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Report: Preliminary results of a study of the structural and sedimentological evolution of the late Proterozoidearly Palaeozoic Gariep Belt, southern Namibia

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The Late Proterozoic/Early Palaeozoic Gariep Belt was formed during the Pan-African orogenic cycle and is believed to be part of the southern .coastal branch of the extensive Damara Orogenic Province, linking with the Saldanha Belt of the southwestern Cape Province. It consists of an eastern para-autochthonous passive continental margin on the western edge of the Kalahari Craton, the Port Nolloth Zone (PNZ), and a western allochthonous ophiolitic terrane, the Mannora Terrane, thrusted on the PNZ at the Schakalsberge thrust. The sedimentary rocks within the PNZ rest with a marked unconformity on the igneous rocks of the Namaqua Metamorphic Complex basement rocks of the Namaqua and Richtersveld provinces. The Gariep Group is stratigraphically subdivided into the Stinkfontein Subgroup, comprising the Rosh Pinah and the Gumchavib Formations, which are both interbedded with amphibolite sills of the Gannakouriep dyke swarm; the ‘Hilda Subgroup, comprising the Pickelhaube, Obib Peak, and Numees Formations; as well as the Holgat Subgroup, a deep-water phase, which will not be described here. Some sediments of the Rosh Pinah Formation contain bimodal volcanics and sedimentary-exhalative Zn-Pb-Cu-mineralisation. The present study has recognised the following facies associations from which palaeoenvironments have been interpreted: (1) a conglomerate/sandstone/mudstone/carbonate facies association, which was deposited as subaqueous fan delta deposits within a lacustrine environment and is restricted to the Rosh Pinah Formation; (2) a mixed sandstone and conglomerate facies association, which generated in a proximal to distal braided plain environment, being confined to the Gumchavib Formation, Obib Peak Formation, and the Numees Formation; (3) a quartz-arenite, conglomerate, and mudstone facies association, whir.h formed within foreshore, shoreface and offshore palaeoenvironments, confined to the Gumchavib Formation; (4) a calcareous facies association, which is interpreted as being deposited within a shallow to moderately deep carbonate shelf environment, being confined to the Gumchavib Formation and Pickelhaube Formations; and (5) a diamictitic facies association, interpreted as being generated in glaciomarine and glaciofluvial palaeoenvironments, which is confined to the Numees Formation. The regional structural pattern is characterised by three phases of deformation. The tectonic grain of the study area is north-northwest to northwest, comprising thrust faults, and medium to large scale, symmetric to asymmetric, tight to isoclinal, and in places recumbent north-northwest-trending D_2 folds. These are refolded by small- to large-scale, open D_3 folds, with fold hinges trending west to southwest. Three phases of deformation have been recognised. D_1 consists of a bedding-subparallel fabric and associated small-scale isoclinal folds and sheath folds with a southeasterly vergence, which are deformed by folds, containing an axial planar fabric (D_2), which were subsequently refolded by the D_3 folds, to form interference fold structures. Lithologies, structural styles, and time-sequence of events indicate a tectonosedimentary evolution which involves the genesis of a rift and subsequent spreading of the Late Proterozoic Adamastor Ocean. The collision following oceanic closure resulted in progressive evolution from the D_1 fabric and fold elements to the D_2 folding and thrusting and a final D_3 sinistral lateral movement. Geothermometry and geobarometry indicate P-T conditions ranging from greenschist facies to the lower amphibolite facies. The resulting geothermal gradient for these P-T estimates is about 20°C/km indicating a Barrovian-type metamorphism. The tectonosedimentary evolution of the PNZ started between ~920 Ma, which is the age of the Richtersveld Complex being unconformably overlain by the Stinkfontein Subgroup, and ~780 Ma, which is the age of the intrusive Lekkersink granites, representing a minimum age for the Stinkfontein Subgroup. The tectonosedimentary evolution of the PNZ terminated at ~520 Ma, which is the age for the Kuboos pluton and the Bremen Complex, which intrude the PNZ in the Richtersveld.

Introduction

The Gariep Belt is an arcuate north-south trending tectonic unit extending along the coast from southeast of Lüderitz in Namibia to Kleinzee in South Africa, a distance of nearly 400 km with a maximum exposed width of about 80 km (Fig. 1).

It represents part of the Late Proterozoic/Early Palaeozoic Pan-African system of orogenic belts and is part of the southern coastal branch of the extensive Damara Orogen which links with the Saldanha Belt of the southwestern Cape Province and extends northwards to join with the northern coastal branch in Kaokoveld in northern Namibia (Clifford, 1967; Stowe *et al.*, 1984).

The Gariep Belt consists of an eastern parautochthonous passive continental margin on the western edge of the Kalahari Craton, the Port Nolloth Zone (PNZ; Von Veh, 1988; Hartnady *et al.*, 1990) and a western allochthonous ophiolitic terrane, the Marmora Terrane (Hartnady *et al.*, 1985), thrusted onto the PNZ along the Schakalsberge thrust (Fig. 1). The sedimentary rocks within the PNZ rest with a marked unconformity on the igneous rocks of the Namaqua Metamorphic Complex basement rocks of the Namaqua and Richtersveld provinces (Kröner, 1975). The PNZ stratigraphically consists of the Stinkfontein Subgroup, comprising the Rosh Pinah and Gumchavib Formations; the Hilda Subgroup, comprising the Pickelhaube, Obib Peak, and Numees Formations (Fig. 2); and the Holgat Subgroup, a deepwater phase, which will not be described in this work. The PNZ is characterised by intensive thrusting and folding.

The Marmora Terrane comprises the volcanosedimentary Chameis Complex, the Oranjemund Complex, composed of metagreywacke rock types varying from little-deformed cyclothemic turbiditic varieties to intensely transposed, poly-deformed mica schist, and along its eastern extent the Schakalsberg Complex, consisting of the ophiolitic Grootderm Formation and the overlying dolomitic Gais Formation (Smith and Hartnady, 1984; Hartnady *et al.*, 1990). Metamorphism within the PNZ ranges from greenschist to lower am-

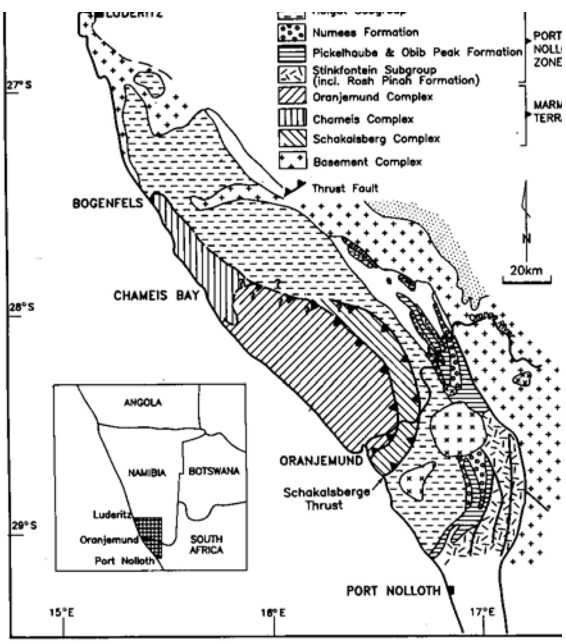


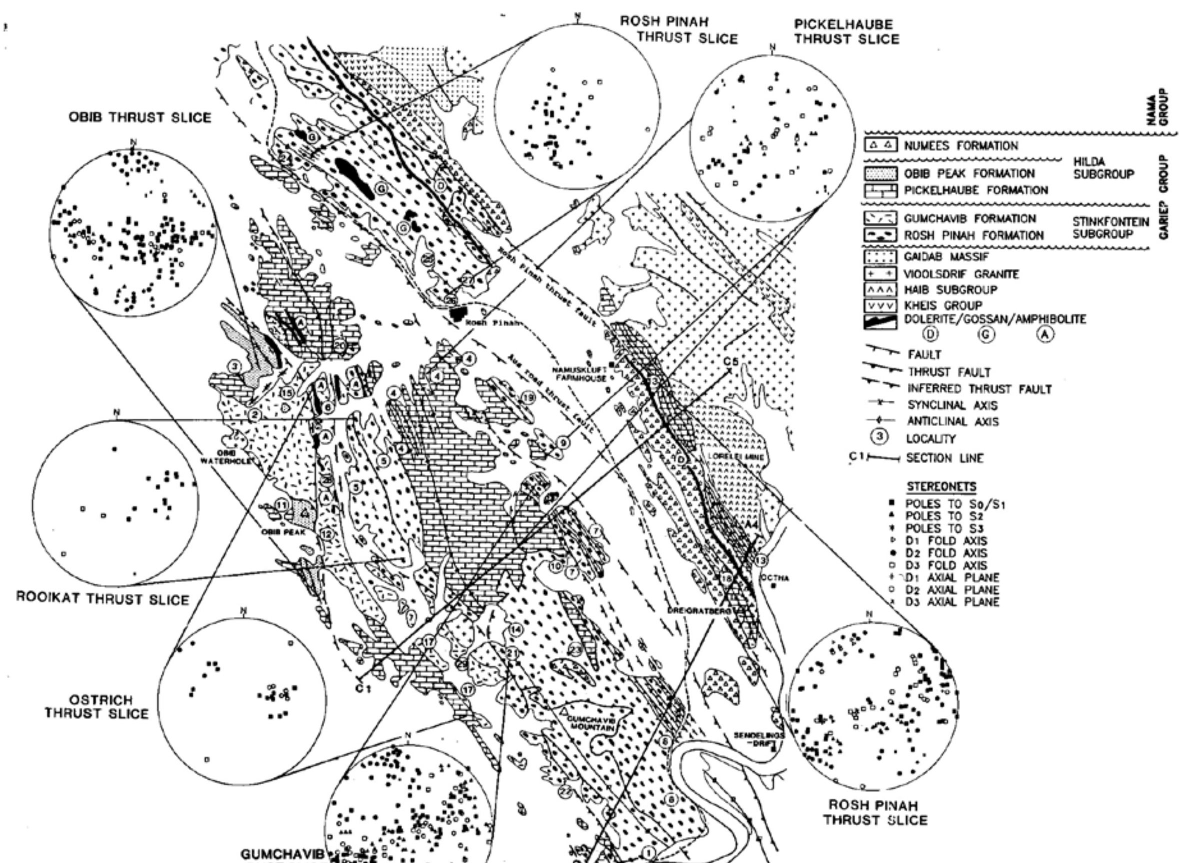
Figure 1: Tectonostratigraphic subdivision of the Gariep (modified after Hartnady *et al.*, 1990)

phibolite facies, thus not affecting the sediments and volcanics dramatically.

Pioneering work on the Gariep Belt was first carried out by Gennan workers (Drews, Klinghardt, Cotz, Runge, Reuning, Sprigade) during a survey of the eastern Sperrgebiet (Diamond Area No.1) south of Lüderitz from 1912 to 1913 (McMillan, 1968). The first geological account of the Gariep Belt was undertaken by Rogers (1916), who mapped the area west of Vioolsdrif on the Orange River. Beetz (1924) concentrated mainly on the Witputs area approximately 40 km north of Rosh Pinah, and Söhnge and De Villiers (1946) worked in the eastern parts of the Sperrgebiet. McMillan (1968) compiled a detailed map and report of the Witputs-Sendelingsdrif area. Further geological studies within the Rosh Pinah mine area and its vicinity have been undertaken by Page and Watson (1976), Watson (1980), Davies and Coward (1982), Van Vuuren (1986), De Kock (1987), Siegfried (1990), and Lickfold (1991). Von Veh (1988) made detailed stratigraphic and structural studies in the adjacent Sendelingsdrif-Annisfontein area in the northern and western Richtersfeld to the south of the Orange River, which defines the southern boundary of the present study area.

No detailed work has so far been undertaken in the

Figure 2 (below): Geological map of the Rosh Pinah/Sendelingsdrif area



Ccs	massive clast-supported conglomerate
Cms	massive matrix-supported conglomeate
Dm	massive diamictite
I	iron formation
Lc	small-scale channels containing calcereous material
Ll	parallel-laminated limestone
Lg	graded limestone beds
Lgi	graphite- and iron-rich carbonate
Lmd	massive dolomitic limestone
Lp	pisolitic limestone
Mfl	fine, parallel-laminated mudstone
Mm	massive mudstone
Msfl	finely tabular-planar cross-laminated siltstone and mudstone
Mstl	finely parallel- and trough cross-laminated siltstone and mudstone
Msg	graded siltstone and mudstone
Sc	crossbedded sandstone
Sng	normal graded sandstone
Sig	inverse graded sandstone
Scq	calcereous quartzitic sandstone
Sms	massive sandstone
Smfq	massive quartz arenite
Spc	tabular planar crossbedded sandstone
Splq	plane-laminated quartz arenite
Spq	tabular planar cross-laminated quartz arenite
Stq	trough cross-laminated quartz arenite
Srm	ripple-marked sandstone
Swr	wave-ripple cross-laminated siltstone/ fine sandstone

Table 1: Facies abbreviations

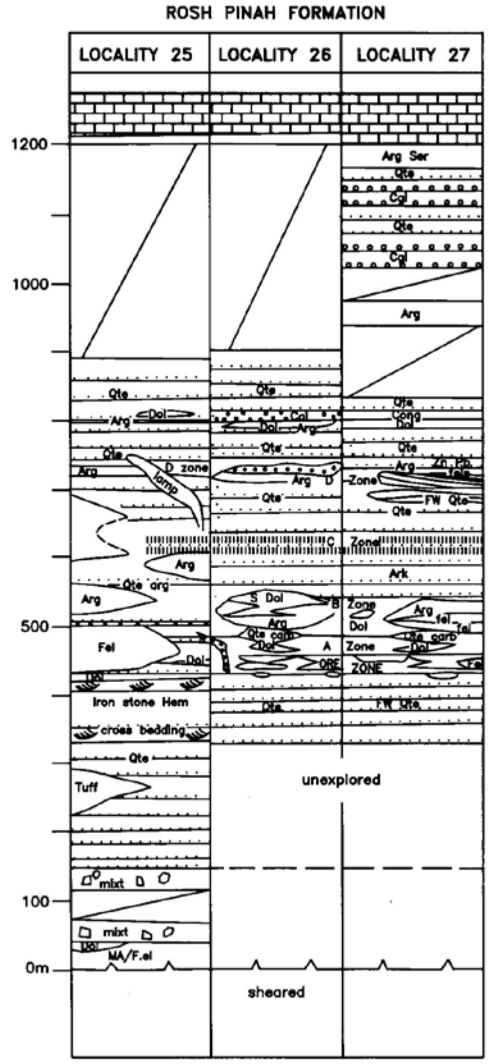


Figure 3: Provisional stratigraphic sketch of the Rosh Pinah unit at the type area at localities 24, 25, and 26 (after Kindl, 1979)

Gariep Belt in Namibia itself. Sedimentological and structural work is being carried out in order to characterise the sedimentation of the Gariep Group and the tectonics which controlled it, and to resolve stratigraphic relationships of the formations of the Gariep Belt in southwestern Namibia. This paper represents the preliminary observations and results of the study.

