THE MATCHLESS AMPHIBOLITE OF THE DAMARA BELT, NAMIBIA: UNIQUE PRESERVATION OF A LATE NEOPROTEROZOIC OPHIOLITIC SUTURE

Francesca Meneghini*,✉, **Åke Fagereng**** and **Alex Kisters*****

* *Dipartimento di Scienze della Terra, Università di Pisa, Italy.*
** *School of Earth & Ocean Sciences, Cardiff University, United Kingdom.*
*** *Department of Earth Sciences, Stellenbosch University, South Africa.*
✉ *Corresponding author, email: meneghini@dst.unipi.it*

Keywords: *ophiolitic suture, ridge subduction, Late Neo-Proterozoic Damara Belt. Namibia.*

ABSTRACT

Ophiolitic sequences are widely recorded from Meso-Cenozoic orogenic belts, but are only rarely documented from Proterozoic-Paleozoic orogens, so that the geodynamic processes responsible for the emplacement of ancient ophiolites are less well understood compared to their younger counterparts.

The Damara belt of Namibia represents a deeply eroded Pan-African (550-500 Ma) collisional belt that records subduction and the eventual collision between the Kalahari and Congo Cratons as part of the amalgamation of the Gondwana supercontinent. The belt has not been affected by later orogenic events so that it preserves the sequence of convergent and collisional tectonics remarkably well. The Southern Zone accretionary prism of the belt records the off-scraping and imbrication of a thick metaturbiditic sequence. Within this sequence, the Matchless Amphibolite Belt forms a narrow, 500-3000 m wide unit of intrusive as well as imbricated mafic metavolcanic and plutonic rocks, with Mid-Ocean Ridge Basalt (MORB) geochemistry, that can be traced almost continuously for over 300 km along strike. Based on the MORB-type geochemistry and preserved textures and rock association, most authors consider the Matchless Amphibolite belt to represent relics of oceanic crust related to the closure of the oceanic basin between the Congo and Kalahari cratons.

We have measured two traverses across the Matchless Amphibolite and we report here the evidence that these ophiolitic slivers emplaced during ridge-trench interaction and ridge subduction. We discuss factors that have most likely contributed to the formation and preservation of such an old ridge-trench encounter and its unique geometry.

INTRODUCTION

The accretionary prism is the tectonically most active region in convergent margins and represents the embryonic stage of what may become a collisional mountain chain (Moore and Sample, 1986; Shevre and Cloos, 1986; Moore and Silver, 1987). Many Mid-Ocean Ridge (MOR) ophiolites preserved in orogens suffered deformation and metamorphism during their underplating to the accretionary wedge (Dilek and Robinson, 2003). A volumetrically relevant ophiolitic component preserved in orogenic belts is also represented by 'Supra-Subduction Zone' (SSZ) ophiolites: they are usually interpreted as slices of oceanic crust generated during subduction rollback in a fore-arc, volcanic arc or back arc setting, and subsequently incorporated into the orogeny during the collisional stages. The discrimination between the two types of ophiolite can be made using both major and trace elements that, showing the presence or absence of a subduction zone geochemical component, can identify the geodynamic setting of origin (Pearce et al., 1984: Dilek and Robinsons, 2003). Ophiolites emplaced into continental margins crops out as relatively "coherent" units/terranes, in which the original ophiolite stratigraphy is maintained, or as ophiolitic mélange, where ophiolite-derived blocks lie within a variably deformed fine-grained matrix.

The Tethian ophiolites of the Alpine-Himalayan orogenic system are some of the best known Meso-Cenozoic ophiolitic complexes, where both MOR and SSZ ophiolites have been reported, as coherent units as well as mélanges, and for which different mechanisms of formation and emplacement have been recognized (Dilek and Robinson, 2003). Similarly, Proterozoic-Paleozoic supercontinents preserve slivers of ophiolitic sequences that might be representative of convergence and accretion during supercontinent assembly and amalgamation, but they are less reported in literature and/or their geodynamic setting is often less defined. Some of the best examples of older (Proterozoic) orogens, possibly related to convergence, accretion and collision processes, come from the Kaoko, Damara and Saldania Belts of southwestern Africa (Gray et al., 2006; 2008), i.e. the Neoproterozoic/Early Cambrian orogenic belts known as Pan-African belts and that formed during the assembly of the Gondwana Supercontinent. There is a growing number of studies that have re-interpreted the deformation and tectonic evolution during the assembly of Gondwana in terms of subduction tectonics (Kukla and Stainstreet, 1991; Belcher and Kisters, 2003; Goscombe et al., 2003; Gray et al., 2006; 2008; Rowe et al., 2010).

