MEMOIRS OF THE
GEOLOGICAL SURVEY OF NAMIBIA

THE GEOLOGY OF THE UGAB-GOANTAGAB AREA, NORTHWESTERN NAMIBIA

MINISTRY OF INDUSTRIES, MINES AND ENERGY

Memoir 24
2025

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Foreword

The stratigraphy and structure of the Ugab - Goantagab area (north-western Namibia) has been an enigma and the subject of many studies for decades (e. g. Jeppe, 1952; Petzel, 1986, Swart, 1987, 1992; Kohonen, 1993), while the occurrence of cassiterite mineralisation has given rise to intense exploration and mapping in the 1980s. The position of the area at the junction of the intracontinental (Damara Belt *s. s.*) and coastal (Kaoko Belt) branches of the Neoproterozoic Damara Orogen, which, in fact, are genetically individual orogens merged together during the amalgamation of Western Gondwana, produced a complex structural pattern and stratigraphy, not easily correlated with the adjoining areas of either the Damara or the Kaoko Belt. Miller (1983), in defining various lithologically, stratigraphically and structurally distinct zones within the Damara Orogen, designated this complex area the "Southern Kaoko Zone", with its own stratigraphy and tectonometamorphic development.

In this memoir, the work of Cees Passchier, Rudolph Trouw, Andre Ribeiro and many others, spanning more than two decades and based on a detailed structural analysis of the Ugab - Goantagab area, is summarised, presenting their solution to the problem of the complex geology of an orogenic triple junction. Over the duration of this long-term project ideas and perceptions naturally underwent change and refinement, as evidenced by the many papers and theses produced during this period (Appendix IV).

Ute Schreiber (Editor)
Windhoek, May 2025

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Cover image: Cretaceous Etendeka Group horizontally and unconformably overlying the folded Neoproterozoic Damara succession north-west of Brandberg, just visible in the background in the upper left corner of the image (photo: R.A.J. Trouw)

The Geology of the Ugab-Goantagab area, Northwestern Namibia: A summary of 23 years of mapping and research

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Abstract :- An area of Neoproterozoic metasedimentary rocks in northwestern Namibia, between the Ugab and Huab Rivers, has been mapped in detail by a Dutch-Brazilian team of geologists between 1998 and 2021. The results are presented in the form of a 1 : 75 000 geological map, based on detailed lithostratigraphic and structural geological investigations, as well as numerous peer-reviewed publications and theses. The lithostratigraphy was captured in several detailed columnar sections and by extensive field mapping, from which distribution and relationship of lithostratigraphic units as well as timing of deformation events were reconstructed. Neoproterozoic slope to deep sea sediments, with facies changes from northeast to south-west, were overprinted by at least four subsequent but partly related deformation events. These events represent different stages in the formation of a tectonic triple junction in the Neoproterozoic sedimentary rocks that lie wedged between the Precambrian Rio de la Plata, Congo/Angola and Kalahari palaeocontinents, now preserved as cratons. The structural model is based on more than 19000 measurements of foliations, lineations, fold axes and axial planes, a representative selection of which is shown on the accompanying map. Initial N-S convergence between the Congo/Angola and Kalahari Cratons (D_1, ~590 Ma) was followed by E-W collision of the Rio de la Plata and Congo/Angola Cratons (D_2, ~570-550 Ma, Kaoko Belt). Subsequently, the Kalahari and Congo/Angola Cratons collided (D_{2a} and D_3, ~540-525 Ma, Damara Belt), contemporaneous with sinistral strike-slip motion and the intrusion of large granite-syenite plutons, possibly associated with slab detachment aided by the strike-slip motion.

Keywords: Triple junction, Kaoko Belt, Damara Belt

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1. Introduction

This memoir accompanies a geological map (Appendix I) of the area between 20°16' and 21°S and 14° 06' and 14° 36' E (NW Namibia). The area was mapped within the framework of a joint research programme between Johannes Gutenberg University (Mainz, Germany) and the Federal University of Rio de Janeiro (Brazil) from 1998 to 2021, with the help of many international colleagues and students (Appendix III). The resulting geological map and data formed the basis for several publications and theses on the geology of Namibia and Gondwana over the past two decades (Appendix IV). Since ideas and concepts gradually evolved with time, this report presents our current interpretation, which in some cases differs from earlier publications. Wherever this is the case, it is indicated in the following text. However, most of what is presented here confirms our earlier views.

2. Regional geology

The geology of Namibia is characterised by two Proterozoic cratons, the Congo/Angola Craton (hereafter referred to as the Angola Craton) and the Kalahari Craton, which are separated by the Damara Orogen, a belt of strongly deformed marine sediments of Neoproterozoic age, which was deformed and metamorphosed in the transitional period between the Ediacaran and the Cambrian (e. g. Porada, 1979; Miller, 1983; Prave, 1996; Frimmel, 2009; Fig. 1). On the southwestern side of the Angola Craton lies another belt of Neoproterozoic rocks, i. e. the Kaoko Belt, which formed between the Rio de la Plata Craton of South America and the Angola Craton (Fig. 1). The Dom Feliciano Belt in Brazil and Uruguay is thought to be a connecting part to the Kaoko Belt, which was separated from the African units by the opening of the South Atlantic Ocean. The Gariep Belt of southern Namibia and South Africa, to the west of the Kalahari Craton, is a southern extension of the Kaoko-Dom Feliciano system (Fig.1). Together, the Damara, Kaoko, Dom Feliciano and Gariep Belts form a tectonic triple junction, the core of which lies in northwestern Namibia between the Huab and Ugab Rivers (Figs 1, 2; Meert, 2003; Hokada *et al.*, 2013).

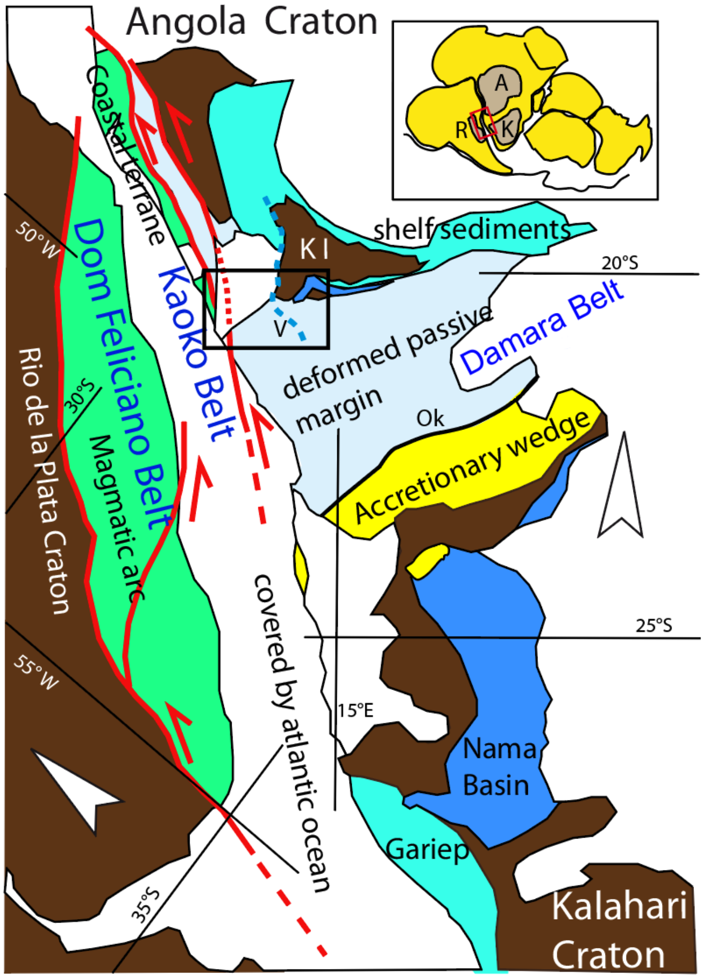

Figure 1. Geological sketch map of the Damara-Kaoko Belt junction, showing geotectonic units. Inset (upper right) shows the most important units in the Kaoko-Damara-Dom Feliciano system within Gondwana (A, R, K: Angola, Rio de la Plata, Kalahari Cratons); the black box indicates approximate location of Fig. 2 (modified after Lehmann *et al.*, 2016; KI – Kamanjab Inlier; V - Vrede-Doros-Brandberg Line; Ok – Okahandja Lineament)

Our research group studied the core of the triple junction along the Huab and Ugab Rivers and the lower reaches of the Goantagab River, a tributary of the Ugab (Figs 2, 4). The area consists of semi-desert with sparse vegetation and thin or absent soil cover. Geologically, it is mostly covered by Mesozoic lavas and associated rocks of the Etendeka Group, and younger sediments; the Brandberg, a large Cretaceous granite intrusion, containing Namibia's highest peak, occurs to the southeast. Mesoproterozoic basement rocks outcrop at Ogden Rocks on the coast and north of the C39, the only major road in the area (Fig. 2). While the basement of the Ogden rocks is of uncertain cratonic affiliation, the gneisses north of the main road belong to the Kamanjab Inlier of the Angola Craton (e. g. Fullgraf *et al.*, 2023). Neoproterozoic metasedimentary rocks of the Damara and Kaoko Belts, intruded by Cambrian syenitic-granitic plutons, are exposed in a strip along the Ugab River and south of the Kamanjab Inlier along the Huab River. The Neoproterozoic rocks along the Ugab, termed here the Lower Ugab Domain (LUD), are dominated by prominent N-S – trending, subhorizontal, kilometre-scale folds, which produce a striking pattern on satellite images; their rather uniform stratigraphy has been interpreted as turbidite deposits (Swart, 1992; Paciullo *et al*., 2007; Passchier *et al*., 2007, 2011). Northeast of the Mesozoic volcanic/intrusive complex known as the Doros "Crater", both the stratigraphy and deformational structures become more complicated, without a clear, dominant trend. This complex domain, which we named the Eastern Domain (ED), is separated from the Lower Ugab Domain by a sharp transition zone, the Vrede-Doros-Brandberg (VDB) Line (Figs 3, 4), interpreted as the transition from an oceanic slope to a deep oceanic basin (Passchier *et al*., 2016).

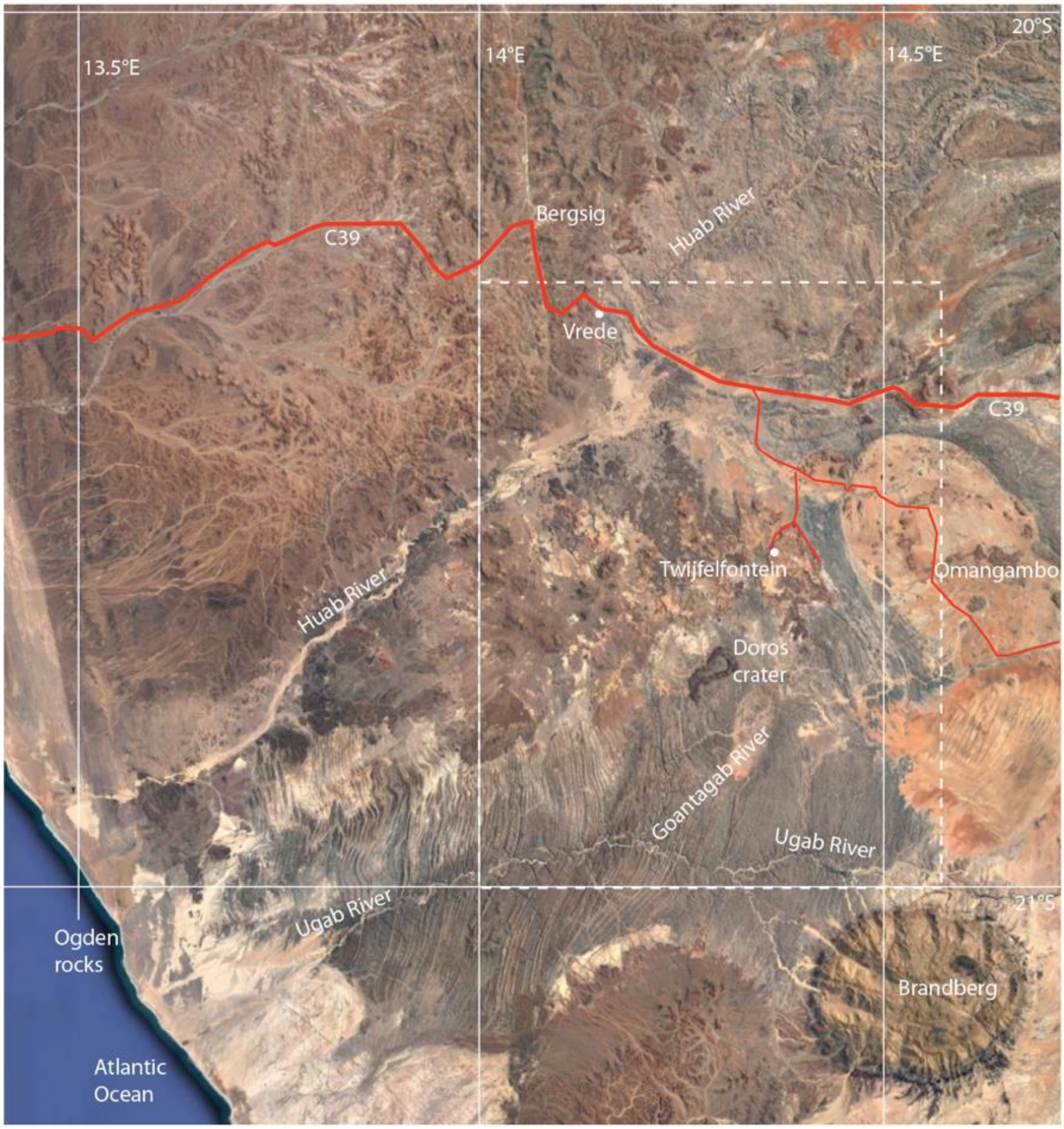

Figure 2. Satellite image of the Huab-Ugab area, indicating sites mentioned in the text; dashed rectangle represents the mapped area (image width ~140 km)

To shed light on the nature of the junction between the Damara and Kaoko Belts, we decided to map an area along the VDB-Line. Towards the north and the exposed basement of the Angola Craton, the stratigraphy and structure show further changes, partly enhanced by faults. These changes are described from four specific areas with outcrops of deep water deposits, named after local farms Vrede, Austerlitz, Bethanis and Toekoms (Fig. 3; Nascimento *et al*., 2016). Additional structural and stratigraphic data were obtained outside the mapped area, mostly along the Ugab River and at Ogden Rocks along the coast, as well as southeast of the Brandberg (Figs 2, 4; Appendix II). In the following chapters, we briefly describe the stratigraphy and structure of the area in explanation of the map (Appendix I). Further details of the stratigraphy, structural development and the Cambrian intrusions are given in the papers published by our group between 2002 and 2018 (e. g. Maeder *et al*., 2014; Paciullo *et al*., 2007; Passchier *et al*., 2011, 2016; Nascimento *et al*., 2016; see also Appendix IV).

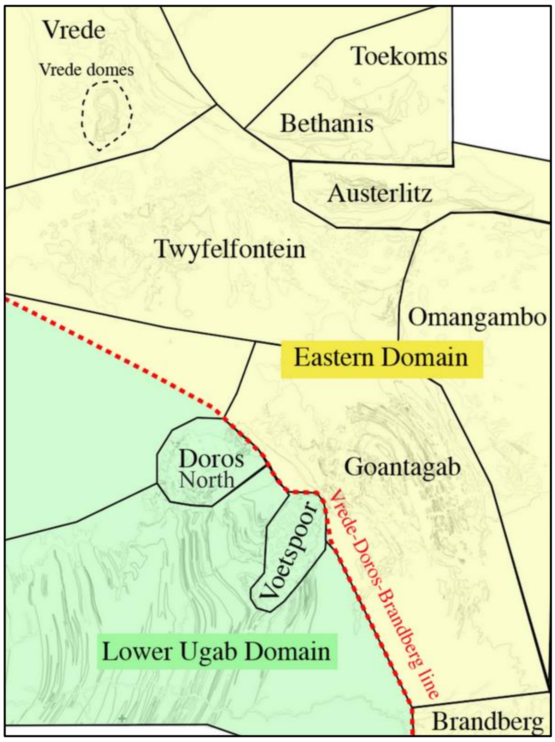

Figure 3. Tectonostratigraphic overview of the study area

3. Methodology

Dating back to the late 1990s, this mapping project was carried out before and at the outset of digital data capture in the field. The initial work was done on 1:5 000 to 1:10 000 enlarged topographic maps, aided by aerial photographs and, to a limited extent, Landsat and Aster satellite imagery. Mapping was done using GPS and a movable transparent grid on the enlarged topographic maps overlaid with a coordinate grid. Field data were transferred to a MapInfo™ GIS environment, where all topographic, stratigraphic and structural information was stored. During the latter part of the project a Trimble handheld field computer with a MapInfo™-linked field mapping programme (Encom Discover Mobile™ 3.0), connected to an external or built-in GPS was used. The fieldwork area is mostly uninhabited, except for some farms occupied only during the wet season. Except for the C39, which cuts across its northern part and a branch road to the World Heritage Site at Twyfelfontein (Fig. 2), the study area lacks major infrastructure; consequently, access was by 4x4 vehicles on often ill-defined dirt tracks. Despite excellent and spectacular satellite images available of this sparsely vegetated area, nearly all parts were mapped on foot from temporary field camps, as - except for the turbidites of the Ugab area - lithologies and structures could not reliably be mapped by remote sensing techniques due to variable weathering and local thin soil cover. Extensive field mapping was also necessary to obtain the required structural information: especially in the siliciclastic metasedimentary rocks, up to five foliations may be present in any one outcrop, and their relationship and significance could only be determined by direct observation. Fig. 3 gives the names used to describe subareas in the following chapters.

4. The Kaoko – Damara Belt junction

Collision between the Angola, Kalahari and Rio de la Plata palaeocontinents produced the Damara-Kaoko triple junction during the Cambrian (Miller, 2008; Fig. 1). The SSE-trending Kaoko Belt (Fig. 1) formed at 580-550 Ma through eastwards directed subduction of the Adamastor ocean floor and final collision of a 650-630 Ma magmatic arc with the passive margin/back arc basin of the Angola Craton (Goscombe *et al*., 2003; Goscombe and Gray, 2007). Remnants of this magmatic arc are known in Namibia as the Coastal Terrane of the Western Kaoko Zone (Fig. 1). In contrast, the Damara Belt is an ENE-trending complex zone formed during northwards directed subduction of the Khomas ocean floor beneath the Angola Craton at 590-520 Ma. It is composed of the deformed passive margin deposits of the Angola palaeocontinent, and an accretionary wedge complex thrust southwards over the Kalahari Craton, which are in contact along the Okahandja Lineament; remains of the suture are exposed in the accretionary wedge (Miller, 2008; Meneghini *et al*., 2014; Fig. 1).

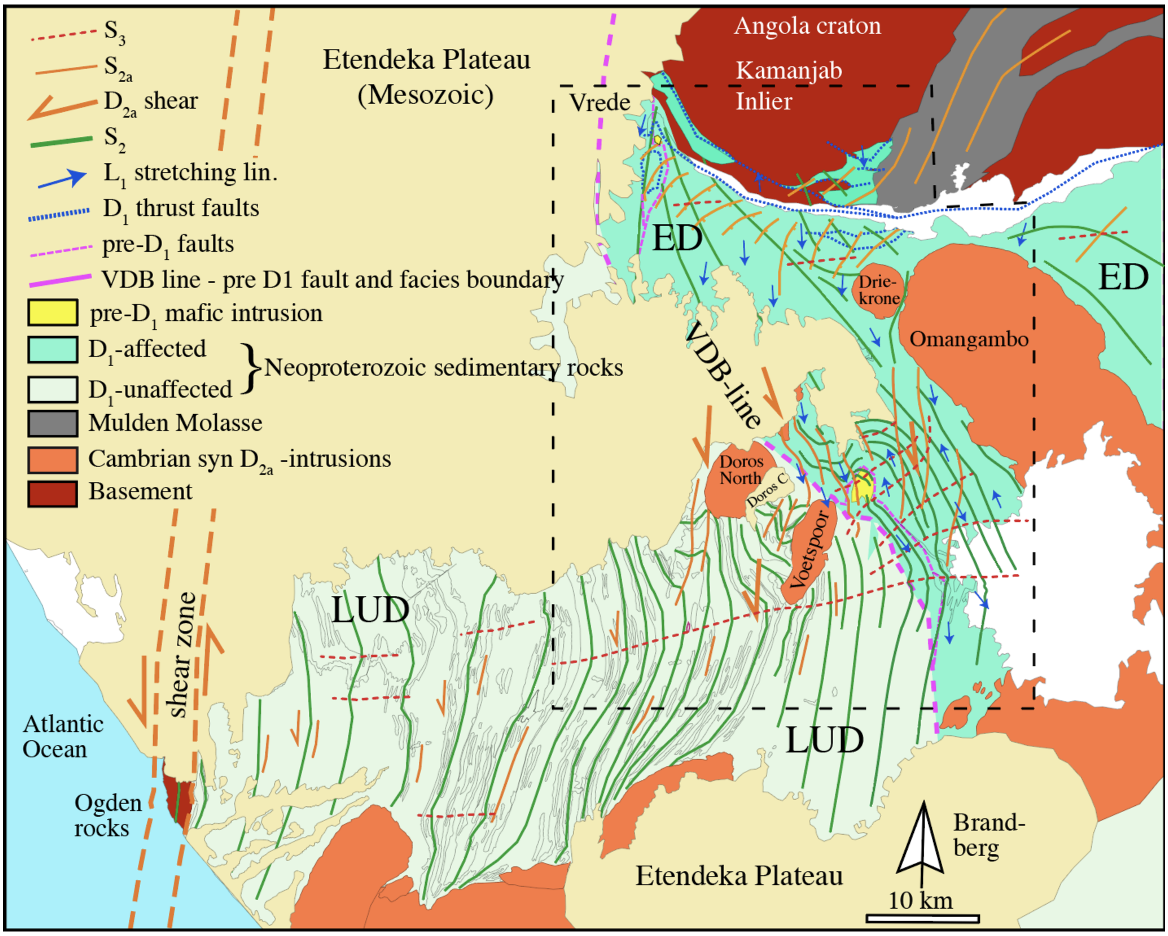

Figure 4. Simplified geological and tectonic map of the Damara-Kaoko Belt junction, showing foliation traces as main structural trends: actual measurements are shown on the main map (Appendix I). Lithological boundaries between formations of Neoproterozoic metasedimentary rocks are shown as grey lines. The dashed rectangle indicates the extent of the main map (modified after Passchier *et al*., 2016).

In the study area, the Damara Belt can be subdivided into two major domains: i. e. the Eastern and the Lower Ugab Domain (Figs 3, 4). In the Lower Ugab Domain (LUD), a 1.6 km thick succession of Neoproterozoic siliciclastic and carbonate turbidites of the Angola palaeocontinent passive margin (Swart, 1992; Paciullo *et al*., 2007; Passchier *et al*., 2007, 2011) is exposed. These are laterally continuous up to a sharp facies boundary named here the Vrede-Doros-Brandberg (VDB) Line (Figs 3, 4). East of this line, in the Eastern Domain (ED), the same formations were recognised, but slope sediments, including very coarse debrites, also occur. The rocks in both domains record orogenic deformation and low-grade metamorphism. Peak regional metamorphic temperatures are estimated at 400–550 ºC, while pressures of 2 to 4 kbar (Gray *et al*., 2006; pers. comm. R. Moraes using Thermocalc) are based on the presence of metamorphic biotite in pelitic assemblages. Contact aureoles around the Cambrian syenitic-granitic intrusives (e. g. Voetspoor, Doros North) contain andalusite, cordierite, garnet and rare staurolite, apart from many metamorphic "spots" within the schists, which usually are composed of white mica, biotite, chlorite and quartz.