Sedimentology

There are no previous detailed sedimentological studies on the Gariep Belt. Sedimentological studies in the study area are based on detailed measured sections on a variety of scales. Several facies associations (Table 1) were recognised in the study area and are described in the following sections.

Conglomerate/sandstone/mudstone/carbonate facies association: fan delta/lacustrine environments

This facies association is confined to the Rosh Pinah Formation (Figs 3 and 4). Eight facies are recognised: (1) massive matrix-supported conglomerate (Cms); (2) massive sandstone (Sms); (3) normal graded sandstone (Sng); (4) inverse graded sandstone (Sig); (5) finely laminated siltstone and mudstone (Mfl); (6) wave-ripple cross-laminated siltstone/fine sandstone (Swr); (7) mudstone (Mm); (8) massive carbonate (Lmd).

The sorting of the massive conglomerates (Cms) and their groundmass is poor. The matrix consists of medium to coarse grains of quartz, feldspar, mica schist, and lithic grains with a quartzitic, calcareous and sericitic cement. The clasts consist of subangular to subrounded clasts and boulders of vein quartz, gneissic granite, granodiorite, quartzite, mica schist, phyllite, and dolomite. The average clast size ranges between 2 to 30 cm, but within some beds large isolated dolomitic boulders (10 x 5 m) and dolomite lenses (Lmd; 100 x 5 m) are present. Bed thicknesses of the sandstones and conglomerates range between 10 cm and 5 m. The massive conglomerates (CmS) also occur in beds with gradational contacts, but sharp scour bases are also present. Beds are structureless but display normal and inverse graded bedding, which is best observed in the coarse fractions (Fig. 4). A plane stratification within the mas-

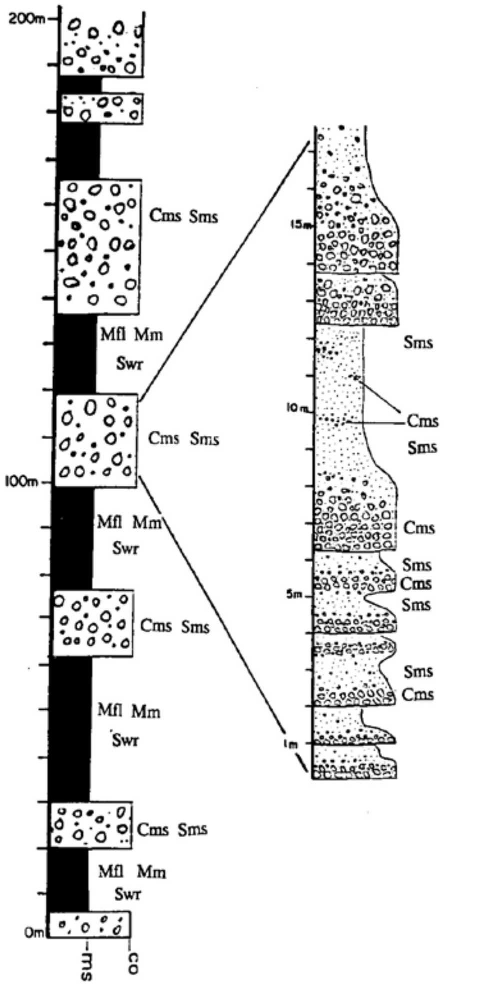


Figure 4: Measured section through the Rosh Pinah Formation at locality 14, 3 km north of Gumchavib mountain (cf. Fig. 2)

sive conglomerates is also apparent, manifested by the weak grading.

The finely interlaminated siltstone and mudstone (Mfl), which are interbedded with the massive conglomerate (Cms), consists of <1 mm to 3-mm-thick laminations (Figs 4 and 5). The wave-ripple cross-laminated siltstones/filled sandstones with fine mudstone inclusions (Swr) range in thickness from 1 to 30 cm and are interbedded with dark grey mudstone beds (Mm; Fig. 5). The massive mudstone is blue-grey-silvery to green-grey and dark-grey and consist of quartz and mica (muscovite-biotite) and small amounts of chlorite and feldspar. Some mudstones contain a high amount of carbonaceous material.

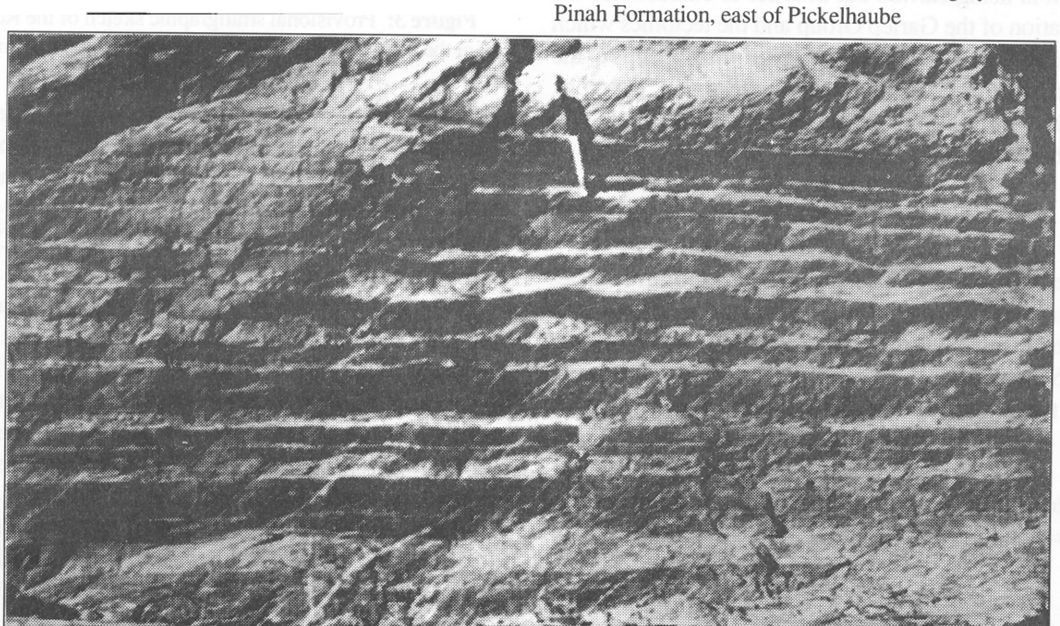
The massive arkosic sandstones (Sms) are poorly sorted. In places they are interbedded with normal graded arkosic sandstone (Sng) and mudstone (Mm) and inverse graded arkosic sandstone (Sig) with occasional sharp contacts. Bed thicknesses range between <10 cm and ~5 m. Near the contact with the overlying mudstones, bed thicknesses increase and plane lamination becomes more abundant within the mudstone (Mfl).

Mineralised carbonate beds of the Rosh Pinah Formation, with maximum thicknesses of approximately 120 m, pinch out laterally within the Rosh Pinah mine area (D. Alchin, pers. commun.).

Interpretation

Normal and inverse grading within the massive conglomerates (Cms), sandstones (Sms, Sng, Sig), and mudstone (Mm), the presence of sand sheets, the subangular to subrounded shape of clasts, the presence of

Figure 5 (below): Wave-ripple cross-laminations in finely laminated siltstones interbedded with dark grey mudstones, Rosh Pinah Formation, east of Pickelhaube



rock fragments within the matrix and the sandstone, the extraordinary large size of some dolomite boulders, as well as the presence of basement-derived clasts, indicate a debris-flow dominated environment, typical of alluvial fans or fan deltas. The abundance of more sandy or conglomeratic material indicates a further distal or proximal deposition within such an environment in which sheet flow and shallow braided-river processes dominated.

Facies Mfl, Swr, and Mm are interpreted as being deposited within a lacustrine environment. The plane-laminated mudstones and, in places; the highly carbonaceous composition of some mudstones, indicate deposition within a deep or quiescent environment. The absence of quartz arenites, often developed as a result of wave action in open coastal marine settings, the immature nature of the siltstones/fine sandstones, as well as the immature composition of the sediments of the Rosh Pinah Formation within the "Mining Concession Area" of the Rosh Pinah mine (McMillan, 1968; Page and Watson, 1976; Watson, 1980; Van Vuuren, 1986; De Kock, 1987; Siegfried, 1990; and Lickfold, 1991), indicate that the fan delta prograded into a lacustrine environment. Wave-ripple cross-lamination with mudstone inclusions within the siltstones/fine sandstones indicate minor wave reworking above lacustrine wave base. Large-scale cycles can be defined within which the facies successions above the conglomerate facies are interleaved with sandstone and mudstone facies, and which comprise the Rosh Pinah Formation south of Rosh Pinah. Similar sequences have been described from the Upper Palaeozoic basins of the Maritime Province of Canada and the Devonian Orcadian Basin of northeast Scotland (Collinson, 1978), where silty to sandy sediments form a transition to the overlying alluvial sediments.

The massive carbonates within the Rosh Pinah Formation may represent either recrystallised stromatolitic mats within a lacustrine environment, as described from the Eocene Greenriver Formation in North America (Eugster and Hardie, 1978; Eugster, 1985) and the Miocene Ries impact crater in Southern Germany (Wolff and Füchtbauer, 1976), where algal mats and dolomite were deposited, Some carbonate beds may also represent reworked stromatolitic carbonate, which were redeposited into deeper parts of lacustrine environments.

Mixed sandstone and conglomeratic facies association: proximal to distal braided-plain environments

This facies association (Figs 3, 6, 7, and 8) is developed within the Rosh Pinah, Gumchavib, Obib Peak, and the Numees Formations. Several facies are recognised: (1) massive, clast-supported, pebble conglomerate (Ccs); (2) massive, matrix-supported conglomerate (Cms); (3) massive arkosic sandstone (Sms); (4) graded arkosic sandstone (Sng); (5) tabular-planar, crossbedded feldspathic sandstone (Spc); and (6) mudstone (Mm).

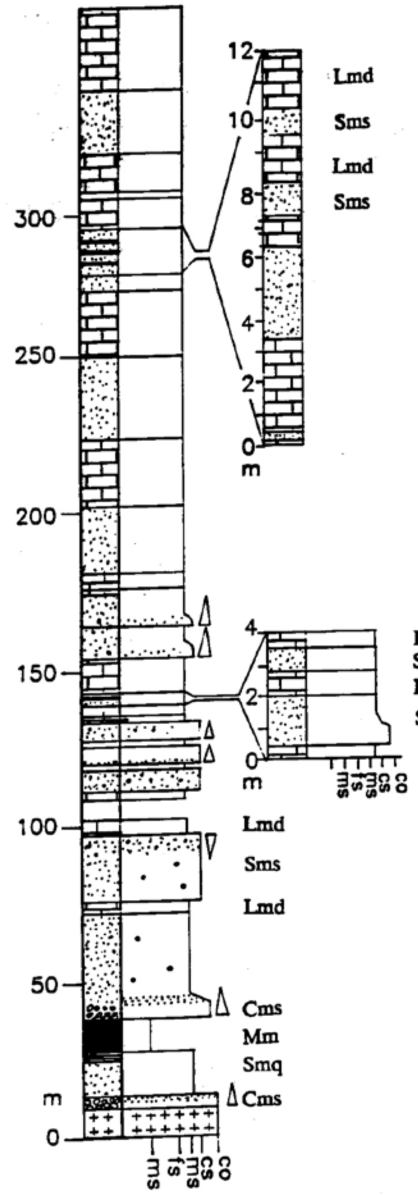


Figure 6: Measured section through the Gumchavib Formation at locality 27, 4 km northwest of Gumchavib mountain (cf. Fig. 2)

Channels of clast-supported conglomerates (Ccs) reveal erosional bases with a maximum width of about 5 m and height of 50 cm. The pebbles are subrounded and consist mainly of quartzite. They have diameters of 2 mm to 5 cm and form a clast-supported framework with a coarse arkosic sand matrix.