In the present paper we report the stratigraphy and structure of the late-Neoproterozoic Southern Zone of the Namibian Damara Belt. For the Southern Zone terrane, an accretionary prism setting has been proposed by Kukla and Stainstreet in the early 90s (Kukla and Stainstreet, 1991). Other than well-preserved accretionary structural and metamorphic signatures (Kasch, 1981; Kukla and Stainstreet, 1991; Meneghini et al., 2014; Cross et al., 2015), the Southern Zone preserves a sliver of meta-ophiolitic sequence, called the Matchless Amphibolite, considered as representative of the ophiolitic suture. The Matchless Amphibolite shows several peculiarities that have not yet been placed in a coherent geodynamic model of MOR formation, deformation, and preservation (see Kukla and Stainstreet, 1991; Meneghini et al., 2014, Cross et al., 2015). The Matchless Amphibolite ophiolitic rocks crop out in a narrow (between 500-3000 m wide) but laterally very extensive system of imbricate tectonic slivers that can be followed along strike for > 300 km. They show a clear tholeiitic affinity

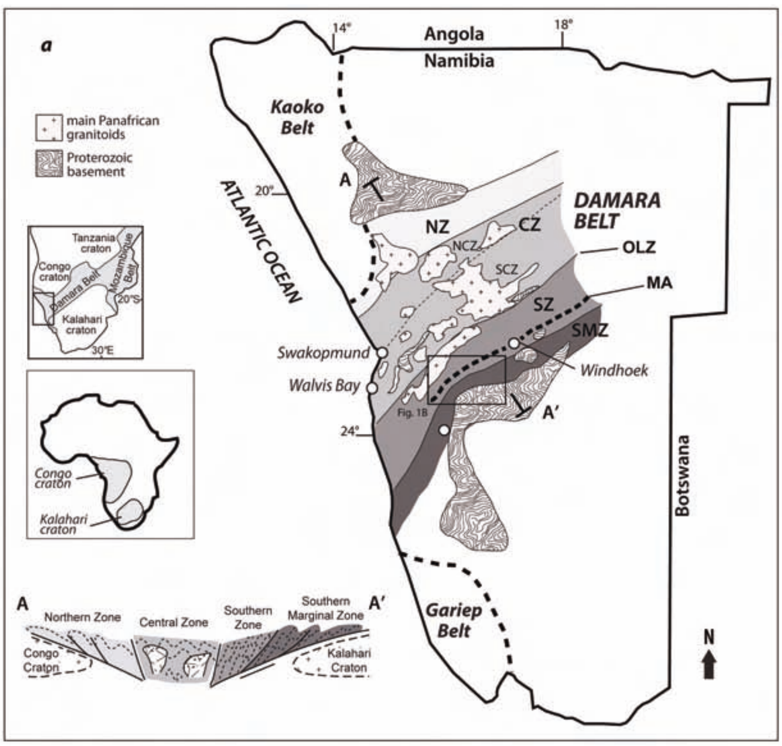
(Miller, 1983; Kukla and Stainstreet, 1991) that has been used to interpret them as slices of an oceanic subducting plate incorporated in an accretionary wedge. Recently, Meneghini et al. (2014) reported evidences of subduction of a ridge and its interaction with the trench prior to subduction, mainly as off-axis igneous activity, in the form of flow basalts, and pillow balasts all interbedded with turbidites and preserving primary interfingering. The study of Cross et al. (2015) reinforces the hypothesis of a ridge-trench encounter by providing a reconstruction of a two-stage tectono-metamorphic history of the Matchless metamafics that includes a prograde stage of tectonic burial through subduction and underplating, followed by relatively rapid, near-isobaric heating to peak metamorphic conditions and not associated with deformation, that the authors interpreted as occurred during ridge subduction and opening of a slab window. Accretion of different depth-sections of the ridge occurred, comprising pillows, as well as extrusive flows/pillows, and deeper gabbros, but only rare intrusive sheets or sheeted dykes, suggesting either subduction of a peculiar oceanic basin, or a selective preservation due to the mechanism of emplacement.