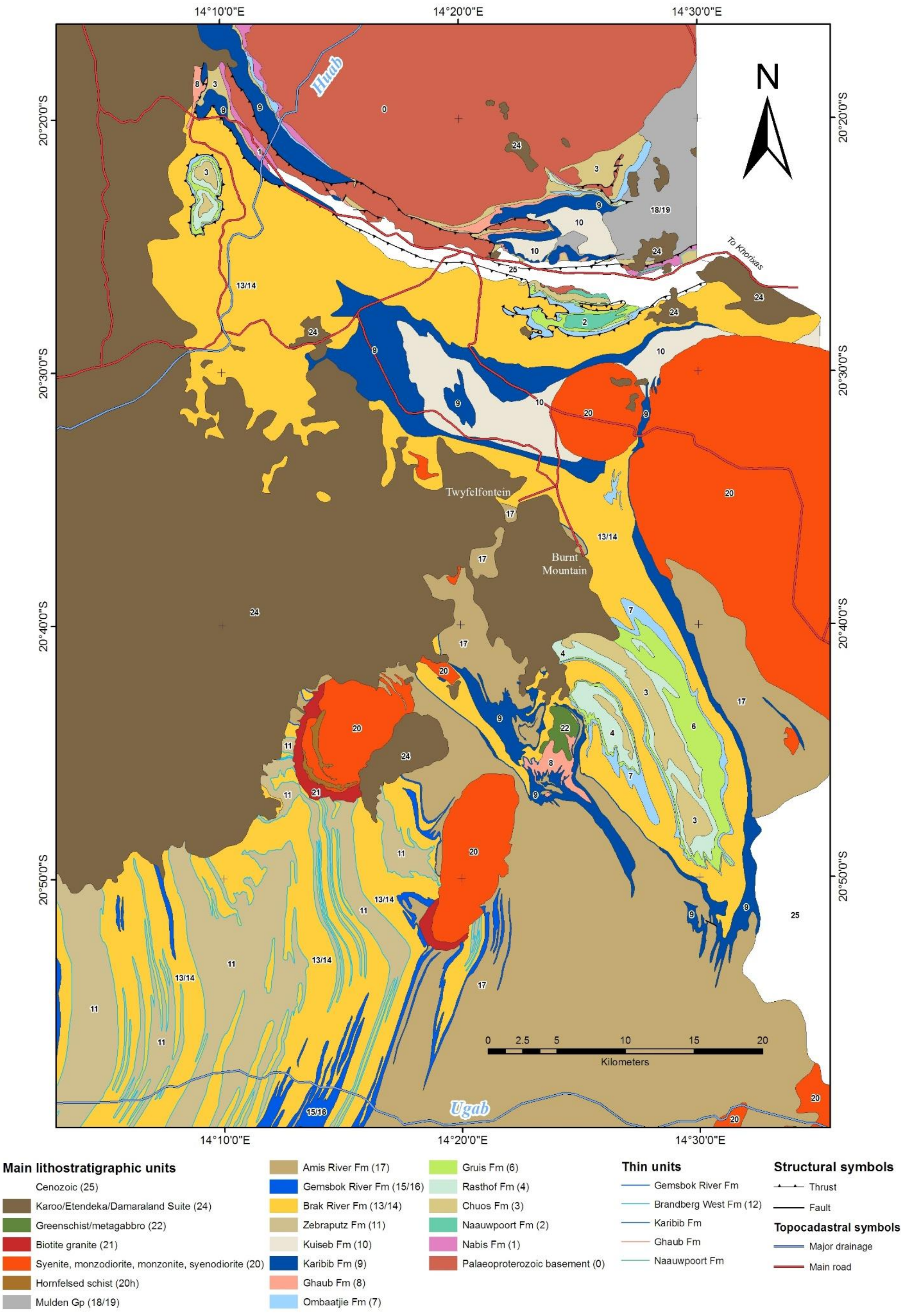

Figure 5. Simplified geological map of the Ugab-Goantagab area

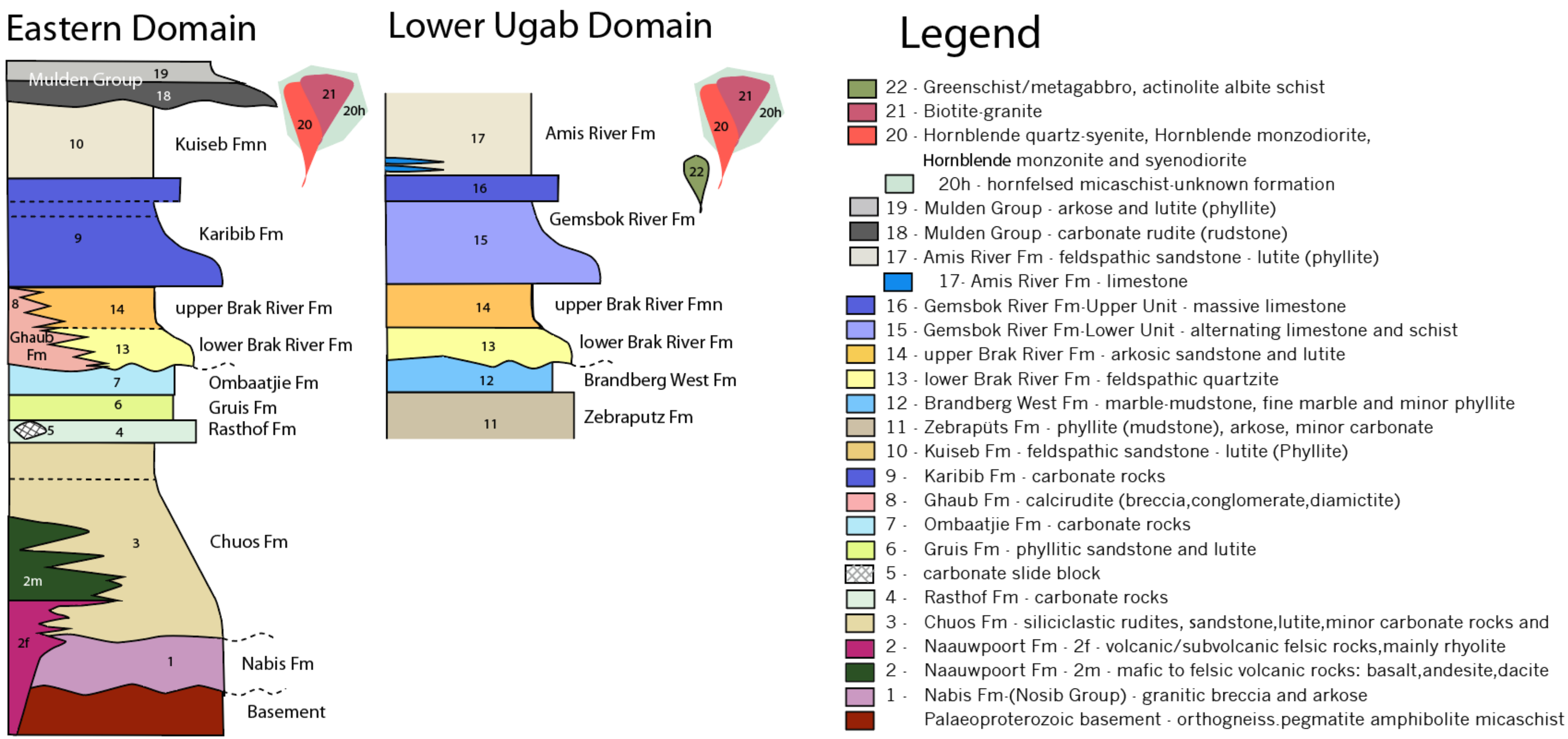

Figure 6. Stratigraphic column of the Eastern and Lower Ugab Domains (see chapter 5; after Nascimento *et al*., 2016)

5. Stratigraphy (A. Ribeiro)

The Lower Ugab Domain (Figs 3, 4) shows a monotonous stratigraphy of deep water turbidites (Zerrissene Turbidite System: Swart, 1992; Paciullo *et al*., 2007; Passchier *et al*., 2007) with very little lateral facies variation from the coast up to the contact with the Eastern Domain along the VDB-Line (Figs 3, 4). It consists of five formations with a total minimum thickness of ca. 1600 m (Swart, 1992; Paciullo *et al*., 2007; Passchier *et al*., 2007). The basement is probably exposed only in the Ogden rocks along the coast (Fig. 4). Two turbidite marble deposits, the Brandberg West and Gemsbok River Formations, separate three formations of sandstone-mudstone turbidite (Zebrapüts, Brak River and Amis River Formations, respectively; Swart, 1992; Figs 5, 6). Regional mapping suggests that the Brandberg West and Gemsbok River marbles possibly correspond to the cap carbonates representing the end of the Sturtian and Marinoan glaciations, which were dated at ca. 720 and 650 Ma, respectively (Kendall *et al*., 2006; Hoffmann *et al*., 2004; Hoffman and Halverson, 2008). The stratigraphically and structurally distinct Eastern Domain adjoins the eastern edge of the Lower Ugab Domain (Figs 3-5). The uppermost Amis River Formation, which is identical in the Lower Ugab and Eastern Domains, is considered equivalent to the Kuiseb Formation in the Austerlitz, Bethanis and Toekoms areas (Fig. 3; Nascimento *et al*., 2016), while the lower units show significant facies changes and are therefore defined in part as distinct formations (Fig. 6). The highest exposed marble, the Karibib Formation, which is correlated with the Gemsbok River Formation, is of greater thickness than the latter, and locally contains lenses of marble breccia, conglomerate and diamictite. A pair of lower marble units, separated by mica schist (Rasthof and Ombaatjie Formations), are correlated with the Brandberg West Formation in the Lower Ugab Domain (Figs 5, 6; Nascimento *et al*., 2016).

The equivalents of the Brak River and Zebrapüts Formations, which separate the marble formations (Fig. 6), have been recognised in the Eastern Domain, but contain numerous discontinuous lenses and layers of coarse immature brown sandstone and quartzite (Nascimento *et al*., 2016). The Zebrapüts Formation is therefore replaced by the Chuos Formation here. In Figures 5 and 6, the lower Brandberg West and Zebrapüts Formation equivalents are presented as a single unit (Chuos Formation) as they are difficult to separate at the scale of mapping. Debrites (diamictite, conglomerate) occur as discontinuous lenses at many levels throughout the stratigraphic column. A unit of mafic schist represents a strongly deformed sill of metagabbro that intruded the Goantagab succession prior to all deformation phases in the area. The change in stratigraphy between the Lower Ugab and the Eastern Domain is probably marked by the VDB-Line, but the older units in both areas are separated by a 6 km - wide syncline of Amis River metasediments hiding the transition.

North of the Goantagab area the units below the Amis River Formation outcrop in three domal structures known as the Austerlitz, Toekoms and Vrede Domes, with a slightly different stratigraphic succession including quartzite and several sills of felsic to mafic volcanics (Nascimento *et al*., 2016). All formations onlap onto mid-Proterozoic gneisses and granites belonging to the Kamanjab Inlier of the Angola Craton in the north. Clearly, the changes in stratigraphy and facies from west to northeast reflect an increasingly proximal setting to the continent and a transition from deep oceanic to continental slope deposits (Fig. 5). All units from the basal Chuos Formation up to the Amis River/Kuiseb Formation record deep water, fine to coarse turbidites and debrites, locally including megablocks and olistoliths.

Olistoliths, some of them mappable at the adopted scale, record catastrophic landslides related to continental slope instability, probably due to seismic activity. Turbidites and debrites register gravitational flows, while lonestones are interpreted as leftovers from the by-passing of debris flows. Whether some of the debrites and lonestones are related to global scale glaciations remains an open question, since evidence for glaciation in deep water deposits tends to be ambiguous.

Major intrusions of syenite and biotite granite occur in the upper formations of the Lower Ugab Domain (Figs 4 and 5). These include the Voetspoor and Doros North Plutons in the west (Passchier *et al*., 2007; Schmitt *et al*., 2012), the Driekrone and Omangambo Plutons in the north and east, as well as several smaller unnamed plutons. Thin, N-S trending granite veins in the centre of the Goantagab area may represent feeder dykes of granite bodies at higher levels, which have been removed by erosion. These veins are shown on the map (Appendix I) with exaggerated width, because of their importance to the tectonic interpretation. The Voetspoor and Doros North Plutons have been dated at approximately 530 Ma (Schmitt *et al*., 2012), while the other plutons in the area are probably of comparable age, or somewhat younger, judged by their similar composition and relative age with respect to the deformation. The Gemsbok River marble in the Goantagab area, east of the metagabbro (Fig. 5; Appendix I), is strongly thinned out and locally split up into isolated parallel lenses. With ductile deformation no stronger at these sites than elsewhere, these effects are interpreted as due to an early synsedimentary extensional fault (Passchier *et al*., 2016), although its exact trace and possible branches cannot be reconstructed because of the intense refolding. North of the Omangambo Granite, the Gemsbok River Formation is cut out along a fault with silicified and brecciated fault rocks, which is indicative of another synsedimentary extensional fault. The first of these faults might argue for the adjacent massive diamictite having originated as a debris flow down the scarp of the normal fault. This fault may also have hosted a feeder dyke for the mafic sill (now altered to greenschist) situated close to it.

6. Stratigraphic units (A. Ribeiro)

The Neoproterozoic Damara Supergroup (>1000 m thick) encompasses siliciclastic and carbonate successions that outcrop in the Damara Orogen of central Namibia. In the study area the successions are subdivided into the Nosib, Otavi, Swakop, Zerrissene and Mulden Groups (e. g. Miller, 2008), which were deformed and metamorphosed under greenschist facies (biotite zone) conditions during the Damara Orogeny. However, preserved primary features, detailed mapping and structural analysis, allow the recognition of stratigraphic units and relationships. The Nosib, Otavi/Swakop and Zerrissene successions are herein interpreted as mainly consisting of gravitational deposits related to the opening of the Outjo Basin. The basal Nabis Formation (Nosib Group) is composed of basement-derived alluvial fan deposits, mainly granitic breccia and arkose. Siliciclastic, carbonate and hybrid (siliciclastic-carbonate) successions of the Otavi/Swakop Groups record slope to basin deposits, while the Zerrissene Group is interpreted as a hybrid turbidite complex (Swart, 1994; Paciullo *et al*., 2007). The youngest unit, the Mulden Group, is inferred to represent a foreland alluvial to fluvial succession related to the Damara Orogen (Lehmann *et al*., 2016).

Lithofacies, stratigraphy and mappable units

Siliciclastic and carbonate rudites, sandstones and lutites constitute the main lithofacies. Calcsilicate rocks, chert and mafic and felsic volcanics are minor occurrences. Siliciclastic sedimentary rocks, mainly lutite and sandstone were altered to metamorphic phyllites, while carbonate rocks were recrystallised to marbles or dolomitised. Surprisingly, and despite strong deformation and metamorphism, both the siliciclastic and carbonate sedimentary rocks retain much of their original primary sedimentary structures and composition, allowing recognition of the main original sedimentary features. The prefix ‘‘meta” (e. g. meta-arkose) is therefore generally omitted. Isolated clasts of variable size and composition, including carbonate olistoliths containing stromatolites, occur in almost all units.

The rocks of the Ugab-Goantagab area were grouped into 25 mappable units (Fig. 5; Appendix I). Each unit contains distinct lithofacies associations and most of them correlate well to established Damara Supergroup formations. The lower units correspond to the Nabis, Naauwpoort, Chuos, Rasthof, Gruis and Ombaatjie Formations as described from the Northern Platform (NP) and Northern Margin Zone (NMZ) of the Damara Orogen by Miller (2008). The upper units are correlated with the Ghaub, Karibib and Kuiseb Formations of the Northern Zone (NZ), and the Zebrapüts, Brandberg West, Brak River, Gemsbok River and Amis River Formations of the Zerrissene Turbidite Complex (Swart, 1994) in the Southern Kaoko Zone (SKZ). The Nabis and Chuos Formations, and locally the Karibib Formation, rest unconformably on gneisses of the Palaeoproterozoic Kamanjab Inlier. Units of the Mulden Group units overlie the Damara Supergroup with an angular unconformity. The following chapter presents short descriptions of the stratigraphic units shown on the map (Appendix I); the terms thin-, medium- and thick-bedded are defined, respectively, as 1-10, 10-30 and 30-100 cm (Ingram, 1954; Collinson *et al*., 2006). Futher details are given in Paciullo *et al*. (2007) and Nascimento *et al*. (2016, 2017, 2018).

Palaeoproterozoic basement - Kamanjab Inlier

Local basement rocks are muscovite-rich granitic orthogneiss with minor proportions of pegmatite, amphibolite, paragneiss, quartzite and quartz-mica schist. In this project, we have not studied the internal relationships and ages of these units but mapped them collectively as "basement". The contact of the basement with the overlying Damara Supergroup is marked by a palaeogeography of hills and valleys.

Damara Supergroup in the Northern and Northern Margin Zones

Vrede, Bethanis, Austerlitz and Toekoms areas

Unit 1: Granitic breccia and arkose - Nabis Formation (Nosib Group)

This unit is essentially composed of granitic breccia and arkose. The breccia contains angular pebble- to boulder-sized fragments of massive or slightly foliated granites and vein quartz in an arkosic matrix (<10%). The arkose contains quartz, K-feldspar, plagioclase, muscovite and a quartz-feldspar-white mica silty matrix (<10%), while the breccia consists of massive or normal-graded (breccia-arkose), up to 5 m thick individual layers, some of them probably constituting amalgamated beds. Transitions into conglomerate occur locally. The arkose forms 1-50 cm thick, massive or normal-graded beds, isolated or stacked in up to 5 m-thick layers, intercalated with the breccia. The breccia-arkose succession forms tabular or lenticular, discontinuous bodies, up to 100 m thick. In some outcrops the arkose has a similar appearance to the underlying fractured granitic basement, which hampers identification of the contact between altered granite and arkose.

Unit 2: Mafic and felsic volcanic rocks - Naauwpoort Formation (Nosib Group)

The second unit outcrops in the Austerlitz Dome and consists of mafic and felsic lavas and subvolcanic bodies, mainly basalt, dacite and rhyolite. Basalts are massive or show centimetre- to metre-sized pillow structures indicative of subaqueous eruption. Felsic rocks are massive or plane-parallel laminated. They occur as individual bodies of centimetre to metre diameter at the base of the section in the Austerlitz Dome. Massive and pillow basalts and porphyritic dacite layers are also intercalated within the lowermost Chuos Formation.

Figure 7. Diamictite of the Chuos Formation, Austerlitz Dome (width of view approximately 4 m)

Unit 3: Chuos Formation and correlated units

Unit 3 includes rudites, sandstones and lutites with minor carbonate rocks and chert, and unconformably overlies both basement and the Nabis Formation. Its thickness varies from ca. 100 m in the Austerlitz and Bethanis areas to as much as 600 m in the Toekoms area (Fig. 3). The minimum thickness in the Vrede area is approximately 130 m, as the base here is not exposed. The correlatives of Unit 3 are the successions of the Ombombo and Ugab Subgroups of the Northern Platform and Northern Zone, respectively (Miller, 2008).

Rudites are polymictic conglomerate and diamictite (Fig. 7), containing (sub)angular to rounded pebbles and cobbles as well as occasional up to boulder-sized clasts. These fragments consist of granitic rocks, arkose, lutites, brown dolostone, grey limestone, vein quartz, quartz and K-feldspar. In the Austerlitz area there are also felsic and mafic volcanic fragments. The conglomerate may transition into breccia; diamictite differs by a light-green to brown arkosic wacke matrix (>10%). The massive or normal-graded up to one-metre thick conglomerate beds may amalgamate to form up to 8 m-thick layers; diamictite appears in centimetre- to metre-thick, massive tabular beds. Both types of rudites may contain thin intercalations of arkose, lutite and carbonate rocks. The basal contact is planar or irregular, locally showing evidence of substratum erosion.

Sandstones are of arkosic composition with (sub)angular quartz, K-feldspar, plagioclase, muscovite and local felsic and mafic volcanic fragments. Metamorphic biotite occurs along the poorly defined foliation. The arkoses consist of massive, thin (usually <10 cm), up to one metre-thick beds. In places, thin beds show normal grading, climbing ripples and convolute folds. The arkoses form metre-thick successions associated with the rudites. They also occur as arkose-lutite graded beds.

Lutites are phyllitic mudrocks, including siltstone and mudstone, which contain quartz, feldspar, fine white mica and metamorphic biotite. They occur as massive or plane-parallel laminae and thin (1–5 cm) tabular layers intercalated with the arkoses. An up to 25 m-thick phyllite package is present in the upper part of Unit 3 (Chuos Formation). This package may correlate with Unit 11 (Zebrapüts Formation of the Zerrissene Turbidite).

Carbonate rocks consist of recrystallised cream- to greyish limestones and brown dolostones, which hampers the recognition of original features. Fine- to coarse-grained pebbly calcarenite and calcarenite-calcilutite beds have been identified. The former includes ooliths, intraclasts and undifferentiated carbonate grains, and may contain quartz and feldspar clasts. It occurs in massive or normal-graded, up to one metre thick beds or as thin composite calcarenite-calcilutite layers. Calcilutite is massive or forms plane-parallel laminae. Climbing ripples, convolute folds and load structures occur locally (Fig. 8).

Figure 8. Climbing ripples within thin-bedded turbidite of the Chuos Formation, Austerlitz area

Chert occurs locally in thin (1–5 cm), massive, isolated or amalgamated beds intercalated with the lutites of the Bethanis and Toekoms areas. At Bethanis there are also occurrences of oolithic chert and very rare stromatolite.

Isolated pebble- to boulder-sized, angular to rounded fragments of granitoid, arkose, lutite, vein quartz, K-feldspar, brown dolomite and greyish limestone occur in the arkose, lutites and carbonate rocks.

Unit 4: Carbonate succession - Rasthof Formation (Otavi Group)

This unit consists of up to one-metre thick beds of creamy dolostone stacked in metric successions, with minor thin to thick intercalations of massive calcarenite, calcarenite-mudstone, arkose and arkose-lutite beds. Massive calcirudite and oolithic chert occur locally. The thickness of Unit 4 varies from 100 m on Austerlitz and Bethanis to 150 m in the Vrede area. It possibly correlates with the Okonguarri Formation of the Northern Zone.

Figure 9. Carbonatic rudite layers intercalated with brown dolostone (Rasthof Formation, Austerlitz Dome)

Unit 5: Carbonate slide blocks

In the Vrede area (Fig. 3), carbonate packages up to 150 m thick occur interbedded within and truncating Unit 4 carbonates. Similar carbonates also occur as isolated megablocks in Unit 13 (Brak River Formation) and in Unit 10/17 (Amis River/Kuiseb Formation; Fig. 5; Appendix I). These packages and blocks consist of stacked one to 70 cm thick beds of massive and laminated cream-coloured dolostone with intercalations of massive oolithic calcarenite, and massive and laminated calcilutite. Columnar stromatolites (*Tungussia*-type) and mudcracks are observed locally. Due to their isolated occurrence and discordant truncations these carbonates are interpreted as shallow marine coastal deposits which were redeposited as a slide in a deeper marine environment by way of underwater landslides.

Unit 6: Sandstone and lutite - Gruis Formation

The Gruis Formation is a phyllitic sandstone-lutite succession similar to that present in Unit 3 (Chuos Formation). Intercalations of conglomerate, calcarenite-calcilutite pairs and massive dolostone are frequent. Isolated pebble- to boulder-sized clasts of granite, sandstone and dolostone are common. Sandstones are of arkose/subarkose composition, while the lutites are mainly feldspathic muddy siltstones. The unit is ca. 250 m thick in the Vrede and Austerlitz areas, but thins laterally towards Bethanis and Toekoms (Fig. 3), where it is not recognised.

Unit 7: Carbonate rocks - Ombaatjie Formation

This unit is dominated by recrystallised massive carbonate with intercalations of calcarenite, calcarenite-calcilutite pairs, phyllitic arkose and phyllitic lutite. The thickness ranges from absent on Bethanis to ca. 200 m on Toekoms; it also occurs in the Vrede and Austerlitz areas. It may correlate to unit 12, the Brandberg West Formation carbonates of the Zerrissene Turbidite Complex in the Lower Ugab Domain (Southern Kaoko Zone; Fig. 5, Appendix I).

Unit 8: Calcirudite - Ghaub Formation

Unit 8, which corresponds to the Ghaub Formation, is composed of calcirudite (breccia, conglomerate, diamictite) containing angular to rounded pebbles, cobbles and locally boulders (Fig. 10). Fragments are of varied types of limestone, carbonate breccia and dolostone. The matrix contains carbonate sand and mud, and locally quartz, feldspar and fine mica. A variety containing granite and arkose clasts, besides carbonate debris, occurs on Bethanis. These rocks form thick, massive, locally graded beds that may be stacked in successions up to 30 m thick. Thin to thick, massive dolostone interlayers occur locally. Unit 8 occurs on Bethanis and north of Vrede. On Vrede, Austerlitz, Toekoms as well as in the Lower Ugab Domain it occurs in thin lenses, not mappable at the compilation scale (Appendix I).

Figure 10. Rare dolomitic fragments in arkosic siliciclastic matrix of the Ghaub Formation (Bethanis area); generally the unit is characterised by carbonatic diamictite with a carbonate matrix.

Unit 9: Karibib Formation

Unit 9 corresponds to the Karibib Formation. The up to 200 m thick carbonate succession overlies the Chuos and Ghaub Formations in the Bethanis and Toekoms areas, and the Ombaatjie and Chuos Formations north of Farm Vrede, respectively (Fig. 5; Appendix I). It consists of thin to thick, stacked limestone-mudstone composite beds and massive to graded, thick, blue-grey to brown dolostone layers. Intraformational breccia and thin chert layers occur locally on Bethanis, while oolithic limestone has been observed north of Vrede. Rudstone, consisting of small, light-grey limestone and brown dolostone pebbles occurs in the Austerlitz area. The Karibib Formation has been correlated to the Gemsbok River Formation (Units 15 and 16) of the Zerrissene Turbidite Complex in the Lower Ugab Domain (Southern Kaoko Zone; Fig. 5, Appendix I).

Unit 10: Kuiseb Formation

The ca. 300 m thick Kuiseb rests conformably on the Karibib Formation. It is composed mainly of 10- to 30 cm-thick, tabular and massive plagioclase arkose-lutite composite beds, with local occurrences of a) normal-graded beds, b) small-scale cross-beds and current ripples recording southwest-directed palaeocurrents, c) thin intercalations of tabular massive lutite and d) calc-silicate rocks besides e) convolute folds (Fig. 11) and f) load structures. The Kuiseb Formation is considered the equivalent of the Amis River Formation (Unit 17) of the Zerrissene Turbidite Complex in the Lower Ugab Domain (Fig. 5; Appendix I).

Figure 11. Convolute folds in thin bedded turbidite of the Kuiseb Formation, Bethanis area

Damara Supergroup in the Southern Kaoko Zone transition (Goantagab & Lower Ugab River Domains)

Unit 11: Zebrapüts Formation

This unit is formed by an up to 100 m-thick lutite package of phyllites and minor massive mudstone, which contains intercalations of thin to thick beds of fine- to medium-grained, massive arkose and arkosic wacke. It may correlate with the phyllite/mudstone succession that occurs in the upper part of Unit 4 (Chuos Formation of the Northern Zone).

Unit 12: Brandberg West Formation

Unit 12 consists of a basal marble-mudstone succession overlain by fine-grained marble. The former is composed of stacks of thin to thick, tabular, massive or normal-graded marble and marble-mudstone composite beds. The upper fine-grained marble forms thin, massive tabular beds. Isolated mudstone (phyllite) intercalations occur in both subunits.

