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EFFECTS OF OCEANIC CLOSURE AND CONTINENTAL COLLISION ALONG THE SOUTHERN COASTAL BRANCH (GARIEP BELT) OF THE LATE PROTEROZOIC/ EARLY PALAEOZOIC DAMARA OROGEN, SOUTHERN NAMIBIA

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by

M.J.U. JASPER[1], E.G. CHARLESWORTH[2] and I.G. STANISTREET[2]

([1] Economic Geology Research Unit, Department of Geology, University of the Witwatersrand, P/Bag 3, WITS 2050, Johannesburg, South Africa
[2] Geology Department, University of the Witwatersrand, P/Bag 3, WITS 2050, Johannesburg, South Africa)

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ABSTRACT

The Pan African Gariep Belt is an arcuate north-south trending tectonic unit extending along the coast from south-east of Lüderitz to Kleinzee for a distance of nearly 400 km with a maximum width of about 80 km. It forms the southerly extension of the northern coastal branch (Kaoko Belt) of the extensive Damara Orogenic Province and probably links with the Saldanha Belt of the south-western Cape Province in South Africa. The Gariep Belt consists of an eastern parautochthonous passive continental margin on the western edge of the Kalahari Craton, the Port Nolloth Zone, and a western allochthonous ophiolitic terrane, the Marmora Superterrane, thrusted on the Port Nolloth Zone along the Schakalsberge thrust. Within the Port Nolloth Zone, field work established the presence of several parautochthonous thrust slices. The regional structural pattern is characterized by three phases of deformation. The earliest deformational event, D_1, is characterized by intrafolial small scale, recumbent and isoclinal F_1 folds, a penetrative bedding-subparallel S1 cleavage, a preferred elongation of boulders, pebbles, grains and minerals (l1) and slickensides. Associated with D_1 are bedding-subparallel thrust faults. The D_2 deformational phase is characterized by small to large scale, N- to NW-trending F_2 folds, which form the tectonic grain of this area. They have a generally easterly vergence, which can change into a westerly direction due to backfolding. The F_2 folds are associated with a penetrative axial planar S_2 cleavage. Field evidence shows that thrusting continued during the D_2 deformational phase. The latest deformational event (D_3) is characterized by small- to large-scale open folds (F_3) with fold axes trending in a southerly to southwesterly direction, forming interference structures with earlier deformations which are dome- and basin-like in form.

The deformational events documented in this paper record the SSE-directed closure of the Adamastor Ocean and the accretion of the Marmora Superterrane during D_1 and eastward-directed tectonic transport during D_2, caused by the collision of proto South America with the Kalahari Craton. The D_3 deformation was caused by sinistral lateral movement along old weakness zones. The tectonic evolution of the Gariep Belt only started after the end of deposition of Gariep Group lithologies, for which a minimum age of 670 Ma is inferred. Metamorphic ages from the overlying Nama and Vanrhynsdorp Groups, which developed as peripheral foreland basins to the advancing Adamastor orogeny, indicate that the tectonic evolution of the Gariep Belt only ceased at about 500 Ma. It was accompanied by Barrovian-type metamorphism with a geothermal gradient of $\sim 20°C/km$.

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INTRODUCTION

The Gariep Belt is an arcuate north-south trending tectonic unit, which extends for almost 400 km along the coast of Namibia and South Africa from immediately south-east of Lüderitz in Namibia to Kleinzee just north of Port Nolloth in South Africa (Fig. 1). The maximum exposed width of the succession is about 80 km. The belt is part of the southern coastal branch of the extensive Damara Orogen, which links with the Saldanha Belt of the south-western Cape Province and northwards with the coastal branch comprising the Kaoko Belt of northern Namibia (Fig. 2). The Gariep Belt forms part of the Late Proterozoic/Early Palaeozoic Pan African system of orogenic belts (Clifford, 1967; Stowe et al., 1984). Porada (1979) has suggested that the western extension of the Damara Orogen is represented by the Ribeira Belt of Brazil (Fig. 2), which is also supported by geochronological data of Cordani et al. (1990).

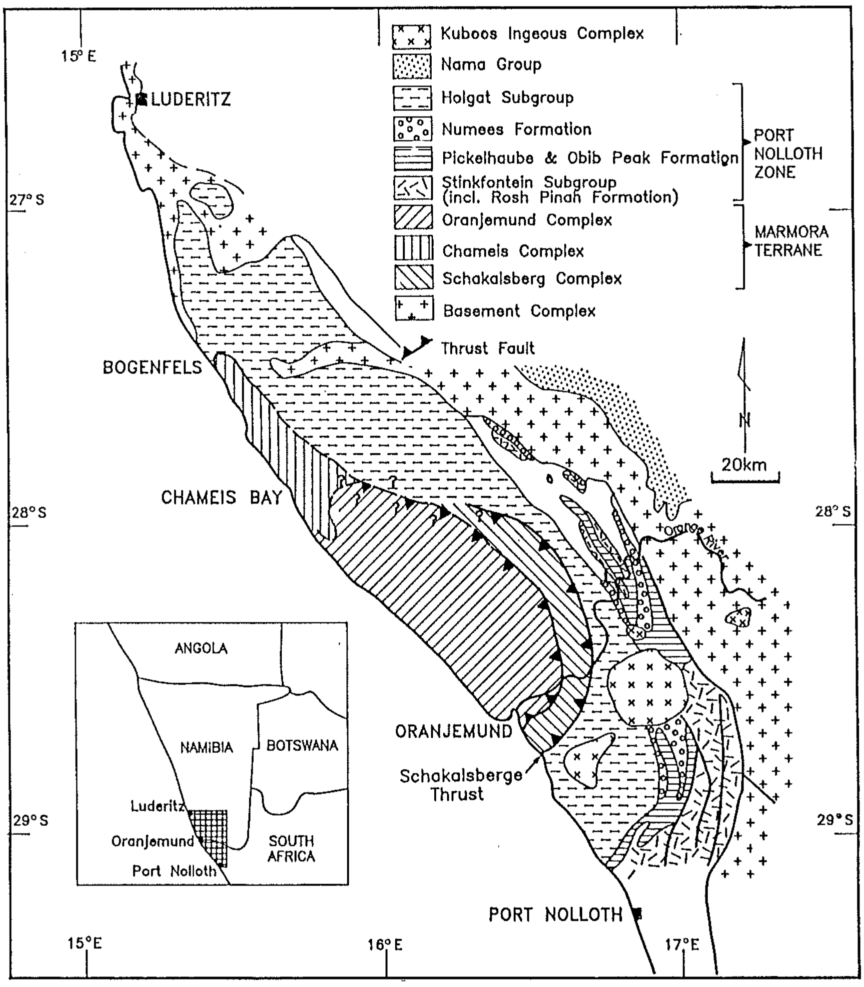


Figure 1: Simplified geological map of the Gariep Belt (modified after Hartnady et al., 1990).

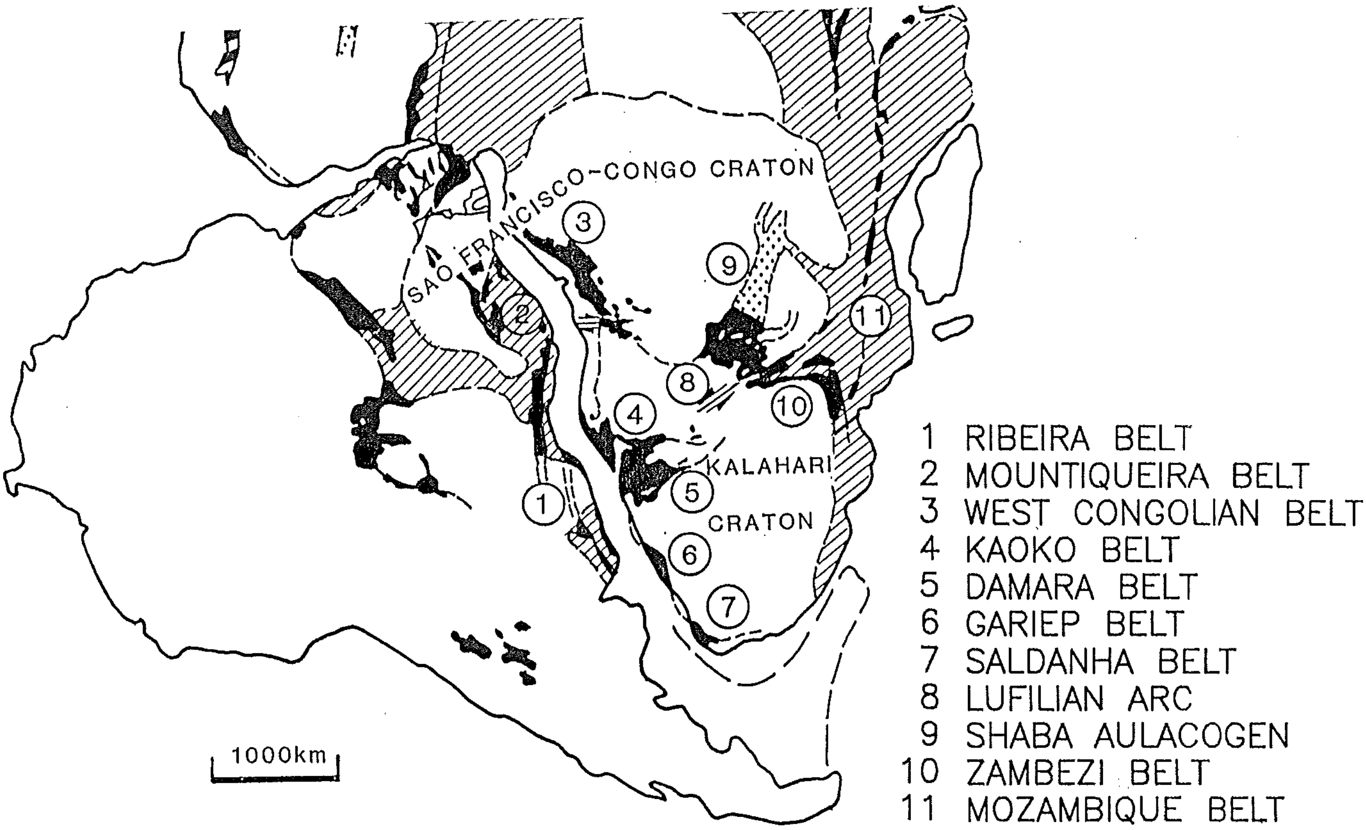


Figure 2: Pan African framework of Southern Africa and South America (modified after Porada, 1979).

The Gariep Belt consists of an eastern, parautochthonous terrane, named the Port Nolloth Zone, developed as a passive continental margin on the western edge of the Kalahari Craton, and a western allochthonous ophiolitic terrane, the Marmora Superterrane (Von Veh, 1988; Hartnady et al., 1990), thrusted onto the Port Nolloth Zone along the Schakalsberge Thrust (Fig. 1).

The Port Nolloth Zone-stratigraphy in southern Namibia (Table 1) consists of the Stinkfontein Subgroup, comprising the Rosh Pinah Formation, a mixed clastic/volcanic rift phase, and the Gumchavib Formation, consisting of mixed terrigenous/marine clastics. The Stinkfontein Subgroup is, in turn, unconformably overlain by the Hilda Subgroup, comprising the Pickelhaube Formation, a platform carbonate and continental shelf clastic phase, the Obib Peak Formation, consisting of continental clastics, and the Numees Formation, comprising mixed glaciomarine/interglacial deposits. In places the Hilda Subgroup also unconformably overlies the basement complex consisting of the Vioolsdrif Igneous Suite and rocks of the Orange River Group (Fig. 3). The extensional evolution of the Gariep Belt took place between 780 Ma, which is the age of the Lekkersink granite, that intrudes the Stinkfontein Subgroup lithologies in the Richtersveld, and 670 Ma - the age of the Varangian glacial episode, with which the Numees Formation has been correlated (Jasper, 1994).

Table 1: Stratigraphic subdivision of the Gariep Group in southern Namibia

SUBGROUP	FORMATION
Hilda	Numees
	Obib Peak
	Pickelhaube
Stinkfontein	Gumchavib
	Rosh Pinah

Within the Gariep Belt, a number of pre-, syn- and post-tectonic intrusions are present. Throughout the Gariep Belt, the up to 100 km wide Gannakouriep dyke and sill swarm, consisting of north- to northeast-trending mafic and ultramafic sills and dykes (De Villiers & Söhnge, 1959; Middlemost, 1964; McMillan, 1968; Kröner & Blignault, 1976; Reid, 1979; Jasper, 1994), is intrusive into the basement rocks and into the rocks of the Stinkfontein and lower Hilda Subgroups. The mafic rocks of the Gannakouriep dyke and sill swarm reveal radiometric ages of $\pm$ 717 Ma. In the Richtersveld, situated in the northwestern parts of the Cape Province of South Africa, immediately south of the Orange River, Gariep Group lithologies are intruded by granitic, syenitic and carbonatitic rocks of the Kuboos-Bremen and Garub complexes (Van Biljon, 1939; Söhnge & De Villiers, 1946; Kröner & Hawkesworth, 1977), which display radiometric ages of 525 $\pm$ 60 Ma and 521 $\pm$ 12 Ma (Allsopp et al., 1979). The latest intrusions into Gariep Group lithologies are Karoo dolerite dykes, which trend in a northerly direction from Dreigratberg to north of Trekpoort Farm, approximately 25 km north of Rosh Pinah (Fig. 3).