We have measured two cross-cutting river sections in the Southern Zone through an imbricated sequence of metamorphosed turbiditic sedimentary sequences and mafic volcanic and igneous rocks: the superb three-dimensional exposure of both sections offers an unique window to study the nature of accretionary processes, the geometries of units, and their mutual stratigraphic and tectonic relationships. The presented data are used to show similarities in styles of deformation between the Khomas Complex and various Meso-Cenozoic complexes well-described in the literature (Kimura, 1994; Hashimoto and Kimura, 1999; Gray and Foster 2004; Gray et al., 2006; Meneghini et al., 2009) as developed through an evolution of subduction and accretion of oceanic slivers and sediments. We document in more detail the evidence of ridge-trench interaction and ridge subduction firstly reported in Meneghini et al. (2014), and we discuss what might be the potential circumstances and/or characteristics of the Khomas oceanic basin that allowed preservation of such an old ridge-trench encounter within an ophiolitic suture.

GEOLOGY OF THE DAMARA BELT

The Damara Belt in Namibia represents one of several late Neoproterozoic/Early Cambrian orogenic belts in Africa, collectively referred to as the Pan-African system, related to the assembly of the Gondwana Supercontinent (Miller, 1983; 2008; Martin, 1983; Gray et al., 2008). The 400 km wide Damara Belt represents the inland, NE-trending arm of the larger Damara Orogen, encompassing the Kaoko-Damara-Gariep orogenic triple junction. The Damara Belt (*sensu stricto*) finds its NE extension through central Namibia and northern Botswana into the Lufillian arc of southern Zambia, forming a ca. 1500 km long orogenic belt developed along the southern, leading margin of the Congo Craton (Fig. 1). The belt is a bivergent collisional orogen that is commonly interpreted to have developed through northward subduction of the Kalahari below the Congo Craton and the eventual soft collision of the cratons between ca. 580 and 510 Ma (Gray et al., 2008).

The Damara Belt shows a well-developed structural and metamorphic zonation that allows distinction of several tectonostratigraphic zones from north to south (i.e. from the Congo to the Kalahari undeformed plateaux), showing different stratigraphy, structure, metamorphic grade and radiometric age (Fig. 1; Miller, 1983; 2008; Gray et al., 2008). The Damara Belt shows the hallmark features of a paired metamophic belt, with a central high-T/low-P Central Zone (T ca. 750-800°C, P ca. 4.5-6 kbar), dominated by voluminous syn- to post-tectonic granitoids (Jung et al., 1999; 2001; 2002), and interpreted as a volcanic arc, juxtaposed against medium-P/medium-T rocks of the Southern Zone suggested to constitute the accretionary prism of the belt (Kasch, 1983; Miller, 1983).



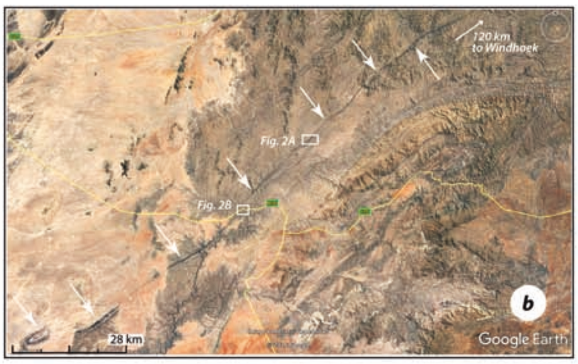


Fig. 1 - (a) Simplified map of the Damara belt with the main tectono-stratigraphic terranes and Pan African granitoids. Upper inset shows the main Pan-African orogens of Southern Africa and the location of the main map; the lower inset shows location of the maps with respect to the Africa continent. A schematic and simplified cross section through the Damara is also shown (modified after Fagereng et al., 2014). NZ- Northern Zone; CZ- Central Zone; NCZ- Northern Central Zone; SCZ- Southern Central Zone; SZ- Southern Zone; SMZ- Southern Margin Zone; MA- Matchless Amphibolite; OLZ- Okahandia Lineament Zone. (b) Google map image of the Khomas Hochland area, ca. 150 km SW of the city of Windhoek, showing lateral, along strike continuity of the Matchless Amphibolite ophiolitic unit (greenish line on Google map, evidenced by the white arrows).

