratum of *Cloudina* and of supposedly related earliest calcareous fossils such as *Namacalathus* (Grotzinger, Watters & Knoll, 2000; Amthor *et al*. 2003). Corsetti & Kaufman (1994) proposed a hiatus in the sequence of the White-Inyo region of California that brackets an interval from the latest Neoproterozoic and the major part of the Tommotian in Siberia. Possible correlation of the Nama Group with the Californian sequence suggests, according to Corsetti & Kaufman (1994), that the hiatus equals the uppermost Kuibis and Schwarzrand subgroups up to the Nomtsas Formation. Hence, the Nomtsas Formation could be an equivalent of the upper Tommotian stage of Siberia (which would be well above the base of the Cambrian). However, those correlations are based on isotopic data that are not entirely persuasive.

A direct age assignment for the Namibian successions comes from a ^{207}Pb–^{206}Pb date on a volcanic ash layer in the upper Spitskop Member of the Urusis Formation. Grotzinger *et al*. (1995) reported a determination of 543 ± 1 Ma for this horizon. An additional ash layer in the lower Nomtsas Formation was dated at 539.4 ± 1 Ma. These interpretions of Grotzinger *et al*. (1995) placed the Proterozoic–Cambrian boundary at the base of the Nomtsas Formation regardless of the fact that biostratigraphic data were not used consistently. At least these dates slightly concur with U–Pb datings of a volcanic breccia from *Cambrotubulus*-bearing, earliest Cambrian (Manykayan) strata of the Olenek Uplift in northern Siberia, although these are also not very well constrained biostratigraphically (Bowring *et al*. 1993).

New carbon isotopic and U–Pb zircon geochronological data from the Ara Group in Oman indicate that the last appearance of *Cloudina* and *Namacalathus* in those successions coincides with a pronounced negative excursion in the carbon isotope composition of the seawater. This short-lived excursion appears to be nearly coincident with the Proterozoic–Cambrian boundary and has been dated by U–Pb zircon age methods to be at 542.0 ± 0.4 Ma (Grotzinger *et al*. 2002; Amthor *et al*. 2003). Although the sections in Oman did not show any index fossils for a Cambrian age, the authors and the International Commission on Stratigraphy used the Oman date as the best value for the Proterozoic–Phanerozoic boundary (Gradstein, Ogg & Smith, 2005). This argument is based on the assumptions that (1) the upper range of *Namacalathus* in the Ara Group sections of Oman indeed portrays the extinction of these and related organisms; (2) this extinction is more or less synchronous with that in Namibia; and (3) the major positive carbon isotope shift in the Oman sections coincides with the 'peak I' in other areas such as Siberia. However, there is currently no evidence that this positive carbon isotope shift correlates more or less precisely with the approved base of the Cambrian because relevant data from the GSSP at Fortune Head, southeastern Newfoundland, are not available for the critical interval. Earlier correlations of this major positive shift from Siberia into other areas (Magaritz, Holser & Kischvink, 1986) have partly been shown to be erroneous (e.g. for Morocco; see Geyer & Landing, 1995). In addition, new data from Siberia (Kouchinsky *et al*. in press) indicate that the situation for the lowermost Cambrian in Siberia is much more complicated than previously assumed. In conclusion, the upper limit of the *Namacalathus* range should not be treated as a precise biostratigraphic date nor should the age of 242 ± 0.3 Ma be used as an exact age for the base of the Phanerozoic.

Meert, Eide & Torsvik (1997) revised the apparent polar wander path for Gondwana and scrutinized data for the Nama Group. They indicated a complex series of overprints which made a reconstruction of the primary direction of the magnetization extremely difficult, so that data from the Nama Group were regarded to be of little significance at that time.

A minimum age of the Fish River Subgroup can be deduced indirectly. In the Vanrhynsdorp area, South Africa, units of the Nama Group are unconformably overlain by the Table Mountain Group, the lower strata of which have been dated locally as Late Cambrian in age (Cocks *et al*. 1970).