The metamorphism within the Port Nolloth Zone is Barrovian-type with a geothermal gradient of 20° C/km and ranges from greenschist to lower amphibolite facies (Jasper, 1994).

Previous structural work within the Gariep Belt of southern Namibia was undertaken by McMillan (1968), Davies & Coward (1982), Siegfried (1990) and Jasper et al. (1992/93). Within the Richtersveld, in the northwestern Cape Province of South Africa, the structural geology of the Gariep Belt was described by Rogers (1916), Kröner (1974) and De Villiers & Söhnge (1959). Von Veh (1988) carried out detailed structural analyses and proposed three kinematic phases for the Gariep Belt in the Richtersveld: (1) transpressive or convergent wrenching; (2) simple parallel wrenching; and (3) transtensive or divergent wrenching.

In this paper, the authors present the first detailed structural analysis of the Gariep Belt in southern Namibia.

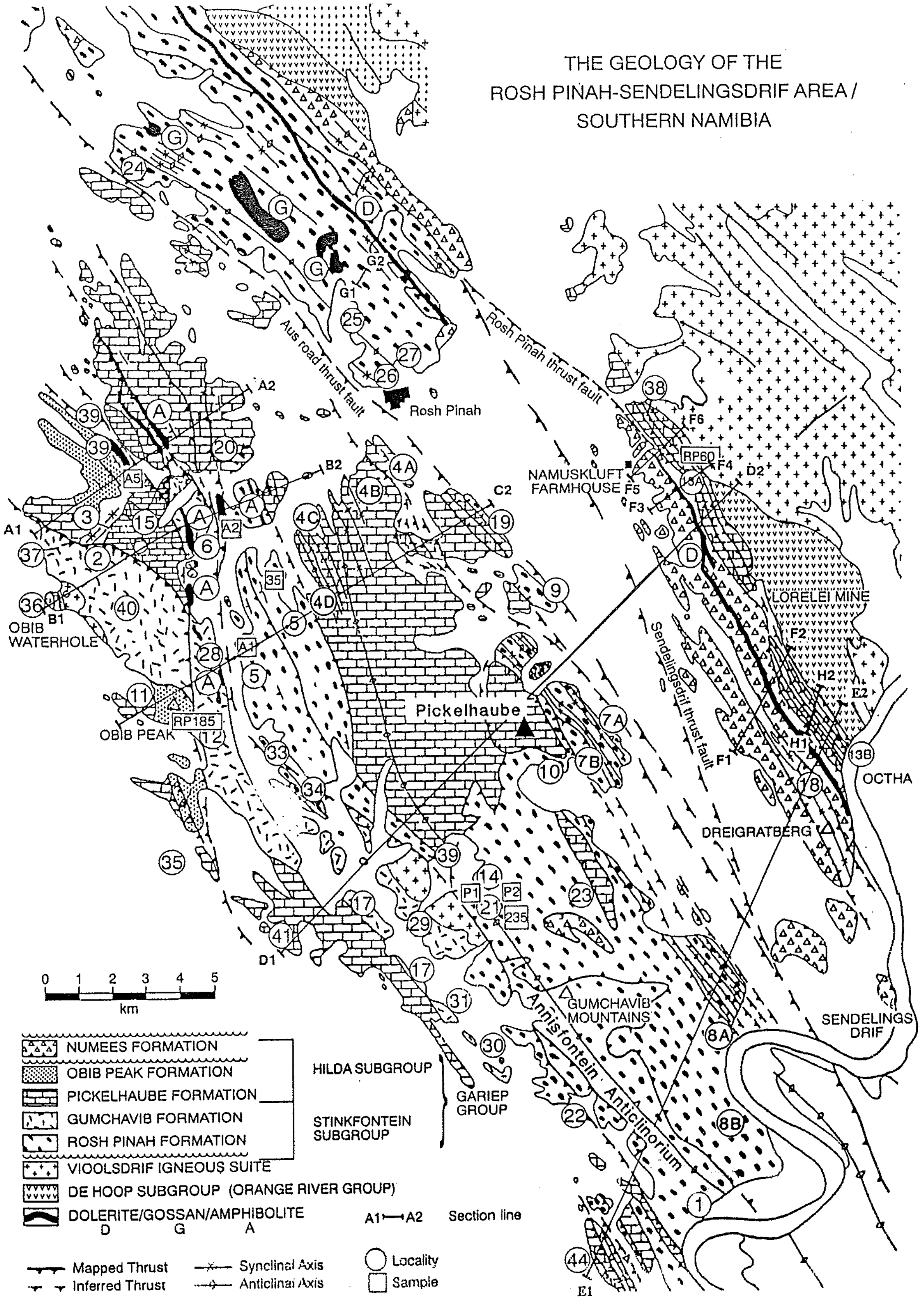


Figure 3: Geological map of the Rosh Pinah - Sendelingsdrif area, southern Namibia.

DEFORMATIONAL EVENTS

Three phases of deformation, D_1, D_2, D_3, have been identified within the Port Nolloth Zone of the Gariep Belt of southern Namibia. The most conspicuous structural elements developed throughout are associated with D_2, which therefore serves as a structural datum or benchmark. The main structural features are summarized in Table 2 and are described in their deduced chronological order.

Table 2: Structural elements associated with the deformational events within the Gariep Belt, southern Namibia

	D1-deformation	D2-deformation	D3-deformation
Fold-shape	recumbent, intrafolial (F1)	upright to recumbent, open to isoclinal (F2)	upright, open (F3)
Fold-trend	all degrees	N to NW	W to SW
Fold-size (wavelength)	centimetre scale to 2m	centimetre scale to 5 km	centimetre to >3km
Fold-vergence	southerly	commonly to the east, occasionally to the west	commonly no vergence, occasionally to the south
Foliation	Bedding-subparallel (S1)	axial-planar (S2)	axial-planar (S3)
Lineation	clast- and grain-elongation (I1)	Intersection lineation of S1/S2 (I2)	Intersection lineation of S1/S3 (I3)
Lineation-trend	NNW and WSW (after rotation to horizontal)	N to NW	W to SW
Thrust-trend	N to NW	N to NW	no thrusting

D_1 Phase of Deformation

The most important feature associated with the earliest recognized D_1 deformational event are F_1 folds. They are typically small scale (1 cm to 2 m wavelength), recumbent and isoclinal in form, and intrafolial with respect to the sedimentary bedding and a bedding-subparallel cleavage. The F_1 folds are best developed in the laminated carbonates of the Pickelhaube Formation (Fig. 4).

Figure 4: Intrafolial, recumbent, southerly verging F_1 folds within dolomitic carbonate at locality 13A, approximately 5 km southeast of Namuskluft Farmhouse.

A bedding-subparallel to -parallel D_1 cleavage (S1) is well developed throughout the study area, but has a highly variable strike and dip (Fig. 5A) as it has been dispersed by subsequent deformation events. In mica schist and siltstones, the S_1 fabric is characterized by a penetrative slaty cleavage associated with the growth of mica, and is developed subparallel or parallel to bedding planes. In coarser sediments, the D_1 deformation is characterized by the preferred orientation and elongation of boulders, pebbles and grains, whose long axes plunge by variable amounts, defining the L_1 stretching lineation. The long axes of clasts, which preferentially trend in a northwesterly direction (Fig. 5D), are best developed within conglomerates of the Rosh Pinah Formation and in pisolitic limestone of the Pickelhaube Formation.

Associated with the D_1 deformational event are bedding-subparallel D_1 thrust faults which are closely associated with F_1 folds and the S_1 foliation and cleavage. These D_1 thrust faults preferably use contacts between lithologies with contrasting competency, i.e. sandstones being thrust over mudstones or carbonates.

D2 Phase of Deformation

The most conspicuous features, which characterize the D_2 deformation, are small- to large-scale folds whose fold axes plunge variably in northwesterly and southeasterly directions (Fig. 5B).

The F_2 folds generally display an easterly vergence and vary in scale from <5 cm wavelength to large structures with wavelengths of up to about 5 km (Annisfontein anticlinorium; Fig. 3). The F_2 folds deform the F_1 folds, S_1 cleavage and the D_1 thrusts and are symmetric to asymmetric, upright to recumbent, and vary from open, to tight, to isoclinal in form. The folds also vary from harmonic to disharmonic and may be polyclinal (box folds and parasitic folds). Small-scale chevron folds are displayed at a locality situated about 2 km south of Pickelhaube (Fig. 3).

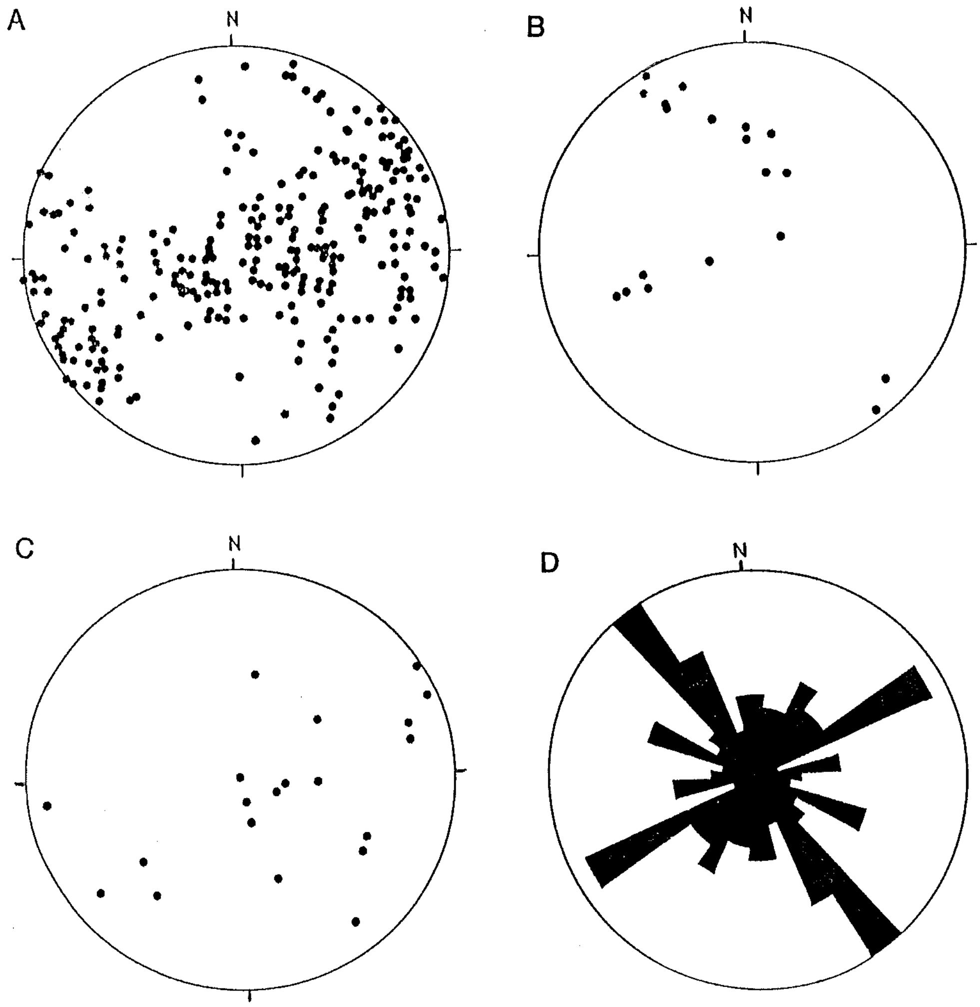


Figure 5: Equal area lower hemisphere stereonet projections of data associated with D_1 throughout the study area: A) poles to S_0/S_1; B) F_1 fold axes; C) poles to F_1 axial planes. C) Rose diagram showing the main trend elongation of clasts of the Rosh Pinah Formation and pisolites of the Pickelhaube Formation from throughout the study area.

The thrust planes of some thrust faults, which have a listric appearance, steepen in an easterly direction and are overturned in places. F_2 folds with an originally easterly vergence and which occur together with some of these steepened or overturned thrust faults, change their vergence in a westerly direction as they "climb up" the listric thrust planes and are referred to as "backfolds". East of the Aus Road thrust and the Sedelingsdrif thrust (Figs. 3 & 6), F_2 folds generally verge in a westerly direction, as a result of backfolding in the proximity of the basement and in the presence of steep thrusts (Figs. 7 & 8).