Units 13 and 14: Brak River Formation

The Brak River Formation can be sub-divided into two mappable units, a) a lower feldspathic quartzite (Unit 13) and b) an upper arkosic sandstone-lutite succession with a phyllite (lutite) at the top (Unit 14). These units are thrusted over the Austerlitz and Vrede successions; the thrust surface truncates contacts between the lower units, and in several places is marked by a tectonic breccia.

Unit 13: Lower Brak River Formation

The Lower Brak River Formation is made up of thick massive feldspathic quartzite beds, amalgamated or separated by laminae or thin beds of lutite, forming an up to 200 m thick package. Dolomite and lutite clasts, isolated or locally forming a breccia, are common at the base of the succession (Fig. 12). The lower quartzite passes upwards into the arkose-lutite succession of Unit 14.

Figure 12. Quartzite with marble intraclasts along its base; lower contact of the Brak River Formation, south of the Austerlitz Dome (width of view ~2 m)

Unit 14: Upper Brak River Formation

Unit 14 is ~300 m thick and consists of (a) a basal succession of thick arkose (Fig. 13) and arkose-lutite beds grading upwards into (b) thin arkose-lutite beds, which are in turn overlain by (c) fine-grained micaceous arkose and lutite (biotite phyllite/schist). These successions contain sporadic intercalations of intraformational breccia, feldspathic quartzite and dolostone. Conglomerate with pebbles of granite, felsite, basalt and carbonate rock occurs in the Zerrissene Complex. Calcirudite similar to that of Unit 8 (Ghaub Formation) and isolated carbonate fragments from pebbles to decametre-sized blocks, some of which contain stromatolite and oolithic calcarenite, have been observed in the Vrede, Austerlitz and Lower Ugab Domain.

Units 15 and 16: Gemsbok River Formation

The Gemsbok River Formation overlies conformably the Brak River Formation and is considered a correlative of the Karibib Formation. The formation is made up of white to cream marble (calcarenite), marble-hybrid mudstone pairs, fine-grained bluish marble, and local calcirudite. These rocks can be subdivided into two ca. 50 m thick units.

Unit 15: Lower Gemsbok River Formation

The lower unit consists of a) massive to normal-graded or plane-parallel laminated marble and b) marble-hybrid mudstone pairs. These rocks form mainly up to one metre-thick, tabular beds, which are stacked in recurrent cycles of marble and marble-mudstone.

Unit 16: Upper Gemsbok River Formation

The upper unit of the Gemsbok River Formation is characterized by a fine-grained blue marble succession. Beds are 5 to 40 cm thick, tabular, massive or graded. Normal grading is defined by a light-blue marble base which grades upwards into dark-blue marble-mudstone. Plane-parallel lamination and current ripples occur locally. Dark-grey siliciclastic and hybrid (siliciclastic-carbonate) mudstone (phyllite/schist) laminae and 50 cm-thick tabular beds occur in both units. Intraformational breccia is present locally.

In the Goantagab area, coarse- and fine-grained calcirudites (rudstones) occur in the lower unit. The coarse calcirudite is composed of white to light-grey carbonate pebbles and cobbles, while the fine variety contains, in addition to grey limestone pebbles, scattered dolomite and minor granite pebbles and cobbles. Both types may contain a sandy-muddy carbonate matrix (< 10%). The pebbles and cobbles are rounded, with the limestones showing an ellipsoidal shape, whereas dolomite and granite fragments tend to be spherical, recording distinct behaviour during weathering and different rheology during deformation.

Figure 13. Scattered dolomite fragments in coarse-grained arkose at the base of the upper Brak River Formation, Austerlitz Dome

Unit 17: Amis River Formation

Unit 17 is mainly composed of arkose and arkose-mudstone composite beds. The beds are tabular, massive or normal-graded, 5 to 30 cm thick and stacked in an up to 150 m-thick succession. Intercalations of thin, massive, tabular marble (calcarenite-calcilutite) and calcsilicate rocks occur locally. A slide block of ca. 50 m diameter is present in the Bethanis area (Appendix I). The Amis River Formation conformably overlies the Gemsbok River Formation and is considered a correlative of the Kuiseb Formation.

Units 18 and 19: Mulden Group

Calcirudite, calcarenite, dolostone, siliciclastic and hybrid breccia, arkose and lutite (phyllites) are the main lithologies of the Mulden Group, which outcrops in the Bethanis and Toekoms areas. Carbonate-dominated successions possibly correlate to the Braklaagte Formation, while siliciclastic successions may correspond to the Renosterberg Formation of the Welkom Subgroup.

Unit 18: Calcirudite succession (Mulden Group)

This unit consists essentially of calcirudite with minor intercalations of calcarenite. The calcirudites are fine to very coarse breccia and rudstone with angular to rounded pebbles and cobbles of beige, light- and dark-grey, bluish, brown and minor greenish carbonate rocks; boulder-sized fragments are present locally. The calcirudites form massive, locally graded, apparently tabular beds, whose thickness varies from ca. 20 cm in the fine pebble variety up to 2 m in the coarse breccia. The calcarenite consists of 30-100 cm thick massive, or locally cross-bedded, tabular and lenticular intercalations. Locally, thin to thick (up to 50 cm), siliciclastic and hybrid mudstone intercalations are present. In many outcrops brown to reddish-brown oxidised zones have been observed. Unit 18 is at least 100 m-thick in the study area.

Unit 19: Breccia, breccia-arkose and arkose successions (Mulden Group)

This unit contains three distinct successions. The lower succession is ca. 20 m thick and consists of carbonate and hybrid rudites, mainly breccias. Beds are massive and up to one metre thick. The rudites are composed of angular to rounded pebbles and cobbles of limestone, dolostone, vein quartz, quartz, feldspar, sandstones and phyllite. The intermediary succession is at least ca. 50 m thick and made up of hybrid breccia and fine-grained arkose/ subarkose. These rocks form 5 to 30 cm thick, tabular or lenticular breccia-arkose composite beds, apparently massive and locally normal-graded. The upper succession comprises an arkose package with a minimum thickness of approximately 50 m. Individual beds are ca. 10 to 50 cm thick, massive, plane-parallel laminated and cross bedded, many of them separated by thin mudstone layers. A well-developed phyllitic cleavage in the arkose and mudstones forms a high angle with the bedding plane in many places.

Units 20 and 21: Granitoids

Apart from a few isolated outcrops, five major granite intrusions were mapped (chapter 10b; Fig. 5; Appendix I). The Voetspoor pluton in the central part of the area is mainly composed of porphyritic hornblende-quartz syenite, locally grading to hornblende monzodiorite, hornblende monzonite and syenodiorite (Unit 20). Along its southwestern border biotite granite is present (Unit 21; Schmitt *et al*., 2012). The Doros North pluton outcrops further to the west. It is also mainly composed of hornblende syenite (Unit 20), with minor biotite granite (Unit 21) along its southwestern border. These two plutons were dated and yielded ages between 528 ± 5 Ma and 534 ± 4.5 Ma (Schmitt *et al*., 2012; Passchier *et al*., 2007), interpreted as the age of emplacement. Although they are syntectonic, they locally produced aureoles of spotted slate containing garnet and andalusite, generally altered to biotite muscovite aggregates. The Doros North and, to a lesser extent, the Voetspoor pluton contain elongate, parallel rafts of hornfelsed mica schist (Unit 20h; Fig. 6) that probably formed during multiphase intrusion (chapter 10b). The Driekrone granite is a circular intrusion, almost in contact with the very large Omangambo granite (Fig. 5, Appendix I). This intrusion was not studied in detail but appears to be mainly composed of similar lithologies as Unit 20 (referred to in the literature as Salem-type granite; Miller, 2008; Lehmann *et al*., 2016), with local patches of younger biotite granite (Unit 21, Sorris Sorris-type) in its centre. Both granites produced contact aureoles with cordierite, andalusite and garnet, as well as from wollastonite in marble country rock. Other small granite intrusions in the extreme southeastern part of the area and to the west of Twyfelfontein were not studied in detail. Apart from the main plutons, several generations of aplite, pegmatite and granite veins occur inside and near these intrusions (Units 20 and 21), cutting the metasedimentary country rocks. Thin N-S trending granite veins occurring in the Goantagab area are shown in exaggerated thickness on the map (Appendix I), because if their relevance to our interpretation.

Unit 22: Greenschist / metagabbro

In the Goantagab Domain an intrusive body of metagabbro, metamorphosed to coarse-grained actinolite schist, was observed. It appears to be pre-tectonic and was dated at 565 ± 3 Ma (Nascimento *et al*., 2017, 2018). An apophysis of this lithotype is also present in the southern part of the northern Vrede Dome.

Unit 23: Diabase and lamprophyre dykes

Diabase (dolerite) dykes, up to 10 m wide, occur throughout the study area, mostly with a steep to subvertical N-S trending orientation. These dykes are non-metamorphic and cross-cut all deformation features in the area, except for late faults. Lamprophyre dykes have been observed in the north of the Bethanis and Toekoms areas. The dykes are thought to have been generated during extension preceding the opening of the South Atlantic Ocean (Salomon *et al*., 2014). On the accompanying map, only the larger, more important dykes are shown; many more dykes are visible on satellite images and aerial photographs.

Unit 24: Other Mesozoic Units

The deformed and metamorphosed Proterozoic rocks are unconformably overlain by rocks of the Karoo Supergroup, mainly lacustrine and fluvial deposits (De Wit *et al*., 1988; Smith, 1990). These sedimentary rocks are succeeded by the up to 100 m thick aeolian sandstones of the Twyfelfontein Formation of Lower Cretaceous age (Dentzien-Dias *et al*., 2007; Perea *et al*., 2009), which is in turn overlain by and interfingers with Etendeka volcanics, mainly extensive flood basalts (Jerram *et al*., 1999; Stanistreet and Stollhofen, 1999) with an age of 133 ± 1 Ma (Renne *et al*., 1996) and a preserved thickness of 700 m in Namibia. Other igneous complexes, such as the Doros "Crater" (not to be confused with the Cambrian Doros North intrusion), also are present in the study area (Fig. 5; Appendix I). Below the unconformity, an up to 10 m thick weathered zone may occur in the Neoproterozoic basement rocks, where sedimentary and structural features are obscured. The younger units that cover the Neoproterozoic and older basement are mostly undeformed and non-metamorphosed, although they are locally affected by minor late-stage brittle deformation (Salomon *et al*., 2014) and contact metamorphism caused by the extrusion of the Etendeka flood basalts. Our studies exclusively focused on the Neoproterozoic rocks, and no details or subdivisions of the overlying younger deposits were recorded (Fig. 5; Appendix I).

Unit 25: Cenozoic Cover

Unit 25 refers to unconsolidated sediments of unspecified Cenozoic age, mainly sand dunes, fluvial deposits and isolated patches of calcrete.

7. Metamorphism (R. A. J. Trouw)

Metamorphism in the Lower Ugab Domain is of middle greenschist facies, as indicated by the presence of abundant biotite in almost all rock types, besides albite/oligoclase, chlorite, and white mica (Passchier *et al*., 2002, 2011, 2016). Garnet is very rare, possibly due to relatively low pressure and to rock composition. Amphiboles, mainly actinolite, actinolithic hornblende and tremolite, form poikiloblastic porphyroblasts in calcsilicates and impure marble. Superposed contact metamorphism around the granitic bodies locally produced cordierite and andalusite porphyroblasts, which generally have been replaced by biotite-muscovite-chlorite aggregates. In a few outcrops staurolite was also detected. In calcsilicate layers hornblende, diopside and garnet are found, while wollastonite occurs locally along the contacts between marble and granitic intrusions. Goscombe *et al*. (2004) give estimates of 540-570 °C and 2.5-3.2 kbar for metamorphic conditions in the Lower Ugab Domain, which corresponds well to our estimates from mineral parageneses observed in contact metamorphic aureoles. For regional metamorphism the pressures were probably similar, although temperatures, based on chemical mineral composition (Renato Moraes, personal communication), are estimated somewhat lower at 400-500 °C. Local contact metamorphic spots in the Lower Ugab Domain, away from outcropping granites, can possibly be attributed to hidden intrusions below the surface. Based on microtectonic criteria, such as porphyroblast-foliation, metamorphic conditions probably reached their peak during D_2 in the Lower Ugab Domain, and during D_{2a} in the Eastern Domain. During D_3 these conditions declined, with cordierite and andalusite porphyroblasts being replaced by biotite and chlorite; the resulting aggregates were deformed during D_3. However, biotite growth during and after D_3 has also been observed locally in the Eastern Domain. The intensity and orientation of D_3 structures is strongly affected by the presence of the granite plutons; the S_3 foliation tends to concentrate between plutons and to wrap around them, proving that S_3 post-dates the intrusions. However, there are local high-strain zones that are unrelated to outcropping granites, which may be associated with buried or eroded plutons or to high-strain zones within the basement.

Sets of deformed quartz-carbonate veins occur throughout the area. Some of these veins have been dated as syn-D_{2a} although most of them pre-date D_2 and may be of D_1 age, or else have a diagenetic origin (Maeder *et al*., 2014). The presence of the later veins points to an enhanced fluid pressure during the early stages of D_{2a} folding, probably associated with the granite plutons. Stable isotope analysis of the veins indicates that the fluids were wall rock derived and did not originate from the intrusions. The fluid pressure pulse was therefore possibly related to to contact metamorphism (Maeder *et al*., 2009).

8. Radiometric dating (R. Schmitt)

Several lithostratigraphic units and intrusive bodies were selected to obtain absolute geological ages in order to constrain the tectonic evolution in the map area. Geochronological data on detrital zircons also produced minimum depositional ages and possible source areas for the metasedimentary rocks. Crystallisation age of igneous bodies provided estimates for the age of successive deformation phases.

Volcanic rocks of the Naauwpoort Formation were sampled with the aim to date rift initiation during the Neoproterozoic and tectonic evolution of the continental margin at the border of the Angola Craton. Sample RP-04-10-12 is from a felsic metavolcanic sill (Unit 2, Naauwpoort Formation) at the base of the succession in the Austerlitz area (Fig. 14). The zircon grains from this sample show a very homogeneous population of euhedral bipyramidal crystals. The U-Pb dates from several grains are concordant and yield a robust U-Pb age of 757 ± 5 Ma (Nascimento *et al*., 2016), which is interpreted as the crystallisation age of the sill, related to the rifting period that opened the basin in which the Damara Supergroup was subsequently deposited.

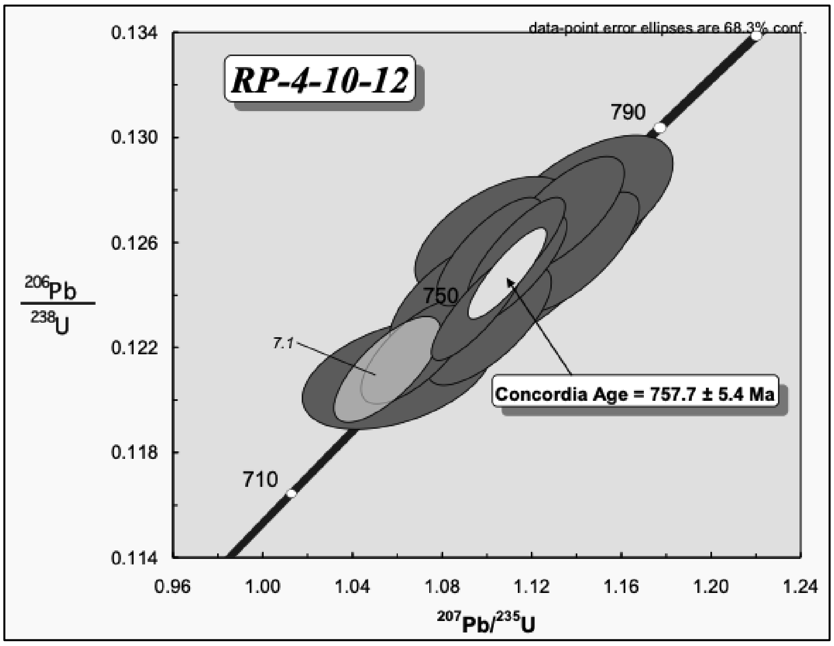

Figure 14. Sample RP-04-10-12: felsic metavolcanic rock from Unit 2 (Naauwpoort Formation, Nosib Group) in the Austerlitz area (Nascimento *et al*., 2016), giving a crystallisation age of ~760 Ma

Seven samples of metasedimentary rocks from the lower to upper Damara Supergroup were selected for U-Pb dating on detrital zircons. Nascimento *et al*. (2017) presented 569 concordant U-Pb detrital zircon ages subdivided into two distinct provenance groups; a) with a predominance of Palaeoproterozoic ages, and b) mainly of Neoproterozoic origin (Fig. 15). The first group corresponds to the samples of Nosib and Otavi/Swakop Group rocks and indicates the Congo/Angola basement as their main provenance. An exception are the ca. 1000 Ma zircon grains of the Nabis Formation thought to originate from the Abbabis High, a structural prominence separating the Outjo and Khomas Basins. This leads to the conclusion that this high prevented influx of sediments from southern source areas. The few provenance ages between ca. 750 Ma and 630 Ma in samples of the Otavi/Swakop Groups are interpreted as being related to syn-rift magmatic rocks and/or grains derived from the Coastal Terrane of the Kaoko Belt.

In contrast, the mainly Neoproterozoic age group is restricted to the Mulden Group. It shows three distinct age clusters; (a) ~2620 Ma and 1860 Ma thought to be derived from the Congo-Angola Craton basement, (b) ca. 1010 Ma possibly related to the Abbabis High (i. e. Kalahari Craton basement), and (c) ~700 Ma and 650 Ma, which are likely to be associated with the Coastal Terrane of the Kaoko Belt.

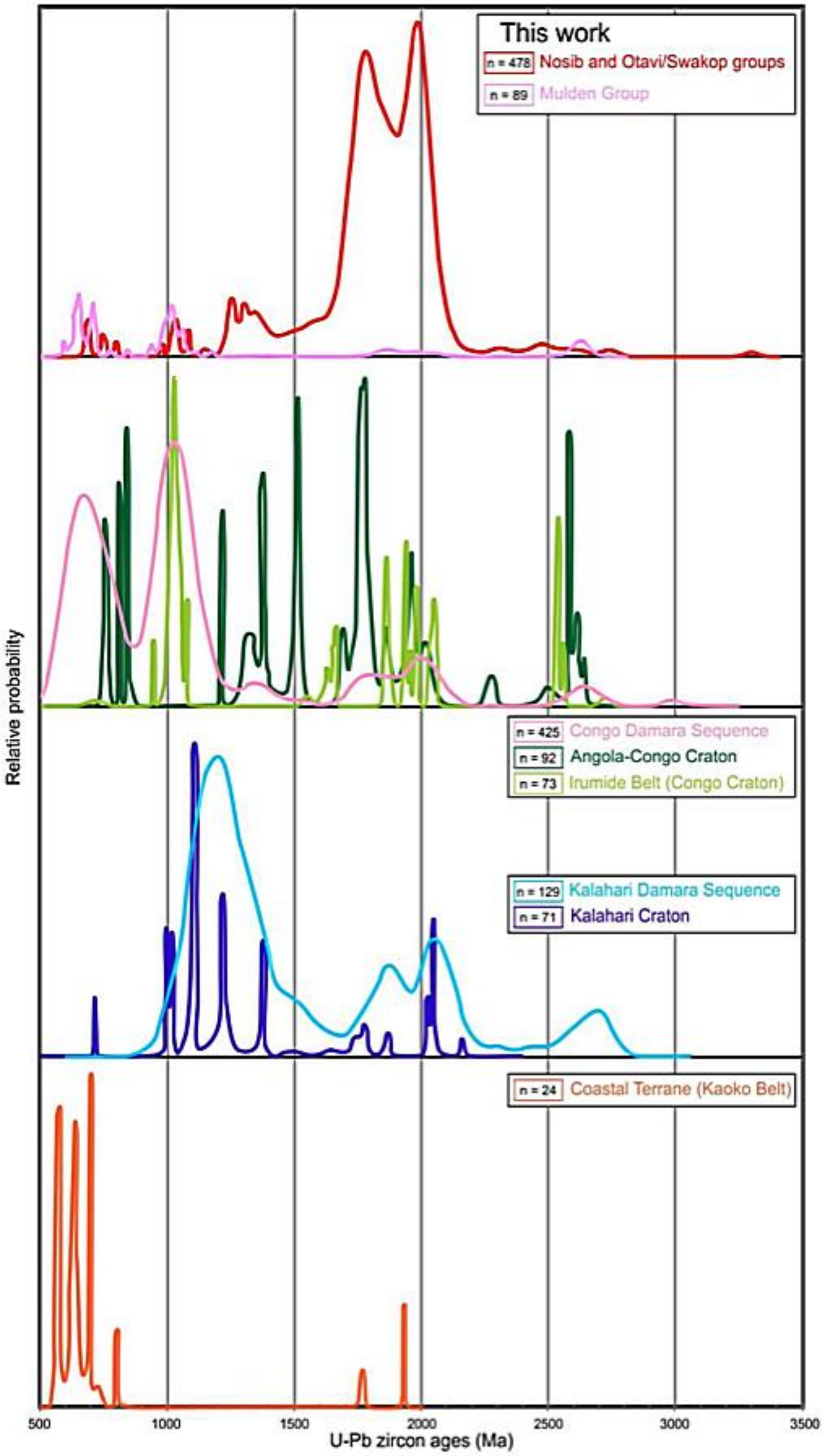

Figure 15. Probability density diagram comparing data from Nascimento *et al*. (2017, "this work") for the southern Angola and Kalahari Cratons and the Coastal Terrane (Kaoko Belt) with previous publications, including detrital zircon ages published by Foster *et al*. (2015) for the Kalahari and Angola-Congo cratons and Damara metasedimentary rocks (vertical axis not to scale)

In the Goantagab area of the Eastern Domain, a metagabbro (Unit 20), intrusive into Unit 14 (Brak River Formation), yielded a few tiny zircon grains that were selected for U-Pb LA-ICPMS dating at the University of Brasilia, Brazil. The dates are distributed along the concordia from 610 to 550 Ma (Nascimento *et al*., 2017, 2018). While the younger dates are most likely represent the crystallisation age of the gabbro, the older ones are interpreted as either xenocrysts from the host rocks or inherited grains. A cluster of the youngest dates yields a concordia age of 565 ± 3 Ma (Fig. 16), which must be younger than Units 14 and 15 as they were intruded by the sill but could possibly be older than the overlying Unit 17 (Amis River Formation). A similar age was published for the Goas gabbro (580-575 Ma) in the central Damara Orogen, which is thought to be related to the magmatic arc of the Kalahari-Angola convergence (Clemens and Kisters, 2021).

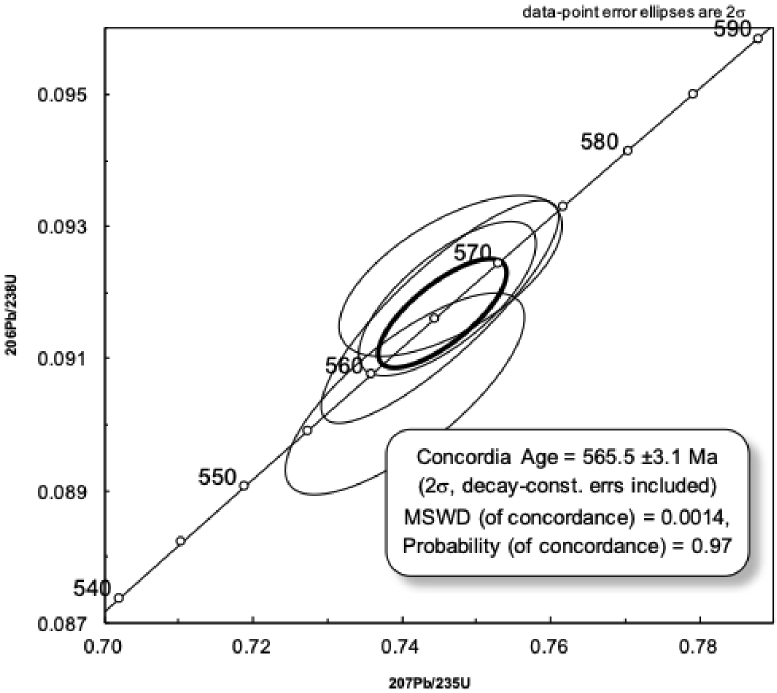

Figure 16. U-Pb concordia diagram of a metagabbro sample from the Goantagab area in the Eastern Domain; concordia age calculated with the younger concordant results

The closure and inversion of the Neoproterozoic basin resulted in the collisional Damara Orogen. Two syn-collisional granitic/ syenitic plutons from the Lower Ugab Domain, which intruded successions of the Zerrissene Complex (Units 14, 15, 16 and 17) and locally generated contact aureoles, were dated. The samples yielded U-Pb SHRIMP ages of 534-529 ± 5 Ma from igneous zircon grains. This age range is interpreted as constraining the tectono-magmatic period related to continental collision and closure of the continental rift margin in the Damara Orogen (Fig. 17; Schmitt *et al*., 2012; Passchier *et al*., 2007).