The chronology of events in the belt is reasonably well constrained. Early continental rifting at ca. 780-740 Ma was succeeded by marine sedimentation from 740 to 600 Ma and followed by convergence and subduction between ca. 580-530 Ma, culminating in a “soft” collision of the cratonic blocks between 530-515 Ma (Miller, 2008; Gray et al., 2008; Longridge et al., 2011; Meneghini et al., 2014).

The Damara Belt shows many characteristics of a high-T, low-P orogen. Particular features as the lack of major crustal thickening, the long-lived and/or episodic high-T/low-P metamorphic evolution and associated voluminous syn-, late- and post-tectonic granite plutonism developed across much of the strike of the orogen (Miller, 1983; 2008; Jung and Mezger, 2003; Jung et al., 2005), have recently been reconciled in an hypothesis of a ridge-trench encounter, with magmatic underplating and opening of a slab window and subsequent slab delamination (Meneghini et al., 2014). As already mentioned, the isobaric heating path that characterizes the late-stage evolution of metapelites in the Southern Zone accretionary prism (Cross et al., 2015) seems to strengthen this model.

The Southern Zone and the Matchless Amphibolite

The Southern Zone of the Damara Belt is composed of a thick, imbricated and multiply folded succession of metasedimentary rocks, collectively referred to as the Kuiseb Formation (Fig. 1). Kuiseb metasediments are associated with the so-called Matchless Amphibolite Belt, an up to 3 km wide zone of mafic metavolcanic rocks that are in both tectonic and intrusive contact with the Kuiseb schists. The Kuiseb Formation (metasediments + intercalated mafic slivers) is the only formal stratigraphic unit recognized in this zone, and many authors considers it as representative of the structurally repeated and disrupted remnants of the Khomas oceanic sequence and its sedimentary cover (e.g., Barnes and Sawyer, 1980; Kukla, 1992; Gray et al., 2008 and references therein). The Southern Zone imbricated and multiply folded sequence and the laterally continuous slivers of Matchless oceanic crust have been interpreted to represent the accretionary wedge that formed at the tip of the overriding Congo plate, during NW-directed subduction of the Kalahari plate (Kukla and Stainstreet, 1991). This interpretation is supported by the detailed stratigraphic and sedimentological analyses conducted by Kukla (1992), and that envisaged the Southern Zone as formed by imbrication of Kuiseb trench sediments with the mafics of the Matchless Amphibolite and the sediments covering the oceanic crust. The MORB affinity, and the tholeiitic trend defined by the amphibolite seem to confirm a mid-ocean ridge origin for the amphibolites (Miller, 1983; Kukla and Stainstreet, 1991; Gray et al., 2008). Subduction closed this oceanic basin, referred to as the Khomas Sea, that consituted a small branch of the bigger Adamastor Ocean (Porada, 1989), with an estimated size of 400 km in length and 100 km width (Miller, 2008).

The Southern Zone is bounded to the N by the Okahandja Lineament Zone (Fig. 1), the backstop of the prism that juxtaposes metaturbidities of the accretionary prism against the granite-dominated, high-T/low-P metamorphic magmatic arc of the Central Zone (Kisters et al., 2004). Large parts of the prism are intruded by late-tectonic, voluminous granites of the Donkerhuk batholith that intruded over a protracted period of time between ca. 530-505 Ma (Clemens et al., 2017). The southern boundary and base of the prism is not well defined, but commonly interpreted to be made up of a series of north to northwest-dipping thrusts along which the Southern Zone is placed over the basement-cored, fold-and-thrust nappes of the Southern Margin Zone (Miller, 1983) (Fig. 1). Because of the high strain transposition of bedding and metamorphic foliations, and the pervasive imbrication of the metaturbidites, the Southern Zone rocks clearly represent a tectonostratigraphic package rather than an ordered stratigraphic sedimentary unit, so that we prefer referring to the Kuiseb Formation with the more general term of Kuiseb schists.