Earlier articles assumed that the Fish River Subgroup brackets the temporal interval between the Schwarzrand Subgroup and overlying Table Mountain Group, which would therefore include a span of roughly 40 million years. According to the environments in which the units of the Fish River Subgroup were deposited, and to the palaeontological data from those rocks, this assumption of a long period represented by the Fish River Subgroup appears illusory. Although direct evidence is lacking, the rocks of the subgroup probably represent a very short interval of time, in which the deposition directly followed that of the uppermost Schwarzrand Subgroup. Analysis of depositional conditions of the Fish River units indicates a fluctuation, or even oscillation between adjoining environments with generally high sediment accumulation.

The inventory of trace fossils remains relatively uniform where found in the different lithostratigraphic units. *Trichophycus pedum* remains a frequent ichnofossil element into the higher portion of the Rosenhof, where the youngest trace fossils were found. By contrast, *Rusophycus* or *Cruziana*, which are indicative of a later ichnofossil assemblage, have not been found, although the environment is generally favourable for such trace fossils.

Body fossils are unknown from the Fish River Subgroup. This could be a result of a relatively low preservation potential. However, shales of the upper Rosenhof Member were certainly suitable to preserve either casts of larger body fossils (such as trilobites or brachiopods) or Small Shelly Fossils. The absence of those fossils is here interpreted as a result of the absence of the animals during the time of deposition. Hence, the Fish River Subgroup is interpreted herein as early, sub-trilobitic Early Cambrian in age.

It remains unknown whether later Cambrian, post-Deurstamp rocks have not been produced, or whether such rocks have been totally eroded. In any case, the relief and general position of the late Palaeozoic Dwyka deposits on the Fish River subgroups clearly indicate that a pronounced erosion took place, removing a considerable amount of rocks in the type area in southern Namibia.

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Appendix. Studied localities (Fig. 1)

BHa. Section along southern main canyon of Gross Brukkaros mountain, Berseba District. Rosenhof Member.

BR. Road cut on Farm Breckhorn, along road C34 from Maltahöhe to Mariental, about 20 km E of Mariental. Breckhorn Formation.

BS. Section at the southern flank of Brukkaros mountain, Berseba District. Gross Aub Formation, Rosenhof Member.

FA, AD. Section along Fish River at Aribdrif, Berseba District, 26°19′ S, 17°48′ E. Gross Aub Formation, Rosenhof Member.

FB. Section in the Fish River valley close to the bridge between Tses and Berseba, 25°51′02″ S, 17°59′01″ E. Gross Aub Formation, Rosenhof Member.

FC, AF. Section along Fish River in the vicinity of Achterfontein, S of Berseba. Gross Aub Formation, Rosenhof Member.

FF, GN. Section along rivier NE of Gainachas, Berseba District, coord. 25°48′ S, 17°42′ E. Rosenhof Member.

GG. Exposures along the highway B4 between Seeheim and Goageb c. 17 to 18 km W of the Fish River bridge. Breckhorn Formation.

GW. Section along road about 11 km W of Gibeon, 25°13′20′′ S, 17°38′ E. Rosenhof Member.

KO. Kosis Farm, along the road about 0.3 to 1.2 km SW of the farmhouse. Gross Aub Formation, Rosenhof Member.

MV. Section at the southern flank of Brukkaros mountain, Berseba District. Gross Aub Formation, Rosenhof Member.

NP. Section on Nauwpoort Farm, 25°59′37′′ S, 17°02′29′′ E. Middle and upper Stockdale Formation.

RO. Section at outlier termed Rotenberg, Friedabrunn Farm, 24°41′51′′ S, 17°33′26′′ E. Gross Aub Formation, Rosenhof Member.

SC. Section along creek S of Brukkaros Mountain, Berseba District. Gross Aub Formation, Rosenhof Member.

ST. Locality on Stockdale Farm, 25°59′37′′ S, 17°02′ 29′′ E. Upper Nomtsas Formation through lower Stockdale Formation.

ZA. Exposures along the highway B4 between Seeheim and Goageb close to district boundary between Keetmanshoop and Bethanie, 10.5 km W of the Fish River bridge. Nababis Fm., Zamnarib Member.

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