9. Structure (C. W. Passchier, R. A. J. Trouw)

All stratigraphic units in the study area show evidence of a complex, polyphase deformation (Figs 4, 5, 18). Excellent outcrop conditions permitted detailed observations of the local structural framework and events. Metapelites provide the most reliable information on deformation history, storing evidence of up to five overprinted fabrics in a single sample, although two to three generations of fabric elements are more common. Deformation structures occur as foliations, shape- and intersection lineations, folds and sets of quartz-carbonate veins (Maeder *et al*., 2009; Passchier *et al*., 2011, 2016; Figs 4, 21-28). Only main foliations and shape lineations (interpreted as stretching lineations, L_{str}) are shown on the accompanying map to avoid confusion. Marbles and meta-psammites are less instructive as they do not develop proper foliations, although their fold pattern, as seen on the map (Fig. 5, Appendix I) does provide useful information. The ca. 530 Ma syenite-granite plutons (Schmitt *et al*., 2012) outcropping in the study area are mostly undeformed due to their rigidity (e. g. see granite pebble in deformed marble diamictite, Fig. 22b) or show weak igneous fabrics, and for this reason have not been used for structural analysis. Within the metapelites, foliations, intersection- and shape-lineations are the main structural elements employed in the reconstruction of the tectonic history.

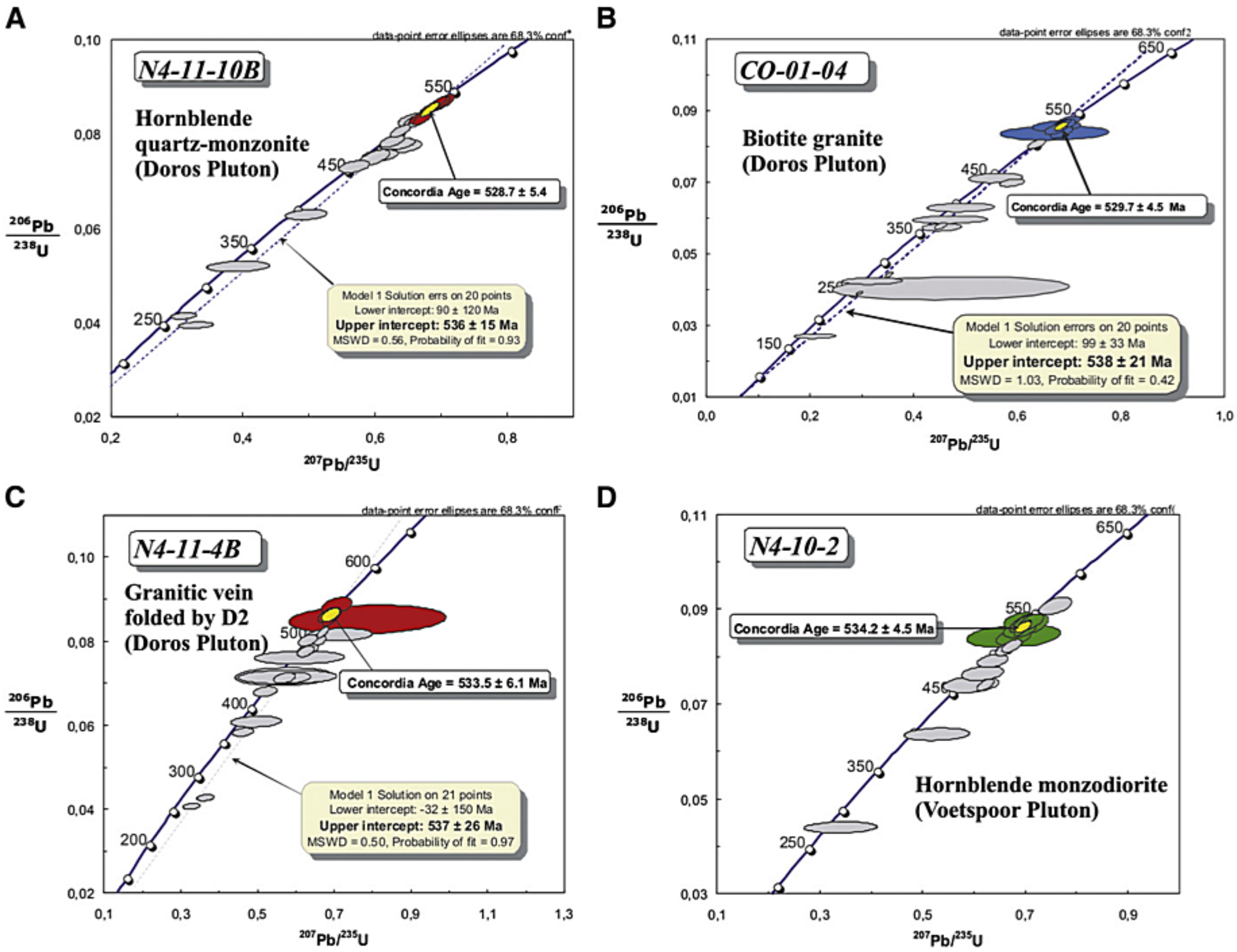

Figure 17. Crystallisation ages of the igneous units intrusive in the Lower Ugab Domain (diagrams after Schmitt *et al*., 2012)

Detailed outcrop observations, including more than 19000 measurements[1] of foliations, intersection- and shape-lineations, fold axes, axial planes and veins were collected in the study area over 23 years (Fig. 19; Appendix II). This dense observation network was needed to resolve the tectonic evolution (Fig. 20). The local deformation history was reconstructed from field and thin section observations of the relationships and orientations of the structures. The relative age of foliations and folds was determined from overprinting relations. Stretching lineations can be attributed to specific generations of foliations or folds by their orientation linked to the vergence of these structures. Finally, metamorphic grade, assessed by the growth and deformation of mineral grains, including porphyroblasts, in thin section, was used to distinguish between successive generations of structures. Because of the tectonic com-

[1] As these measurements were collected by different workers over an extended period of time during which interpretation changed and evolved, we cannot attribute all of them with certainty to specific deformation phases in the tectonic history presented here. The complete data set, only part of which has been used in the current analysis, is available from the authors.

plexity of the study area, the deformation history as summarised below was compiled by field correlation of reconstructed sequences of localised events. However, the outline given in this paper differs from pre-2016 publications, where we favoured another scheme (Fig. 45). Here, we distinguish four regional deformation phases, which can be recognised throughout the mapped area and dated with respect to each other by means of overprinting relations; most of them can also be laterally correlated to similar structures in adjacent regions. We named the successive tectonic phases responsible for the observed structures D_1, D_2, D_{2a} and D_3[2]. Each stage is thought to represent a characteristic stress field and deformational regime, although they may to some extent be diachronous and/or continuous, especially on the scale of the entire triple junction formed by the Damara and Kaoko Belts.

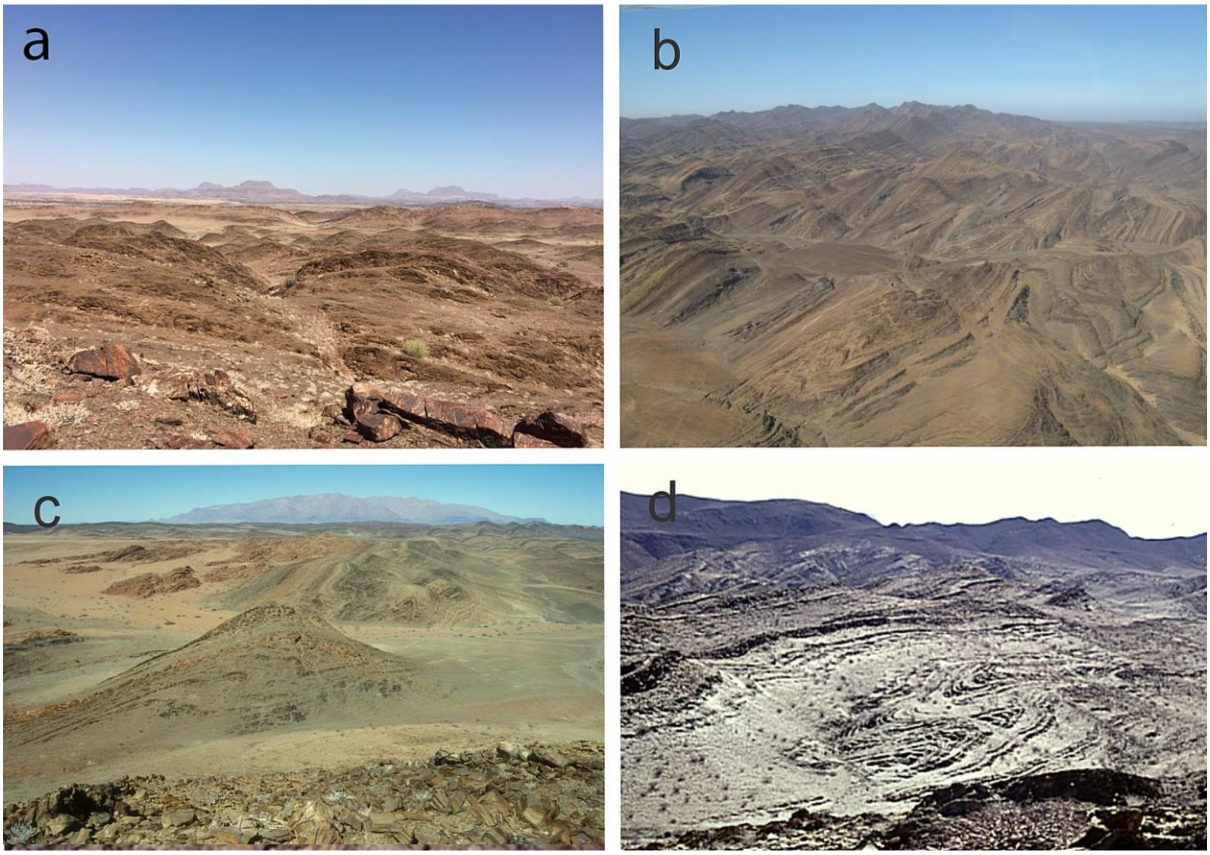

Figure 18. Large-scale field aspects: (a) Typical landscape in the Eastern Domain – excellent outcrop conditions in mica schist of the Brak River and Amis River Formations allowing detailed structural analysis. Etendeka mountains showing in the background; (b) Typical field aspect of the Lower Ugab Domain (LUD), with km-scale D_2 folds forming the dominating structures; (c) Interference pattern of D_2 and D_{2a} folds in the Brak River and Gemsbok River Formations, SW limit of the Voetspoor intrusion. Outcrops of biotite granite are visible at the left image margin (image looking east); the Mesozoic Brandberg Granite Complex can be seen in the background; (d) Landscape west of the Voespoor intrusion - large D_2 folds (Zebrapütz Formation) refolded by gentle, small-scale D_{2a} folds (image looking west)

[2] Note that we use D_1, D_2, D_{2a} and D_3 for the successive deformation phases in the study area rather than the conventional D_1, D_2, D_3 and D_4. This is because many older publications on the geology of NW Namibia use D_1 to D_3 which largely fit the phases of the same name described by us; in addition, we distinguish a fourth phase termed D_{2a}: by using this label, we attempt to avoid confusion, which might have resulted from renaming D_3 to D_4 in our publications. Note also that D_{2a} is in no way a subphase of D_2, but refers to structures related to an event entirely independent from D_2.

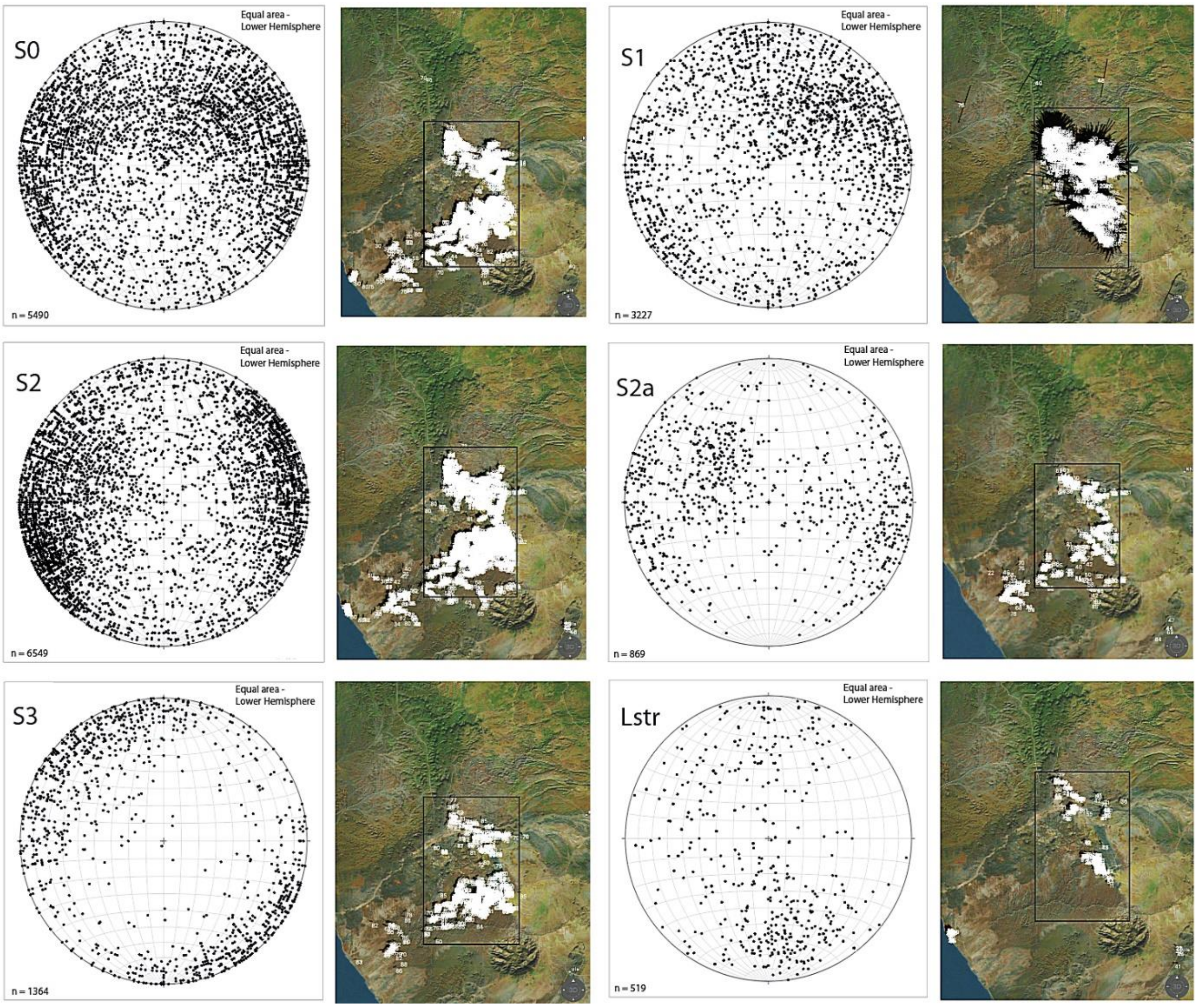

Figure 19. Stereograms summarising the structural data collected in the study area. Only stereograms of the more common structural features are shown. The rectangle on the satellite image indicates the position of the mapped area (locations of measurements as white dots). A complete set of all measurements is shown in Appendix II.

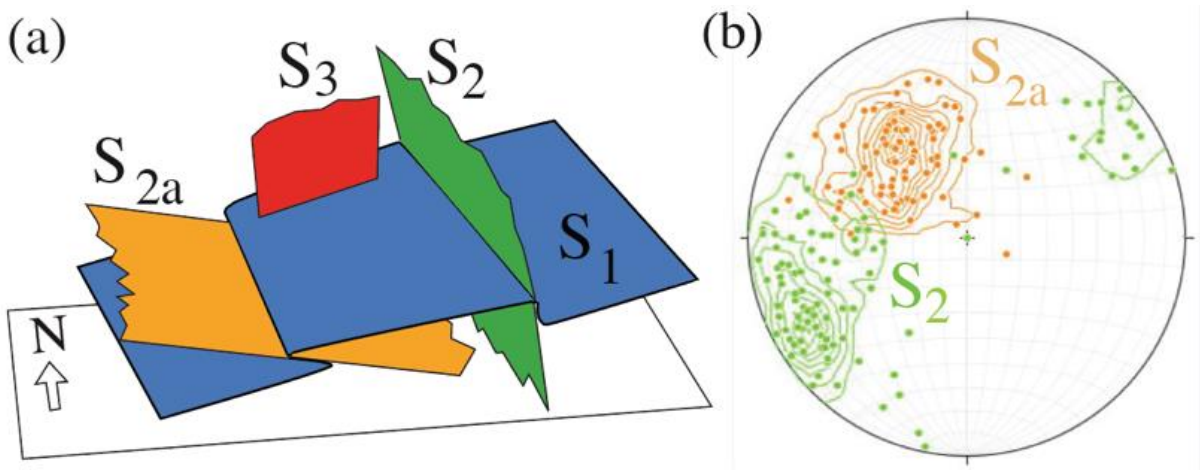

Figure 20. (a) Schematic presentation of the most common orientation of structural elements in the Eastern Domain; (a) Surfaces refer to axial planar foliations generated during successive deformation phases: S_1 is usually gently dipping, at a small angle to bedding; S_2 produces steep structures, while S_{2a} is characterised by shallower ones. Intersection lineations of S_{2a} and S_2 with S_1 are subparallel; S_3 is oblique to the earlier phases; (b) Stereogram of S_2 and S_{2a} as observed in the area between Vrede and the Omangambo Pluton

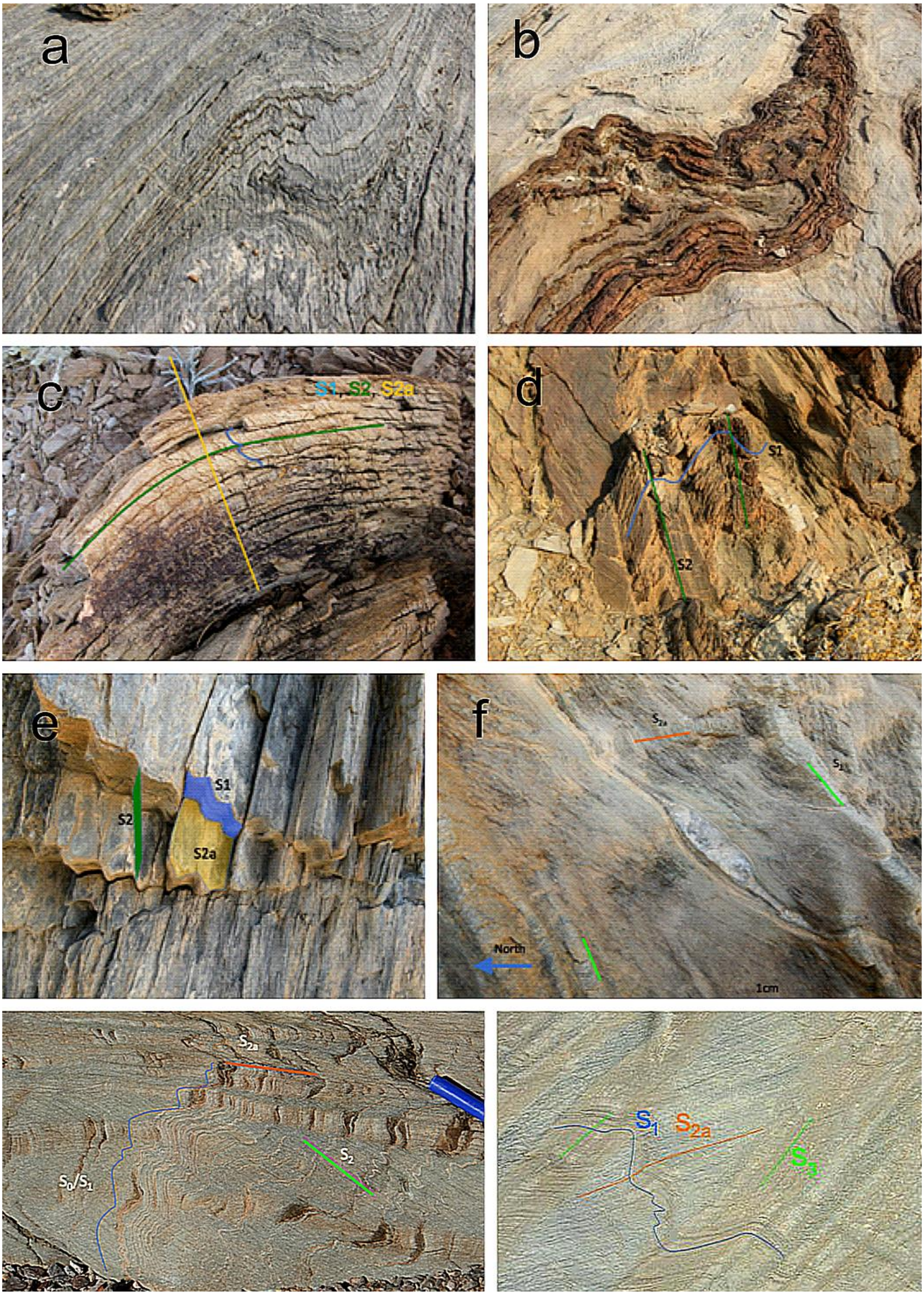

Figure 21. (a, b) Typical outcrops of the Eastern Domain (ED): Gemsbok River Formation marble with two generations of folds, i. e. tight D_2 folds, overprinted by D_{2a}; (c-h) Three generations of foliations and folds in mica schist of the Brak River Formation (blue = S_1; green = S_2; orange = S_{2a} (widths of view: (a) 2 m; (b) 1.7 m; (c) 0.6 m; (d) 1.8 m; (e) 1 m; (f) 0.5 m; (g) 1m; (h) 0.8 m)

Regional D_1

The Eastern Domain contains structures belonging to the oldest phase of deformation. The oldest foliation, S_1, dips to the south and is associated with a N-S trending stretching lineation, L_1, (Figs 4, 20, 21) and top to the north shear sense indicators (Fig. 21f, 23b); according to the latter, it is related to N-directed thrusting. D_1 is characterised by initial brittle, followed by ductile thrusting and imbrication, onto the southern edge of the Angola Craton with at least 50 km of N-S shortening. Much of this thrusting reactivated original normal faults related to the opening of the basin, inverting the sense of movement (chapter 10a).

D_1 structures, such as S_1 and L_1, are mostly absent west of the Vrede-Doros-Brandberg (VDB) Line (Fig. 4): these structures vanish towards the west over a distance of less than one kilometre, although S_1 may be present locally in some metapelite outcrops (labelled pre-S_1 by Maeder *et al*., 2014).

Despite intense subsequent deformation, the tectonic expression of the VDB-Line can be recognised as a series of 1 to 2 km-spaced parallel breccia zones, a steep low-temperature mylonite zone of probable D_1 age, dismembered lenses of some of the stratigraphic units, and small mafic intrusions (Fig. 4). The VDB-Line approximately coincides with an important facies change as outlined in the stratigraphy section above. This suggests that the VDB-Line is a transcurrent syn-sedimentary fault zone that was reactivated during D_1. It is also possible that the sharp transition is partly due to a NNW-SSE striking dextral transfer fault related to tectonic N-S shortening during D_1.

The VDB-Line and D_1 structures are overprinted by three foliations on a regional scale, i. e. D_2, D_{2a} and D_3. D_2 and D_{2a} formed under middle greenschist facies conditions, while D_3 was associated with a lower metamorphic grade.