Rocks of the Kuiseb schists comprise metagreywakes, metasiltstones and pelites. The original turbiditic character of the metasediments is well preserved in low-strain domains (see also Kukla, 1992, who provides a detailed acccount of the stratigraphic and sedimentologic characteristics of the Kuiseb schists along several traverses through the Southern Zone). Calcsilicate layers are widespread and interbedded with the sequence; minor graphitic schists, scapolite schists and layers of marble are also reported (Kukla, 1992).

The Matchless Amphibolite shows remarkably high along-strike continuity (Fig. 1), cropping out for over 350 km from the Namib Desert in the SW to the Kalahari basin in the NE, with a tectonic thickness between 500-3000 m, and in a stratigraphically fairly consistent position within the Southern Zone (Miller, 2008; Meneghini et al., 2014). The unit consists of variably deformed metabasalts, including massive and pillowed amphibolites and sheeted dykes as well as metagabbros, with locally dispersed serpentinite bodies, that are regarded by most authors as the uppermost section of the ophiolitic sequence characterizing the Khomas Through oceanic crust, in accordance with the MORB geochemical signature recorded by all analysed mafic rocks (Kukla and Stainstreet, 1991; Kukla, 1992; Gray et al., 2008). The Matchless Amphibolite is economically important and known for its massive, sulphide (Besshi-type) deposits, such as those of Gorob, Hope, Matchless, Kupferberg, Otjihase and Ongombo mines (e.g., Killick, 2000 among many others).

Intermediate-T/intermediate-P, Barrovian-type, metamorphism characterize the Southern Zone, with estimated peak conditions of ca. 400-600°C and ca. 10 kbar (Kasch, 1983). Recently, a two-stage prograde metamorphic history, with climax at ca. 10 kbar and 540-560°C and 10-10.5 kbar and 600°C, was recognized as preserved in metapelites and metamafics from the Kuiseb schists (Cross et al., 2015). U-Pb data on metamorphic monazite from the Kuiseb Schist suggests an age of 525-515 Ma for peak metamorphism (Kukla, 1992).

MEASURED SECTIONS ACROSS THE MATCHLESS AMPHIBOLITE: ROCK-TYPES AND STRATIGRAPHY

We measured two sections through the Matchless Amphibolite along two riverbeds located approximately 160 km west of Windhoek, in the Khomas Region (Fig. 2): the first section is located in the canyon of the Kuiseb River, in the Niedersachsen Farm property (23°09.326’S, 15°54.414’E); the second traverse is located in the canyon of the Rutile River (23°17.799’S, 15°44.682’E). In both localities, the Kuiseb and Rutile rivers form two canyons running sub-perpendicular to the main structural strike, allowing the reconstruction of stratigraphic-structural sections with meter-scale detail (Fig. 2). Upper and lower boundaries of the sections were placed in Kuiseb schists above or below where bodies