The massive, matrix-supported conglomerate facies (Cms) comprises upward-fining and upward-coarsening pebbly beds, with units varying in thickness between 15 cm and 10m. The matrix is a medium to coarse arkose. The pebbles consist mainly of quartzite with an average size ranging between 2 mm and 5 cm, but dolomite boulders measuring 40 cm in diameter also occur within the Obib Peak Formation at its type locality (Fig, 7). The base of these beds can be sharp with scour sur-

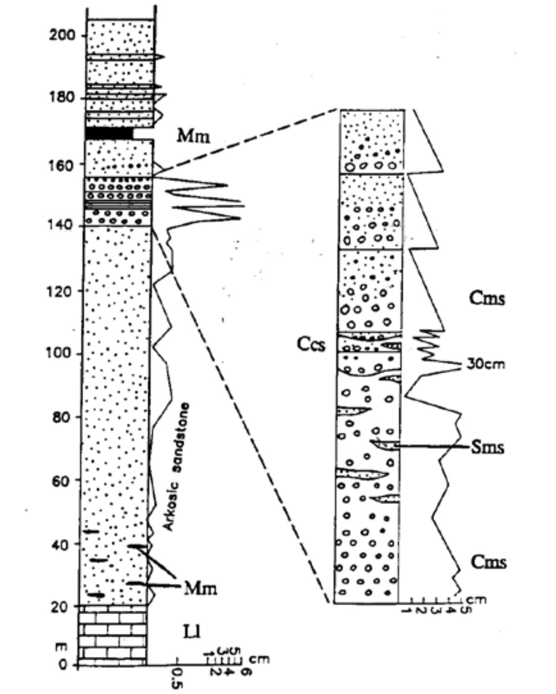


Figure 7: Measured section of the Obib Peak Formation at locality 3, about 4 km northeast of Obib waterhole (cf. Fig. 2)

faces. Some patches of matrix-supported conglomerate (Cms) are recognised within the massive sandstone (Sms) units.

The massive sandstones (Sms) within the Rosh Pinah, Gumchavib, and Obib Peak Formations consist of medium to coarse subarkose or arkose. Sorting is poor, and no sedimentary structures are recognised, except graded beds (Sg) with bed thicknesses of 2 cm to 2 m and ripple marks (Fig. 9). Set thicknesses of the tabular planar, crossbedded sandstone (Spc; Fig. 10) within the Rosh Pinah Formation vary from 10 cm to ~50 cm.

Bed thicknesses of the mudstones (Mm) range between 5 cm to over 10m. The mudstones are green-grey to grey and massive and consist of quartz, feldspar, and mica.

Carbonates, varying in thickness from a few cm to >10m are interbedded with the sandstones and conglomerates of the Gumchavib Formation and separated by sharp contacts (Fig. 6).

Interpretation

The mineralogy of the pebbly feldspathic sandstones and the presence of graded beds together with ripple marks indicate a fluvial environment, generated in a braided fluvial system representing both channel and overbank sedimentation. Massive, clast- and matrix-supported conglomerates (Ccs, Cms) and tabular planar crossbedded arkosic sandstones (Spq) represent the most proximal environment of deposition and reflect growth of longitudinal bars. Ccs, Crns form the core of the bars, whereas the tabular planar and crossbedded sandstones may represent the migration of mega

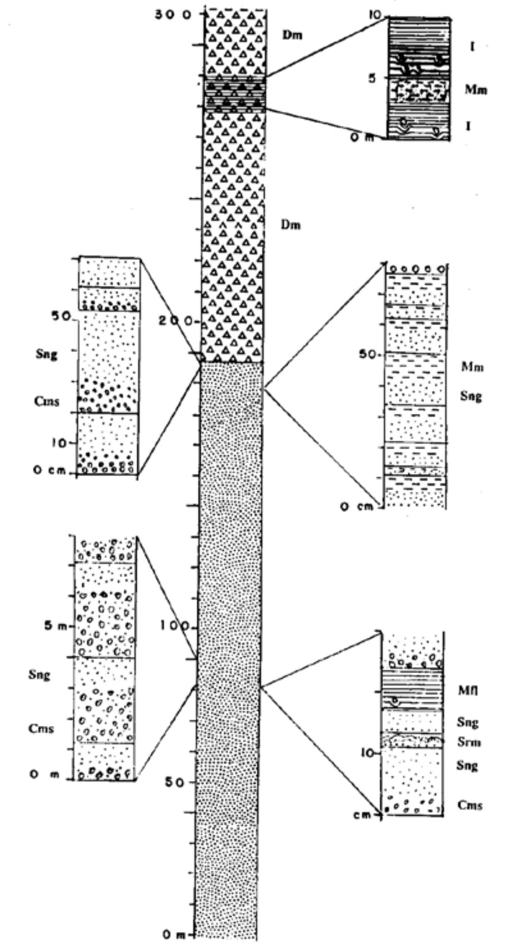


Figure 8: Measured section through the Numees Formation at Trekpoort Farm approximately 30 km northwest of Rosh Pinah (cf. Fig. 2)

ripples (compare Boothroyd and Ashley, 1975). The massive, matrix -supported conglomerates, developed in upward-fining units, probably represent debris-flow deposits. Each upward-fining sequence might reflect a single flood cycle.

The coarser grained arkosic sandstones (Sms) appear to have been deposited in the lower flow regime, with the Mm facies representing overbank deposits. The predominance of massive sandstones (Sms) may also represent sheet flooding.

The carbonates within the Gumchavib Formation may represent recrystallised algal mats, generated during transgressional sea-level changes, possibly eustatic in nature, and drowned by clastic input during regressional periods.

Quartz arenite, mudstone, and conglomerate facies association: foreshore and shoreface environments

This facies association is confined to the Gumchavib Formation. Six facies are developed: (1) massive quartz arenite (Smq); (2) trough cross-laminated quartz arenite (Stq); (3) tabular planar cross-laminated quartz arenite

(Spq); (4) plane-laminated quartz arenite (Splq); (5) matrix-supported conglomerate (Cms); and (6) mudstone (Mm).

At Obib waterhole, where this facies association is best developed, it comprises at the base a matrix-supported conglomerate, consisting of a quartzitic matrix and subrounded granite clasts, up to 30 cm in diameter, lying unconformably on the granitic basement. In places, a massive, medium-grained quartz arenitic sandstone (Smq) laps unconformably onto the basement. The trough cross-laminated sandstone facies (Stq; Fig. 11) consists of fine- to medium-grained, quartz-arenitic sandstone. Tabular, planar cross-laminated and plane-laminated quartz arenites (Spq, Splq; Fig. 11) are interbedded with the trough cross-laminated quartz arenites (Fig. 11) and illustrated in Fig. 12. The trough axes are oriented towards the west and southwest. Bed thicknesses range from less than 10 cm to 5 m. All the lami-

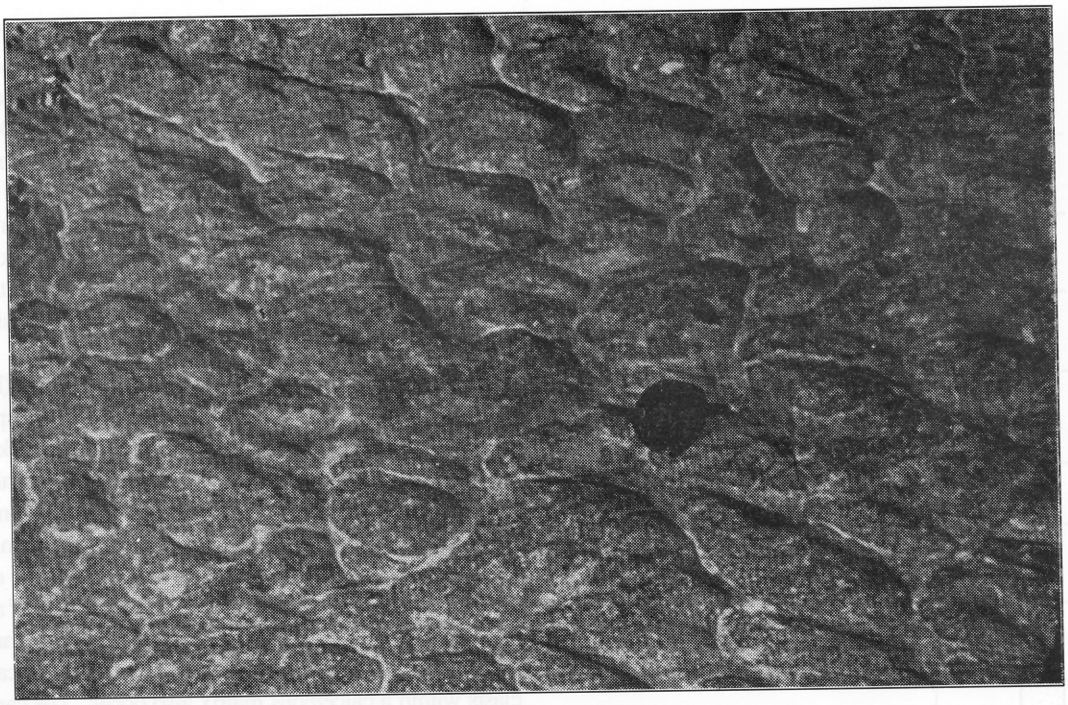


Figure 9: Linguoid out-of-phase ripple marks within arkosic sandstone of the Rosh Pinah Formation south of Gumchavib mountain

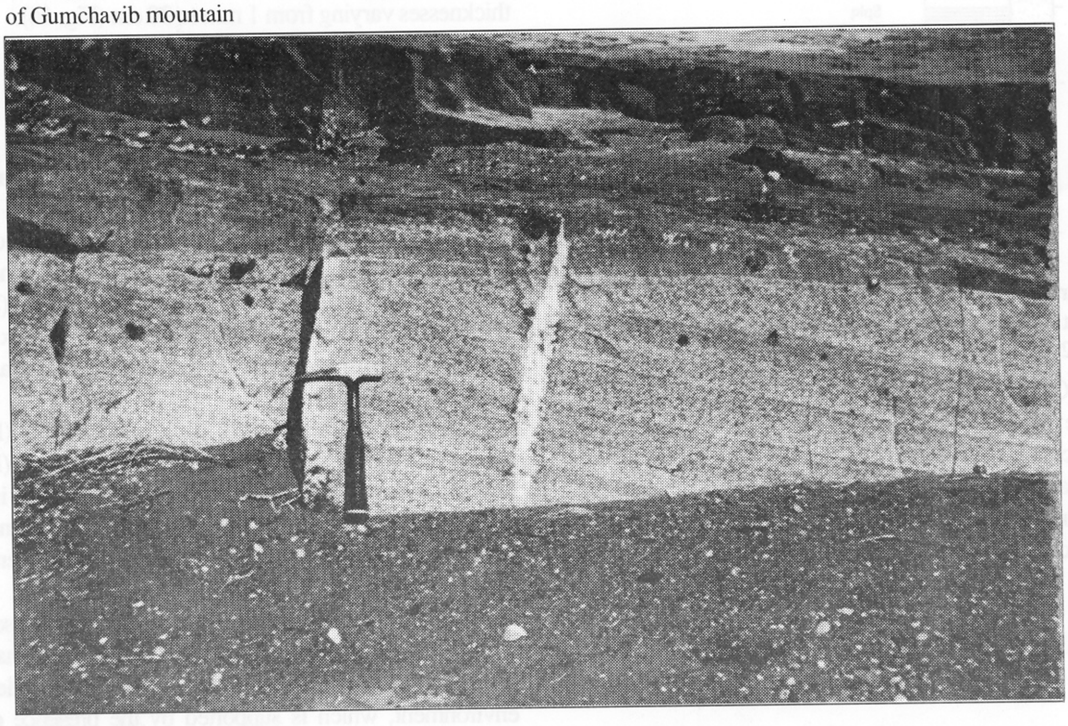


Figure 10: Crossbedding within feldspathic quartzitic sandstone of the Rosh Pinah Formation southwest of Gumchavib mountain

nated sandstones contain heavy mineral concentrations, defining the laminations. The grain size increases and massive sandstones become more abundant vertically, where they are interbedded with grey-green mudstone (Mm). Massive, dolomitic limestones (Lmd), with bed thicknesses ranging from 10 cm to 5 m, become more abundant towards the top of the succession (Fig. 11) and define the boundary to the overlying Pickelhaube Formation.

Interpretation

The basal conglomerate is interpreted as a transgressive conglomerate. The quartz-arenitic sandstone facies (Smq, Stq, Splq) represents low-energy wave activity within the foreshore and upper and lower shoreface, influenced by low-energy wave activity and longshore currents generated by waves and storms. Such a low wave energy shoreline facies succession has been documented from the modem day Gulf of Gaeta, Italy, by Reineck and Singh (1975) and from the Late Ordovician Oslo Basin by Stanistreet (1990). Indirect evidence for swash-zone activity is provided by the heavy mineral concentrations, even though no swash laminations are present, as swash deposits have a low preservation

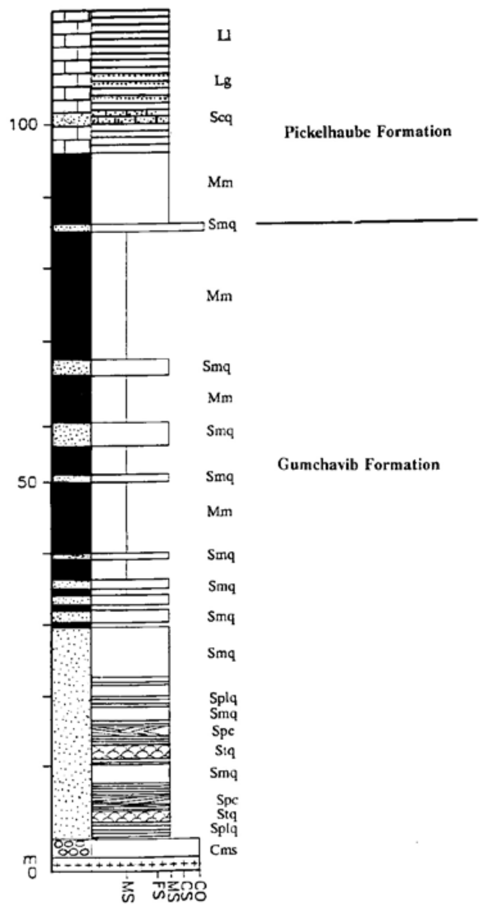


Figure 11: Measured section through the Gumchavib Formation at locality 28 immediately northwest of Obib waterhole (cf. Fig. 2)

potential along transgressive coastlines (Davis and Clifton, 1984). The abundance of massive sandstone (Smq) and mudstone (Mm) indicates a lower shoreface environment