An S_2 axial planar cleavage and foliation is developed within the pelitic and psammitic rocks. The S_2 axial planar cleavage within the pelitic rocks is defined by a penetrative slaty cleavage within argillaceous units and by an axial planar fracture cleavage or a preferred orientation of grains in arenites (Fig. 9). The S_2 axial planar cleavages and associated F_2 axial planes strike at about 140 to 190° and dip with variable amounts in westerly and easterly directions (Fig. 10).

An S_2 crenulation cleavage, deforming the pre-existing S_1 bedding-subparallel cleavage, is present throughout the study area. The intersection of the two cleavages, which defines the lineation (L_2), plunges moderately in northerly and southerly directions.

Thrusts, which are associated with the D_2 deformational event, will be described later.

D3 Phase of Deformation

A D_3 phase of deformation has been recognized throughout the study area. Stereonet projections of data associated with this deformational phase are shown in Figure 11 and display a trend of F_3 fold axes ranging from WNW to SW. F_3 axial planes are generally upright, but occasionally may show a northerly and, more commonly, southerly vergence.

The most conspicuous features of this phase of deformation are open, upright, small- to large-scale cross folds, referred to as F_3 folds, which range from <5 cm wavelength, mainly developed in argillaceous rocks, to medium- and large-scale folds with wavelengths of several kilometres. Open, small-scale,chevron-like folds are also present (Fig. 12).

The F_3 folds form interference structures due to deformation of the pre-existing F_2 folds (Fig. 13). The interference structures are dome-like in form and the superposition of the F_3 folds on F_2 folds is mainly responsible for the variable plunge directions of the F_2 folds. An S_3 crenulation cleavage, associated with the development of F_3 folds, was observed about 2 km northeast of Obib waterhole (Fig. 3), and could only be recognized where the S_1 cleavage was overprinted by a weak axial planar S_3 cleavage, defining the L_3 intersection lineation.

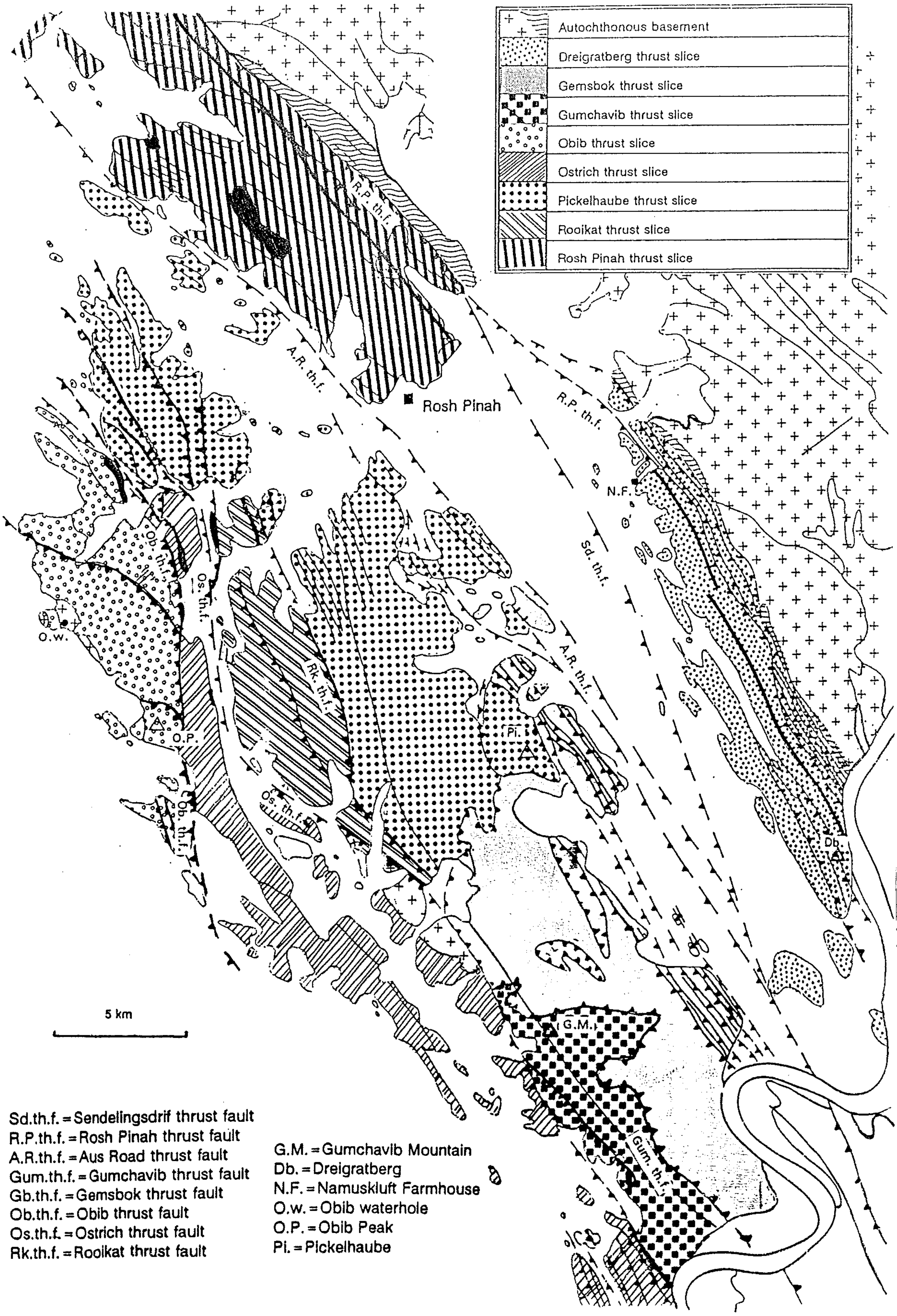


Figure 6: Delineation of the various thrust slices and the parautochthonous unit within the study area.

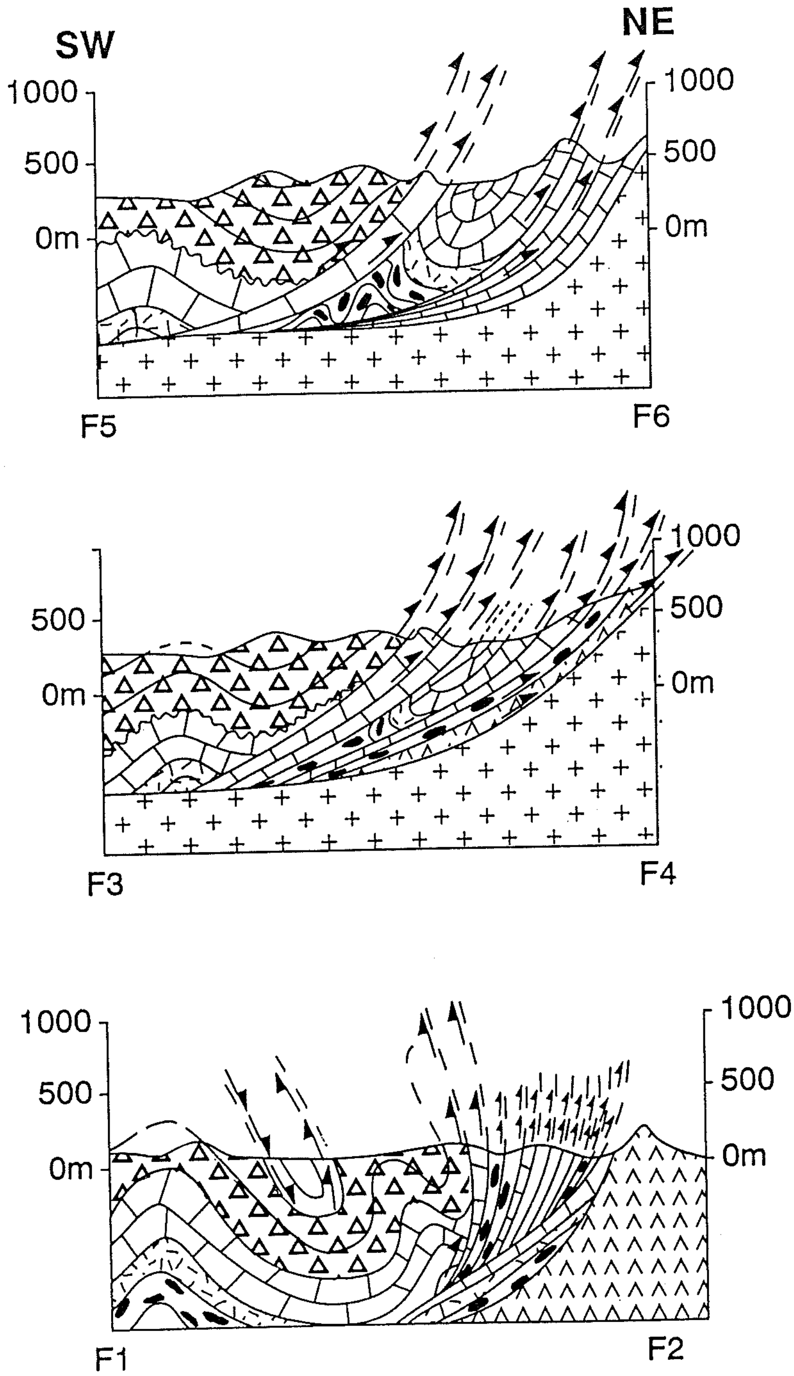


Figure 7: Structural SW to NE cross-sections F_1-F_2, F_3-F_4, F_5-F_6 situated within the imbricate zone in the east of the Dreigratberg thrust slice. Positions of cross-sections are shown in Figure 3.

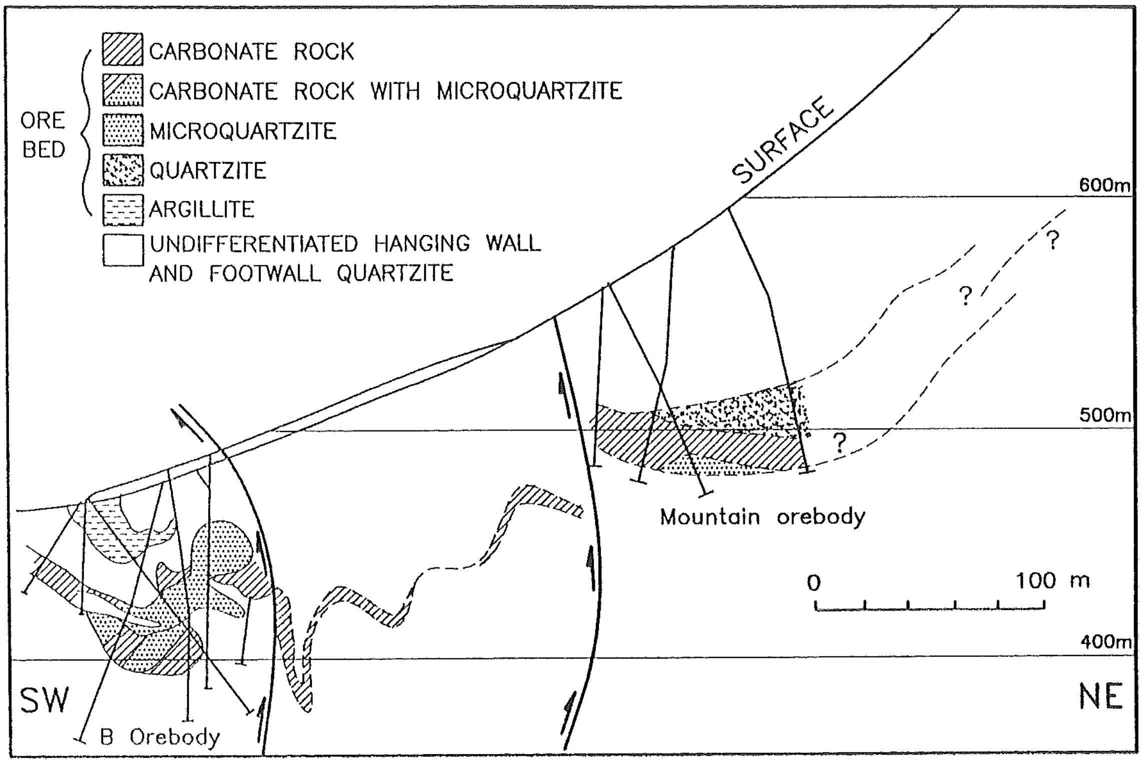


Figure 8: Structural profile G1-G2 through parts of the Rosh Pinah thrust slice (modified after Van Vuuren, 1986). Position of cross-section is shown in Figure 3.

Figure 9: Penetrative S_2 axial planar cleavage within a northwest-plunging, overturned tight fold developed in sandstones and mudstones of the Pickelhaube Formation near Daberas, about 40 km NE of Oranjemund.