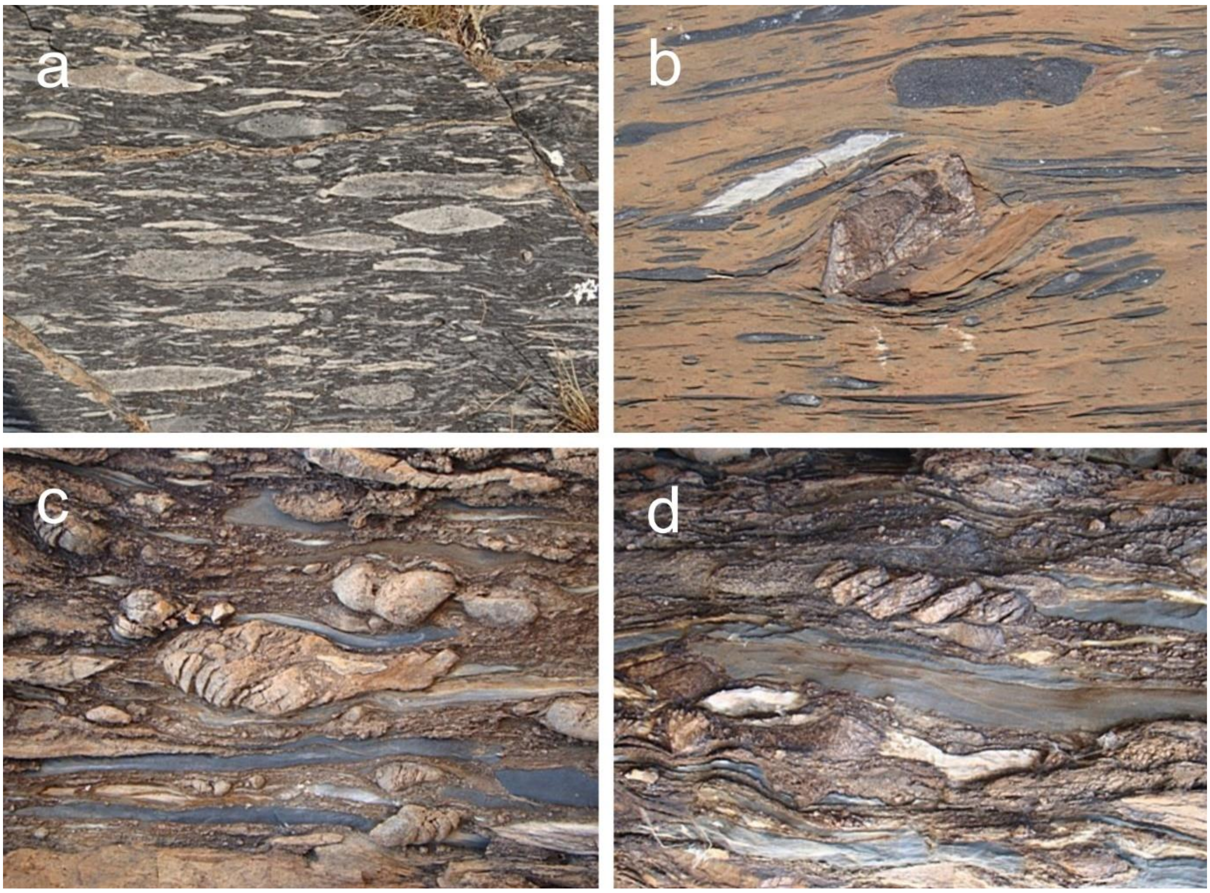

Figure 22. Deformation features in conglomerate and diamictite: (a) Deformed pebbles in the Karibib Formation, north of the Driekrone Granite; (b) Strongly stretched carbonate pebbles and undeformed granite fragment in the Ghaub Formation, Bethanis area; (c, d) Deformed conglomerate with dextral sense of shear and sinistral displacement of rotated fragments (domino boudinage), Chuos Formation, Bethanis area (width of view approximately 20 cm in all photos)

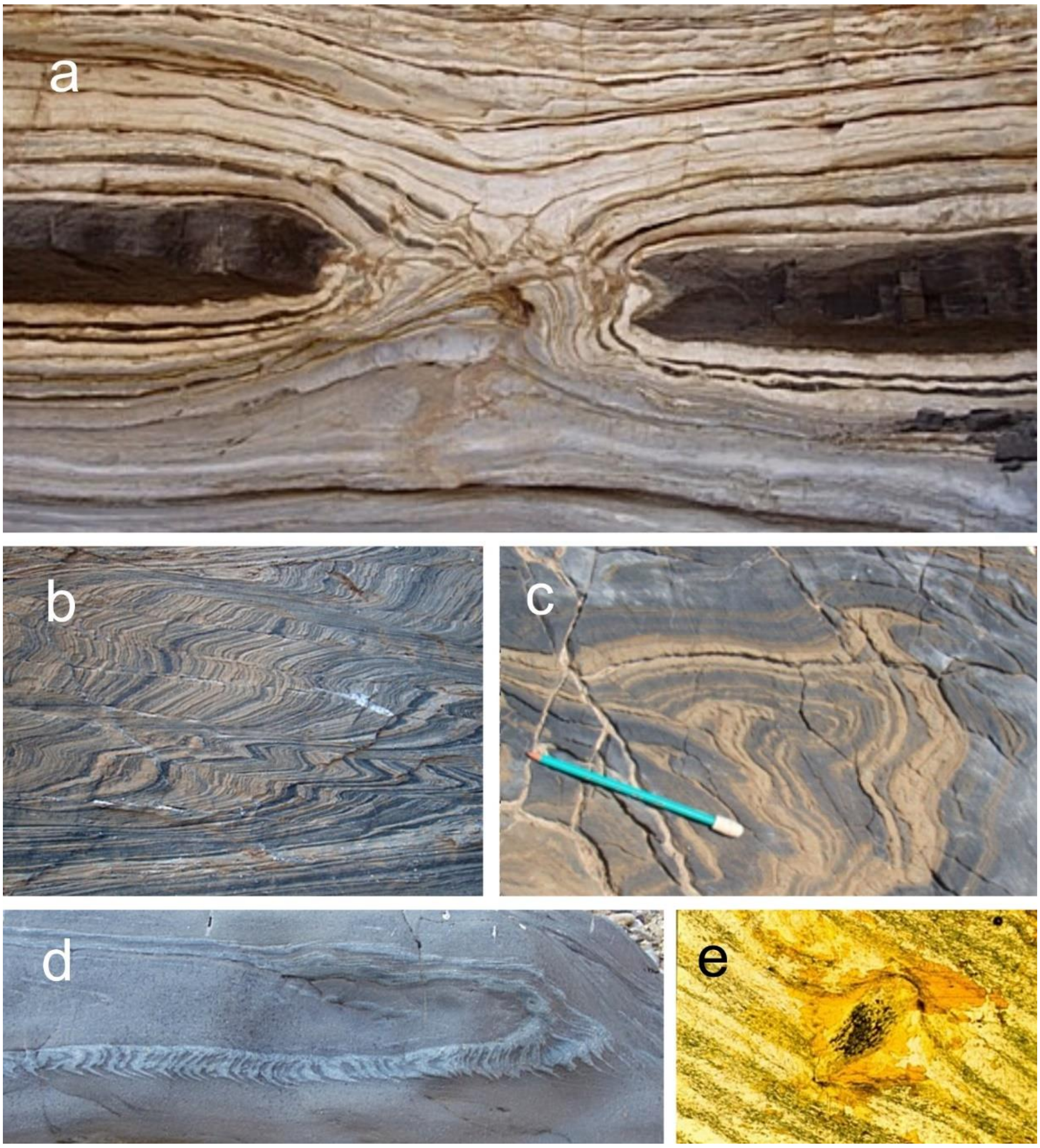

Figure 23. (a) Boudinaged pelitic layer in marble of the Gemsbok River Formation due to D_2 deformation, Lower Ugab Domain, width of view ~40 cm; (b) Strong folding and shearing in thin bedded marble due to D_1 deformation, Karibib Formation, Bethanis area, width of view ~50 cm; (c) D_2 fold refolded by D_{2a}, Karibib Formation, Vrede area; (d) D_1 fold in pelitic layer of the Kuiseb Formation north of the Omangambo Granite; the axial plane cleavage is folded in the lower limb, showing the progressive development of the folding and the generation of axial plane cleavage, with a rotational component, width of view ~1.5 m; (e) Biotite porphyroblast with S_1 foliation (perpendicular to the main foliation S_2) overlapping S_2, thus indicating continuous growth from pre- to post-D_2 (width of view 1.2 cm).

Regional D_2

D_2 forms upright folds and steep foliations (S_2) in the Lower Ugab (LUD) and Eastern Domains (ED) in response to E-W compression, orthogonal to previous N-S compression during D_1 (Figs 4, 18b, 21, 22a, b). D_2 is responsible for the spectacular N-S trending, upright folds (Figs 18b-d, 24b, c) visible in satellite images of the Lower Ugab Valley (Fig. 24a), as well as for the penetrative slaty cleavage (Fig. 24d) and related boudinage (Fig 23a). It is also the first and dominant phase of deformation in the LUD, west of the VDB-Line (Fig. 4). East of the VDB-Line, in the ED, D_2 folds overprint S_1 and L_1 (Fig. 21). S_2 and D_2 folds swing from a general N-S trend (Figs 19, 20) to a NW-SE trend near the southwestern corner of the Kamanjab Inlier of the Angola Craton, probably by deflection around a spur of the craton (Fig. 4). In summary, S_2 is the first cleavage west of the VDB-Line, along the Lower Ugab River, and the second generation east of the VDB-Line.

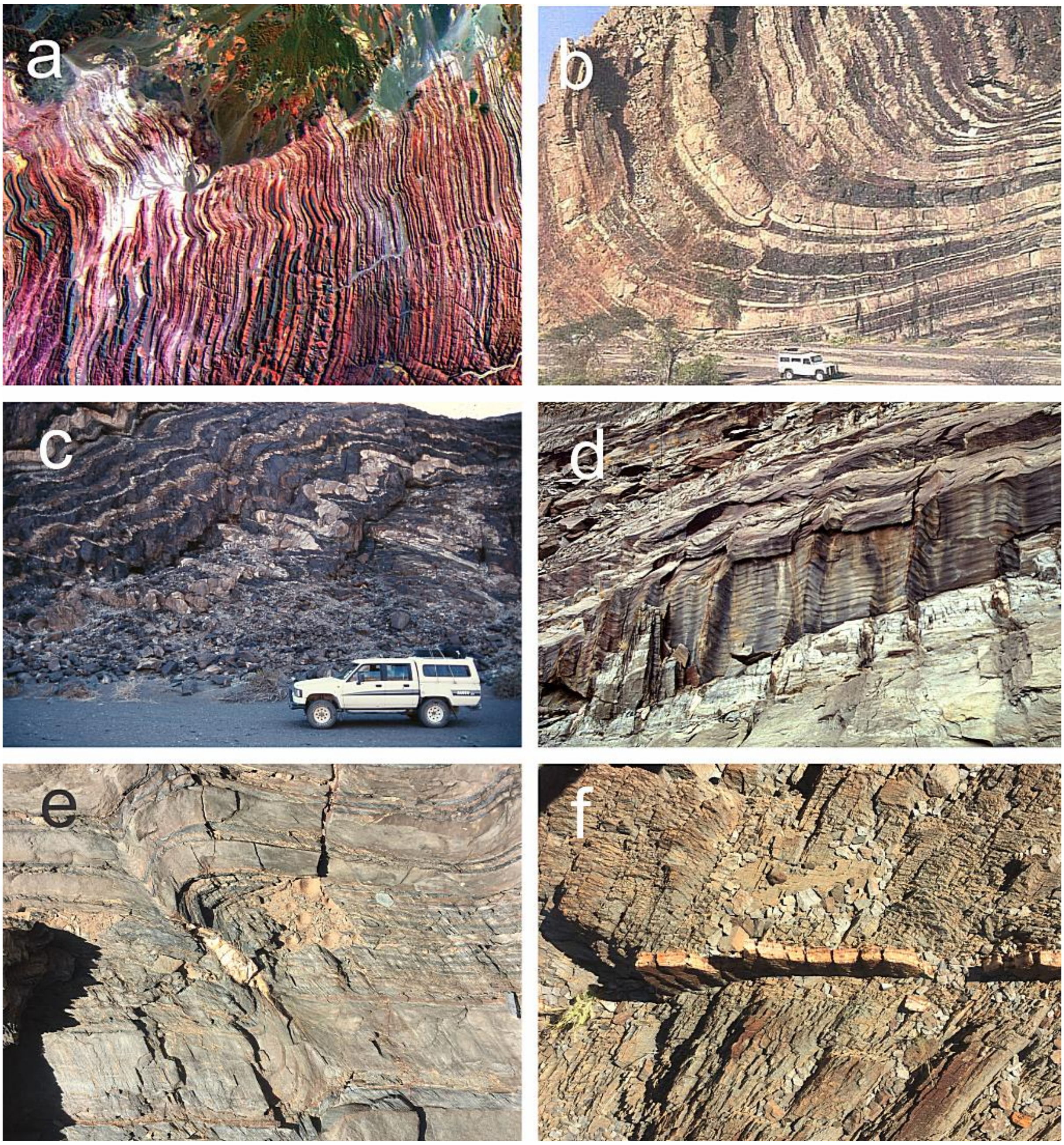

Figure 24. Outcrops of the Lower Ugab Domain: (a) Satellite image showing the interference of D_2 folds (N-S) and D_3 folds (E-W and NE-SW); (b) Typical asymmetric W-facing D_2 fold (Rhino Wash); (c) Minor D_2 folds in marble and metapelite (Rhino Wash). Complex interference of three foliations (S_2-S_{2a}-S_3): (d) Zebrapütz Formation mica schist with vertical pre-D_2 boudin necks on an S_2 cleavage plane, with subhorizontal L_{02} lineations (width of view ~6 m); (e) quartz-carbonate vein within pre-D_2 boudin vein, with S_{2a} slightly oblique to the vein (Rhino Wash, width of view ~1.5 m; see also Fig. 29); (f) quartz vein within pre-D_2 boudin neck, itself boudinaged during D_{2a}; S_{2a} subparallel to the vein (Rhino Wash, width of view ~2 m)

Regional D_{2a}

S_2 is not associated with stretching lineations and is overprinted by D_{2a} structures. D_{2a} produced mostly NW-facing folds and SE-dipping foliations (Figs 19, 20) at a small angle to S_2 (Fig. 21). The D_2-D_{2a} transition coincides with a change from coaxial E-W shortening to sinistral strike-slip dominated transpression associated with NW-SE shortening (Passchier *et al*., 2007, 2011; Maeder *et al*., 2014). This deformation may locally produce asymmetric shear sense indicators and even stretching lineations, or modify those of D_1 (Passchier *et al*., 2011; chapter 11, this paper).

In the LUD, D_2 folds were reoriented, tightened and overprinted by D_{2a}, changing from an original open upright geometry to closed WNW-facing folds in the west, and causing development of local S_{2a} and sinistral shear sense markers in the steep limbs of D_2 folds (Passchier *et al*., 2007, 2011; Schmitt *et al*., 2012). D_{2a} shortening is oriented ESE-WNW or E-W in the LUD. Locally, high-strain D_{2a} sinistral strike-slip shear zones developed, with a subhorizontal L_{2a} stretching lineation (chapter 10c). These zones are associated with development of km-scale sheath folds along the VDB-Line (Passchier *et al*., 2011). The Mulden Group foreland and molasse sediments (Unit 19; Miller, 2008; Fig. 5) were deposited after D_2, and were only deformed by D_{2a} and D_3.

Regional D_3

D_3 is a phase of minor coaxial NNW-SSE shortening, forming mostly cm to 10 m-scale upright chevron and kink-folds throughout the area (Fig. 25). D_3 structures have sharper hinged folds, with less recrystallisation of biotite. D_3 is regarded as a lower metamorphic grade phase of deformation (Fig. 25), which has not been recognised in the Kaoko Belt further north; it seems to represent simple late NNW-SSE shortening between the Angola and Kalahari cratons. Locally, because of the presence of older structures such as the large rigid plutons, D_3 can create asymmetric non-coaxial fabrics, as on the west side of the Doros North Granite (Passchier *et al*., 2007).

Figure 25. (a) Typical low-T chevron-type D_3 folds overprinting S_2 in metapelite (width of view ca. 10 m); (b) Bedding within D_2 fold, overprinted by S_3 (both pictures: Brak River Formation, Rhino Wash)

Younger structures

After the Cambrian deformation and a period of erosion, the area was affected by events associated with the opening of the Atlantic Ocean during the Cretaceous, which led to intrusion of numerous diabase dykes (Unit 23; Fig. 26) and local brittle tectonics including the formation of small extensional basins (Salomon *et al*., 2014, 2014a, 2016, 2017). These small. younger structures are not shown on the map.

Figure 26. Asymmetric deformed train of quartz-carbonate veins in pelite horizon within metapsammite - short limb of a D_2 fold, cut by 40 cm wide Mesozoic diabase dyke (Lower Ugab Domain, Ugab River)

Relationship with intrusions

Granite-syenite plutons intruded early during D_{2a}, accompanied by mobilisation of fluids leading to the intrusion of veins and formation of “flame foliation” (Schmitt *et al*., 2012; Maeder *et al*., 2014; see chapter 10b).

The relationships between deformation phases and the timing of major granite-syenite intrusions are not easy to establish, because the larger intrusions change the deformation pattern in the country rock by their large, deformation-resistant mass (Fig. 4). Locally, shear zones developed along the contact of major plutons due to relative displacement between the relatively rigid plutons and the less competent wall rocks (chapter 10b). The relation of small-scale features, such as minor intrusive veins, with deformation structures is also problematic as contact metamorphism has erased much of the structural detail close to the larger intrusions where veins are common. Further away from the plutons, isolated intrusive veins can be dated with respect to deformation (Fig. 27) but are hard to associate with a specific intrusion as their composition and grain size may deviate from the composition of the main pluton and larger dykes. Nevertheless, a relative age of intrusion could be determined by combining data from several sites. It was established that open, upright D_2 folds in the Lower Ugab Domain are cut by granite-syenite plutons, e. g. the Voetspoor and Doros North granites (Fig. 5); during D_{2a}, these D_2 folds were wrapped around the plutons, which was accompanied by sinistral rotation of the intrusive bodies. The re-orientation of D_2 folds is demonstrated by the fold cut by the southern Voetspoor Pluton (Passchier *et al*., 2007; Figs 4, 5). This sinistral rotation fits the general observation that D_{2a} was a phase of sinistral transpression (see chapter 10b).

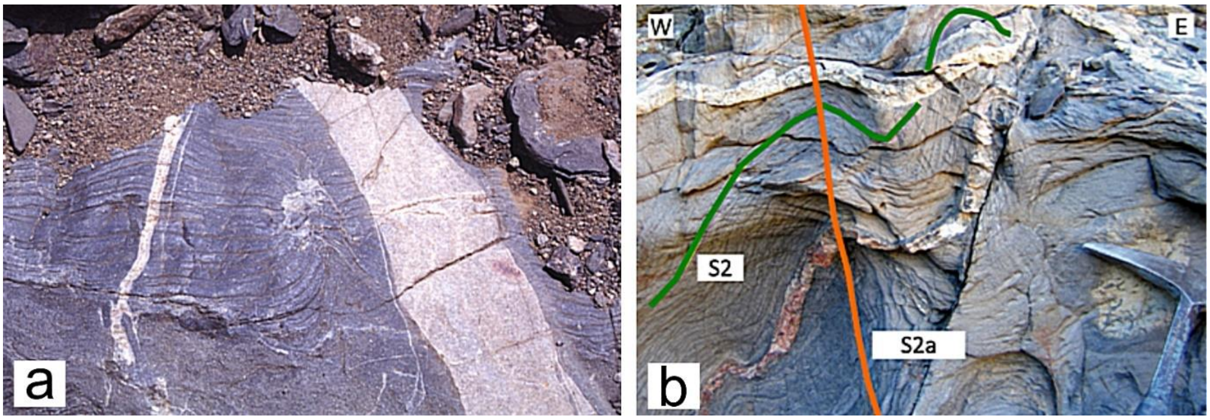

Figure 27. (a) D_2 boudin structure overprinted by an intruding aplite dyke, related to a major granite body; (b) Detail of the interaction of deformation and minor intrusive veins at some distance from the main pluton; older quartz veins and S_2 are folded by D_{2a}, but an intrusive granite vein (subhorizontal, in upper part of the image) is only gently folded, indicating its syntectonic age.

Quartz-carbonate veins

All stratigraphic units in the LUD and ED contain several generations of deformed quartz-carbonate veins. Their age is hard to establish in the ED, because of the complex and intense later deformation. In the LUD, deformation intensity is less, allowing more accurate determination of their relative age. There seem to be at least two main generations of vein-related structures in the LUD, i. e. the first predating D_2, and the second postdating it.

Several sets of veins predate D_2 folds (Maeder *et al*., 2007, 2014) and may be associated with D_1 in the ED, or with diagenesis (Fig. 28). In alternating psammitic and pelitic rocks, veins mostly develop in the metapelites, probably because of high fluid pressures (Maeder *et al*., 2007, 2009, 2014; Fig. 29). These older veins are deformed in a complex manner and have helped to establish the sequence of development of the large folds in the LUD (Fig. 29). Many veins developed as necks in boudin or mullion-like structures, which subsequently developed an asymmetric shape during D_{2a} or D_3 (Figs 24e, 28c, 29). These veins were in some cases themselves boudinaged (Fig. 24f). A separate, minor set of veins formed during late D_2 or early D_{2a} as they cut S_2 and are deformed by D_{2a} and D_3 (Fig. 29). These veinlets locally formed a separate, special foliation ("flame foliation", S_{2f}) composed of biotite selvages around thin vein-related fractures (Maeder *et al*., 2007). This flame foliation is thought to be associated with granite intrusion and associated locally increased fluid pressures. S_{2f} locally modified into S_{2a}, which then developed into a spaced crenulation cleavage (Fig. 29; Maeder *et al*., 2007, 2009). Details of these vein networks are given by Maeder *et al*. (2014), but as veins are small and observations locally restricted, they have been omitted from the map (Appendix I).

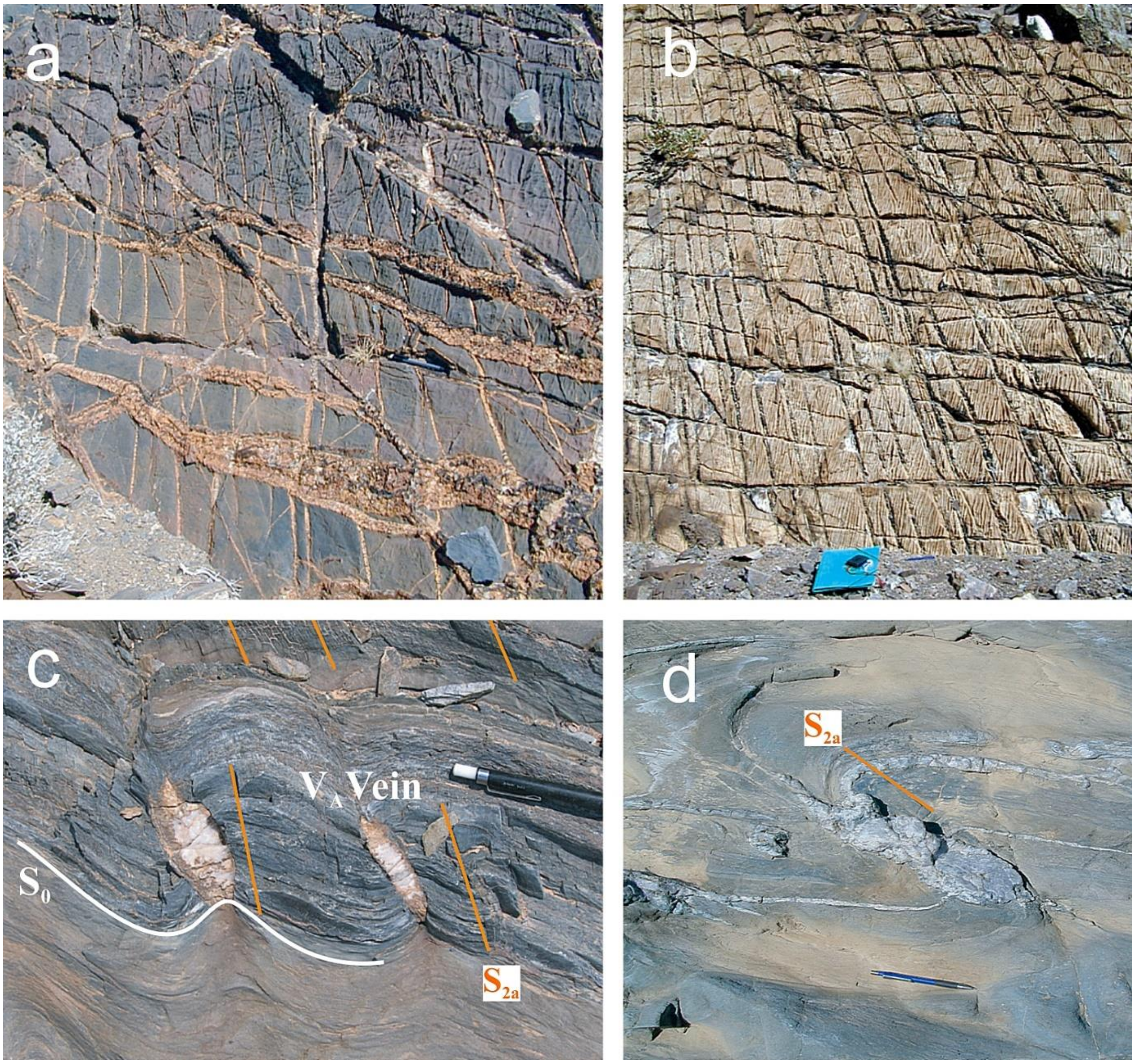

Figure 28. Aspects of quartz-carbonate veins in the LUD north of the Ugab River seen parallel (a, b) and oblique (c, d) to bedding: (a, b) Several sets of cross-cutting early-D_2 veins seen on bedding surfaces, Brandberg West (a) and lower Gemsbok River Formation (b); (c) Asymmetric boudins in metapelite, with pre D_2 quartz-carbonate veins in the boudin necks; S_2 is subhorizontal and S_{2a} is axial planar to the folds; (d) Two sets of veins seen oblique to bedding, folded by D_{2a} (after Maeder *et al*., 2014)

10. Local Geology

10a) D_1 thrusting along the Kamanjab inlier (C.W. Passchier, R. A. J. Trouw)

Fig. 30 shows the southern limit of the Kamanjab Basement Inlier, exposed in the northern part of the mapped area, where, contrary to the areas further south, clear thrust planes are present. Thrust planes are gently dipping to subvertical, probably as a result of back-tilting of hanging wall blocks. The basement is locally present in the hanging wall to the thrusts, indicating N-directed shortening. Although some of the thrust planes are developed as brittle faults, with breccia and gouge, most of them are low-grade thin mylonite zones with N-S trending or subvertical stretching lineations. The structures are interpreted as being associated with N-directed thrusting during the D_1 deformation phase. Some of the thrust planes, especially the one in the Holocene-filled graben which contains the C39 main road (Figs 5, 30; Appendix I), were apparently affected by reactivation as dextral ductile shear zones during D_{2a} (Figs 31, 32).