Calcareous facies association: carbonate shelf environment

This facies association is confined to the Pickelhaube Formation. Ten facies are recognised: (1) Plane-laminated carbonate (Lpl); (2) graded calcareous beds (Lg); (3) small-scale channels containing calcareous material (Lc); (4) calcareous quartzitic sandstone (Scq); (5) graphite- and iron-rich carbonate (Lgi); (6) pisolitic limestone (Lp); and (7) matrix-supported conglomerate (Cms), (8) massive mica schist (Mm), (9) finely plane-laminated carbonate (Mfl), and (10) graded calcareous arkosic sandstone (Sg). The plane-laminated carbonate (Lpl) forms the bulk of the Pickelhaube Formation consisting of laterally continuous blue-grey dolomitic limestone, often associated with 2- to 10-cm-thick graded calcareous beds (Lg) and small-scale channels (~30 cm wide, 3 cm high) containing light-grey to dark-grey calcareous material (Lc). Dark grey to red-brown graphite- and iron-rich beds (Lgi) occur at locality 3 approximately 2 km north of Obib waterhole. The more iron-rich beds are 1 to 20 cm thick, while the graphite-rich beds can exceed 5 m. A 30- to 50-m-thick pisolitic limestone (Lp; Fig. 14) in the Pickelhaube Formation, with light-grey pisolite grains measuring 1 mm to 2 cm in diameter within blue-grey limestone measuring 1 mm to 2 cm in diameter, is present within the imbricate zone at locality 13. Laterally discontinuous lenticular, medium quartzitic sandstone beds (Scq) occur, from less than 5 cm to 10m thick, with a varying calcareous composition and gradational contacts with the underlying and overlying carbonate beds (Fig. 15). Erosive channels of calcareous quartzitic sandstone, up to 20 m long and 5 m high also occur within the lower Pickelhaube Formation. Plane-laminated carbonates, graded calcareous arkoses, massive and finely plane-laminated mudstones (Mm and Mfl), as well as carbonate conglomerates containing subrounded quartzite clasts with a maximum diameter of about 4 m, and carbonate clasts with an average diameter of approximately 30 cm within a calcareous matrix (Cms), are interbedded (Fig. 13). Breccias comprising angular carbonate clasts within a calcereous matrix also occur. The carbonates are often interlaminated with calc-siliciclastics with lamination thicknesses varying from 1 mm to 30 cm (Fig. 16).

Interpretation

Pisolitic limestone beds (Lp) indicate a very shallow, possibly emergent marine depositional setting on a carbonate shelf platform. Channels containing siliciclastic material (Scq) with sharp erosional contacts indicate periodic influxes of siliciclastic sediments, probably related to relative sea level change, possibly eustatic in nature. The highly calcareous composition of the quartzitic sandstones (Scq) implies a deposition within a zone of siliciclastic influx near the zone of optimum carbonate production, indicating a shallow marine shelf setting.

The laminated carbonates (Lpl), graded beds (Lg), and small-scale channels containing calcareous material (Lc) indicate a moderately deep shelf environment, as is also indicated by the graphitic and iron-rich composition of some of the carbonate beds (Lgi), which may indicate an even deeper setting away from terrigenous input

The beds, consisting of graded calcareous arkoses, interlaminated carbonates and calcsiliciclastic black shale, may have been deposited by turbidity currents within a deep shelf environment, which is supported by

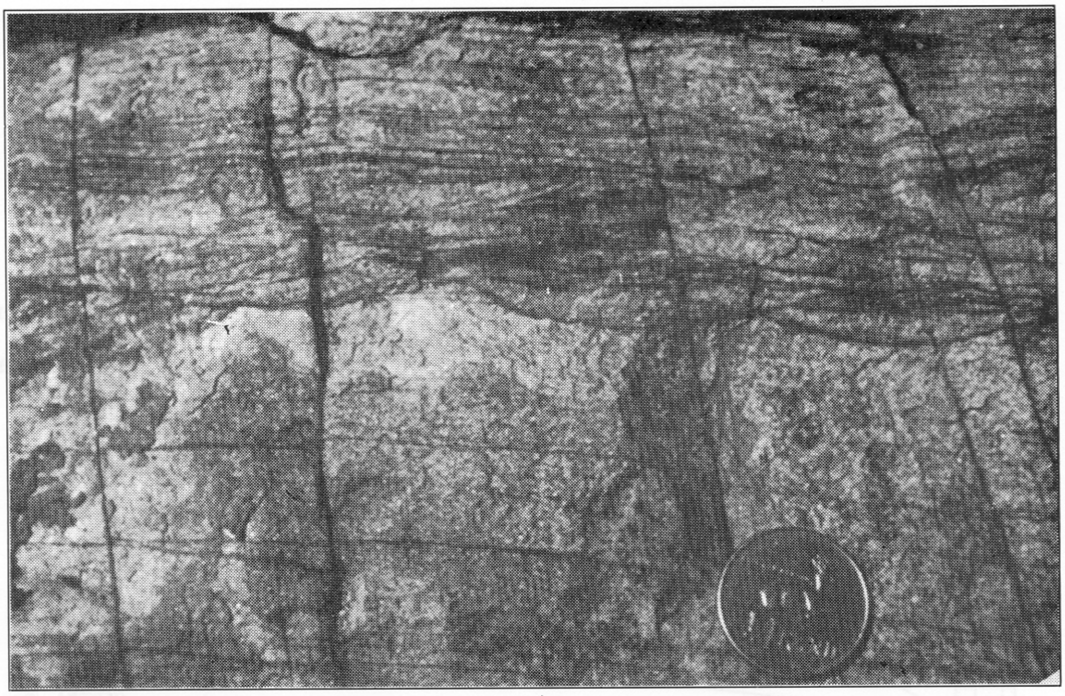


Figure 12: Trough cross- and plane-laminated quartz-arenite of the Gumchavib Formation at locality 2, immediately northwest of Obib waterhole (cf. Fig. 2)

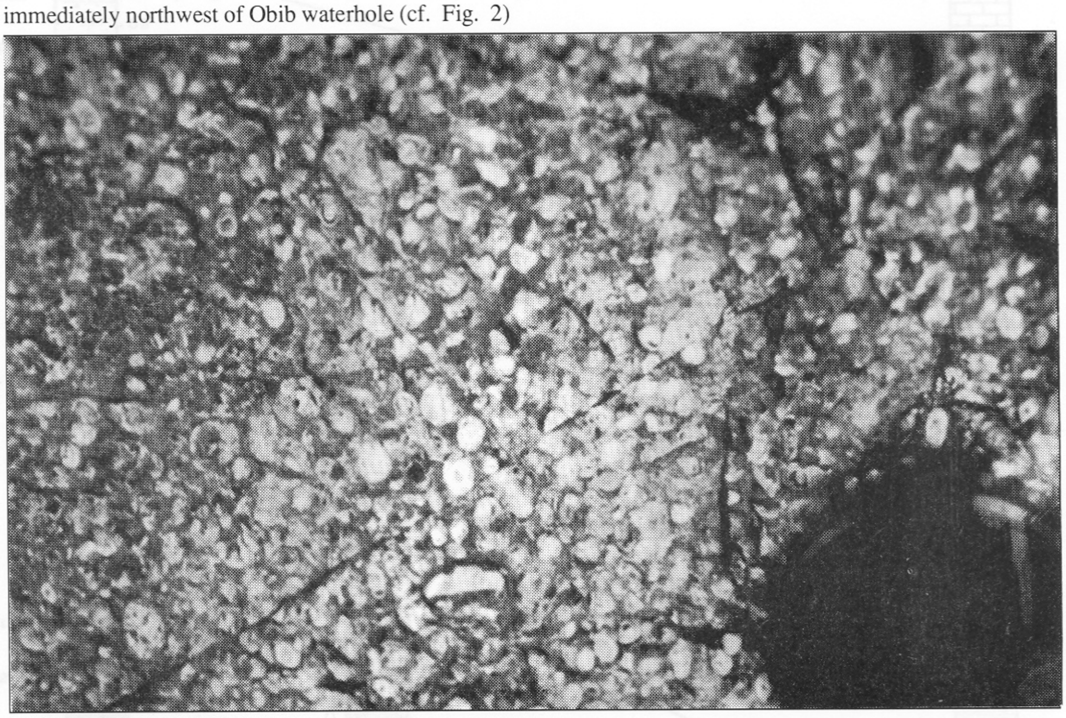


Figure 14: Pisolitic limestone and carbonate rock fragments within the Pickelhaube Formation at locality 13, 3 km north of Dreigratberg

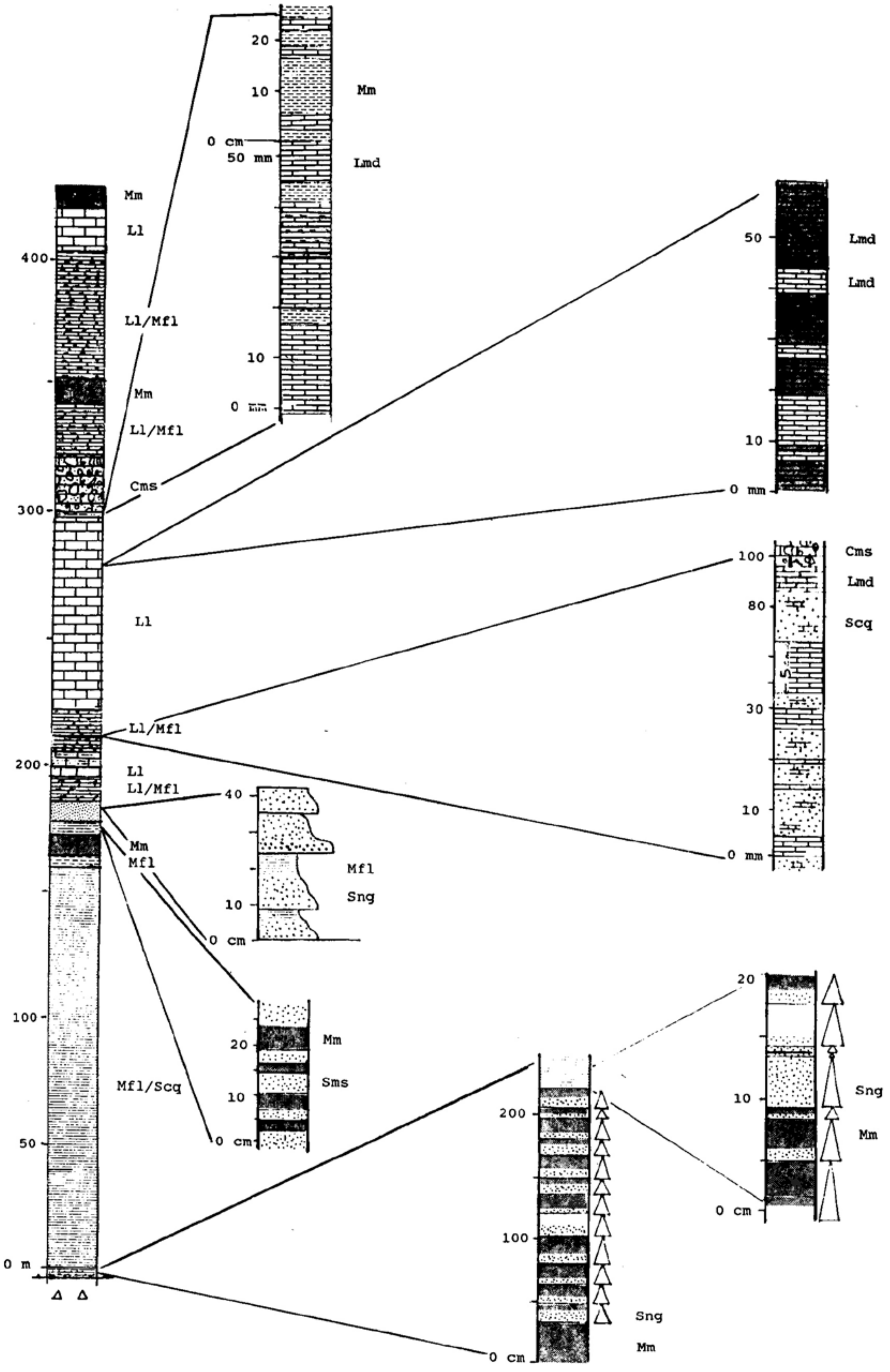


Figure 13: Measured section through the Pickelhaube Formation at Dreigratberg

the presence of black shales, or even under deep-sea conditions, whereas the conglomerates and breccias (Cms) may have been deposited as mudflows in a shelf or continental slope environment. The similarity of the beds with the sediments of the Holgat Subgroup underlines the assumption that the latter are a more distal time-equivalent of sediments of the Pickelhaube Formation, deposited within more shallow and proximal environments.

Diamictitic facies association: glacial environment

This facies association is confined to the Numees Formation. Thirteen facies have been recognised: (1) massive diamictite (Dm); (2) iron formation (I); (3) graded siltstone and mudstone (Msg); (4) finely parallel-laminated, and trough cross-laminated siltstone and mudstone (Mstl); (5) matrix-supported conglomerate (Cms); (6) crossbedded sandstone (Sc); (7) ripple-marked sandstone (Srm), (8) graded, magnetite-rich coarse sandstone (Sng), (9) wave-ripple cross-laminated siltstone (Swr), (10) massive carbonate (Lmd), (11) laminated carbonate (Ll), (12) graded limestone (Lg), and (13) graphite-rich limestone (Lgi).

Massive diamictite (Dm; Fig. 8) forms the bulk of this facies association. It consists of a massive, poorly sorted, clast-bearing rock with a massive to poorly bedded grey to blue-grey groundmass consisting of muddy fine to medium subangular feldspar, muscovite, biotite, quartz and iron oxide grains. The subrounded 2 mm granules to 10-m large clasts and boulders consist mainly of granite, basement pegmatite, gneiss, brown-weathering carbonate and quartzite. The average clast size is generally less than 30 cm. The clasts and boulders are subangular to subrounded, and are generally sporadically dispersed throughout the rock, forming from 5 per cent to over 50 per cent of the rock volume. No relationships between clast type and abundance and matrix type were observed nor was there any variation in clast size from bottom to top of the diamictites.