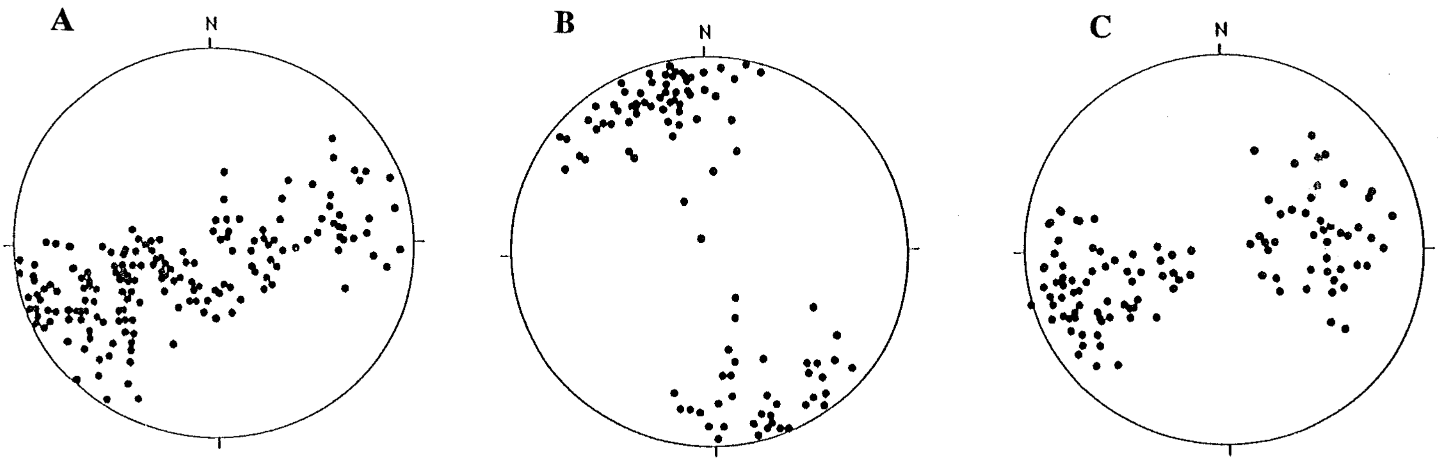


Figure 10: Equal area lower hemisphere stereonet projections of data associated with D_2 throughout the area: A) poles to bedding; B) F_2 fold axes; C) poles to F_2 axial planes.

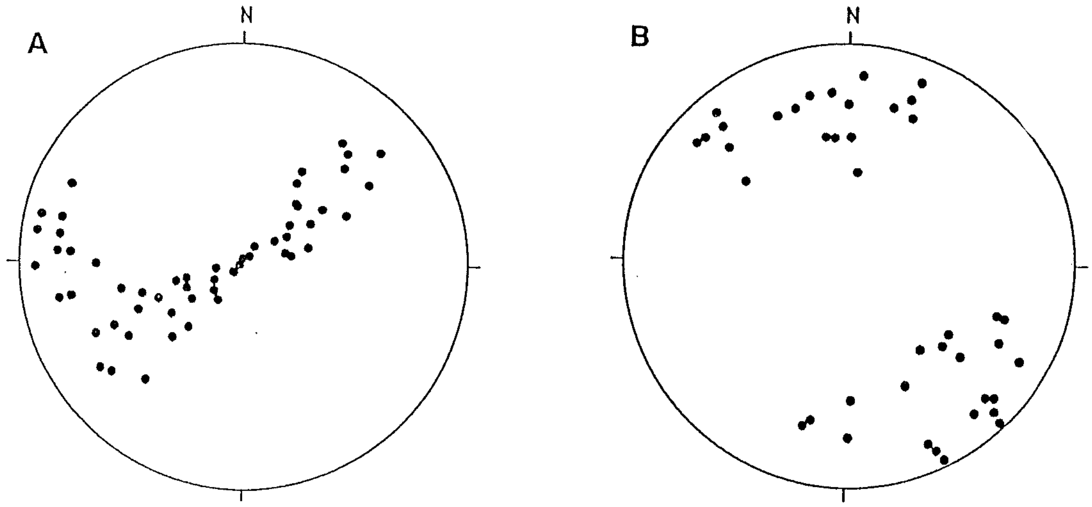


Figure 11: Equal area lower hemisphere stereonet projections of data associated with D_3 throughout the area; A) F_3 fold axes (n = 68); B) poles to F_3 axial planes (n = 46).

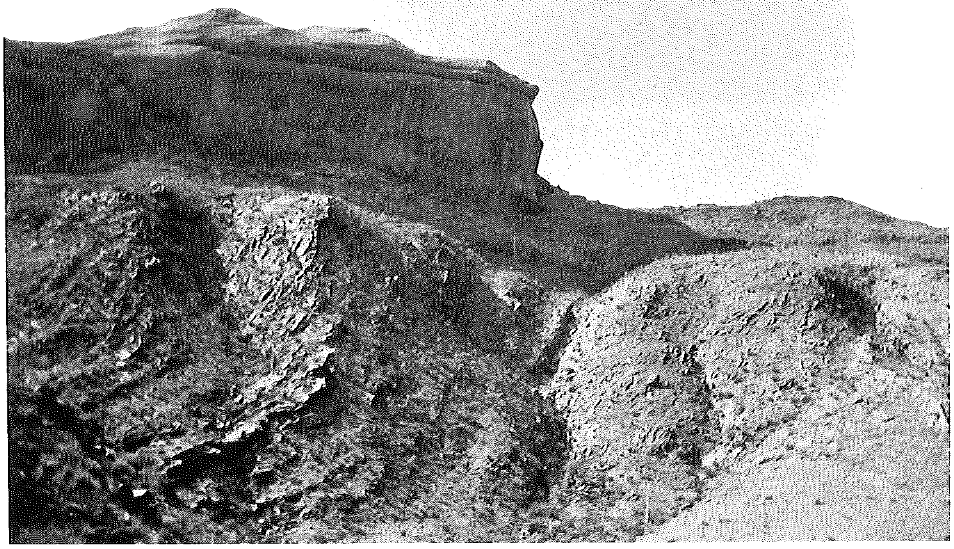
Recognition of Thrust Faults

Thrust faults, associated with the D_1 and D_2 deformational events, are amongst the most important structural elements within the study area. Their recognition and the understanding of the time sequence of the activity of these thrust faults is most important for the understanding of the structural evolution and kinematic interpretation of the Adamastor orogenesis in the Gariep Belt.

Figure 12: *D_2 thrust fault immediately south of Pickelhaube (Locality 10, Figure 3), which thrusts carbonates of the Pickelhaube Formation over sandstones and conglomerates of the Rosh Pinah Formation. Note the relatively undeformed carbonate in the upper thrust slice overlying folded sandstones and conglomerates with a clearly developed axial planar foliation beneath the thrust fault.*

Figure 13: *F_3 open chevron fold within carbonates of the Pickelhaube Formation at locality 10 (Figure 3) in the Ostrich thrust slice; note the intrafolial F_1 folds are deformed around an F_3 hinge line.*

Figure 14: *Fold interference structure, probably caused by a F_3 fold deforming fold hinge of a F_2 fold at Dreigratberg.*



The major D_1 and D_2 thrusts within the study area generally trend north-south to northwest-southeast (Fig. 3), with thrust planes generally dipping in a westerly direction. Thrusts are in some cases steeply inclined towards the east as a result of intense compression in the vicinity of the basement or within imbricate thrust zones. D_1 thrusts and the associated S_1 cleavage are, in places, deformed by the D_2 deformational event, thus dipping with variable angles in an easterly direction.

The thrust faults are marked by: (1) intrafolial folds, shear zones, the presence of quartz veins, and feldspar pegmatoids in the vicinity of thrust faults; (2) mylonite zones; (3) stratigraphic discordances associated with ramping; (4) a conspicuously developed foliation within and in the vicinity of shear and thrust zones; (5) the presence of an intense silicification of sandstones; (6) the alteration of limestones to marbles; (7) the occurrence of actinolite schist in association with amphibolite sills; (8) the presence of tight to isoclinal and recumbent F_2 folds; and (9) the change of fold vergence from east to west. D_1 thrusts commonly develop parallel or subparallel to bedding and frequently steepen with a westerly dip, taking the shape of listric thrust faults. In the east of the study area, within imbricate thrust zones and in the immediate vicinity of the competent basement, the westerly dip of thrust planes steepens and can even be steeply inclined towards the east. The listric thrust faults occasionally form ramps, which cut across the stratigraphy and may be caused by successive failure in the footwall. Imbricate zones, present at various locations throughout the study area, may be a subsequent result of the progressive failure of footwall ramps. Intrafolial F_1 folds, a bedding-subparallel S_1 cleavage and the elongation of grains and clasts (L_1) are associated with bedding-parallel thrusting in the vicinity of thrust contacts.

Within the Dreigratberg syncline (Fig. 3), D_1 thrusts and the associated S_1 cleavage were deformed around fold hinges during D_2. Folding and the development of a penetrative axial planar S_2 cleavage and foliation is intimately associated with thrusting during D_2. In places, F_2 fold limbs are truncated by associated thrust faults at high angles, showing that thrusting occurred concurrently with folding during D_2.

At Pickelhaube (Fig. 3), relatively undeformed carbonate of the Pickelhaube Formation is thrust over sandstones and conglomerates of the Rosh Pinah Formation. The latter sediments have been folded during D_2 and display a clear axial planar S_2 foliation (Fig. 14), demonstrating that thrusting continued until the late stages of D_2.

Thrusting occurred from the early stages of D_1, through the main phases of D2 until the late stages of the D_2 deformational event, showing that D_1 and D_2 took place progressively.

TECTONOSTRATIGRAPHY OF THE PORT NOLLOTH ZONE

Major thrusts within the study area define the boundaries of several tectonostratigraphic units, juxtaposing the various thrust slices.

Major changes in fabric and fold morphology occur between the different parautochthonous thrust slices and the basement-floored sequence east of the Rosh Pinah thrust fault (Figs. 3 & 6). The thrust slices are parautochthonous, whereas the basement-floored unit is autochthonous. The thrust slices are named after the floor thrust fault of each thrust slice. From east to west the structural units (Fig. 6) comprise: (1) the autochthonous unit in the east of the study area, immediately east of the Rosh Pinah thrust fault and the associated imbricate thrust zone; (2) the parautochthonous Dreigratberg thrust slice; (3) the Pickelhaube thrust slice; (4) the Gumchavib thrust slice; (5) the Rooikat thrust slice; (6) the Ostrich thrust slice; (7) the Obib thrust slice; and (8) the Gemsbok thrust slice.

As most structural fabrics associated with the various deformational phases are well developed throughout the study area, only the main structural elements characterizing the different tectonic units, together with the stratigraphy, will be portrayed.

The Autochthonous Unit

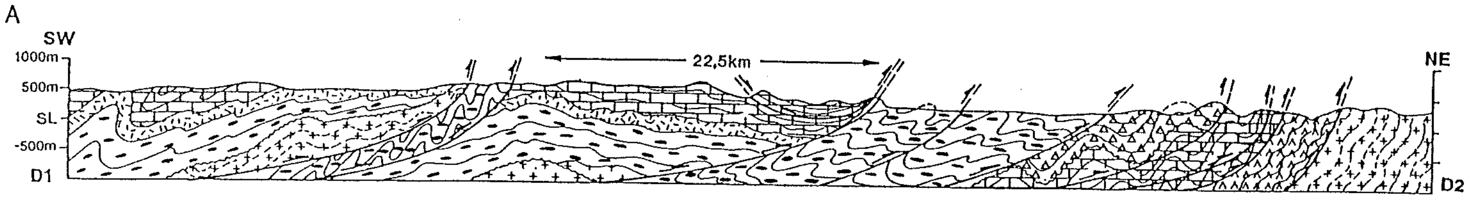
Unconformable sedimentary relationships are recognized east of Namuskluft Farmhouse where carbonates of the Pickelhaube Formation overlie granitic basement (locality 38; Fig. 3), as well as sediments of the Numees Formation, the latter overlying the basement unconformably north and NNE of Rosh Pinah (Fig. 3; Van Vuuren, 1986). Numees Formation lithologies also overlie the basement at Namuskluft waterhole, approximately 10 km northeast of Rosh Pinah.

Structurally, the autochthonous unit is characterized by NNW-trending reverse faults and small- to medium- scale open F_2 folds (<50 m wavelength). Shear zones and the effects of shearing can be observed in the fine-grained units (carbonates and phyllites) at several places near the basement contact.