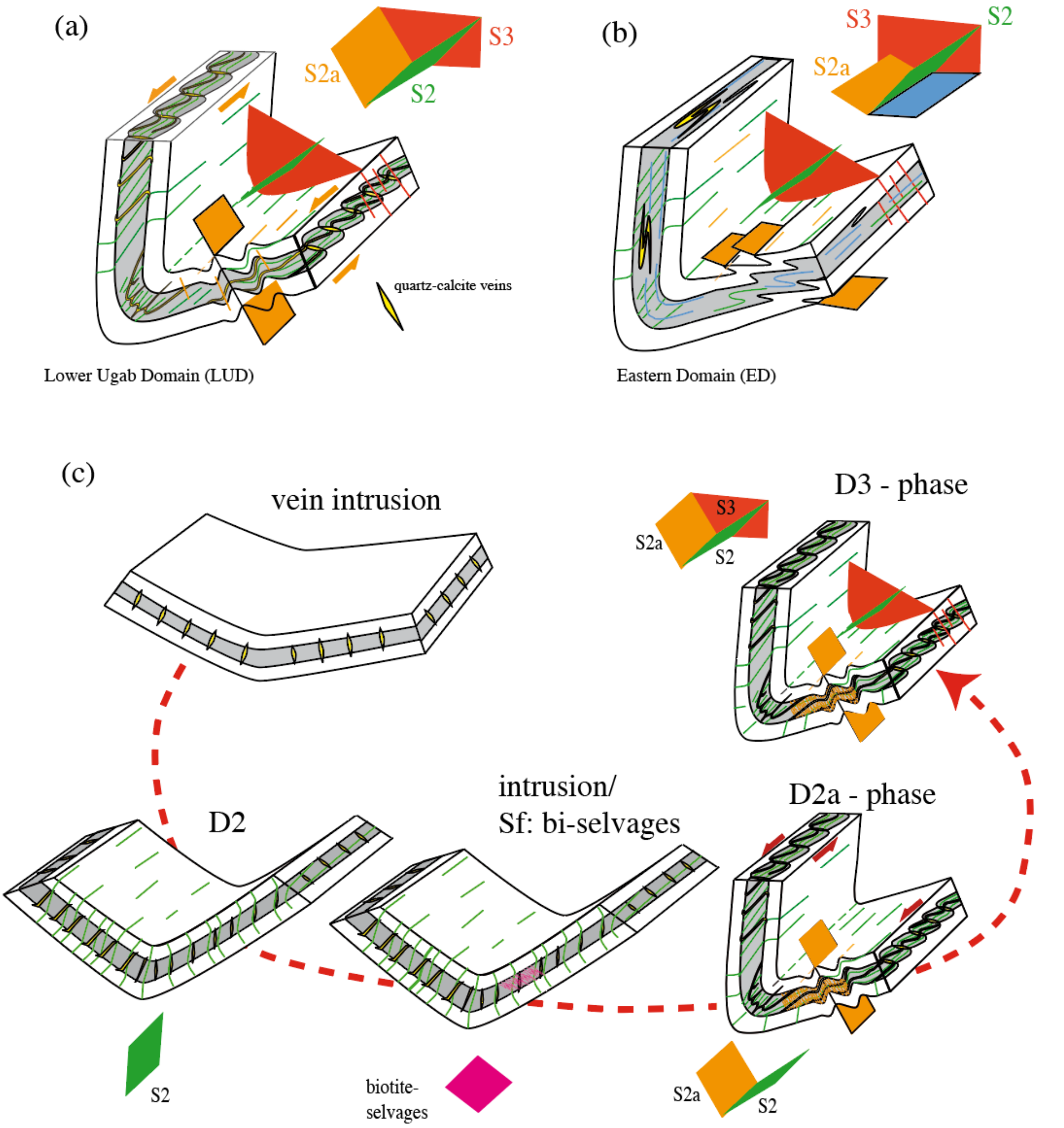

Figure 29. Schematic summary of the main generations of vein-related structures in (a) the Lower Ugab Domain and (b) the Eastern Domain; (c) shows the inferred sequence of development in the LUD.

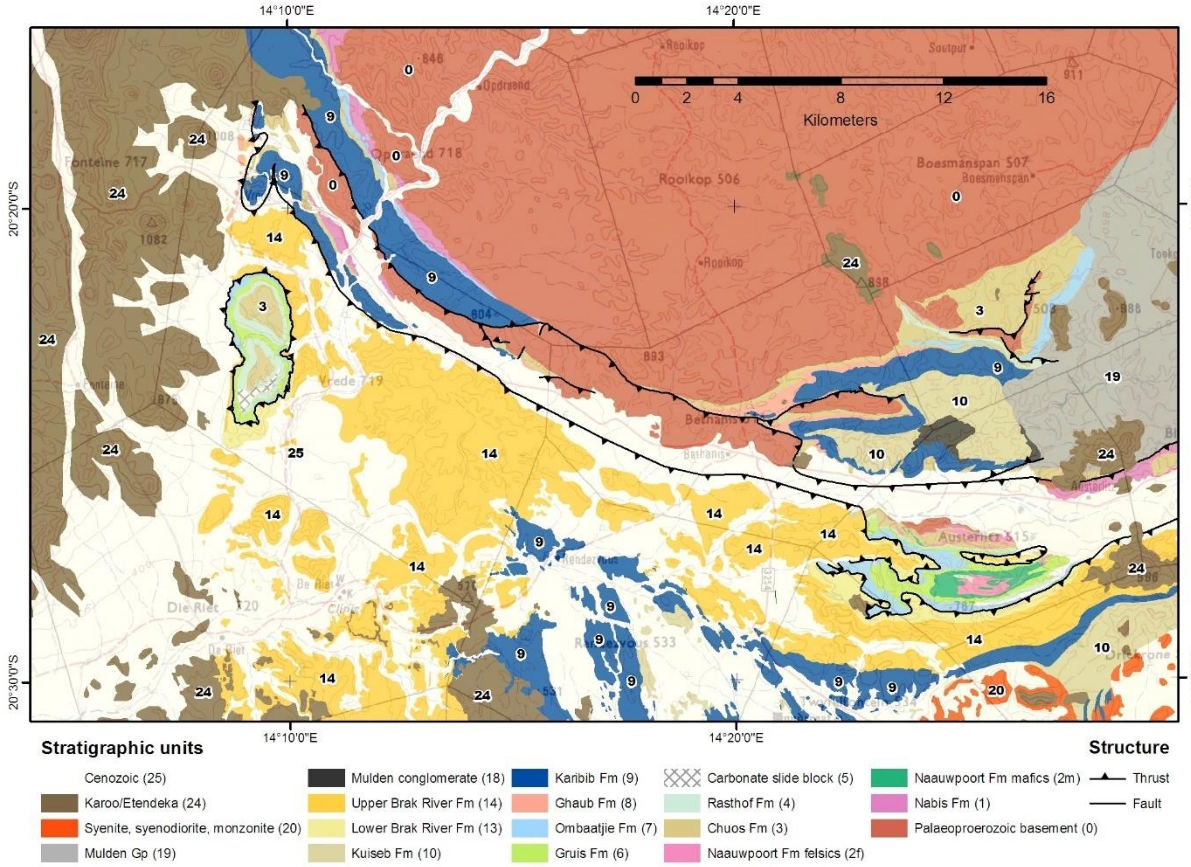

Figure 30. Southern limit of the Kamanjab Basement Inlier

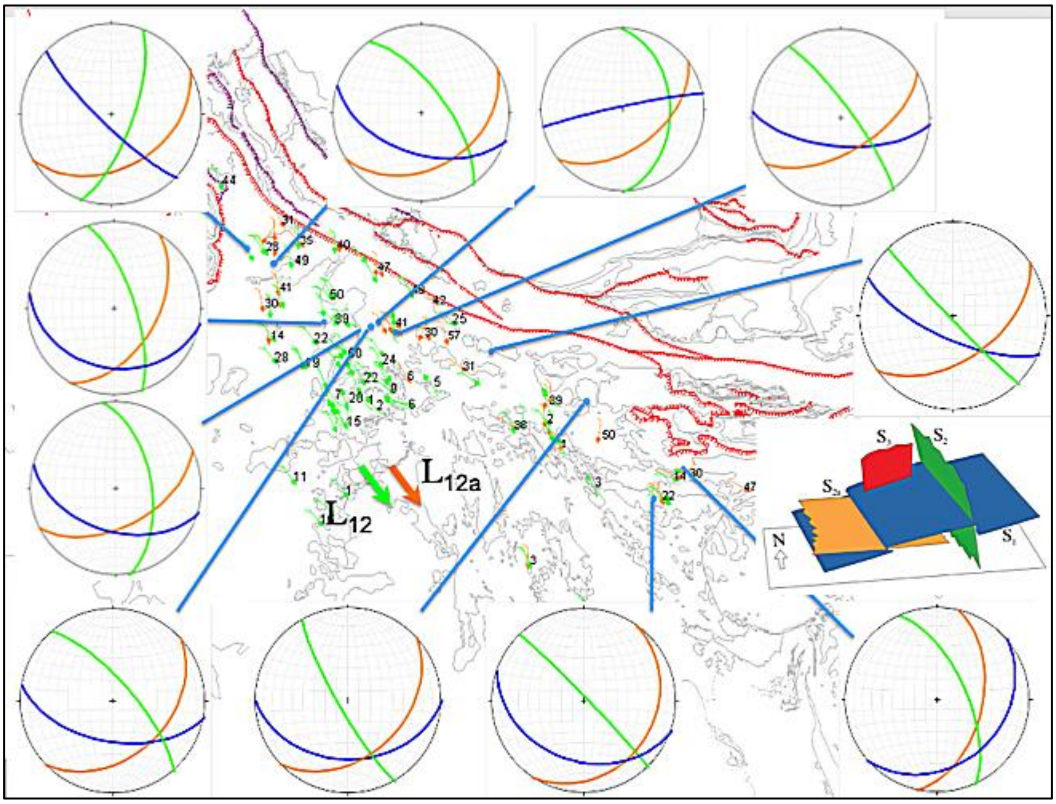

Figure 31. Representative foliations south of the Kamanjab Inlier, with simplified stereograms showing the local orientation of the main foliations. Arrows indicate intersection lineations of foliation surfaces

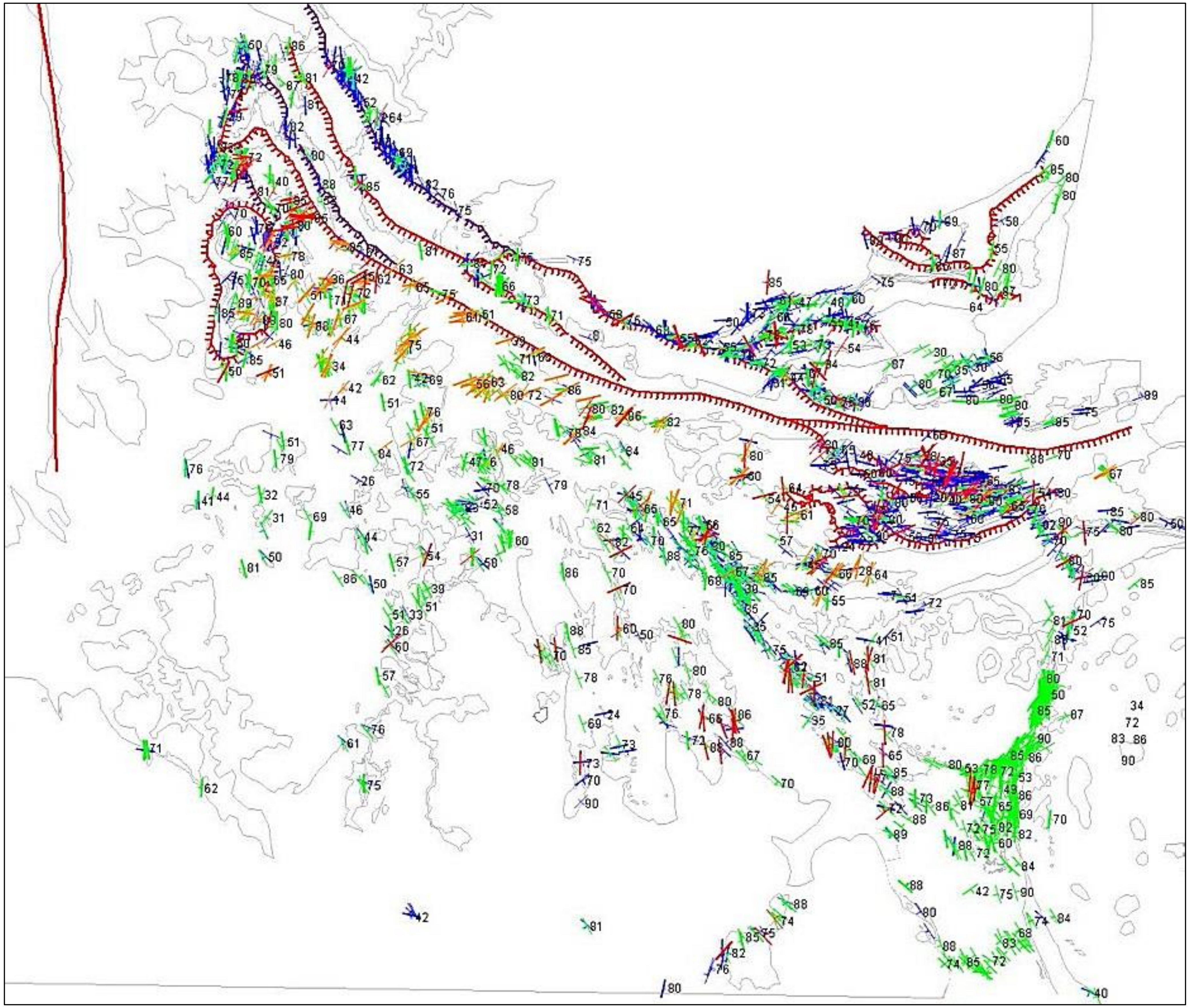

Figure 32. Foliation south of the Kamanjab Inlier; colours of measurements correspond to Fig. 20a. The deflection of S_{2a} planes along the southern thrust plane in the C39 valley suggests reactivation of the thrust planes as dextral shear zones during D_{2a}.

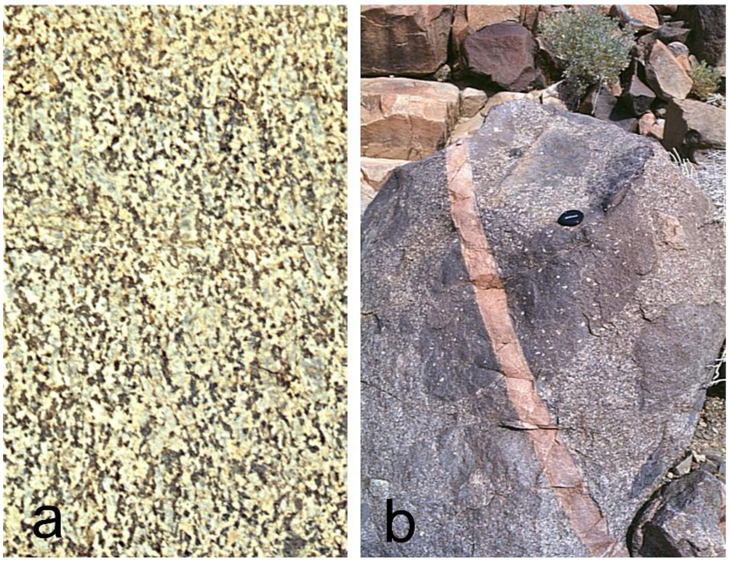

Figure 33. (a) Typical syenite of the Voetspoor Pluton (width of view ~15 cm); (b) Darker, dioritic part of the Voetspoor Pluton, with more mafic xenoliths, cut by a vein of biotite granite (width of view ~60 cm)

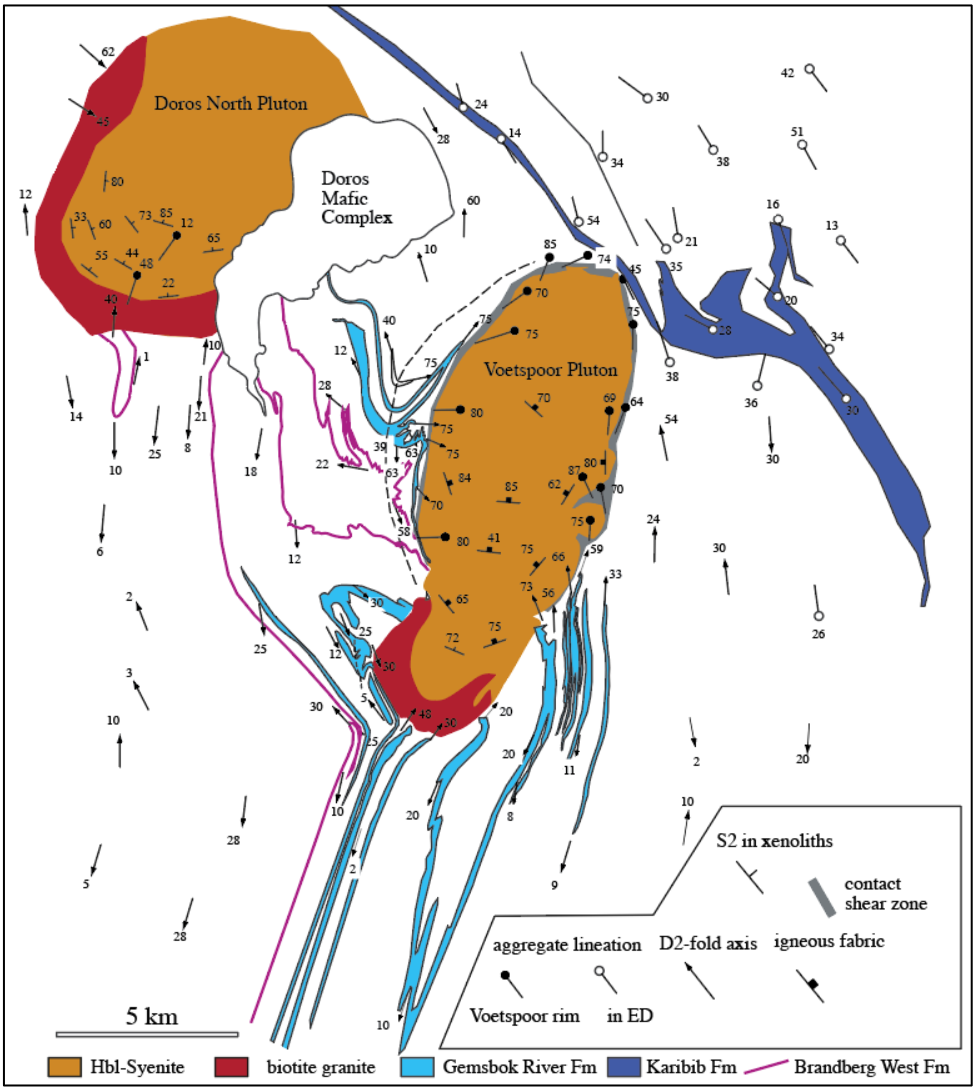

Figure 34. Orientation of D_2 fold axes and lineations around the Voetspoor and Doros North Plutons, showing a representative selection of S_2 measurements in metasedimentary rock panels and of igneous foliation in the syenite; selected lithological contacts are traced for reference (after Passchier *et al*., 2007).

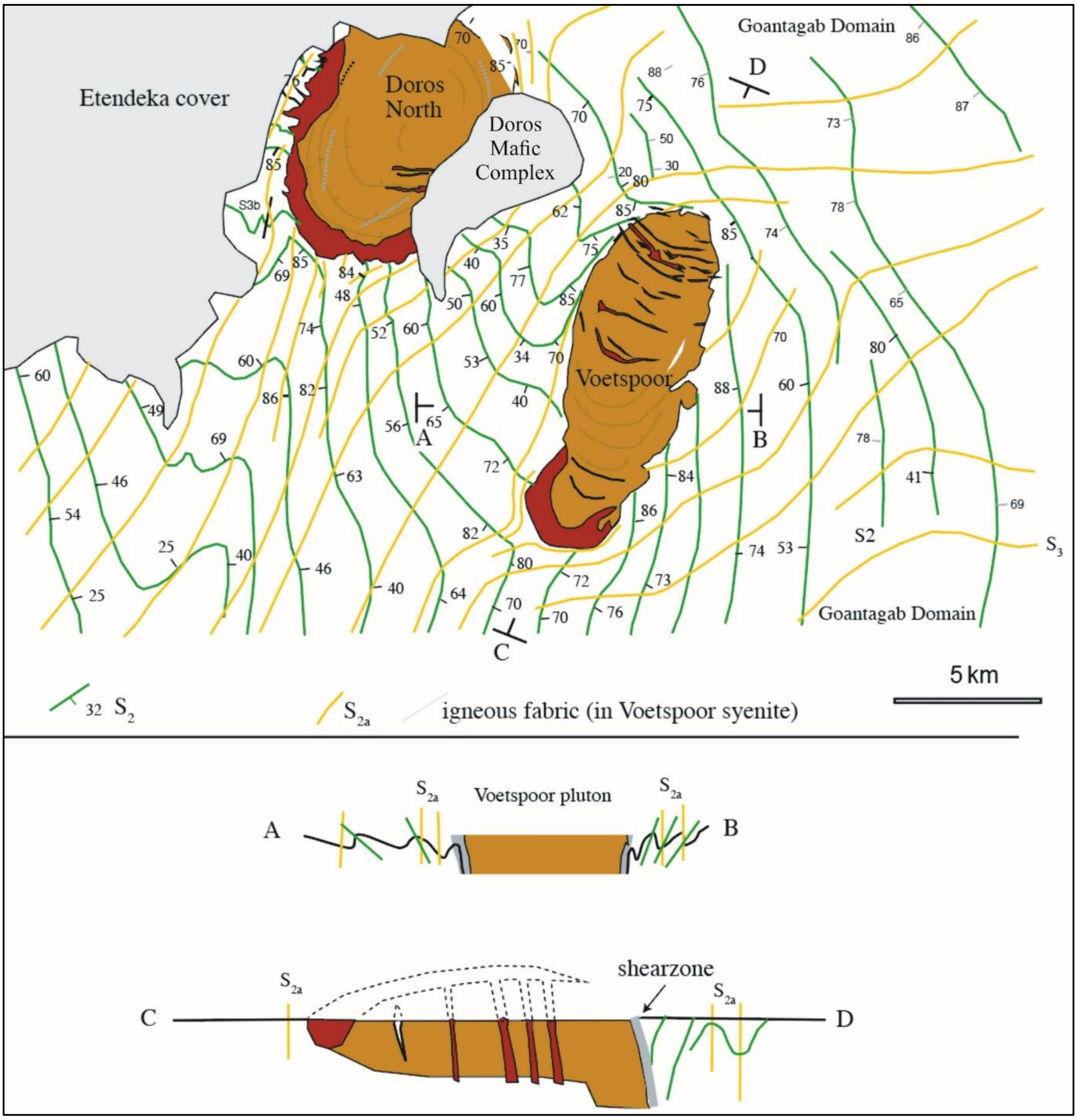

Figure. 35. Structural setting of the Doros North and Voetspoor Plutons. Foliation traces (strike trends) of S_2 and S_{2a} are shown in green and orange, respectively. Each pluton is composed of older hornblende syenite (brown) and younger biotite granite (red). Flow foliation in the syenite is shown as contour lines. The lower part of the figure shows reconstructed profiles through the Voetspoor Pluton (after Passchier *et al*., 2007)

10b) <u>Arrangement and internal structure of the Doros North and Voetspoor Plutons (C. W. Passchier, R. A. J. Trouw)</u>

The Doros North and Voetspoor Plutons are composed of two compositional intrusive phases, i. e. hornblende syenite and younger biotite granite (Figs 33-35). Both show an internal flow fabric within the syenite, marked by the preferred orientation of large K-feldspar crystals. This flow fabric lies parallel to the outer edge of the pluton, but dips inwards, with increasing steepness, towards the centre (Fig. 34). Besides this flow fabric, panels of metasediment, some with foliation and folds parallel to the panels, occur within the syenite parallel to the flow fabric (Fig. 4). In the Voetspoor Pluton, the mafic fraction increases from the rim to the core of the northern part of the intrusion. Biotite granite is more homogeneous and displays a half-moon shaped geometry along the southern side of the intrusions; it also occurs as NW-SE trending major dykes within the syenite (Figs 34, 35).

The eastern wall rocks of the Voetspoor Pluton are marked by a subvertical ductile shear zone with steep stretching lineations (Fig. 34; Passchier *et al*., 2007). D_2 folds with subhorizontal axes away from the body show steepening of axes close to the pluton. This is especially evident on the SE side, where an isoclinal D_2 fold closure lies close to, but does not reach the pluton (Fig. 34); these are anticlines with axes plunging towards the pluton. Shear zone and orientation change of D_2 folds suggest that the pluton descended with respect to the wall rocks.

The syenite apparently intruded as sill-like bodies in several sheets, mainly by displacing the footwall. This may be partly due to D_{2a} constriction around the solidified pluton, and partly to descent of the lower part of the pluton, disrupting existing open upright D_2 folds and S_2 foliation in the metaturbidites (Fig. 36). During this descent, more sheets of syenite, and possibly biotite granite intruded at higher, now eroded levels (Figs 35, 36). Numerous sheets of the intrusion can be partially recognised by large panels of metasedimentary wall rock separating them (Appendix I; Fig. 36). The Doros North Pluton may have formed in a similar manner, but lack of outcrop on its north and east sides precludes further conclusions.