Approximately 10-m-thick iron formations (I), which pinch out laterally after several hundreds of metres, are present at Trekpoort Farm, approximately 30 km northwest of Rosh Pinah. The iron formations consist of dark-brown magnetite quartzite and fine-grained, interlaminated bands of quartz, hematite, chlorite, amphibole and carbonate. Within the iron formation, dropstone erratics up to 1 m in diameter disrupt the stratification (Fig. 17). On Trekpoort Farm, 10- to 15-cm-thick graded beds of fine, subrounded conglomerate (Cms) with clasts measuring up to 1 cm in diameter and coarse magnetite-rich graded sandstone (Sg) are present within the iron formation (Fig. 18). Two km southeast of Namuskluft Farmhouse, 20- to 180-m-thick beds of conglomerates, sandstones and mudstones are interbedded within the massive diamictitic beds (Dm; Fig. 19). The matrix -supported conglomeratic beds vary in thickness from 2 cm to 3 m and display normal grad-

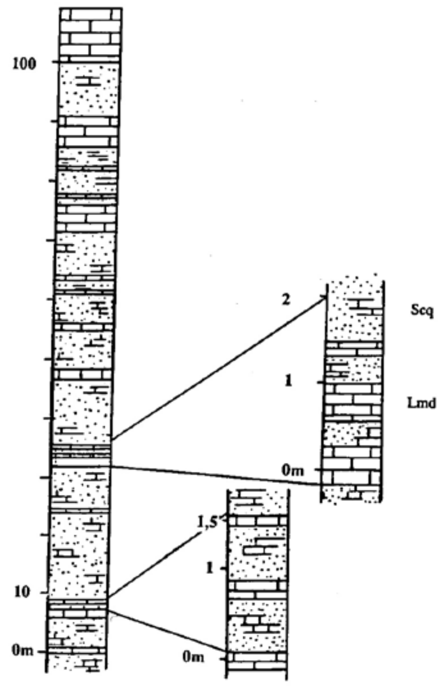


Figure 15: Measured section through interbedded carbonates and calcsiliciclastics of the Pickelhaube Formation at locality 4, 4 km southwest of Rosh Pinah (cf. Fig. 2)

ing from conglomerate to mudstone towards the top. The matrix consists of a dark-grey medium feldspathic quartzitic sandstone, which may grade into mudstone. The clasts are subangular to subrounded and generally 5 cm in diameter, however, boulders with diameters of 1.5 m are also present. The conglomerate beds pinch out laterally. On Trekpoort Farm, ripple-marked sandstones (Srm) are interbedded with matrix-supported conglomerates (Cms), sandstones (Sms, Srm, Spc), siltstones and mudstones (Mstl), and carbonates (Ll). The ripples, measuring approximately 10 x 2 cm, are asymmetric and vary in shape from sinuous out-of-phase to linguoid. The feldspar-rich quartzitic sandstones (Sms) are generally massive, but crossbedding is present. Within the massive (Sms) and crossbedded sandstones (Spc), conglomeratic channels (Cms) are developed containing clasts of granite, granodiorite, quartzite, and brown-weathering dolomite. The maximum clast size is about 30 cm, but the average size of the clasts is generally less than 5 cm. Graded, finely laminated tabular-planar cross-laminated siltstones and mudstones (Msfl) were also recognised. Set thicknesses range between 5 and 10 cm.

Wave-ripple cross- and parallel-laminated biotite schist (Swr, Mfl), as well as finely parallel and trough cross-laminated siltstone and mudstone (Mstl) with troughs measuring approximately 10 x 1 cm containing drops tone erratics at localities near Witputs, approximately 40 km north of Rosh Pinah (McMillan, 1968) and Trekpoort Farm, are present. These beds (Swr, Mfl) are interbedded with carbonates (Lmd, Ll, Lgi, Lg) and calcareous quartzitic sandstone (Scq). The carbonate is finely laminated and in places massive. Graphitic units up to 30 cm thick (Lgi) and graded beds 10 to 20 cm thick (Lg) containing subangular to subrounded clasts with diameters of 2 mm to 50 cm are present within the carbonates. Bed thick-nesses vary from 1 cm to 15 m and contacts between these beds are sharp.

Interpretation

Although striations on rocks, a typical feature of ice scouring by overriding glaciers and a reliable indicator for glacial activity, have not yet been recognised, a glacial origin of this facies association has been proposed by McMillan (1968), Kröner (1974), and Von Veh (1988) and is supported by the authors for the following reasons:

1) Dropstones are present in pelagic ironstone; 2)

Figure 16: Interlaminated carbonates and calcsiliciclastics of the Pickelhaube Formation at Dreigratberg

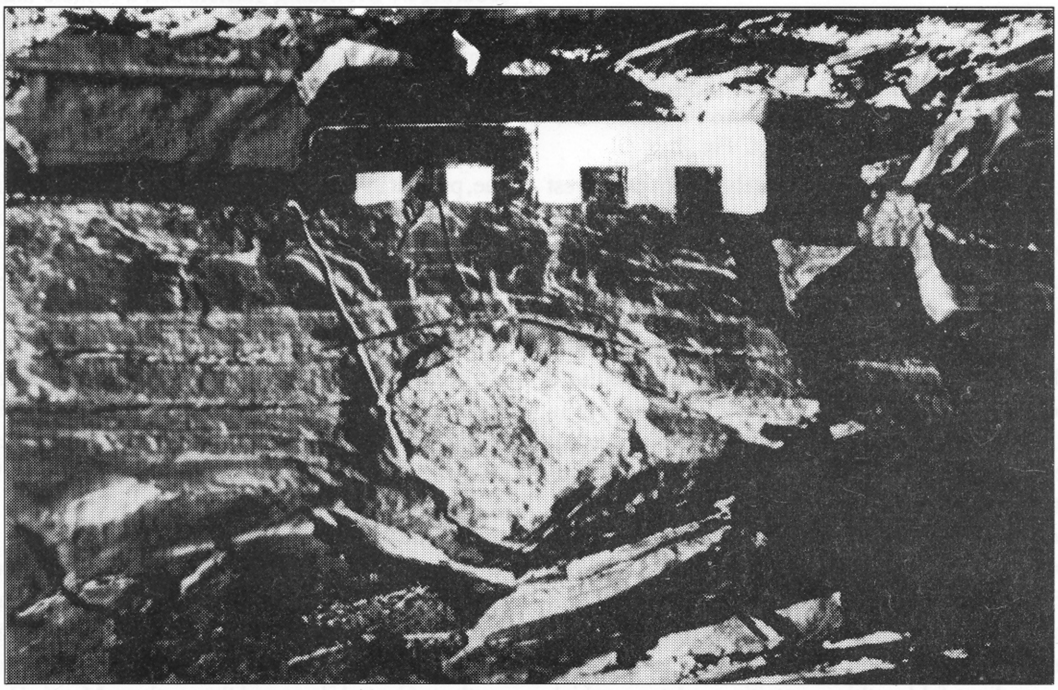


Figure 17: Granitic dropstones disrupting laminations of iron formation of the Numees Formation on Trekpoort Farm

laminae, present in varved shales (Msg), and laminated matrixes, have been disturbed and ruptured by dropstone erratics; 3) outsized extrabasinal lonestones and clusters of clasts of a particular lithology indicate transport by floating icerafts; 4) the diamictite (Dm) is massive and unbedded; 5) there is a variety of intrabasinal and extrabasinal clasts; 6) the clasts are extremely poorly sorted; 7) clasts are subangular to subrounded; 8) the diamictite (Dm) is widely distributed in the same stratigraphic position throughout the Damara Orogen (Miller *et al.*, 1983; Stanistreet *et al.*, 1991); 9) graded beds, deposited by turbidity current flows from the glacial source (Henry *et al.*,1986) are present.

The massive diamictitic (Dm) beds are interpreted here as glaciomarine deposits, deposited by proglacial mudflows and ice-rafted fragments dropping into mud (Henry *et al.*, 1986) and ironstones of the Numees Formation. In the southern Central Zone and the southern

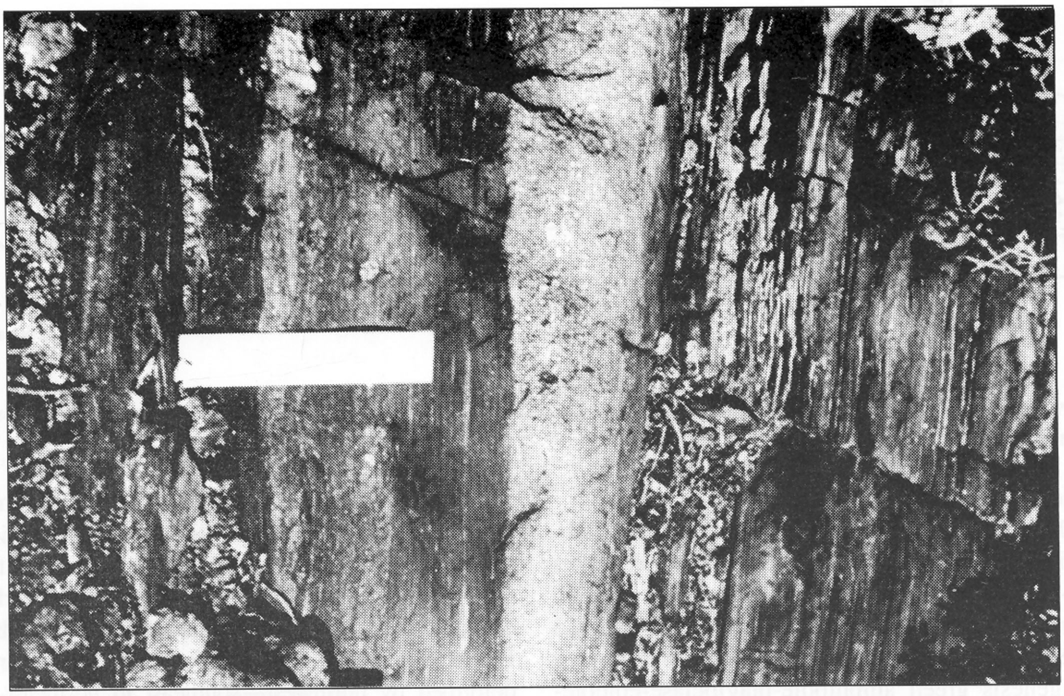


Figure 18: Graded beds of fine conglomerate and sandstone (Cms, Sng) within iron formation (I) of the Numees Formation on Trekpoort Farm (Ref. Figure 2)

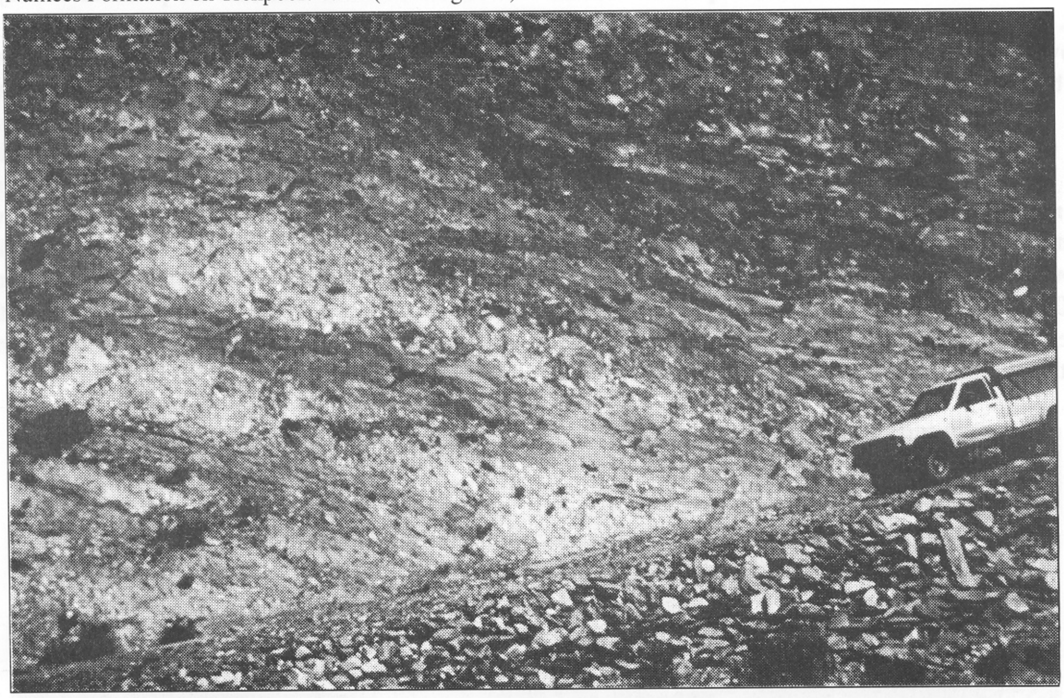


Figure 19: Graded beds ranging from coarse conglomerate to mudstone within massive diamictite of the Numees Formation, 2 km southeast of Namuskluft farmhouse

Margin Zone of the Damara Orogen, Breitkopf (1986), Henry *et al.* (1986) and Badenhorst (1988) described iron formations within the Chuos diamictite and concluded that the iron formation could have had a sedimentary origin with possible volcanic exhalation as a distal source of iron and manganese (Bühn *et al.*, 1992). The graded beds of fine conglomerates and coarse sandstones are interpreted as being generated by turbidity currents.

The mainly massive, ripple-marked and crossbedded sandy (Sms, Srm, Spc) and conglomeratic beds (Cms), forming erosional channels in places, are interpreted as glaciofluvial deposits. This may represent the first time that terrestrial glacial sedimentary features have been recognised in the Damara Sequence. Previous authors have recognised only glaciomarine settings (Henry *et al.*, 1986; Badenhorst, 1988).