Parautochthonous Units

Dreigratberg Thrust Slice

The Dreigratberg thrust slice is located in the east of the study area, extending from north of Octha along the basement contact to about 4 km north of Namuskluft Farmhouse (Figs. 3 & 6). To the east, this thrust slice is bounded by an imbricate thrust zone, which is situated immediately east of the basement. This imbricate thrust zone forms the southerly continuation of the Rosh Pinah thrust and defines the floor thrust of the Dreigratberg thrust slice. The western boundary of this thrust slice is defined by the Sendelingsdrif thrust, which forms the roof thrust of the thrust slice. The floor and roof thrusts join north of Namuskluft Farmhouse, restricting the northerly extension of the Dreigratberg thrust slice. West of the Sendelingsdrif thrust, the vergence of F_2 folds is generally easterly, whereas to the east of it the folds generally verge in a westerly direction. The Dreigratberg thrust slice extends in a southerly direction into the Richtersveld and comprises diamictite and iron formation of the Numees Formation, structurally overlain by a clastic/calcareous succession of the Pickelhaube Formation. The northwest-trending Dreigratberg syncline (locality 18; Fig. 3) forms the core of this thrust slice, which also folds the thrusted contact between the Numees Formation and the overlying Pickelhaube Formation lithologies (Figs. 3, 6, 7 & 15). The Dreigratberg syncline, the fold limbs of which dip in an easterly direction and have a wavelength of at least 3 km, has a westerly vergence. The fold hinge plunges at a shallow angle in a southerly direction, explaining the pinching-out of the Pickelhaube lithologies towards the



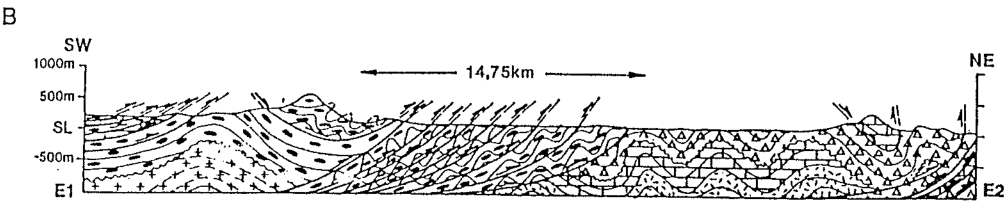


Figure 15: A) Structural SW-to-NE cross-section D1-D2 cutting through parts of the Obib thrust slice south of Obib Peak in the SW, and parts of the Ostrich, Rooikat, Pickelhaube, Gemsbok, and Dreigratberg thrust slices, as well as the parautochthonous zone in the NE.

B) Structural SW-to-NE cross-section E1-E2 cutting through the Ostrich thrust slice approximately 8 km south of Gumchavib in the SW, and parts of the Gumchavib, Gemsbok, and Dreigratberg thrust slices, as well as the parautochthonous zone in the NE.

Position of cross-sections are shown in Figure 3.

the north. A prominent imbricate zone with steep (65-89°), generally west-dipping faults is situated to the east of the Dreigratberg syncline, near the thrust contact with the autochthonous unit (Figs. 3, 6, 7 & 15). Field evidence shows that these thrusts are deformed in the vicinity of the highly competent basement such that they may be vertical or dip in an easterly direction. A south-southeasterly and easterly directed thrust movement took place along these thrusts. The various thrust slices within this imbricate zone are each uniform in their lithological composition, comprising either sandstones and conglomerates of the Rosh Pinah Formation, massive and pisolitic carbonates of the Pickelhaube Formation, or massive diamictite of the Numees Formation. Towards the north, in an area extending from southeast to northeast of Namuskluft Farmhouse (Fig. 3), the Dreigratberg thrust slice comprises massive diamictite of the Numees Formation and carbonate and calcareous conglomerate of the Pickelhaube Formation. At the easternmost exposure the carbonates of the Pickelhaube Formation have a thrusted contact with the autochthonous unit (Figs. 3 and 15). Towards the east, an F_2 synclinal box fold measuring about 100 m from one fold limb to the other, with a steeply westerly dipping axial plane, folds the sediments of the Pickelhaube Formation. East of this syncline, the basement and the lithologies dip towards the west. About 0,5 km northeast of Namuskluft Farmhouse (Fig. 3), 5 m-thick granitic basement, overlain by Pickelhaube carbonate, is thrust over a thick succession of similar Pickelhaube lithologies, thus emphasizing the parautochthonous nature of this thrust slice.

Structural cross sections (Figs. 7 & 15) constructed across the Dreigratberg thrust slice (Figs. 3 & 6) show how the several imbricate thrust slices pinch-out laterally. The only continuous thrust within the imbricate thrust zone, which does not splay, is the westernmost thrust fault, juxtaposing the Numees diamictite and the imbricate thrust slices (Figs. 7 & 15).

A later, Phanerozoic tectonic phase, which has affected the area, is indicated by the presence of two NNW-trending dolerite dykes of Karoo age, which intrude the sediments of the Numees Formation along the eastern limb of the Dreigratberg syncline (Fig. 3).

Rosh Pinah Thrust Slice

The Rosh Pinah thrust slice, located about 5 km northwest of the Dreigratberg thrust slice, forms the floor thrust of this thrust slice and defines the eastern boundary of this tectonostratigraphic unit. The Aus Road thrust fault forms the roof thrust and delineates its western extensions (Figs. 3 & 6). The Rosh Pinah thrust slice extends from south of Rosh Pinah Mountain to northwest of Spitskop Farm, which is situated approximately 15 km north of Rosh Pinah (Fig. 1). West of the Aus Road thrust fault, F_2 folds generally verge in an easterly direction, whereas east of it, the fold vergence is directed towards the west.

At Spitzkop Farm (Fig. 1), the Rosh Pinah thrust slice comprises a mixed succession of 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; Lickfold, 1990). In the Rosh Pinah area, the Rosh Pinah thrust slice consists of a mixed coarse- to fine-clastics/carbonate succession and bimodal volcanics of the Rosh Pinah Formation, the latter associated with massive Zn-Pb-Cu-Ag sulphide (+Ba) mineralization. The contact between the basement and the volcanics, and the sediments of the Rosh Pinah and the Numees Formations north and northwest of Rosh Pinah is thrusted. In the Rosh Pinah area, large-scale northwest-trending, open F_2 backfolds are recognized with axial planes dipping in a north-easterly direction (Figs. 3 and 8). Southwest-trending F_3 folds, deforming earlier structures, were described by Siegfried (1990). Thrusts, trending in a northwesterly direction with northeasterly dipping thrust planes, were also recognized. The northeasterly dip of the thrusts is related to overturning of thrust faults in the immediate vicinity of the highly competent basement. F_2 fold axes show a wide dispersion in trend from generally SSE to E within the Rosh Pinah thrust slice, as well as a random dispersion of S_o/S_1. F_3 folds have a westerly trend and only occasionally display a southerly vergence. A later, Phanerozoic tectonic phase, which has affected the area, is also indicated within the Rosh Pinah thrust slice by the presence of a northwest-trending Karoo dolerite dyke, which links with the dolerite dykes in the Dreigratberg thrust slice, intruding rocks of the Rosh Pinah Formation at Rosh Pinah Mountain. This dolerite dyke can be followed to Trekpoort Farm, situated approximately 25 km northwest of Rosh Pinah.

Pickelhaube Thrust Slice

The Aus Road thrust, which changes its trend from northwest in the area north of Rosh Pinah to NNW south of Rosh Pinah, separates the Rosh Pinah thrust slice to the east from the Pickelhaube thrust slice to the west (Figs. 3 & 6). The Aus Road thrust forms the floor thrust of this tectonostratigraphic unit. The Rooikat thrust forms the roof thrust, which also defines the western boundary of the Pickelhaube thrust slice, linking with the Ostrich thrust further south (Fig. 3). Along the Aus Road thrust the dip of axial planes of F_2 folds changes drastically from a generally easterly direction west of the thrust to a westerly direction east of it.

Lithologically, the Pickelhaube thrust slice comprises calcareous quartzitic sandstones, laminated carbonates and graphitic black shale of the Pickelhaube Formation.

The Aus Road thrust links with the Sendelingsdrif thrust about 7 km north of the Orange River (Figs. 3 & 6), where it was delineated by Von Veh (1988) in the Richtersveld. South of Rosh Pinah, the Pickelhaube thrust slice and the continuation of the Gemsbok thrust slice are juxtaposed along northwest- to NNW-trending thrusts with steep westerly dipping and in some cases overturned fault planes. The most prominent fold structure is the northerly continuation of the F_2 Annisfontein anticlinorium, delineated by Von Veh (1988) in the Richtersveld, which folds pre-existing D_1 fabrics and thrust planes. The F_2 folds in this area trend NNW- to-northwest and range from small to large scale (> 200 m). They are open and upright folds and verge towards the east. Pickelhaube trigonometrical beacon (Fig. 3) is situated in the centre of a conspicuous thrust slice (Figs. 3 & 6), which consists of carbonates and calcareous quartzitic sandstones of the Pickelhaube Formation and, in turn, is thrusted over carbonates of the Pickelhaube Formation and clastics of the Rosh Pinah Formation (Fig. 15). North of Pickelhaube, at localities 9 and 19 (Fig. 3), carbonates of the Pickelhaube Formation are duplicated by steep easterly dipping, overturned thrust faults. F_3 fold trends range from west to southwest and associated D_3 axial planes dip steeply in northerly and southerly directions.

Gemsbok Thrust Slice

The Gemsbok thrust slice can be traced from the Orange River to about 5 km southeast of Rosh Pinah in the north (Fig. 6). The Aus Road thrust and an associated conspicuous imbricate zone, as well as the Sendelingsdrif thrust immediately north of the Orange River, form the floor thrust in the east of the Gemsbok thrust slice (Fig. 6). The roof thrust in the north of this thrust slice is defined by thrust faults, thrusting the Pickelhaube thrust slice over the Gemsbok thrust slice (Figs. 3, 6 & 15). The western boundary of the Gemsbok thrust slice in the area south of Pickelhaube is marked by the Gumchavib thrust, which can be traced southwards into the Richtersveld, where it was delineated by Von Veh (1988), and northwards to Gumchavib Mountain and southwest of Pickelhaube (Figs. 3 & 6).

Lithologically, the Gemsbok thrust slice consists of conglomerates, arkosic sandstones, and mudstones of the Rosh Pinah Formation. At locality 8A (Fig. 3), recumbent F_2 folds with wavelengths of 100 to 200 m and an easterly vergence are present just east of the imbricate thrust zone associated with the Aus Road and Sendelingsdrif thrusts. Within the different thrust sheets of this imbricate thrust zone, asymmetric folds change their vergence from a generally easterly to a westerly vergence due to backfolding. Near locality 23, NNW of Gumchavib Mountain (Fig. 3), two small thrust slices, the one comprising laminated carbonates of the Pickelhaube Formation and the other consisting of diamictite of the Numees Formation, are thrust over conglomerates, sandstones and mudstones of the Rosh

Pinah Formation. At locality 7A (Fig. 3), large-scale, overturned to recumbent, isoclinal F_2 folds with wavelengths of over 100 m are situated immediately west of the imbricate thrust zone to the east of Pickelhaube trigonometrical beacon (Figs. 15 & 16). Large scale (>200 m) box folds are developed about 2 km NNW of Pickelhaube and southwest of Pickelhaube small-scale chevron folds and medium- to large-scale (< 200 m) folds were recognized. In the vicinity of listric thrust faults, the F_2 folds change their vergence from an easterly to a westerly direction due to backfolding (Fig. 15).

The trend of F_3 folds ranges from ESE to SW, with associated axial planes only occasionally verging in a generally southerly direction.

Figure 16: Large-scale isoclinal overturned-to-recumbent F_2 fold within the imbricate thrust zone west of Pickelhaube (locality 7A, Fig. 3).

Gumchavib Thrust Slice

The Gumchavib thrust slice extends from north of the Orange River to northwest of Gumchavib Mountain (Fig. 6). In the east, it is bounded by the Gumchavib thrust. The roof thrust to the west of this thrust slice is defined by a northwest-trending thrust, which splays from the Ostrich thrust into the Gumchavib thrust and the southerly continuation of the Ostrich thrust about 3 km northwest of Gumchavib Mountain (Figs. 3 & 6). The Gumchavib thrust slice comprises a mixed succession of conglomerates, sandstones, mudstones and isolated carbonate beds of the Rosh Pinah Formation, as well as carbonates and calcareous sandstones of the Pickelhaube Formation. Immediately south of Gumchavib trigonometrical beacon, carbonates and calcareous quartzite are interbedded within the Rosh Pinah Formation. Structural elements associated with the D_1, D_2 and D_3 deformational phases display a similar pattern as within the Gemsbok thrust slice.

The most conspicuous structural feature within this thrust slice is the northwest-trending continuation of the Annisfontein anticlinorium, which was delineated by Von Veh (1988) in the northwestern Richtersveld (Figs. 3 and 15). West of the central parts of the thrust slice, sediments of the Rosh Pinah Formation are juxtaposed with each other along the northwest-trending roof thrust of the Gumchavib thrust slice (Figs. 3 and 15).

Ostrich Thrust Slice

The Ostrich thrust slice changes its trend from northwest in the south to a northerly trend north of the area situated about 3 km northeast of Obib Peak. It can be traced from the Orange River to the area northeast of Obib waterhole (Fig. 6). In the northern parts of the Ostrich thrust slice the northerly trending Ostrich thrust juxtaposes the Ostrich and Rooikat thrust slices and defines the floor thrust of this tectonic unit. About 3 km southeast of Obib Peak , the Ostrich thrust continues in a southeasterly direction, where it thrusts granitic basement over sandstones and conglomerates of the Rosh Pinah Formation (Figs. 3 and 6). The Ostrich thrust can be followed further to the southeast, where it links with an imbricate thrust zone west of locality 1, immediately north of the Orange River (Fig. 3). The roof thrust in the west of this thrust slice is delineated by the Obib thrust.