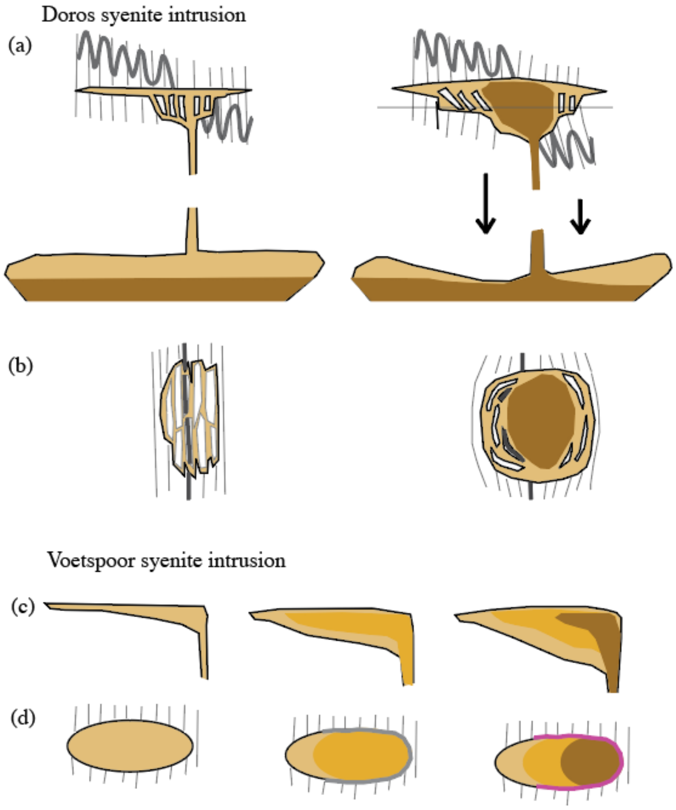

Figure 36. Schematic representation of the hornblende syenite intrusions at the Doros North (a, b) and Voetspoor (c, d) Plutons: (a, c) SW-NE cross-sections at several development stages of the plutons; (b, d) Planar horizontal cross-sections. In the Doros North Pluton (a) magma detached many panels of metasedimentary rock parallel to the foliation, which were subsequently transported to the outer parts of the pluton. In this model, space for the intruding magma is made mainly by descent of the floor into a compositionally layered magma chamber at depth. In the Voetspoor Pluton (c, d) development is similar but descent and intrusion are asymmetric. Darker colours indicate increasingly mafic composition of the syenite intrusion. The faint grey/purple line in (d) indicates the developing rim shear zone. The rotation of the plutons by D_{2a} is omitted for clarity (after Passchier *et al*., 2007).

D_2 folds surrounding the Voetspoor Pluton are deformed in a complex manner (Figs 34-36). Open D_2 folds are transected by the main body of the intrusion, and by minor veins thought to be derived from the main intrusion (Fig. 37). Folds and foliations interpreted to belong to the D_{2a} phase wrap around the syenitic part of the pluton (Fig. 35) but are locally cut by the biotite granite (Passchier *et al*., 2007). Some D_2 folds are open adjacent to the pluton and tighten away from it (Figs 34, 35); this is especially obvious in folds NW and SE of the Voetspoor Pluton (Fig. 37). Besides a change in tightness, the D_2 folds also change orientation, from nearly E-W trending close to the pluton to N-S trending at a distance (Figs 34, 37). The overall geometry can be explained by a 45-60° anti-clockwise rotation of the Voetspoor Pluton during D_{2a}, which is a phase of sinistral transpression (Fig. 37). The Doros North Pluton may also have undergone some rotation, as indicated by deflection of D_2 folds on its southern side, but lack of outcrop on the northern side prevents further deductions. Km-scale D_{2a} strain shadows formed on the NE and SW sides of the Voetspoor and on the S side of the Doros North Plutons (Fig. 35).

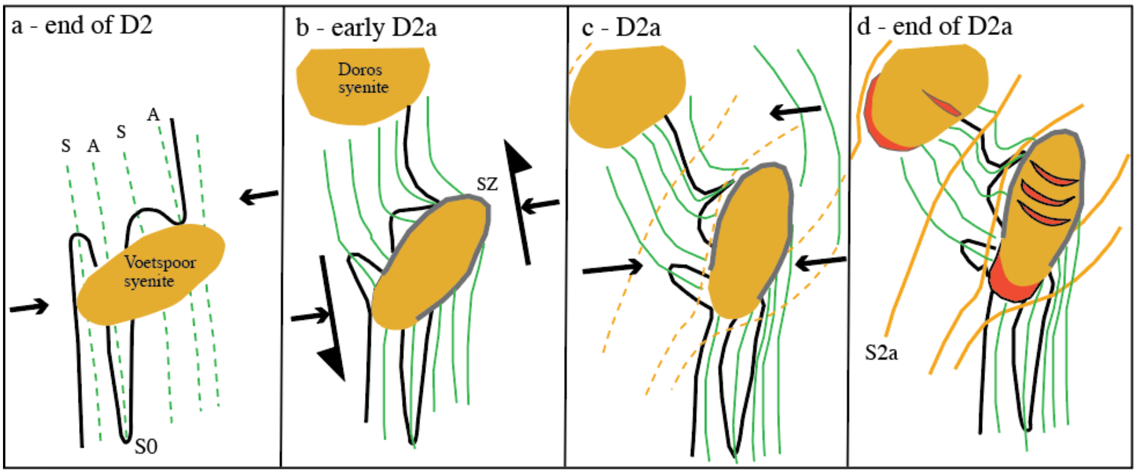

Figure 37. Schematic representation of the structural development surrounding the Doros North and Voetspoor Plutons; original intrusion into open D_2 folds was followed by sinistral D_{2a} transpression, rotating the plutons, as well as tightening and changing the orientation of D_2 folds. Close to the Voetspoor Pluton, D_2 fold closures were protected from D_{2a} deformation. Biotite granite intruded relatively late during D_{2a}.

10c) Sheath folds in the Eastern Domain (C. W. Passchier, R. A. J. Trouw)

The western part of the ED, close to the VDB-Line, is known as the Goantagab complex (Fig. 3), schematically shown in Fig. 38. Stratigraphically it consists of the four lower formations of the ED, with a large volume of diamictite and a mafic intrusive complex on its western edges (Fig. 38). The Goantagab complex is a large-scale D_2 anticlinorium. Its eastern side consists of two D_2 domes with N- and S-plunging axes, while its western side shows a very complex outcrop pattern (Fig. 38). Its structure is envisaged as the result of five interfering deformation events. The western edge of the Goantagab complex may have acted as a syn-depositional normal fault in the original sedimentary succession, possibly as a fault scarp, along which diamictite accumulated and mafic magma intruded. These structures were overprinted by N-directed thrusting, possibly by inversion of normal faults, creating S_1 foliations and subhorizontal fold structures, stretching lineations and N-vergent shear sense indicators; the latter in turn were superimposed by upright open D_2 folds, developing an S_2 crenulation cleavage. Subsequent intrusion of syenite-granite plutons was followed by non-coaxial D_{2a} deformation, which formed simple upright structures and even stretching lineations and shear sense indictors close to the Omangambo Pluton (Fig. 41). In the western part of the ED, D_{2a} gave rise to development of sheath fold-like D_1-D_2-D_{2a} interference patterns, refolding the D_1 stretching lineations and all older structures (Fig. 39a). The reconstructed 3D-geometry of the complex western part of the ED is shown in Fig. 40. It is thought that the intense refolding structures along the western edge of the ED may be due to the presence of granite plutons, which pinned part of the structures but moved with respect to each other during D_{2a}. Further details are given by Passchier *et al.* (2011); note, however, that the structural reconstruction in this paper was replaced by the one outlined above. Figures 38 to 40 from Passchier *et al.* (2011) were also updated here. The interpretation of S_2-S_{2a} as "key ring foliations" (Passchier *et al.*, 2011) has been abandoned.

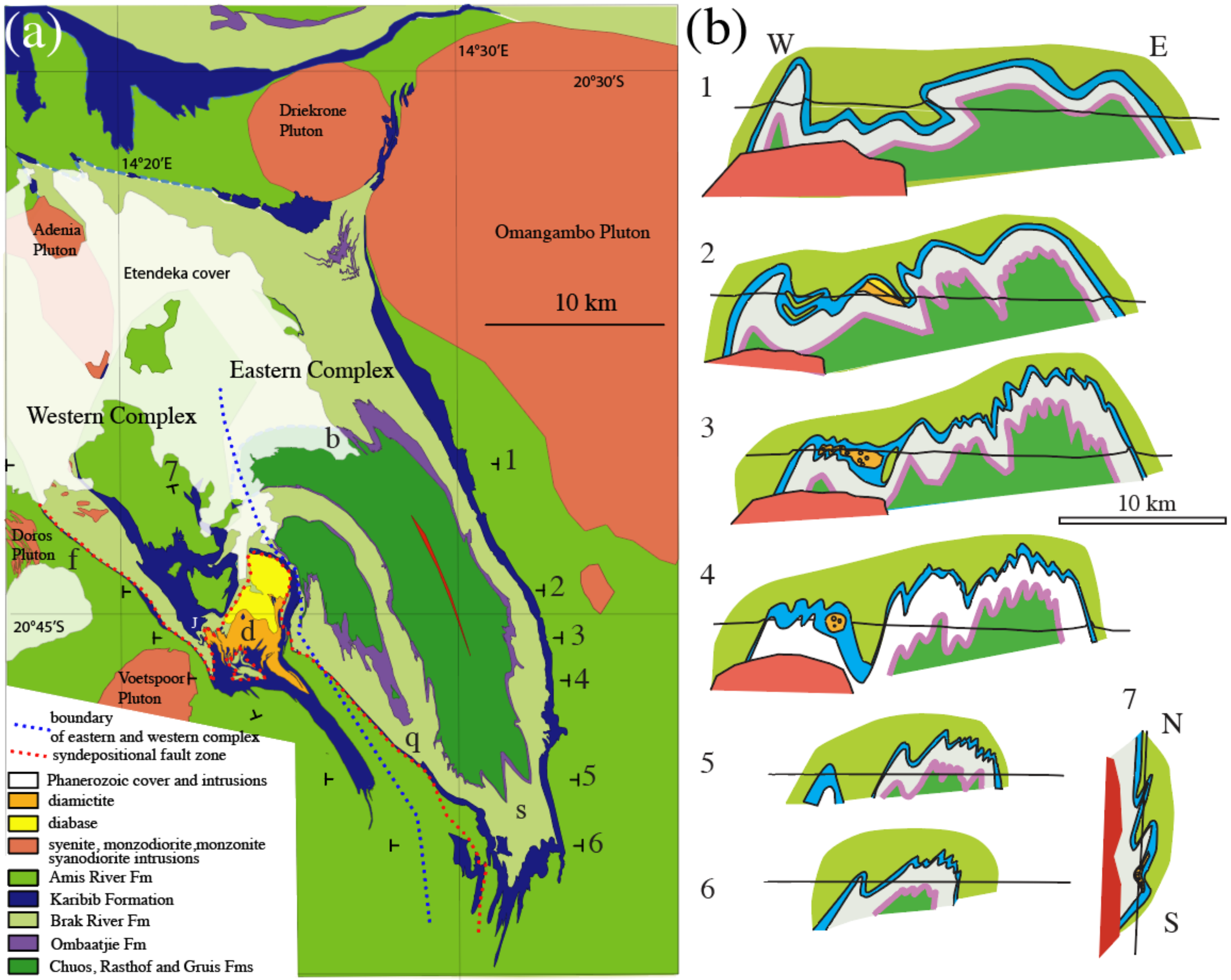

Figure 38. (a) Simplified structure of the western edge of the Eastern Domain. Lower case letters mark locations shown in Fig. 40b (b) Schematic profiles through the western edge of the Eastern Domain, marked in (a) with numbers (modified after Passchier *et al*., 2011)

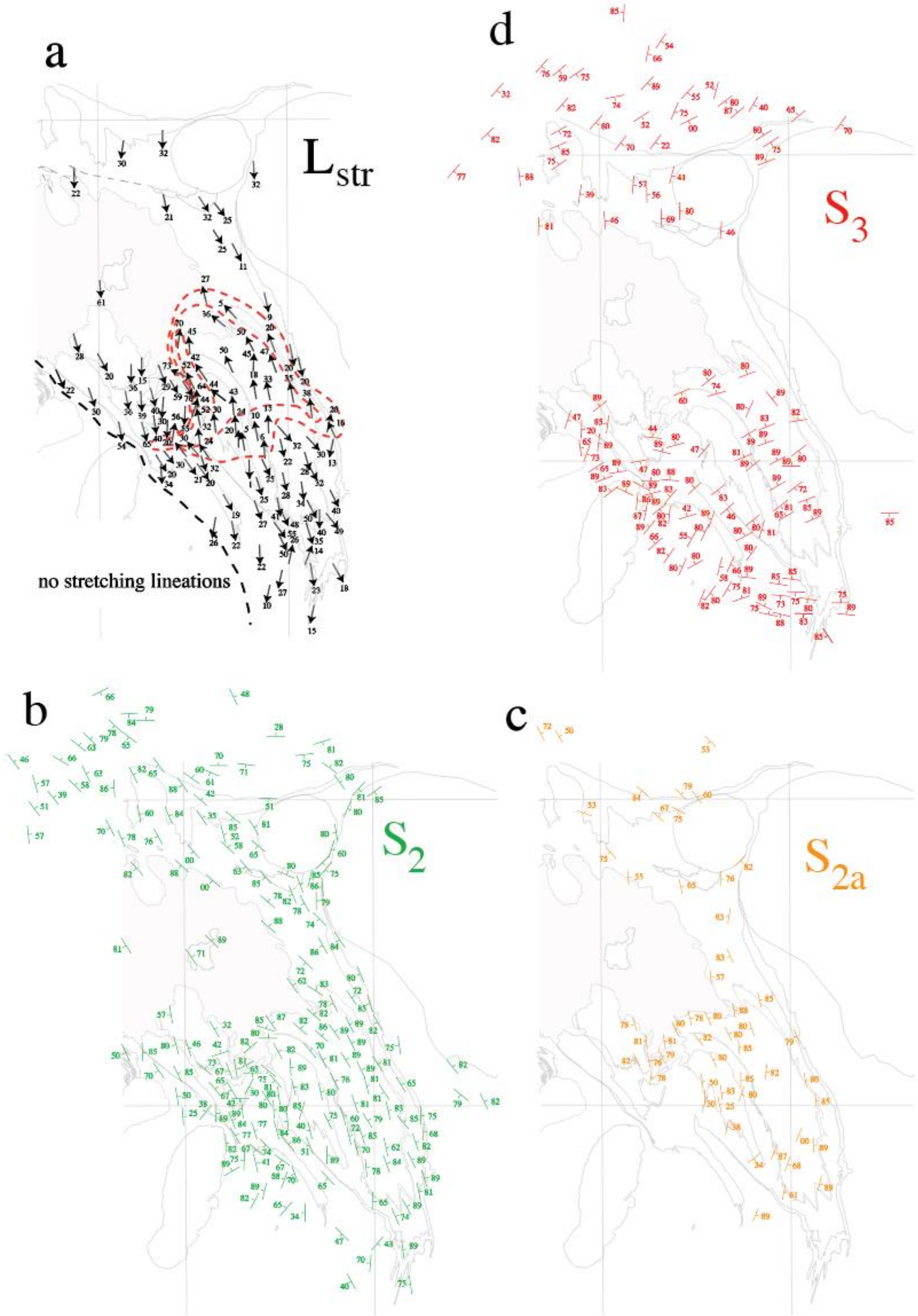

Figure 39. Distribution of stretching lineations and foliations in the ED; L_{str} shows an uncommon change in orientation indicated by contour lines of plunge (modified after Passchier *et al*., 2011; see also Appendix II).

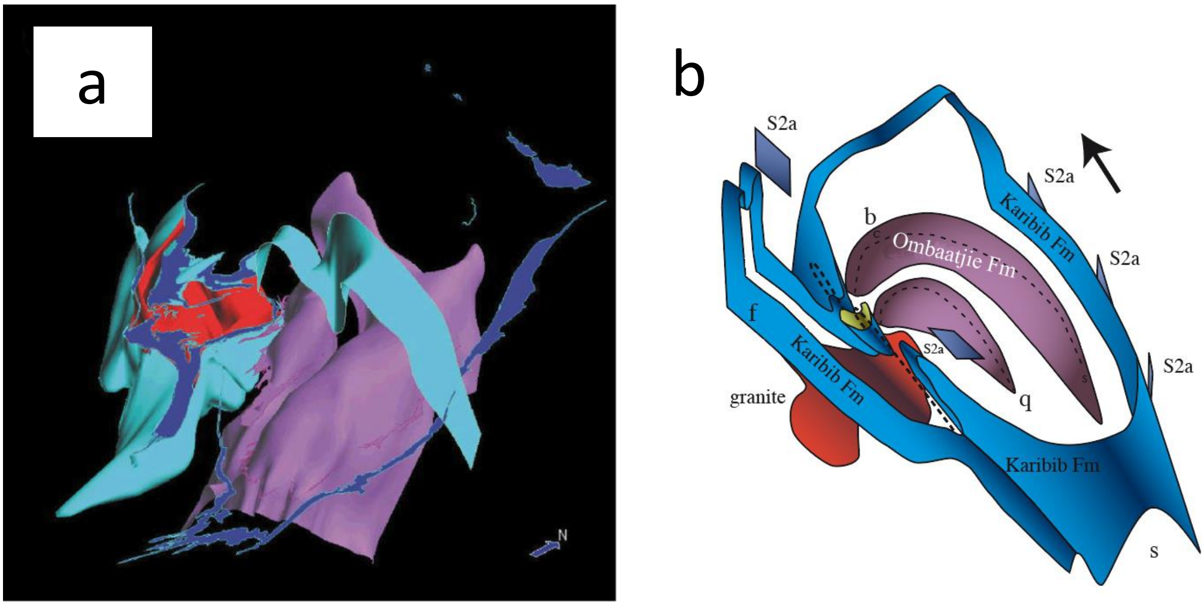

Figure 40. Schematic 3D-diagram of the main structure of the Eastern Domain. (a) computer-generated image; (b) simplified version with cutaway fold. Blue represents the Karibib Formation, purple the Ombaatjie Formation marble. The two subsidiary D_2 domes in the centre of the Eastern Domain were refolded to an E-W orientation, while in the western part, km-scale sheath fold-like structures developed. Lower case letters mark locations shown in Fig. 38a (modified after Passchier, *et al*., 2011).

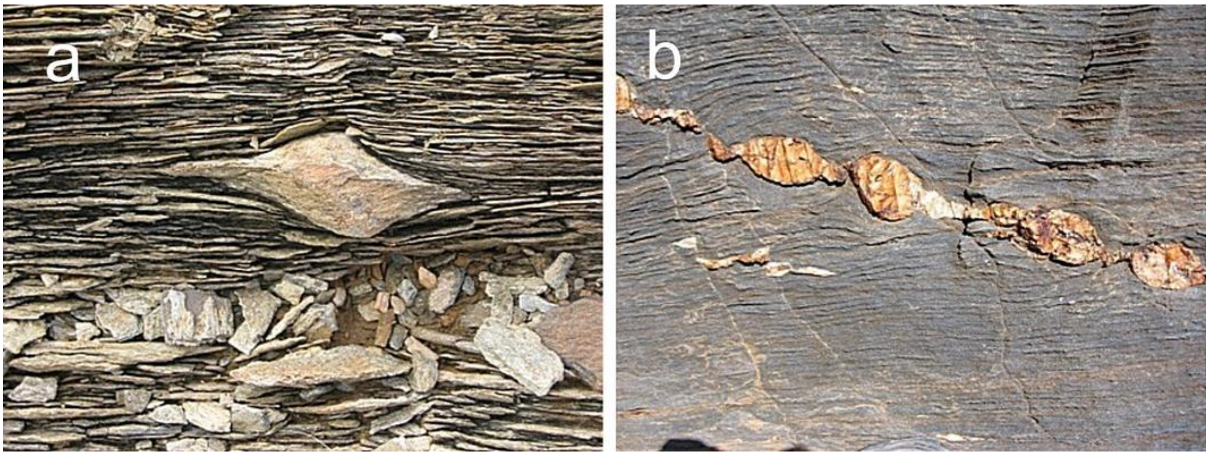

Figure 41. Sinistral shear sense indicators of D_{2a} age in the Eastern Domain: (a) Asymmetric deformed pebble in diamictite (Ghaub Formation – locality d in Fig. 38a; width of view ~40 cm); (b) Asymmetric boudinaged vein fragments in marble (Ombaatjie Formation – locality b in Fig. 38a; width of view ~1.2 m)

10d) <u>The Vrede Domes (R. A. J. Trouw)</u>

Two ring-shaped structures in the NW corner of the map are known as the Vrede Domes and informally as the "donuts" (Figs 3, 42). These structures are two adjacent anticlinal domes, where deeper portions of the stratigraphy are exposed. The Vrede Domes have been interpreted as interference structures between two orthogonal deformation phases, which we labelled D_1 (E-W trending) and D_2 (NE-SW trending; Maloof, 2000; Nascimento *et al*., 2016). However, a close inspection of the measurements in and around the domes (Fig. 42) reveals some inconsistencies in this interpretation.

The interference hypothesis proposes an early phase of N-S shortening, producing large folds with E-W axes and S-dipping axial planes. A later phase of E-W shortening and N-S axes, with subvertical axial planes would have refolded the early folds to produce the dome-like interference structures (Maloof, 2000; Nascimento *et a*l., 2016).

Detailed regional mapping resulted in the recognition of three major deformation phases (Passchier *et al*., 2002, 2011, 2016). D_1 is mainly concentrated in the northern part of the region, with S-dipping axial planes and E-W axes. D_2 is the result of E-W shortening, producing large folds, especially in the Lower Ugab Domain, with N-S axes and steep axial planes dipping either to the west or to the east. Towards the north of the area, around the Vrede Domes, structures produced during this phase curve into a NW-SE orientation, probably because of the resistance of the Kamanjab Inlier. The fold axes of the third phase, labelled D_{2a} (Passchier *et al*., 2016) follow a SW-NE trend, while the axial planes dip to the SE.

The structures in and around the domes usually strike in NE-SW direction, with the hinge line of the elongated northern dome showing the same orientation, consistent with regional D_2 (Fig. 42). Few D_1 folds were recognised in this dome and D_{2a} crenulation is rare inside the dome, but relatively common in incompetent layers of its surroundings.

The hinge line of the more elongated southern dome curves from a NW-SE orientation in the north to N-S further south (Fig. 42). Observations at the southern closure show it to be characterised by the presence of a slaty cleavage along the axial plane, consistent with the large D_2 folds in the Lower Ugab Domain (Fig. 43). Hence, the main fold of this dome with its N-S axis and steep axial plane is not a D_3 fold (D_{2a} in our present nomenclature) as interpreted by Nascimento *et al*. (2016) but of D_2 origin. Accordingly, we conclude that both domes are essentially D_2 folds with strongly curved axes (Fig. 43).

This curvature can be explained either as interference between D_1 and D_2, interference between D_2 and D_{2a}, or as D_2 sheath folding. The first explanation might, at least partly, apply to the northern dome, where several D_1 folds were recognised in its centre. However, the lack of D_1 folds around the dome as well as their tightness argues against this interpretation. In the southern dome, no D_1 folds were recognised making this interpretation unlikely. Interference between D_2 and D_{2a} folds seems a further possibility; however, very few D_{2a} crenulations were detected inside the domes, although these crenulations are common in the incompetent layers around them. Also, the strong, almost isoclinal curvature of the D_2 axes in both domes does not accord well with the attitude of the regional D_{2a} axial planes, which show moderate to shallow dips to the southeast.

The last explanation, interpreting the domes mainly as large D_2 sheath folds, has several points in its favour. In the adjacent Goantagab area, with similar stratigraphy and metamorphic grade, large fold-like structures were recognised, showing that this type of folding is not uncommon in the relatively incompetent turbiditic successions. An additional argument to re-enforce this interpretation is the large slide block in the core of the southern dome, which certainly caused a dome-like deviation of the layers on top of it in the original subhorizontal sedimentary layering. During later shortening by subsequent deformation phases, this deviation could well have initiated a major dome-like sheath fold. In the northern dome no such slide block was found, but apophysis of a gabbroic intrusion may be indicate a major gabbro body underneath, causing a similar effect as the slide block. The large sheath fold in the Goantagab area appears also to have formed on top of the extensive metagabbro body mapped in this area.

The Austerlitz Dome, east of the Vrede Domes, is cored by igneous rocks of probable sill or laccolith shape, which may have influenced the E-W elongated shape of this dome-like structure in a similar way. It may be concluded that the strongly curved axes of both domes are possibly the result of sheath folding during D_2, enhanced by D_{2a} deformation.

11. Large-scale tectonic interpretation

Using the detailed structural reconstruction made in the Eastern and Lower Ugab Domains, we attempt here to correlate them with larger-scale tectonic events, including geological information from a much wider area. Based on the available data, including our observations, we envisage events in the amalgamation of this part of Gondwana as follows (Figs 4, 44). A first phase of constriction between the Angola and Kalahari Cratons around 590 Ma (Lehmann *et al*., 2016) caused N-directed inversion of normal faults and thrusting in the Neoproterozoic platform sediments of the Angola palaeocontinent, as well as strong shallow southwards dipping foliations with down-dip plunging stretching lineations in the Eastern Domain. The VDB-Line may have acted as an accommodating transcurrent fault during D_1 or D_{2a} through reactivation of an earlier syn-sedimentary fault, which may have represented the western boundary of the Kamanjab Inlier and extended as a transform fault into the Khomas Ocean (Passchier *et al*., 2016). The D_1 event was restricted to the Eastern Domain situated east of this fault (Fig. 44).