Asymmetric ripple marks within some arkosic siltstones and sandstones may represent wave-ripple cross-lamination, indicating minor wave reworking above wave base. The trough cross-laminated siltstones and mudstones (Mstl) possibly represent low-energy wave activity and longshore currents generated by storms and waves. The abundance of finely laminated siltstone and mudstone (Mstl) indicates a lower shoreface environment. The highly calcareous composition of the quartzitic sandstones (Scq) and interlaminated carbonates (Lmd, Ll, Lg) suggest deposition within a zone of siliciclastic influx near the zone of optimum carbonate production, possibly indicating a shallow marine shelf setting.

Volcanics and Zn-Pb-Cu-mineralisation

Zn-Pb-Cu-mineralisation is restricted to the Rosh Pinah Formation. Within the "Rosh Pinah Mine Concession Area" and on Spitzkop Farm, the Rosh Pinah Formation consists essentially of a thick lower volcanic phase and an upper phase of mainly sedimentary origin, with a total thickness of approximately 1000 m (Fig. 3) at Rosh Pinah. The lower volcanic sequence comprises a basal conglomerate overlain by a succession of felsites and pyroclastics interbedded with quartzite, phyllite, and limestone (Page and Watson, 1976). The upper sedimentary phase consists mainly of a well- to poorly sorted gritty feldspathic quartzite. Inconsistent layers of black argillite, chert, limestone, quartz-muscovite schist, quartz-biotite schist, biotite-albite schist, amphibolite, and felsite are interbedded with the grits (page and Watson, 1976). Outcrops of mineralised rocks were found in the upper phase of the Rosh Pinah Formation, confined to the following rock types:

1) light grey to black carbonaceous cherty quartzite; 2) argillite; 3) quartzite; 4) carbonates; 5) sugary quartz rock; 6) massive sulphide ores.

The average metal content varies from 2 to 18% Zn, 0.5 to 6% Pb, and 0.05 to 0.8% Cu (Page and Watson, 1976). The mineralisation consists of pyrite, sphalerite, galena, chalcopyrite, tennantite-tetrahedrite, bornite, arseno-pyrite, stromeyerite, pyrrhotite, and rutile (page and Watson, 1976). Sedimentary structures are often displayed within the ore bodies, emphasising its synsedimentary nature. Barium-bearing minerals occur sporadically in the dolomitic limestones of the ore bodies and may also constitute an important group of gangue minerals comprising norsethite, barite, barytocalcite, benstonite and witherite (Watson, 1980).

Amphibolite sills are restricted to the Stinkfontein Subgroup (Fig. 2) and are up to 50 m thick. The amphibolites are grey-green to dark green, coarse grained and in some cases contain well-developed up to 5-cm-long oriented actinolite minerals.,h thin section the amphibolites display the paragenesis green amphibole-plagioclase-epidote-chlorite-quartz, ± biotite, ± calcite. Accessory minerals include tables of ilmenite, hematite and sphene. In some samples, relics of magmatic pyroxene were detected. The pale-brownish pyroxenes are strongly retrograded and rimmed by hornblende and epidote.

Structural geology

The most conspicuous structural features which form the structural grain of the study area are north-north-

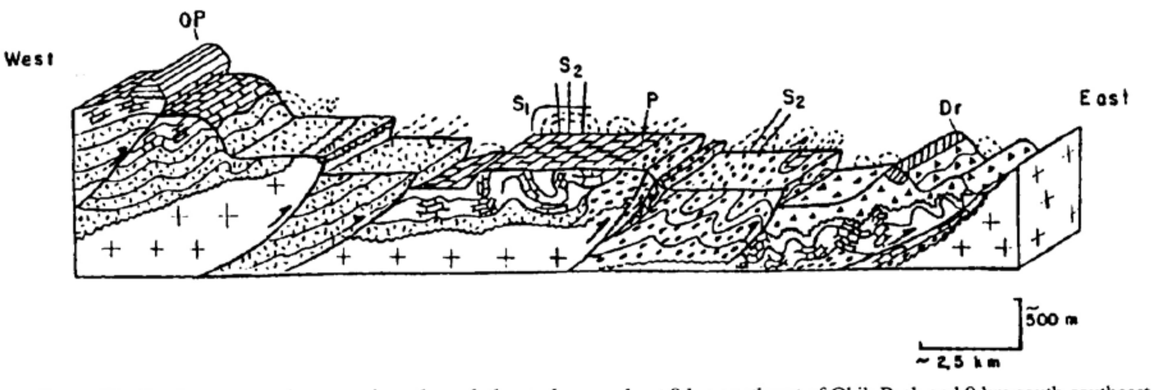


Figure 20: Southwest—northeast sections through the study area about 9 km southeast of Obib Peak and 9 km south-southeast of Gumchavib mountain

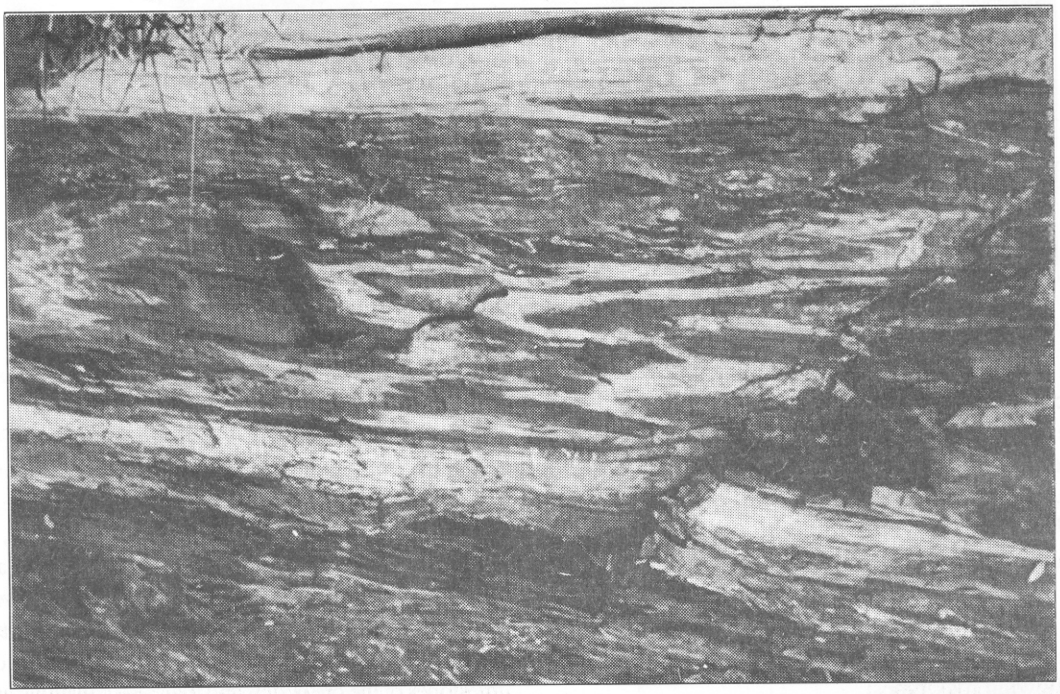


Figure 21: D_1 fabric within carbonate of the Pickelhaube Formation; note S_0, S_0-subparallel axial planes of recumbent folds and S_0-subparallel cleavage

west-south-southeast striking, medium- (1 to 10 m) to large-scale (10 to 200 m) folds with northerly and southerly plunging fold axes and major north-north-west-south-southeast striking thrust faults with thrust planes dipping towards the west-southwest (Figs 2 and 20); These folds deform around their hinge line an earlier, bedding-subparallel fabric, which is axial planar to minor isoclinal folds. Therefore, the latter deformational event must be an earlier event and will be called D_1, and the main deformational event will be called D_2. Subsequently, the D_2 deformational structures were deformed by northwest-southeast to northeast-southwest trending folds (Fig. 2), which are classified as D_3 folds.

Field evidence indicates the presence of major thrust faults within the study area (Figs 2 and 20). These are marked by: (1) shear zones and the presence of quartz veins and feldspar pegmatoids; (2) stratigraphic discordances; (3) a conspicuously developed foliation within and in the vicinity of shear and thrust zones; (4) intense silicification of sandstones; (5) the alteration of limestones to marbles; (6) the occurrence of actinolite schist in association with amphibolite sills; (7) the presence of tight to isoclinal and recumbent folds. The thrust faults trend north-northwest-south-southeast and the thrust planes dip toward the west-southwest. The thrust faults are both bedding-parallel and cut up across stratigraphy and fold limbs.

Major changes in fabric and fold morphology occur between the different thrust slices and the parautochthonous assemblage adjacent to the basement in the east of the study area (Fig. 2). These thrust slices and the parautochthonous unit are named after conspicuous geographic points and, where this is impossible, indigenous animals within the study area. They are described in the sections below. The structural units comprise (1) the parautochthonous unit in the east of the study area, and to the west the allochthonous (2) Pickelhaube thrust slice, (3) Gumchavib thrust slice, (4) Rooikat thrust slice, (5) Ostrich thrust slice, and (6) Obib thrust slice.

Deformation phases

Three phases of deformation, D_1, D_2 and D_3, have been identified within the study area. The most conspicuous structural elements developed throughout the study area are associated with D_2, which therefore serves as a structural datum or benchmark. The relationships and the occurrences of planar and linear elements and folds within the study area are plotted on stereonets (Fig. 2) and described in the following sections. The deformation phases are described in their deduced chronological order.

D_1 Deformation

The earliest recognised deformation phase is characterised by a bedding-subparallel s_1 fabric, which strikes 160° to 280° and dips variably throughout the study area. In mica schist and greywacke this fabric is a continuous slaty cleavage. In coarser sediments, the D_1 deformation is characterised by the preferred orientation and elongation of boulders, pebbles and grains, whose long axes plunge variably at about 180°. The preferred

Figure 22: D_2 fold near Obib waterhole; note S_0-subparallel S_1 cleavage and S_2 axial planar cleavage

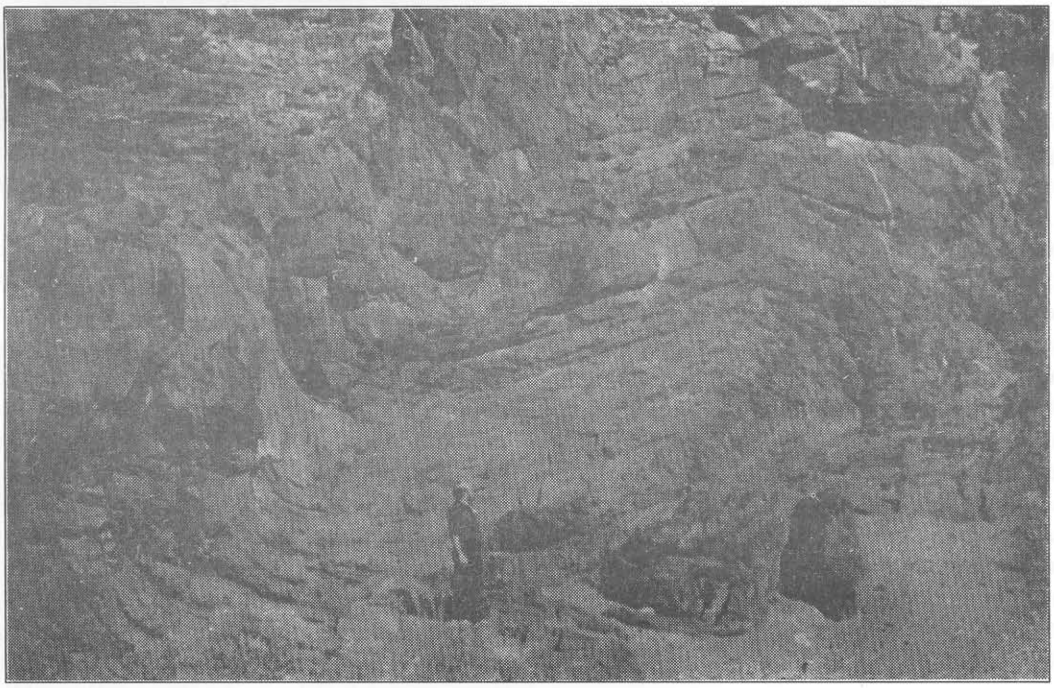


Figure 23: D_2-associated thrust displacing fold limb of associated D_2 fold

orientation of boulders is best developed within the conglomerates of the Rosh Pinah Formation, and in the pisolitic limestone 3 km northwest of Octha (Fig. 2). D_1 folds are typically small-scale (1 cm to 2 m wavelength), recumbent and isoclinal in form, intrafolial to the bedding-subparallel s_1 fabric. At one locality south of Namuskluft Farmhouse an axial planar cleavage cutting the bedding-subparallel s_1 fabric is developed. The D_1 folds are best developed in the laminated carbonates of the Pickelhaube Formation.

D_2 Deformation

The most conspicuous features characterising the D_2 deformation are medium- (1 to 10 m) to large-scale (10 to 200 m) folds, with fold axes trending at about 160° to 180° and plunging moderately at about 10° to the north-northwest and south-southeast, and axial planes, which dip mainly to the west-southwest in the allochthonous thrust slices, and to the east-northeast on the parauthochthonous assemblage in the east of the study area. The folds, which refold among others the earliest D_1 thrust faults, are symmetric to asymmetric, tight to isoclinal, and in places overturned (Fig. 20). In the Pickelhaube thrust slice large-scale (>200 m) boxfolds and small-scale (<1m) chevron folds are developed in the immediate vicinity and north of Pickelhaube. Throughout the study area an s_2 axial planar cleavage is developed (Fig. 22). The s_2 axial planar cleavage is defined by a slaty cleavage within argillic units and by a preferred orientation of mica and grains in arenites, striking at about 160 to 180° and dipping steeply to the west (Fig. 2). In the Obib thrust slice approximately 2 km northeast of Obib waterhole an s_2 crenulation cleavage, closely associated with kink folds, is developed within mica schist units, both trending at 0° to 025°. The crenulation cleavage deforms the pre-existing S 1 bedding-subparallel cleavage. In places D_2 fold limbs are cut by thrust faults, indicating that thrusting also occurred associated with D_2 folding, as shown in Figure 23.