Lithologically, the Ostrich thrust slice consists of a thick succession of conglomerates, arkosic and quartzitic sandstones, mudstones and carbonates of the Rosh Pinah and Gumchavib Formations, and carbonates, calcareous sandstones and conglomerates of the Pickelhaube Formation. In the central parts of the thrust slice, in a south-westerly direction perpendicular to strike, carbonates of the Pickelhaube Formation are abundant. Basic sills of the Gannakouriep dyke and sill swarm, up to several tens of metres thick, which underwent metamorphism of the upper greenschist facies (Jasper, 1994), are interbedded with the sediments of the Gumchavib Formation (Fig. 3). A mixed succession of clastic and carbonate rocks unconformably overlie the granitic basement northwest of Gumchavib Mountain (Fig. 3). The granitic basement structurally overlies sediments of the Rosh Pinah Formation along a thrust fault and thus emphasizes the parautochthonous nature of this thrust slice. The beds within this thrust slice change their strike from north, in the northern parts of the thrust slice, to northwest further south and dip in a westerly and southwesterly direction. Minor small- to medium-scale F_2 folds are present throughout the thrust slice. F_2 folds display a northwesterly trend with associated easterly verging axial planes. At locality 7 (Fig. 3) and south of it, a large-scale (approximately 200 m wavelength), isoclinal and overturned F_2 fold is exposed (Fig. 17), folding sediments of the Gumchavib Formation. The fold hinges of the F_2 folds plunge gently ($< 10°$) in various directions due to the refolding of the fold hinges by the D_3 deformational event. Immediately north of the Orange River the Ostrich thrust slice is characterized by an imbricate thrust zone (Fig. 15) consisting of arkosic sandstones of the Rosh Pinah Formation, carbonates of the Pickelhaube Formation, diamictite of the Numees Formation and carbonate of the Pickelhaube Formation. The Numees Formation sediments, which overlie carbonates of the Pickelhaube Formation, form the southernmost outcrop of Numees diamictite in southern Namibia. F_3 folds, though scarce, are upright with fold hinges trending in a southwesterly direction.

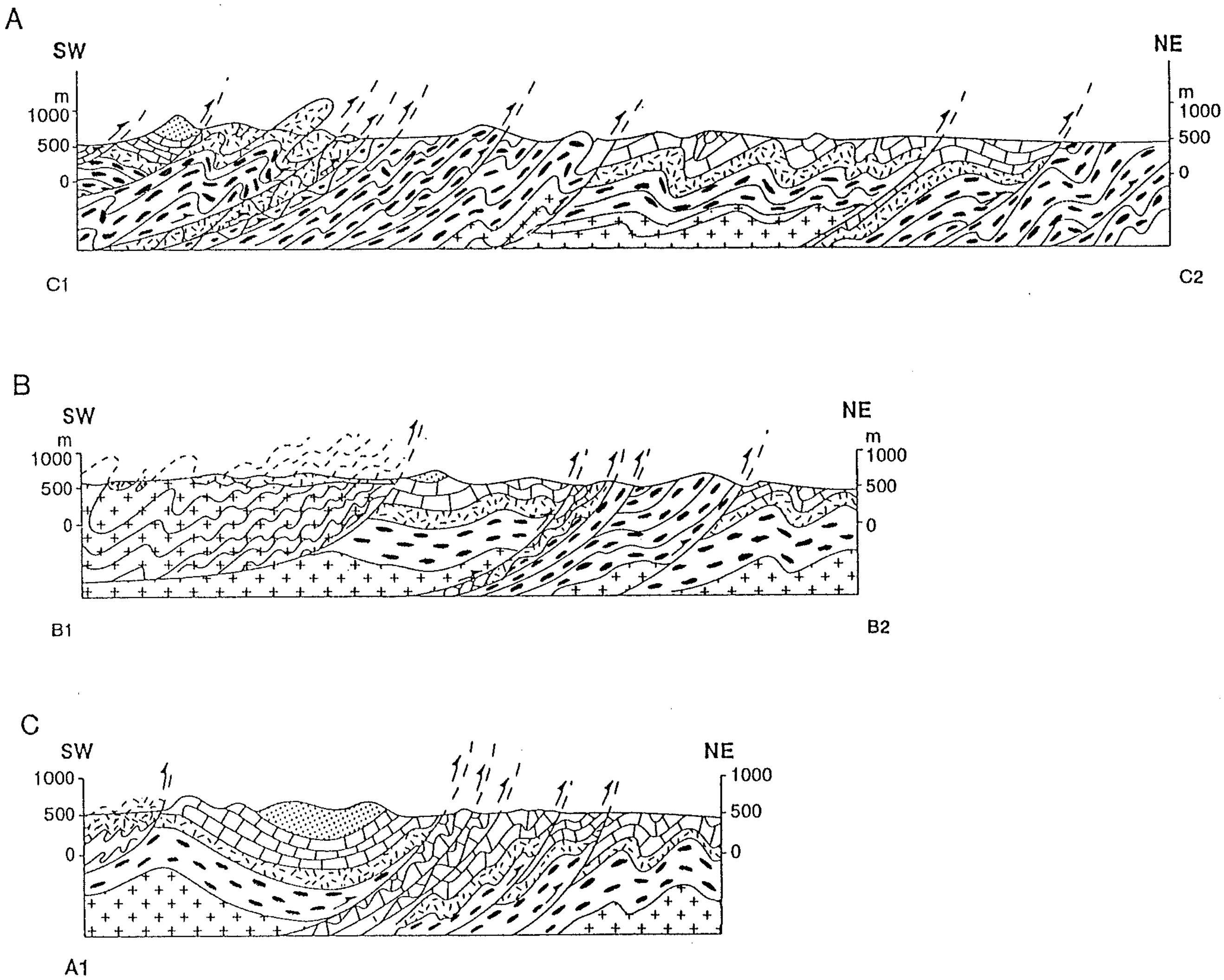


Figure 17: *A) Structural SW-to-NE cross-sections A1-A2 through parts of the Obib and Pickelhaube thrust slices.*
B) Structural SW-to-NE cross-section B1-B2 through parts of the Obib, Ostrich, Rooikat, and Pickelhaube thrust slices.
C) Structural, SW-to-NE cross-section C1-C2 through parts of the Obib, Ostrich, Rooikat, Pickelhaube, and Gemsbok thrust slices. Position of cross-sections are shown in Figure 3.

Rooikat Thrust Slice

The boundaries of the Rooikat thrust slice are defined by the Rooikat thrust in the east of this tectonic unit, which forms the floor thrust, juxtaposing the Rooikat and Pickelhaube thrust slices, and by the Ostrich thrust slice in the west, delineating the roof thrust of this tectono-stratigraphic unit (Fig. 6).

The Rooikat thrust slice comprises an approximately 1000 m-thick succession of clastic, carbonate, and basic and minor acid volcanic rocks associated with mineralized gossans and collectively comprise the Rosh Pinah Formation. This formation is duplicated by the NNW-trending Ostrich thrust (Figs. 3 & 17). Towards the top of the succession several limestone beds are interbedded with the arkosic sandstone. Basic sills of the Gannakouriep dyke and sill swarm, up to 30 m thick, have been intruded into the sediments of the Rosh Pinah Formation in the northern parts of the Rooikat thrust slice (Fig. 3). Bedding generally strikes NNW and dips to the west, but is folded in the south of the Rooikat thrust slice (Figs. 15 & 17). The scarce F_2 folds trend in a northerly direction and display an easterly vergence. Small- to medium-scale (1 to 10 m), open asymmetric folds, trending NNW with axial planes dipping to the WSW, are observed in some places (Fig. 17). Approximately 1 km west of the Rooikat thrust fault, a large-scale, tight and east-vergent F_2 fold with a wavelength of about 100 m is displayed (Fig. 17). Bedding (S_o) and bedding-subparallel S_1 foliation dips west to southwest. F_3 folds are generally upright and occasionally south-vergent, with the trend of fold axes ranging from west to southwest.

Obib Thrust Slice

In the east the base of the Obib thrust slice is defined by the Obib thrust, which strikes north immediately east of Obib Peak, and which changes its strike to northwest about 6 km northeast of Obib waterhole where it links with the Ostrich thrust (Fig. 6).

Around Obib waterhole and towards Obib Peak (Fig. 3), the Obib thrust slice comprises interbedded quartzarenites and mudstones of the Gumchavib Formation, which are thrust over carbonates of the Pickelhaube Formation along a northwest-striking thrust fault north of Obib waterhole. This thrust links with the Obib thrust about 4 km east of Obib waterhole. The Pickelhaube carbonates are overlain by clastics of the Obib Peak Formation. The westernmost granitic outcrop near Obib waterhole is overlain by intensely sheared basal conglomerate of the Rosh Pinah Formation and interbedded quartzarenites and mudstones of the Gumchavib Formation in the west. Towards the east, the contact of Rosh Pinah and Gumchavib lithologies and the granitic basement is intensely deformed by overturned isoclinal F_2 folds with wavelengths of several tens of metres. The trend of F_2 fold axes within this thrust slice ranges from north to northwest. F_2 folds with wavelengths of up to 150 m change their easterly vergence to a westerly vergence due to backfolding in the vicinity of a northwest-striking thrust fault situated about 2 km northeast of Obib waterhole. This thrust juxtaposes the quartzarenites and mudstones of the Gumchavib Formation and the carbonates of the Pickelhaube Formation. At Obib Peak, clastics of the Obib Peak Formation are thrusted over sandstones and mudstones of the Gumchavib Formation. The westernmost Numees Formation diamictites crop out about 3 km south of Obib Peak (Fig. 3), where they show thrusted contacts with carbonates of the Pickelhaube Formation and arkosic sandstones of the Obib Peak Formation. Structural cross-sections through parts of the Obib thrust slice are presented in Figures 15 and 17. The trend of F_3 folds within this thrust slice ranges from west to southwest and axial planes and the associated axial planar cleavage (S_3) occasionally verge in a southerly direction.

TECTONOSTRATIGRAPHY OF THE MARMORA SUPERTERRANE

The Marmora Terrane is subdivided into three tectonostratigraphic units (Hartnady et al., 1990), namely: the Schakalsberge Complex in the southeast and the Oranjemund and Chamais Complexes in the northwest (Fig. 1). These fault-bounded tectonostratigraphic units are significantly different in character, to the extent that they have been regarded as subterranes or even separate accreted terranes within a composite Marmora Superterrane (Hartnady et al., 1990).

The *Schakalsberge Complex* has been subdivided into metabasic lavas of the Grootderm Formation, which are capped by and interfinger with dolomites of the Gais Formation (Hartnady et al., 1990).

The Grootderm Formation comprises an up to 6 km-thick pile of metabasic lavas, including pillow lavas, pillow breccia, tuffs and lava-flows. The metavolcanics are tholeiitic in composition, but in the upper sequences alkali basalts have been recorded (Smith & Hartnady, 1984), which may be related to a series of vesicular alkali-gabbroic dykes, acting as high-level volcanic feeders during a post-shield stage of volcanic activity (Hartnady et al., 1990). Geochemical analysis of the Grootderm metabasalts indicates that the lavas were erupted in an ocean floor environment (Smith & Hartnady, 1984). The absence of siliciclastic terrigeneous material within the Gais Formation suggests an origin in an intraplate environment away from a continental margin, possibly similar to a Hawaiian-type sea-mount chain, a Walvis-type aseismic ridge, or an Ontong Java-type oceanic plateau. Kröner (1974, 1975, 1979) also interpreted the metabasalts as having originated as oceanic seapeaks or guyots, subsequently incorporated in a subduction complex. The Gais Formation comprises a pinkish dolomite, including abundant cherty intercalations, fine laminations, and and stromatolite bioherms which locally contain intertidal channels and oolitic dolomite, thus indicating reef-growth and deposition possibly capping the guyot or seapeak during dwindling phases of Grootderm volcanism.

The Grootderm Formation was intruded as dykes and sills by the Rooilepel bostonite suite. Hartnady et al. (1990) maintained that the bostonites were emplaced late in the history of the Grootderm volcanic pile, prior to the deposition of the overlying Gais Formation.

Detailed metamorphic studies in the Marmora Superterrane, undertaken by Frimmel and Hartnady (1992), indicated a multiphase metamorphic history. The first metamorphic event, M_1, has been interpreted as a very low-pressure hydrothermal oceanic metamorphism that affected the igneous protoliths at up to amphibolite facies temperatures. The following M_2 metamorphic event was syn-tectonic and characterized by temperatures similar to those reached during M_1 but with higher pressures, indicating burial to 10 to 15 km. This event has been interpreted as being related to a subduction process. A third metamorphic event, M_3, was low grade and of a regional nature. These results indicate that subduction and subsequent obduction occurred in the Gariep Belt, although blueschist facies metamorphism was not reached (Frimmel and Hartnady, 1992).