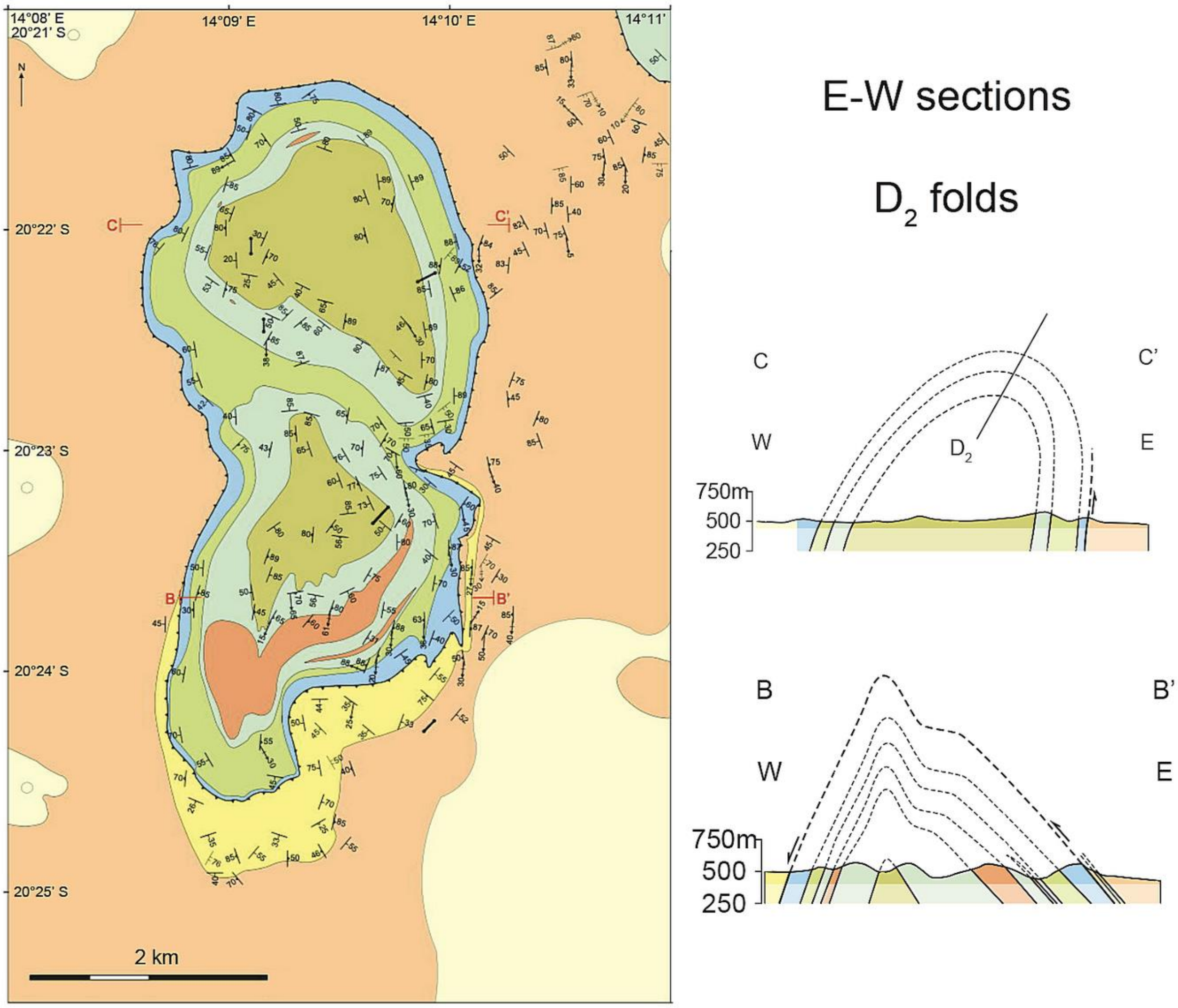

Figure 42. Detailed structural map of the Vrede Domes (left); E-W sections of the large D_2 folds with curved axes which constitute the domes, as shown in Fig. 43 below (right)

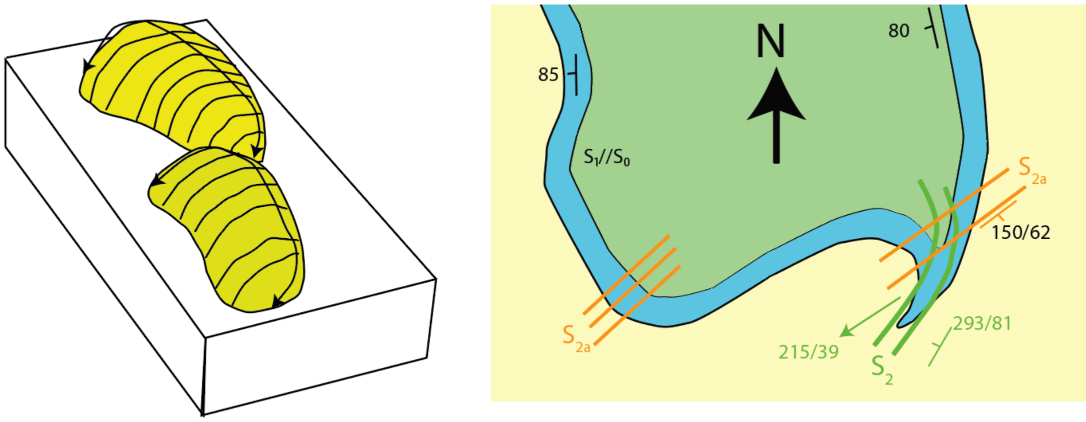

Figure 43. 3D sketch of the Vrede domes, showing the hinge line of the elongated domes, which coincide with the curved D_2 axes (left); Detailed map of the southern closure of the southern dome depicting the closure as a D_2 fold hinge with slaty cleavage along the axial plane, refolded by D_{2a} (right)

At 580-550 Ma, collision took place in the Kaoko Belt, resulting in D_2 E-W shortening (Goscombe and Gray, 2007; Gray *et al*., 2008), which later developed into the constrictional sinistral strike-slip motion of D_{2a}. Eastwards directed thrusting of the Coastal Terrane-Dom Feliciano arc onto the western Angola palaeocontinent passive margin caused intense deformation and metamorphism in the Kaoko Belt, while further south, in the Lower Ugab Domain, only open D_2 folds formed, either because of distance to the arc in the north, or because the LUD was protected by a westward spur of the Angola palaeocontinent (Fig. 4, 44). At 540 Ma a change in kinematics, from E-W constriction to a sinistral strike-slip movement in the Kaoko Belt (Kröner *et al*., 2004; Konopásek *et al*., 2005), combined with NW-SE shortening and collision in the Damara Belt, generated D_{2a} structures. Finally, minor shortening followed by uplift in the Damara Belt caused the formation of lower-grade D_3 folds around 520 Ma (Maeder *et al*., 2014).

D_{2a} coincides with the massive intrusion of granite and syenite plutons and fluid infiltration in the LUD that may be attributed to northward ridge subduction and related slab detachment in the Damara Belt (Meneghini *et al*., 2014). A minimum E-W shortening during D_2 of about 40 km in the 1.6 km thick succession is estimated for the LUD by straightening the km-scale folds, without exposure of the basement or internal thrusting. This uncommon deformation suggests an abnormally ductile middle and lower crust during D_2.

Slab detachment-related asthenospheric infiltration could explain the granitic intrusions, the fluid infiltration and the strong, ductile NW-SE / E-W shortening causing the spectacular folds and homogeneous crustal shortening during D_{2a}. The latter produced penetrative sinistral strike-slip deformation throughout the Damara Belt, as well as major crustal-scale shear zones in Namibia, Uruguay and Brazil (Fig. 1; Schmitt *et al*., 2023): minimum displacement along these shear zones exceeds 100 km (Oyhantçabal *et al*., 2011). Some of these shear zones may have originated on older zones of similar orientation as the VDB-Line, possibly on transform faults along the edge of the Khomas Ocean (Fig. 44). This hypothesis is supported by the fact that the VDB-Line was originally parallel to the transcurrent faults and bounds the Kamanjab Inlier to the west (Fig. 1). The combination of southward motion of the Coastal Terrane and of the Rio de la Plata Craton along crustal scale shear zones (e. g. the Purros Shear Zone), seems kinematically related to D_{2a} constriction in the Damara Belt.

The present T-shape of the Kaoko-Damara junction (Fig. 1) was formed by N-S constriction (D_1), followed by E-W shortening (D_2), and finally, by NW-SE constriction (D_{2a}) and strike-slip to lateral displacement of the Kaoko Belt along the termination of the Damara Belt. This implies that T-shaped triple junctions may not only form by the transection of older mobile belts, followed by frontal continental collision as in "oblique triple junctions". Instead, they may form by a combination of constriction in one leg of the junction and contemporaneous strike-slip in the other. Transform faults may have acted as precursors for these strike-slip shear zones. Other Neoproterozoic - Early Palaeozoic orogenic junctions in Gondwana may represent similar "transverse triple junctions" (Passchier *et al*., 2016). The best example is the junction of the Southern Brasília Belt and the central Ribeira Belt of South America with its strong dextral shear component (Schmitt *et al*., 2008; Trouw *et al*., 2013). Other triple junctions, such as the East African - Australia and Kuunga Orogens (Meert, 2003; Meert and Lieberman, 2008), and the Lufilian Arc and Zambezi Belts (Naydenov *et al*., 2014) formed in a similar time frame, but little is known about their kinematic details. In conclusion, transverse triple junctions may represent a common mechanism to form T-shaped junctions of mobile belts (Passchier *et al*., 2016).

12. Reinterpretation of the structural history

An important modification in the structural interpretation of the project area took place in the course of our work from 2002 onwards, because of the growing accumulation of data. The present structural schedule was first published in 2016 (Passchier *et al*., 2016). Changes made to the previous schedule affected mainly pre-D_3 deformation (Fig. 45). Initially, we regarded S_1 as a dominant phase in the entire area, with a gradual orientation change from W-facing folds (and E-dipping S_1) in the west of the LUD near the ocean through upright to E-facing folds (and W-dipping foliations) in the vicinity of the VDB-Line, to subhorizontal orientations and stretching lineations in the ED. S_2 was thought to be always orthogonal to S_1, i. e. gently dipping in the LUD, and steeply in the ED. This view was based on the assumption that the same structural phases were present throughout the area, since the intermediate-aged foliation S_{2b} (later renamed S_{2a}) had not been recognised then.

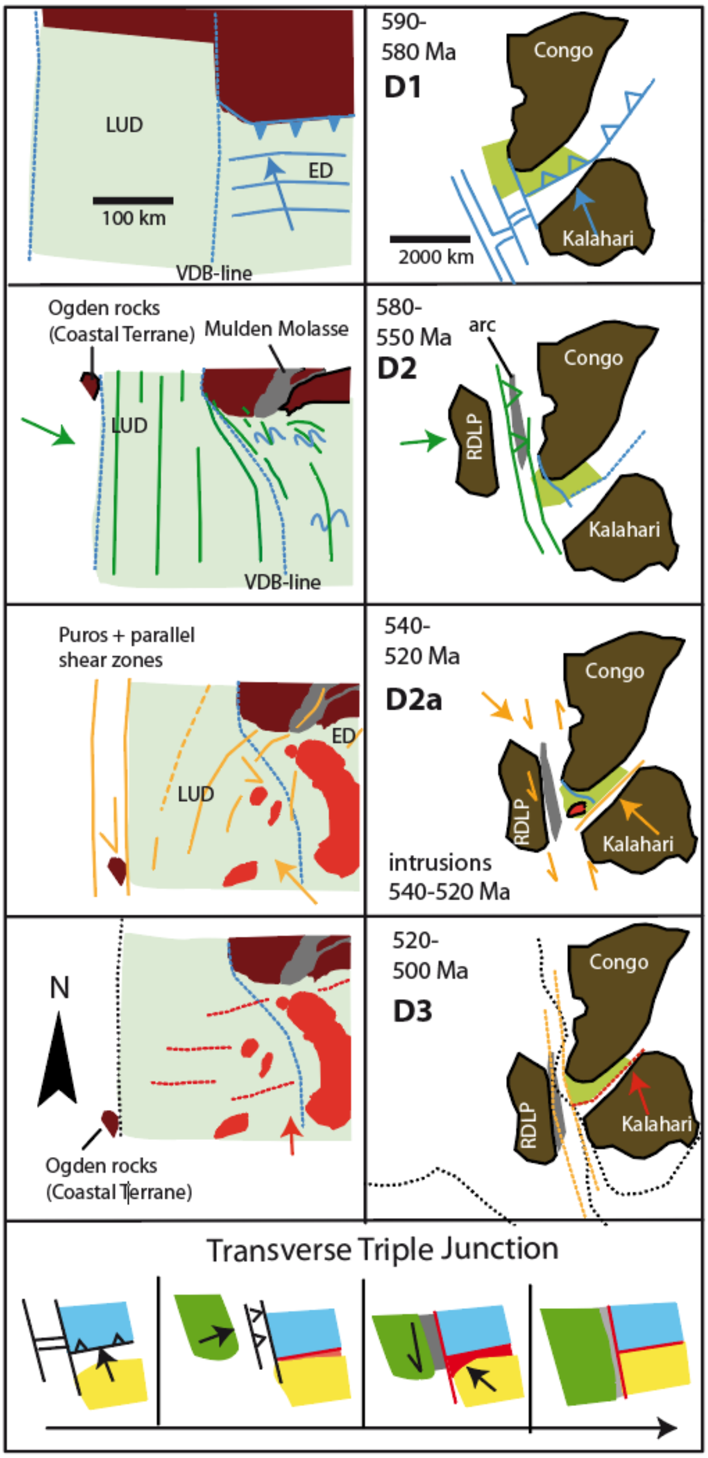

Figure 44. Schematic reconstruction of the tectonic development of the Kaoko-Damara junction (left) and the geotectonic model of craton interference, leading to the present geometry (right); a cartoon of the formation of a transform triple junction is shown at the bottom.

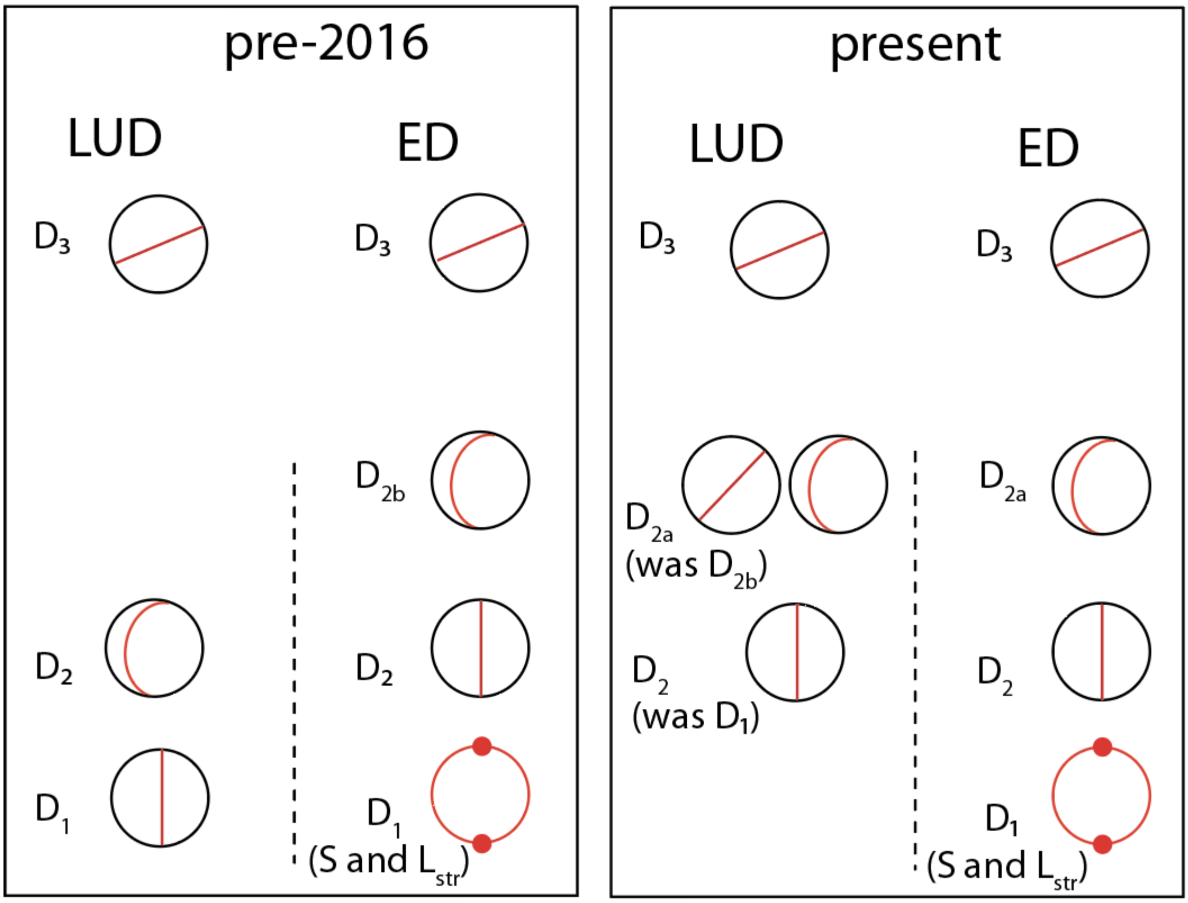

Figure. 45. Re-interpretation of the structural model on the Lower Ugab (LUD) and Eastern (ED) Domains by our group, contrasting the initial pre-2016 interpretation (left) and the present one (right). Stereograms show the approximate mean orientation of respective foliations and lineations.

During later stages of the work, an intermediate-aged foliation S_{2b} was recognised in the central part of the Eastern Domain (ED), suggesting that it was the effect of a local phase. However, between 2014 and 2016, more and more locations in the ED showed the presence of S_{2b}, making a reinterpretation necessary. Our present view is that S_1 is only dominantly present in the ED, with some traces in the Lower Ugab Domain (LUD), and that the spectacular, main folds in the LUD correspond to regional D_2, as in the ED. This means that structures originally labelled as S_2 in the LUD are, in fact, related to S_{2b} in the ED. In order to minimise confusion between the earlier classification and the new one, we relabelled S_{2b} to S_{2a} throughout the area; this schedule is also used on the map shown in Appendix I.

Locally, some D_{2a} fold structures and foliations have been erroneously attributed to S_3, mainly by Passchier *et al*. (2007). This chiefly applies to the structures surrounding the Doros North and Voetspoor Plutons. Because of this error, the biotite granite of the Doros and Voetspoor Plutons was thought to be syn-D_3, while in fact it is syn-D_{2a} as the syenites, but slightly younger in age (Fig. 37).

13. Conclusions

The Neoproterozoic Damara Supergroup, composed of siliciclastic and carbonate rocks, was mapped in the Ugab-Goantagab area, differentiating mapping units that are generally corresponding to previously defined formations. The following conclusions can be drawn:

- The Neoproterozoic Damara Supergroup in the study area was deformed and metamorphosed at greenschist facies conditions (biotite zone) during the Ediacaran - Cambrian (Pan-African) Damara Orogeny.

- The mapped area can be divided into two domains, i. e. the Lower Ugab and the Eastern Domain, which are separated by the Vrede-Doros-Brandberg Line. This line is interpreted to mark the transition, during the earliest stage of basin evolution, between a slope in the Eastern Domain and a distal fan in the Lower Ugab Domain.
- Numerous rudstone beds in the Chuos, Ghaub, Gruis, Brak River, Rasthof and Karibib Formations probably represent gravitational subaqueous mass flows, not necessarily related to glaciation. Large blocks, some of which contain stromatolites, are interpreted as olistoliths.
- Detailed mapping of superimposed structures led to the identification of four deformational events, taking into consideration the possibility of continuous deformation having generated these overprinting structures.
- During the first stage (D_1, ~590 Ma; Lehmann *et al*., 2016) N-S contraction caused northward thrusting along the southern limit of the Kamanjab Inlier and south-dipping folds and foliation to the south of it.
- Stage D_2 produced E-W shortening related to collision in the Kaoko Belt (580-550 Ma; Goscombe and Gray, 2007). This phase generated the spectacular folds in the Lower Ugab Domain (where they were originally labelled D_1), and caused refolding in the Eastern Domain.
- Stage D_{2a} is characterised by NW-SE shortening in the northwestern part of the area and by renewed E-W constriction further south. It reflects the collision between the Angola and Kalahari Cratons between 540 and 520 Ma.
- Stage D_3 saw the continuation of a similar stress field as prevailed during D_{2a} but at a lower metamorphic grade, producing brittle-ductile structures.
- Igneous intrusions were dated as follows: I) a felsic sill within the Naauwpoort Formation yielded a crystallisation age of 757 ± 5 Ma; II) zircons from a metagabbro intrusive into the Brak River Formation were dated at 565 ± 3 Ma; III) the Doros North and Voetspoor granites, which intruded during D_{2a} yielded an age of ~532 ± 7 Ma.

14. Final remarks

It will be amply clear from the previous pages that the mapped area between the Ugab and Huab Rivers in north-western Namibia shows an extremely rich and complex pattern of deformation phases and relationships with local intrusions and metamorphism. This rich complexity could be unravelled and the tectono-metamorphic history reconstructed because of the excellent outcrop conditions in this part of Namibia, in conjunction with a relatively flat terrain with many drivable tracks. It seems incongruous, that an area with excellent outcrop and covered by high-resolution satellite imagery would take 23 field seasons of 2-6 weeks to map and explore. Indeed, when we started in 1998, we envisaged two- to three seasons of fieldwork to unravel the geology of the area, especially because of the availability of high-quality air photos and satellite images. However, satellite images cannot be relied upon to make structural interpretations in an area with locally five deformation phases observable in a single outcrop. Also, the fact that outcrops are so good and plentiful means a wealth of detail to be noted, which would have remained hidden in poorly exposed areas. Indeed, the better the outcrops in a metamorphic terrain like the Ugab-Goantagab area, the more time is needed, mapping on foot, to build a reliable, robust model for its tectonic and metamorphic development. In a poorly exposed area, we would have finished 20 years earlier, but with less accurate and reliable results. Information obtained from outcrop mapping as presented here, cannot be substituted by the analysis of isolated samples or remote sensing, although the latter remains essential for large-scale tectonic interpretations - food for thought at a time, when extended field mapping is under pressure for a variety of reasons, chiefly financial ones.

Acknowledgments

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Appendix III. List of participating scientists

AU – RWTH Aachen University, Germany
FUA – Free University Amsterdam, Netherlands
FUB – Freie Universität Berlin, Germany
GSN – Geological Survey of Namibia
GSC – Geological Survey of Canada
JGU – Johannes Gutenberg University, Mainz, Germany
MU – Monash University, Melbourne, Australia
UERJ – State University of Rio de Janeiro, Brazil
UFRJ - Federal University of Rio de Janeiro, Brazil
UU - University of Utrecht, Netherlands

<u>Project leaders (years)</u>
Cees W. Passchier - JGU
Rudolph A. J. Trouw - UFRJ
André Ribeiro - UFRJ

<u>Staff with significant contributions</u>
Prof. Dr. Fábio V.P. Paciullo - UFRJ (1998-2008)
Prof. Dr. Renata da Silva Schmitt – UERJ and UFRJ (2004-2015)
Prof. Dr. D. Gray - MU (1999)
Dr. Ben Goscombe - GSN (1999)

<u>Other contributing staff</u>
Dr. Erik de Kemp - GSC (2003)
Dr. Jiri Konopasek – JGU (2003)
Shawn Kitt - GSN (2003)
Evereth Muvangua – GSN (2004)
Kombadayedu Mhopjeni - GSN (2004)
Aphary Muyongo - GSN (2004)

<u>PhD students</u>
Sara Coelho – JGU (2007)
Xavier Maeder – JGU (2007)
Camilo Correia Trouw – UFRJ (2008)
Eric Salomon – JGU (2014)
Débora Barros Nascimento – UFRJ (2016)
Felipe Nepomuceno – UFRJ (2021)

<u>MSc students</u>
Martine Vernooij - UU (2000)
Janneke Salemans - UU (2000, 2001)
Rianne Brunt - UU (2002)
Vincent Heesackers - UU (2002)
Hazel Goethart - FUA (2003)
Eveline Vermeer - FUA (2003)
Mathijs Boden - FUA (2003)
Hugo Beentje - FUA (2003)
Suzanne Lint - FUA (2003)
Pedro Rossi Cezar - UFRJ (2004)
Kerstin Schemman - FUB (2004)
Martin Koelman - FUA (2005)
Stefan Lutz - FUA (2005)
Camilo C. Trouw - UFRJ (2005)
Gabriel Matos - UFRJ (2006)
Gustavo Pinto - UERJ (2007)
Debora Nascimento - UFRJ (2008)
Rüdiger Kilian - JGU (2009)
Christoph Bauer - MU (2009)
Eric Salomon – JGU (2011)
Martijn Passchier – AU (2012)

Appendix IV. List of publications/theses produced through the project

Peer-reviewed publications (in chronological order)

Goscombe, B. and Trouw, R.A.J. 1999. The geometry of folded tectonic shear sense indicators. *Journal of Structural Geology* **21**, 123-127.

Passchier, C.W., Trouw, R.A.J., Ribeiro, A. and Paciullo, F. 2002. Tectonic evolution of the southern Kaoko belt, Namibia. *Journal of African Earth Sciences*, **35**, 61-75.

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Goscombe, B. D., Passchier, C.W. and Hand, M. 2004. Boudinage classification: end-member boudin types and modified boudin structures. *Journal of Structural Geology*, **26**, 739-763.

Kröner, S., Konopásek, J., Kröner, A., Passchier, C.W., Poller, U., Wingate, M.T.D. and Hoffmann, K.H. 2004. U-Pb and Pb-Pb zircon ages for metamorphic rocks in the Kaoko Belt of Northwestern Namibia: A Palaeo- to Mesoproterozoic basement reworked during the Pan-African orogeny. *South African Journal of Geology*, **107**, 455-476.

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Simoes dos Santos Coelho, S. 2007. *Quantification Tools in Structural Geology based on field examples from Namibia*. Johannes Gutenberg University, Mainz, Germany.

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Vermeer; E.M.C. and Booden, M.A. 2005. *Deformation and Intrusion in the Goantagab Domain, North-Western Namibia*. Free University of Amsterdam, Netherlands.

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