D_3 Deformation

A D_3 deformation phase has been recognised within the Obib and Ostrich thrust slices, and the parauthochthonous unit. The major features of this phase of deformation are open, upright small-scale to large-scale cross-folds, ranging from kink folds, mainly developed in argillic rocks, to folds with wavelengths of several hundreds of metres, which have refolded pre-existing D_2 folds forming fold interference structures (Fig. 24). The fold hinges of these folds trend at 045° to 090°. An s_3 kink banding, associated with the D_3 folds, was observed about 2 km northeast of Obib waterhole and could only be recognised where the s_1 cleavage was overprinted.

Tectonostratigraphic synthesis

Authochthonous unit

Unconformable sedimentary relationships are recognised between the basement, consisting of the Gaidab Massif, the Vioolsdrif granite, and the Haib Supergroup of the Namaqua Metamorphic Complex, and arkosic sandstone and conglomerate of the Nama Group and diamictite of the Numees Formation. The authochthonous unit is defined by north-north west-trending reverse faults and open small-scale (5 m wavelength) and large-scale folds (50 m wave-length). Shearing can be observed in some places near the basement contact. Geothermometry and geobarometry of samples taken in the Namuskluft waterhole area in the east of the study area reveal very low pressures, indicating that this formation is probably part of the Nama Group.

Parauthochthonous units

A *parauthochthonous unit* is located in the east of the study area, extending from north of Octha along the basement contact to the east of the Rosh Pinah mountain (Fig. 2). North of the Orange River it comprises carbonates of the Pickelhaube Formation, and northeast of Rosh Pinah it consists of diamictite of the Numees Formation. These sediments have an unconformable sedimentary relationship with the basement, consisting of the Gaidab Massif and the Haib Supergroup of the Namaqua Metamorphic Complex. They are characterised by large-scale folds (100 m wave-length) with a westerly vergence, changing trend from north-northwest north of the Orange River to northwest, northeast of Rosh Pinah. Shearing and reverse faulting can be observed near the basement contact.

The *Rosh Pinah thrust* slice is located in the east of the study area and stretches from north of the Orange River near Octha to north of Rosh Pinah (Fig. 2). The eastern boundary of this thrust slice is defined by a north-northwest-trending thrust zone approximately 500 m east of the authochthonous basement immediately north of the Orange River northeast of Octha, linking into the northwest-trending Rosh Pinah thrust fault northeast of Rosh Pinah. Immediately north of the Orange River, the Rosh Pinah thrust fault is defined by an imbricate zone comprising slices of arkosic sandstones and conglomerates of the Rosh Pinah Formation, laminated and pisolitic carbonates of the Pickelhaube Formation, and diamictites, sandstones and conglomerates as well as carbonates of the Numees Formation. This imbricate thrust zone is approximately 1 km wide. East of Namuskluft Farmhouse, 5-m-thick granitic basement is thrusted on Numees diamictite, emphasising the parauthochthonous nature of this thrust slice. Between the Orange River and Namuskluft Farmhouse the Rosh Pinah thrust slice comprises conglomerates of the Rosh Pinah Formation, laminated carbonates, pisolitic and stromatolitic carbonate, graded calcareous arkose, carbonate and quartzite clast-bearing conglomerate with a carbonate matrix, as well as graphitic black shale of the Pickelhaube Formation, and diamictite, minor conglomerates, sandstones and ironstone of the Numees Formation. Two north-north west-trending dolerite dykes cut through the sediments of the Numees Formation. The southern part of the Rosh Pinah thrust slice is characterised by north-northwest-south-southest-trending large-scale (>200 m) open folds with easterly dipping axial planes and superimposed northwest-trending D_3 folds varying from small-scale folds to folds with wavelengths >100 m (Figs 2 and 20). A bedding-subparallel fabric (D_1) and small-scale «1 m) recumbent folds with a southeasterly vergence, subparallel to the D_1 fabric, as well as an axial planar cleavage (D_2) are dominant within the southern part of the Rosh Pinah thrust slice. Several thrust faults, with westerly dipping thrust planes are recognised within this unit. Slickensides within calcareous units indicate a southeasterly trans-

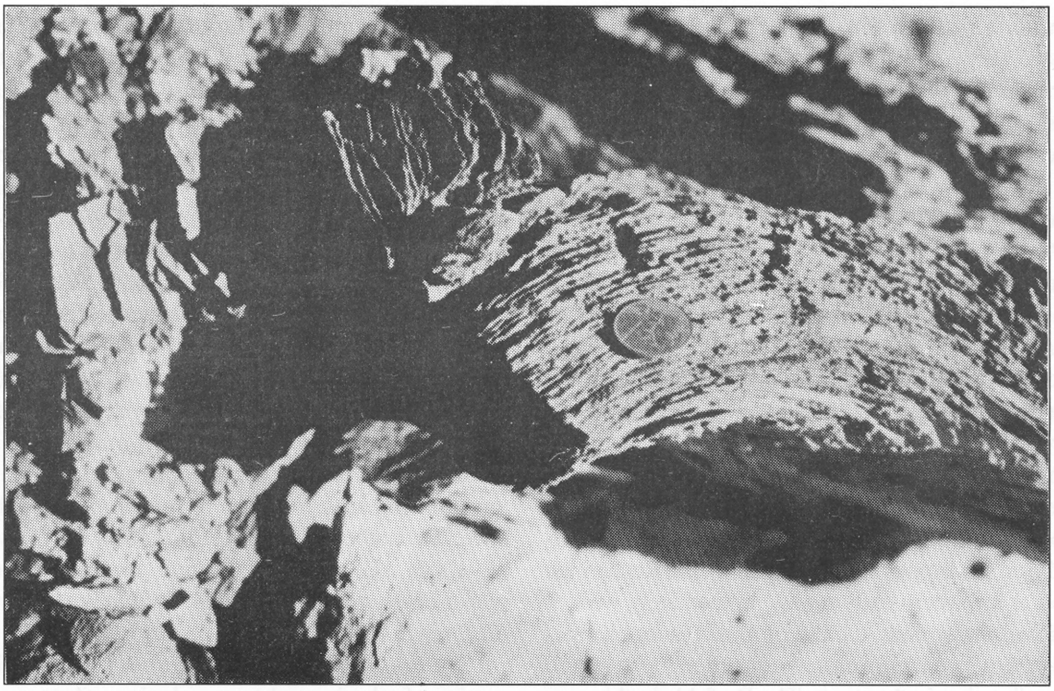


Figure 24: Fold interference structure of D_2 and D_3 folds at Dreigratberg

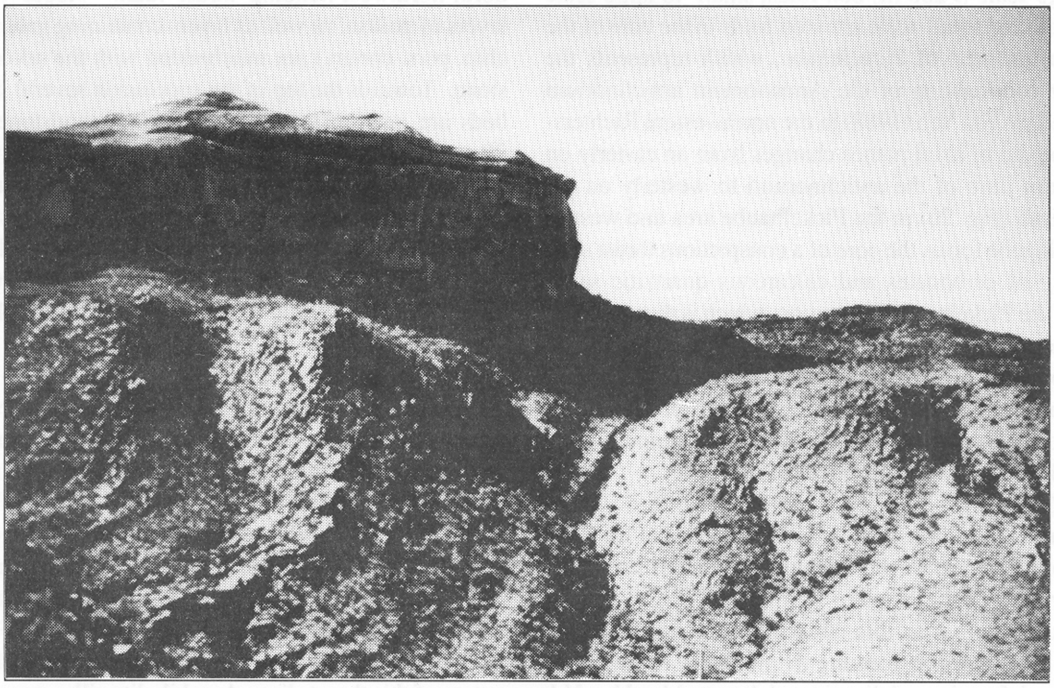


Figure 25: Little-deformed carbonates of the Pickelhaube Formation thrusted over strongly folded and foliated sandstones and conglomerates of the Rosh Pinah Formation at Pickelhaube

port direction. Near Rosh Pinah and Spitzkop, the Rosh Pinah thrust slice comprises the mixed volcanic and sedimentary rocks of the Rosh Pinah Formation (Page and Watson, 1976; Watson, 1980; Davies and Coward, 1982; Van Vuuren, 1986; De Kock, 1987; Siegfried, 1990; and Lickfold, 1991). In the Rosh Pinah area, the Rosh Pinah thrust slice consists of a mixed conglomerate/mudstone/arkosic sandstone/carbonate succession of the Rosh Pinah Formation associated with sulphide mineralisation. A northwest-trending dolerite dyke cuts through the rocks. The contact between the basement and the volcanics and sediments of the Rosh Pinah Formation and the Numees Formation north and northwest of Rosh Pinah is thrusted. The fold trend in the. Rosh

Pinah mountain north of Rosh Pinah differs from that south of Rosh Pinah. Large-scale northwest-trending open D_2 folds with northeasterly dipping axial planes are recognised. Southwest-trending D_3 folds deforming the former folds were described by Siegfried (1990). A bedding-subparallel foliation (D_1) and an axial planar cleavage (D_2) are recognised (Siegfried, 1990).

The Aus Road thrust fault, which changes its trend from - northwest north of Rosh Pinah to north-northwest south of Rosh Pinah, separates the Rosh Pinah thrust slice to the east from the *Pickelhaube thrust* slice to the west. The Aus Road thrust fault can be traced from the Orange River, where it was delineated by Von Veh (1988) in the Richtersveld, northwards along the Aus Road. The Pickelhaube thrust slice comprises calcareous quartzitic sandstones, laminated carbonates and graphitic black shale of the Pickelhaube Formation north and west of Pickelhaube and conglomerates, arkosic sandstones and mudstones of the Rosh Pinah Formation at its eastern extremities. Immediately west of the Aus Road thrust fault, the dip of axial planes changes drastically from a generally easterly direction in the east to a westerly direction in the west. The D_2 folds in this area trend in a north-northwesterly direction. The folds comprise large-scale (>200 m) box folds, small- to large-scale open folds, and small-scale chevron folds in the core of the anticlinorium west of Pickelhaube, which represents the northerly continuation of the Annisfontein anticlinorium delineated by Von Veh (1988) in the northwestern Richtersveld. The dip of axial planes changes from an easterly on the western limb of the anticlinorium to westerly on the eastern limb (Fig. 20) in the Pickelhaube area and west of it. Pickelhaube forms the core of a conspicuous thrust slice consisting of carbonates and calcareous quartzitic sandstones of the Pickelhaube Formation, which is thrusted over conglomerates and sandstones of the Rosh Pinah Formation and carbonates of the Pickelhaube Formation (Fig. 25). North-northwest of Pickelhaube, carbonates of the Pickelhaube Formation are duplicated by easterly dipping steep thrust folds, which were refolded by D_2.

The *Gumchavib thrust slice* comprises a mixed succession of arkoses, conglomerates, and mudstones of the Rosh Pinah Formation, carbonates of the Pickelhaube Formation, and diamictite of the Numees Formation. The most conspicuous feature within this thrust slice is a northwesterly trending anticlinorium, forming the northerly continuation of the Annisfontein anticlinorium delineated by Von Veh (1988) in the northwestern Richtersveld. Another dominant tectonic feature is a thrust slice, thrusting conglomerates and mudstones of the upper Rosh Pinah Formation over granitic basement, arkoses of the Rosh Pinah Formation, and carbonates of the Pickelhaube Formation (Figs 2 and 20). South-southeast of Pickelhaube a thrust slice consisting of carbonates of the Pickelhaube Formation and a thrust slice consisting of diamictite of the Numees Formation are thrust over conglomerates and mudstones of the upper Rosh Pinah Formation. A bedding-subparallel fabric is recognised throughout this thrust slice, best developed in the pelitic units of the Rosh Pinah Formation. Its eastern boundary is defined by an arcuate thrust zone stretching from north of the Orange River to the area immediately east of Pickelhaube, duplicating sediments of the Rosh Pinah Formation. The eastern boundary of the Gumchavib thrust slice is confined by the Aus Road thrust fault, which changes its trend from north-northwest north of the Orange River to northwest, northeast of Pickelhaube. The area west of this thrust fault and east of Pickelhaube is characterised by a strong, thrust-parallel foliation and westward-verging, north-north west-trending open folds with easterly dipping axial planes and wavelengths of about 50 m. Structural elements within this area are characterised by large-scale (100 to 200 m), north-northwest-trending isoclinal, overturned folds with axial planes dipping to the west (Fig. 20). A D_1 bedding -subparallel and a D_2 axial planar cleavage are recognised within the Rosh Pinah mudstones. Pebbles within the Rosh Pinah conglomerate are elongated along an axis trending at approximately 180° throughout this thrust slice. Recumbent easterly verging folds with wavelengths of -100 m, a D_1 bedding -subparallel cleavage and a D_2 axial planar cleavage characterise the area immediately north of the Orange River.