The *Oranjemund Complex* comprises metagreywacke rock types varying from little-deformed cyclothemic turbiditic varieties to intensely transposed, poly-deformed, mica-schists, and locally minor intercalations of metavolcanic chlorite schists (Hartnady et al., 1990), as well as phyllites, schists and minor quartzite, resembling the deep sea deposits of the Pickelhaube Formation (Holgat Sequence; Von Veh, 1988) of the Port Nolloth Zone.

The *Chameis Complex* was interpreted by Hartnady et al. (1990) as a heterogeneous mélange, consisting of various exotic blocks, 0.1-100 m in size, from different oceanic environments in close proximity to each other. These blocks occur within a highly tectonized metasedimentary sequence, incorporating interbedded chloritic, talcose, quartzitic, quartzo-feldspathic, dolomitic, graphitic and ferruginous schists. The blocks within this heterogeneous mélange show evidence of a distinct metamorphic history prior to that recorded by the metasedimentary country rocks, which experienced a regional metamorphic event under lower greenschist facies conditions. This latter metamorphic event is similar to the metamorphism experienced by the Schakalsberge nappe and has, therefore, been interpreted as syntectonic metamorphism which occurred during Marmora Terrane emplacement (Hartnady et al., 1990). Geochemical data from serpentinized metapyroxenites, metaperidotites, massive and layered metagabbros, metadolerites and metabasalts, which in places are amygdaloidal, delineate a tholeiitic trend consistent with an oceanic origin (Frimmel & Hartnady, 1992).

The structural relationships within the Marmora Terrane were first described by Davies & Coward (1982) and later by Hartnady et al. (1990). The most prominent structural elements characterizing the Marmora Terrane are major arcuate thrust faults juxtaposing the Oranjemund, Chameis and Schakalsberg Complexes. The most prominent thrust is the Schakalsberge thrust, which juxtaposes the Marmora Terrane and the Port Nolloth Zone (Fig. 1). The thrust fault at the contact between the Chameis and Oranjemund Complexes dips in a southeasterly direction, whereas the thrust faults at the contact between the Oranjemund and Schakalsberge Complexes dips in a westerly to northwesterly direction (Hartnady et al., 1990), possibly representing a "pop up" structure of major dimensions.

Three deformational phases were described by Hartnady et al. (1990) within the Marmora Superterrane. Near the contact between the Oranjemund and Chameis Complexes and at the Schakalsberge sole thrust, the D_1 deformation is characterized by an early NW-dipping S_1 cleavage, which is co-planar to the axial planes of minor D_1 folds (F_1; Fig. 14). The S_1 schistosities in both the Oranjemund and Schakalsberge Complexes are approximately co-planar to the F_1 axial planes within Bogenfels footwall lithologies and are nearly co-planar with the Chameis thrust fault. Near the contact between the Oranjemund and Chameis Complex, the D_2 deformational phase is characterized by a pentrative S_2 schistosity, which trends in a northerly direction with a southeasterly dip, transposing the S_1 cleavage and minor F_1 folds. At the Schakalsberge sole thrust near Bogenfels, D_2 folds (F_2) are truncated by the thrust fault in the hangingwall of the Bogenfels lithologies. In both the Oranjemund and Schakalsberge Complexes, minor F_2 kink-bands locally affected the co-planar S_1 schistosities.

Hartnady et al. (1990) described late-stage D_3 backfolding with folds verging in a northwesterly direction (F_3) for both the Chameis and Oranjemund Complexes. Near the contact of the Chamais and Oranjemund Complexes, the S_2 schistosity was deformed by F_3 folds. At the Schakalsberge sole thrust near Bogenfels, D_2 folds (F_2) are truncated by the thrust fault in the hangingwall of the Bogenfels lithologies. In both the Oranjemund and Schakalsberge Complexes, minor F_2 kink-bands locally affected the co-planar S_1 schistosities.

Hartnady et al. (1990) described late-stage D_3 backfolding with folds verging in a northwesterly direction (F_3) for both the Chameis and Oranjemund Complexes. Near the

contact of the Chameis and Oranjemund Complexes, the S_2 schistosity was deformed by F_3 folds. At the Schakalsberge sole thrust near Bogenfels (Fig. 1), F_2 and possibly F_3 folds were truncated by the thrust fault in the hangingwall of the Bogenfels lithologies. According to Hartnady et al. (1990), structural evidence shows that the Schakalsberge sole thrust in the north post-dates the late juxtaposition of the Oranjemund Complex over the Chameis Complex by D_3 back-thrusting. These thrust nappes or subterranes may have been originally juxtaposed in reverse order during D_1. In the south, the juxtaposition of the Oranjemund Complex over the Schakalsberge Complex could have taken place either before or after the D_3 backthrusting event (Hartnady et al., 1990).

Field evidence in the area immediately south of Bogenfels has shown that the earliest deformation phase (D_1-Bo) is characterized by an intense bedding-subparallel foliation (Fig. 18), indicated by mineral and grain elongation, and the growth of mica. This foliation is associated with bedding-subparallel quartz-veinlets, which in places display fish structures indicating shearing in a southerly to southeasterly direction. This foliation is subparallel to thrust faults (D_1-Bo), which are associated with quartz veins up to several metres thick, containing quartz-feldspar pegmatoids, mylonites, intense shearing and a strong D_1-Bo cleavage. Small-to large-scale, open-to-isoclinal and in places overturned folds (<5 cm to 100 m wavelength) have deformed this earliest bedding-subparallel foliation (D_1-Bo; Fig. 18) and are thus ascribed to a later D_2-Bo deformational event. The D_2-Bo folds (F_2) plunge moderately in a southerly direction (Fig. 18). A weak S_2 axial planar cleavage dips in a westerly direction and is indicated by the elongation of minerals and grains.

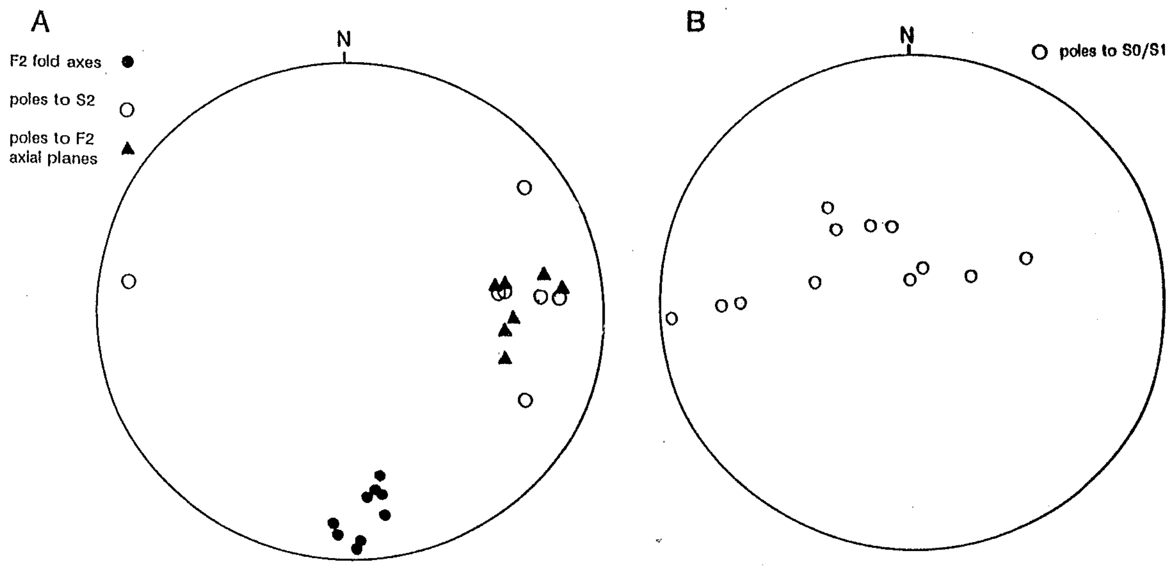


Figure 18: Equal area lower hemisphere stereonet projections showing D_1-Bo and D_2-Bo structural elements in the area approximately 7 km south of Bogenfels; A) poles to F_2 fold axes; B) F_2 fold axes.

KINEMATIC INTERPRETATION

Within the study area three kinematic phases were identified from the analysis of finite strain ellipsoids, slickensides, dip and strike directions of D_1 and D_2 thrust faults, the sense of vergence of the F_1, F_2 and F_3 folds, the trend of fold hinges, their shape along strike over long distances and the variations in strain ellipsoid shape from prolate to oblate within the entire Gariep Belt. The two earliest kinematic phases took place progressively.

Finite Strain Analysis

Within the study area, unfolding of F_2 folds with the help of balanced cross-sections, amounted to an approximate shortening of about 90 to 100%.

Because of the paucity of marker horizons within the Gariep Belt, it is not possible to delineate the exact amount of displacement which took place along the thrust faults. Using the bow and arrow method of Elliott (1976) for the prominent Schakalsberge thrust fault, which juxtaposes the Marmora Superterrane and the Port Nolloth Zone, the displacement is more than 100 km in an easterly direction. Applying the rule of Elliott and Johnson (1980), stating that the displacement of a thrust fault is equal to the length of the thrust fault multiplied by the factor 0.07, a displacement of 16 km results for the Schakalsberg thrust fault.

Within the Gariep Belt north of the Orange River, X (long)-, Y (intermediate)-, and Z (short)-axes of clasts and boulders of conglomerates of the Rosh Pinah Formation and pisoliths of the Pickelhaube Formation were measured. The plunge of the axes were measured and rotated back into the horizontal. Figure 13B shows two main trends of strain ellipsoids at two oblique angles. The main trend strikes NNW, and the second trend at WNW, showing that differential movement took place during D_1. The main tectonic transport component of the differential movement is towards the southeast to SSE, whereas the minor component is directed towards the east. The X/Y and Y/Z ratios of the measured ellipsoids were plotted on a Flinn diagram (Fig. 19) and show that the measurements at localities 13B and 7 (Fig. 3) plot in both the flattening and the constrictional fields and straddle the line defining plain strain. At locality 8 (Fig. 3), which lies further southwest and perpendicular to strike, measurements plot in the constrictional field. A trend is recognizable, displaying a change from a flattening strain field in the vicinity of the basement in the east to the constrictional strain field to the west of the study area away from the basement.

Rigid Body Analysis

The structural limits of the Gariep Belt outline an arcuate form in relation to the present coastline of southern Namibia and the northern Cape Province of South Africa (Fig. 1). In southern Namibia, the Gariep Belt and associated deformation is restricted to the area southwest of a line from Lüderitz to Dreigratberg at the Orange River. South of Lüderitz and in the vicinity of Bogenfels the structural trend of the main structural elements such as thrust faults and F_2 folds ranges from N-S to NNW-SSE. In the Witputs-Dreigratberg area, which also includes the study area, the general trend of thrust faults and F_2 folds ranges from

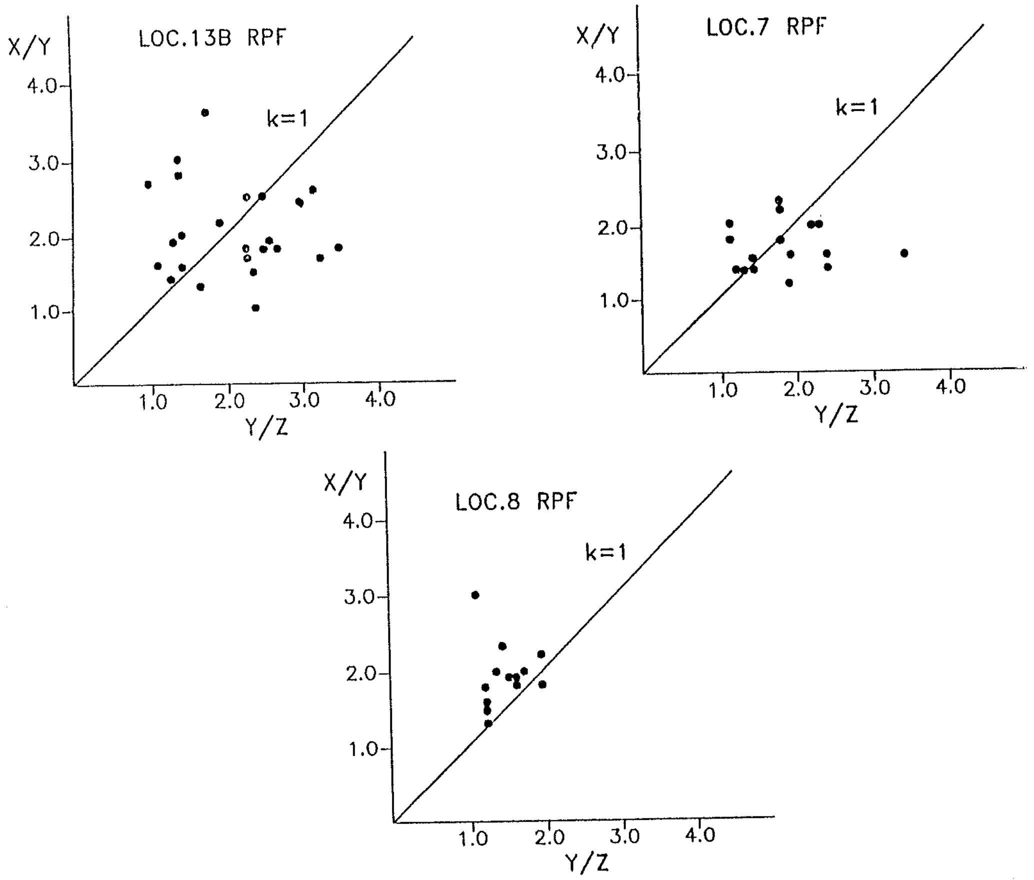


Figure 19: Flinn plots of strain data from (A) locality 13B; (B) locality 7; and (C) locality 8 (localities are shown in Figure 3).

NW-SE to N-S, and swinging to NE-SW in the coastal outcrops from Cape Voltas to the mouth of the Holgat River further south in the western Richtersveld of South Africa (Von Veh, 1988). The arcuate shape of the Gariep Belt could not have developed as a late bending event on a regional scale, as basement rocks southeast of the arc provide no evidence for such bending strains (Davies and Coward, 1982). The post-Gariep Kuboos and Swartbank plutons may be partially responsible for a change in structural trends in their immediate vicinity as a result of diapiric activity. However, it seems highly unlikely that they have caused the present arcuate shape of the entire Gariep Belt. Differential movement, detected within several thrust sheets, can only be partially liable for the concave form of the structural features within the Gariep Belt. On the grounds of the bow and arrow method of Elliott (1976) it is suggested that an eastward-directed tectonic transport during D_2 was mainly responsible for the concave form of the structural features within the Gariep Belt and for the arcuate shape of the Gariep Belt as a whole.

Strike-Slip Phase

The latest tectonic event within the study area is recorded by D_3, the latter being responsible for small- to large-scale E-W to SW-NE trending open folds, which trend at oblique angles to the D_1 and D_2 structures. A sinistral strike-slip phase localized along existing zones of weaknesses is probably responsible for these structural features. Sinistral wrenching may have continued until after the deposition of the upper Schwarzrand Subgroup of the Nama Group, as indicated by the presence of warping of Schwarzrand Subgroup lithologies, shown in a N-S section through the Nama Group by Germs and Gresse (1991).

DISCUSSION

The results of the finite strain analyses of D_1-related strain ellipsoids show the presence of differential movement with two main components during the D_1 deformational event (Fig. 13B). The main tectonic transport was directed southeast to SSE. Extreme compression in the vicinity of the basement, associated with the difference in ductility of the compressed lithologies and the basement itself, is thought to be responsible for the presence of a second, easterly directed movement of differential movement.

Subsequent eastward directed tectonic transport during the D_2 deformational phase is liable for the concave shape of tectonic features such as the trend and vergence of F_2 folds, the trend and dip of the thrust faults throughout the Gariep Belt and for the arcuate shape of the Gariep Belt as a whole.

The tectonic evolution of the Gariep Belt terminated with a sinistral strike-slip movement along existing weakness zones, ceasing only after the deposition of the Schwarzrand Subgroup of the Nama Group.

Strain markers in the Richtersveld have very variable shapes, ranging from strongly deformed prolate ellipsoids in the northern parts of the Richtersveld to oblate ellipsoids in the south, with the average strain ellipsoid trending NNW (Von Veh, 1988). Considering the swing in structural trend and the presence of prolate and oblate ellipsoids deformed during the D_1 deformational phase in the area immediately north of the Orange River, the study area was situated in the transitional zone between the frontal and the lateral edge of a southeast- to SSE- directed tectonic unit during the D_1 deformational event (Fig. 20). Davies and Coward (1982) recognized no effects of Gariep deformation within the granites of the Aurus Mountains approximately 60 km northwest of Rosh Pinah and concluded that the deformation associated with thrusting dies out not only to the north along the strike of the thrusts, but also to the northwest. Davies and Coward (1982), therefore, suggested that the movement of thrusts increases to the south and southeast, giving rise to extensional flow in the area southeast of the Aurus Mountains (Fig. 1). Field evidence in the Bogenfels area and the area immediately south of Lüderitz shows, however, that early D_1-related southeast- to SSE-directed thrusting, as well as eastward directed tectonic transport during the D_2 deformational event, also took place in the northwestern parts of the Gariep Belt. Further, it was established that the direction of tectonic movement in the Gariep Belt was not restricted towards the SSE, as postulated by Von Veh (1988), but that it changed from SSE during D_1 to E during D_2, and to southerly directed strike-slip movement during D_3.

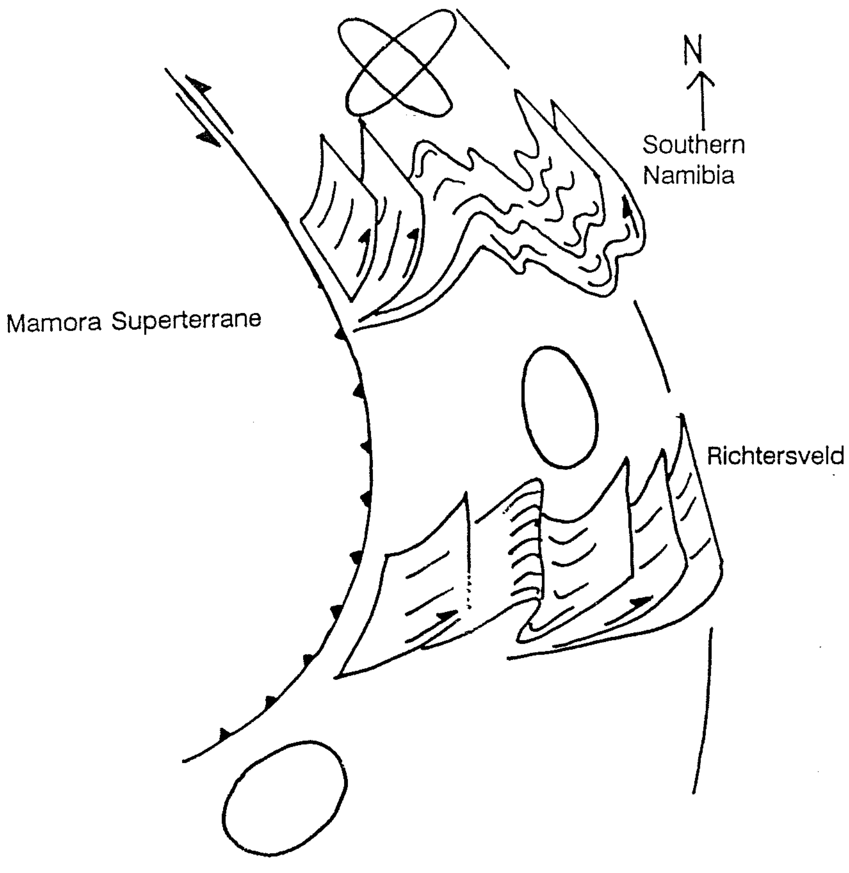


Figure 20: Schematic diagram summarizing the structural variations and change of strain ellipsoids during the earliest kinematic phase (D_1) in the central and southern parts of the Port Nolloth Zone.

EFFECTS OF OCEANIC CLOSURE AND CONTINENTAL COLLISION

Rifting and spreading within the southern coastal branch of the Damara Orogen was followed by the closure of the Adamastor Ocean, associated with a southeastward-directed subduction of oceanic crust under the Kalahari Craton (Fig. 21). Subduction was associated with the development of tectonic melanges and the accretion of three allochthonous exotic terranes, namely the Chamais, Oranjemund, and Schakalsberge terranes, which form the Marmora Superterrane (Hartnady et al., 1990). Oceanic closure culminated in the collision of the Marmora Superterrane with the Port Nolloth Zone continental margin as an accreted, allochthonous tectonic block along the Schakalsberge thrust (Fig. 1). The collision of the South American Craton with the Port Nolloth Zone continental margin was associated with the obduction of ophiolitic material on top of the Schakalsberge thrust fault. The collisional event was accompanied by intense southeastward and subsequently, eastward-directed tectonic

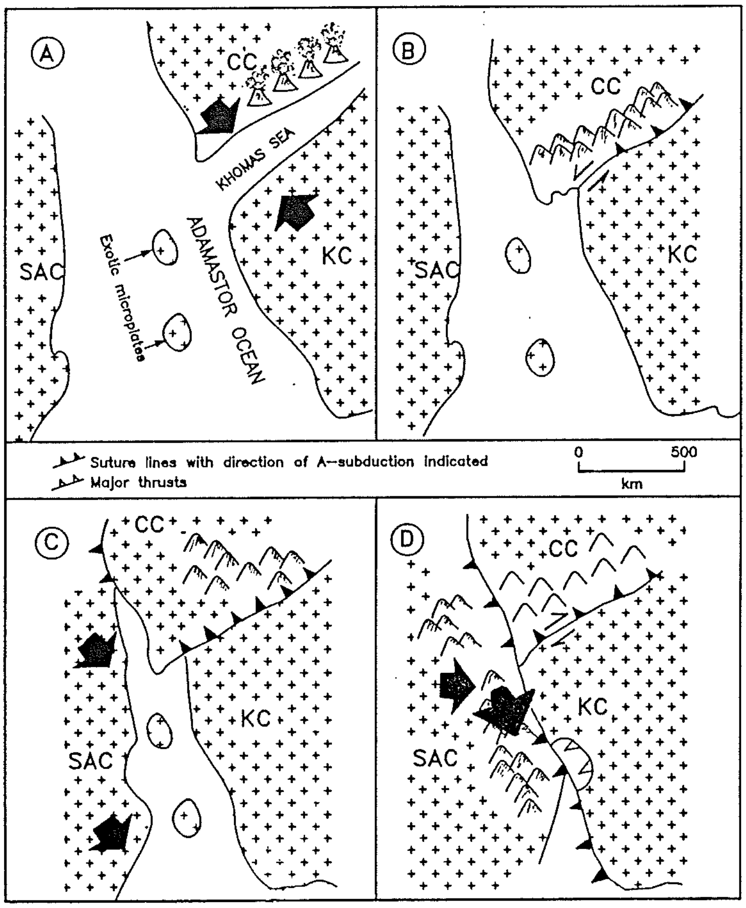


Figure 21: Schematic diagram showing the cratonic motions during the closure and collisional phases of the Khomas Sea and Adamastor Ocean (modified after Stanistreet et al., 1991). KC = Kalahari Craton; CC = Congo Craton; SAC = South American Continent.

transport (D_1 and D_2), resulting in intense folding and thrusting of Port Nolloth Zone sediments and volcanics during the Adamastor Orogeny. Associated with the Adamastor orogenic event is the development of peripheral retroarc foreland basins to the east, into which sediments of the Schwarzrand and Fish River Formations of the Nama Group were deposited (Stanistreet et al., 1991). Folding and thrusting, associated with the D_2 deformational event, also affected Nama Group sediments in the eastern parts of the Nama basin. After the collision of the South American and the Kalahari Cratons, a sinistral movement developed along the major fault zones, deforming both Gariep and Nama Group sediments as far east as Vioolsdrif, approximately 50 km east of the easternmost Gariep Belt outcrop in the Richtersveld.

The collisional event was accompanied by a Barrovian-type metamorphism with a geothermal gradient of about 20° C/km (Jasper, 1994). The tectonic evolution of the Gariep Belt continued with the emplacement of the granitoids of the "Kuboos-Bremen-line" (525 $\pm$ 60 Ma; 521 $\pm$ 12 Ma) and the younger part of the Bremen Complex intrusives (521 $\pm$ 12 Ma; Allsopp et al., 1979) during the deposition of upper Nama Group sediments. Ages from Nama Group sediments, which were shed into peripheral foreland basins marginal to the advancing Adamastor orogeny, range from 547 to 443 Ma (compiled by Miller & Grote,

1988) and were reinterpreted by Stanistreet et al. (1991) as metamorphic ages. Similar metamorphic ages from the Vanrhynsdorp Group sediments, which represent the southern correlative of the Nama Group in Namaqualand, South Africa, range from 552 to 476 Ma with a peak at 496 Ma (Gresse et al., 1988) and also indicate that the Adamastor orogeny within the Gariep Belt only ceased at about 500 Ma. Horstmann et al. (1990) reported K/Ar ages of upper Nama Group sediments from southern Namibia, which may be indistiguishable, within the limits of experimental error, from the 496 Ma peak metamorphism of Gresse et al. (1988). These ages may, however, also indicate that a time trangressive collision from north to south occurred during the final stages of the geodynamic evolution of the Gariep Belt and the associated Nama foreland basins (Stanistreet et al., 1991).

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