The *Rooikat thrust slice* comprises a 2000-m-thick succession of arkosic sandstone and minor siltstone and mudstone of the Rosh Pinah Formation, duplicated by a north-northwest-trending thrust fault. About I-m-thick layers of gossan, as well as layers containing galena (D. Alchin, pers. comm.) are interbedded with the arkosic sandstone. Towards the top of the succession several limestone beds are interbedded with the arkosic sandstone. Up to 30-m-thick amphibolite sills are present within the sediments of the Rosh Pinah Formation (Fig. 2). Bedding planes generally strike north-northwest and dip to the west. Small- to medium-scale (1 to 10 m), open asymmetric folds trending north-northwest with axial planes dipping to the west-southwest are observed in some places. The Rooikat thrust slice is bounded by the Pickelhaube thrust slice along its eastern extremity (Fig. 2).

The Ostrich thrust slice comprises a thick succession of arkoses, greywackes (meta-arkose), quartzites, mudstones and carbonates of the Rosh Pinah, the Gumchavib, and the Pickelhaube Formations. A mixed succession of arkoses, mudstones and carbonates unconformably overlie the granitic basement 2 km northwest of Gumchavib mountain (Fig. 2). The northern part of this granitic basement structurally overlies sediments of the Rosh Pinah Formation along a thrust fault, and emphasises the parauthochthonous nature of this thrust slice. Amphibolite sills, several tens of metres thick, are interbedded with the sediments of the Gumchavib and the Pickelhaube Formations (Fig. 2). The eastern boundary of the Ostrich thrust slice is defined by an extensive thrust fault, trending in a northerly direction in the northern part of the thrust slice and changing its orientation to southeasterly 3 km southeast of Obib Peak. The western part of the Ostrich thrust slice is characterised by medium- (1 to 10 m) to large-scale (10 to 200 m), tight to isoclinal D_2 folds with axial planes dipping to the west-southwest with hinge lines plunging gently (<10°) north. An axial planar cleavage is developed within these folds. Small- (<1 m) to medium-scale (1 to 10 m), east-trending open D_3 folds are recognised. West of the basement unconformity the sediments of the Gumchavib and Pickelhaube Formations strike north-northwest to northwest and dip to the southwest. The area immediately north of the Orange River is characterised by a thrust zone. The thrust slices consist of arkoses of the Rosh Pinah Formation, carbonates of the Pickelhaube Formation, and diamictite of the Numees Formation.

The *Obib thrust slice* comprises quartzarenites, conglomerates and mudstones of the Gumchavib Formation, the former unconformably overlying the granitic basement near Obib waterhole; carbonates and calcareous quartzitic sandstones of the Pickelhaube Formation; arkoses and conglomerates of the Obib Peak Formation; as well as diamictite of the Numees Formation, the latter representing the western-most Numees diamictite in the study area, about 2 km south of Obib Peak. The granitic basement is intensely sheared and folded west of Obib waterhole. The eastern boundary of the Obib thrust slice is defined by a thrust fault which changes its orientation from north-northwest in the north to north-south in the south (Fig. 2). The main structural features of this thrust slice are small (<1 m) to large scale (>20 m) open, asymmetric D_2 folds. The fold axes strike north-northwest and axial planes dip to the west (Fig. 2). Medium scale (1 to m), east-west trending open, symmetric folds were also identified. North of Obib Peak, a penetrative D_1 bedding-subparallel cleavage is developed. Northeast of Obib waterhole, a D_2 crenulation cleavage is recognised. A kink banding, associated with D_3 folds, was observed northeast of Obib waterhole.

Metamorphic evolution

Microprobe analyses were carried out by Franz and Jasper (in prep.). Amphibolites, psammites and pelites from different tectonic units were investigated. Samples collected from the Rosh Pinah Formation within the Rooikat thrust slice testify to the lower amphibolite facies with peak metamorphic temperatures at 500° to 550°C and pressures of more than 8 kbar. In the Obib Peak Formation within the Obib thrust slice, P-T conditions of the epidote-amphibolite facies with temperatures of 450° to 500°C and pressures of up to 7 kbar are revealed. Samples of the Rosh Pinah Formation from the Gumchavib thrust slice point to P-T conditions of the greenschist facies at about 400° to 450°C and 4 to 6 kbar. Textural evidence shows that these P-T conditions were consistent during the D_1 and D_2 deformation. All these P-T estimates reveal a Barrovian-type metamorphism with a geothermal gradient of about 20°C/km.

Summary and preliminary conclusions

Enough evidence is so far available from the Gariep Group to give an initial appraisal of the depositional palaeoenvironmental and structural history of the Gariep Belt.

The Rosh Pinah, Gumchavib, and Pickelhaube Formations record the evolution from rift sedimentation and volcanism to passive margin sedimentation associated with an initial rifting and subsequent opening of the Adamastor Ocean (Hartnady *et al.*, 1985). Thick alluvial fan deltas prograding into a lake within the rift, bimodal volcanics, and feldspathic sandstones in the Rosh Pinah Formation reflect rifting of the Late Proterozoic supercontinent. The incipient phase of passive-margin sedimentation during thermal cooling is represented by transgressive deposits of the Gumchavib Formation at the top of the Rosh Pinah Formation. Initial transgressive facies consisted of braided plain, foreshore and shoreface deposits. Continued cratonward transgression is indicated by the deposition of shallow to moderately deep carbonate shelf facies of the Pickelhaube Formation, and deep-sea carbonate sediments of the Holgat Subgroup south of the study area. Palaeocurrents indicate sediment transport in a westerly direction.

A major sudden progradational change in palaeoenvironmental conditions is indicated by the incoming of fluvial sediments of the Obib Peak Formation, overlying the sediments of the Pickelhaube Formation. The glaciomarine and glaciofluvial sediments of the Numees Formation, resting unconformably on Hilda sediments and basement, indicate a major climatic change.

The deformational events documented in this paper record the closure history of the Late Proterozoic/Early Palaeozoic ocean (Kröner, 1974; Hartnady *et al.*, 1985). D_1 folds verging in a southeasterly direction, mineral lineations, clast elongations and slickensides, as well as D_2 folds verging in a easterly direction in the western parts of, the study area, tight to isoclinal folds developed along the margins of the thrust slices, and recognised thrust faults indicate thrusting in a southeasterly direction. Westwardverging folds near the autochthonous basement are related to backthrusting. A late subsequent sinistral lateral movement is indicated by the D_3 folds.

Microprobe analyses indicate metamorphic conditions of the lower amphibolite facies with peak metamorphic temperatures of 500 to 550°C and pressures of more than 8 kbar, of the epidote-amphibolite facies with temperatures of 450 to 500°C and pressures of up to 7 kbar, as well as conditions of the greenschist facies with temperatures of 400 to 450°C and pressures of 4 to 6 kbar. Textural evidence shows that these P-T estimates indicate a Barrovian-type metamorphism with a general geothermal gradient of about 20°C/km.

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References

Badenhorst, F.P. 1988. The lithostratigraphy of the Chuos mixtite in part of the southern Central Zone of the Damara Orogen, South West Africa. *Communs geol. Surv. S.W.A./Namibia*, **4**, 103-110.

Beetz, P.F.W. 1924. On a great trough valley in the Namib. *Trans geol. Soc. S.Afr*., **27**, 1-38.

Boothroyd, J.C. and Ashley, G.M. 1975. Processes, bar morphology and sedimentary structures on braided outwash fans, north-eastern Gulf of Alaska. *In*: Jopling, A.V. and McDonald, B.C. Eds. *Glaciofluvial and glaciolacustrine sedimentation*. Society of Economic Palaeontologists and Mineralogists Special Publication, **23**, 193-222.

Breitkopf, J. 1986. *Iron Formations and associated amphibolites in the southern part of the Damara Orogen of SWA/Namibia*. Unpubl. PhD. thesis, Univ. Witwatersrand, Johannesburg, 350pp.

Bühn, B., Stanistreet, I.G. and Okrusch, M. 1992. Late Proterozoic outer shelf manganese and iron deposits at Otjosondu (Namibia) related to Damara oceanic opening. *Econ. Geol. (in press*).

Clifford, T.N. 1967. The Damaran episode in the Upper Proterozoic-Lower Palaeozoic structural history of Southern Africa. *Spec. Pap. geol. Soc. Am*., **92**, 100pp.

Collinson, J.D. 1978. Alluvial sediments. *In*: Reading, H.G., *Sedimentary environments and facies*. Elsevier, New York.

Davis, R.A., Jr. and Clifton, H.E. 1984. Sea-level changes and preservation potential of wave-dominated and tide-dominated coastal sequences. *Society of Economic Palaeontologists and Mineralogists Annual Midyear Meeting Abstracts*, **I**, p. 23.

Davies, C. and Coward, M.P. 1982. The structural evolution of the Gariep Arc in southern Namibia. *Precambr. Res*., **17**, 173-198.

De Villiers, J. and Söhnge, P.G. 1959. The geology of the Richtersfeld. *Mem. geol. Surv. of S.A*., **48**.

De Kock, N.J. 1987. *Die veranderinge van die wandgesteentes in die omgewing van die ertsliggame van Rosh Pinah*. Unpubl. Msc. thesis, Univ. Pretoria, 155pp.

Eugster, R.P. and Hardie, L.A. 1978. Saline lakes. *In*: Lerman, A. Ed. *Lakes: chemistry, geology, physics*. Springer, Berlin Heidelberg, 237 -293.

Eugster, H.P. 1985. Oil shales, evaporites and ore deposits. *Geochim. Cosmochim. Acta*, **49**, 619-635.

Franz, L. and Jasper, M.J.U. (in prep.). Metamorphic evolution of the Late Proterozoic/Early Palaeozoic Gariep Belt in the Sendelingsdrif/Rosh Pinah area, Southern Namibia.

Hartnady, C.J.H., Joubert, P. and Stowe, C.W. 1985. Proterozoic crustal evolution in southwestern Africa. *Episodes*, **8**, 236-244.

Hartnady, C.J.R, Ransome, I.G.D. and Frimmel, R 1990. Accreted Composite Terranes - An example from the Gariep Orogenic Belt. *Abstracts, Geocongress 1990, Cape Town*, 218-221.

Henry, G., Stanistreet, I.G. and Maiden, K.J. 1986. Preliminary results of a sedimentological study of the Chuos Formation in the Central Zone of the Damara Orogen: Evidence for mass flow processes and glacial activity. *Communs geol Surv. S.W. Africa/Namibia*, **2**, 75-92.

Kindl, S. 1979. *Provisional stratigraphic sketch of the Rosh Pinah unit in the type area*. Interim report, IMCOR Zinc, Namibia.

Kröner, A. 1974. Late Precambrian Formations in the western Richtersfeld, northern Cape Province. *Trans. roy. Soc. S. Afr*., **41**, 375-433.

Lickfold, V. 1990. *A geological study of the Rosh Pinah Zn-Pb-Cu-Ag mine, Namibia*. Unpubl. BSc (Hon) report, Univ. of the Witwatersrand, 70pp.

McMillan, M.D. 1968. The geology of the Witputs-Sendelingsdrif area. *Bull. Prec. Res. Unit, Univ. Cape Town*, **4**, 177pp.

Page, D.C. and Watson, M.D. 1976. The Pb-Zn Deposit of Rosh Pinah,South West Africa. *Econ. Geol*., **71**, 306-327.

Reading, H.G. 1986. *Sedimentary environments and facies*. Blackwell Scientific Publications, 557 pp.

Reineck, H.E. and Singh, I.B. 1975. *Depositional sedimentary environments*. Springer-Verlag, Heidelberg, 439 pp.

Rogers, A.W. 1915. The geology of part of Namaqualand. *Trans. geol. Soc. S. Afr*., **18**, 72-101.

Smith, R.S. and Hartnady, C.J.R 1984. Geochemistry of Grootderm Formation lavas: indication of tectonic environment of extrusion. *Abstracts, Conference on Middle to Late Proterozoic Lithosphere Evolution*, 20-21.

Söhnge, P.G. and de Villiers, J. 1946. Resume of the geology of the Richtersveld and the eastern Sperrgebiet. *Trans. geol. Soc. S.Afr*., **49**, 263-276.

Stanistreet, I.G., Kukla, P.A. and Henry, G. 1991. Sedimentary basinal responses to a Late Precambrian Wilson Cycle: the Damara Orogen and Nama Foreland, Namibia. *J. Afr. Earth. Sci*., **13**, 141-156.

Stowe, C.W., Hartnady, CJ.N. and Joubert, P. 1984. Proterozoic tectonic provinces of Southern Africa. *Abstract, Precambr. Res. Unit*, **25**, 229-231.

Van Vuuren, C.U. 1986. Regional setting and structure of the Rosh Pinah Zinc-Lead deposit, South West Africa/Namibia. *In*: Anhaeusser, C.R. and Maske, S. Eds. *Mineral Deposits of Southern Africa*. Vol II. Geol. Soc. S. Afr., Johannesburg, 1593-1607.

Von Veh, M.W. 1988. *The stratigraphy and structural evolution of the late Proterozoic Gariep Belt in the Sendelingsdrif - Annisfontein area, northwestern Cape Province*. Unpubl. PhD. thesis, Univ. Cape Town, 121 pp.

Watson, M.D. 1980. *The geology, mineralogy and origin of the Zn-Pb-Cu deposit at Rosh Pinah, South West Africa*. Unpubl. PhD. thesis, Univ. Pretoria, 250pp.

Wolff, M. and Füchtbauer, H. 1976. Die karbonatische Randfazies der tertiren Silwasserseen des Nordlinger Ries und des Steinheimer Beckens. *Geol. lahrb. (Hannover)*, **D 14**, 3-3.