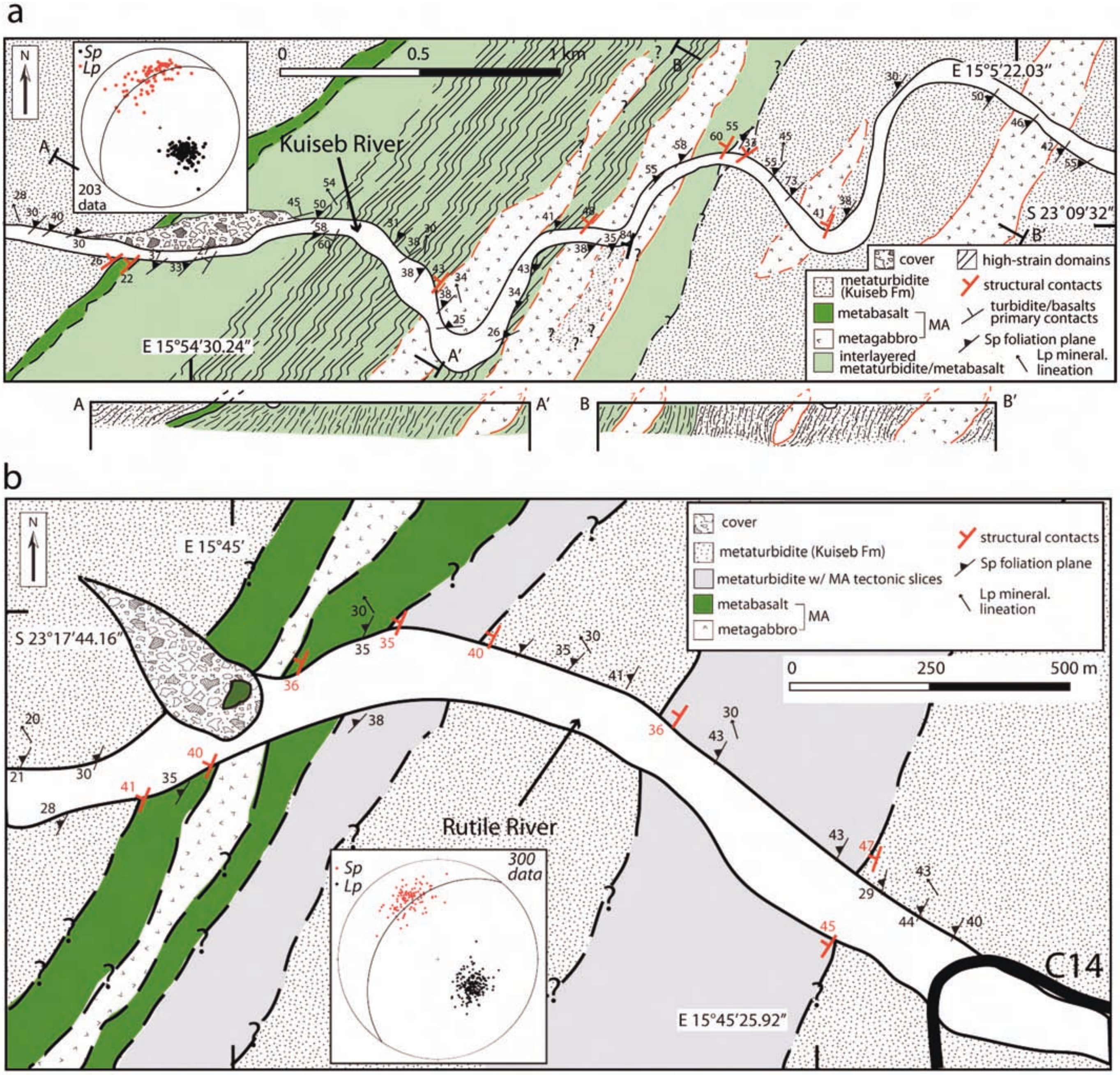


Fig. 2 - Geology of the two studied traverses: (a) section along the Kuised River at Niedersachsen Farm; (b) section along the Rutile River. The location of the traverses is shown in Fig. 1b. The equal area, lower hemisphere projections of the main structural elements (S_p principal foliation and the associated, L_p mineralogical lineation) are also shown for both localities. C14 in lower right corner of b indicates a secondary, un-tarred road in the Namibia road system.

of volcanic and intrusive rocks, ascribable to the Matchless, were not encountered. The measured total thickness is ca. 2000 m and 2400 m for the Rutile River and Kuised River sections (Fig. 2), respectively. Due to structural imbrication, the estimated thickness is tectonic and therefore not representative of the original stratigraphic thickness.

The sections are mainly occupied by the Kuiseb schists, that in this part of the Southern Zone are represented by alternation of metapsammites, 40 cm up to 2 m thick, with metapelite or metasiltstone intervals, rarely reaching 1 m of thickness, to form turbidite sequences (Fig. 3a, b). At Rutile River an increase of metasandstone thickness is observed when moving upsection from E to W. The metasandstones are light- to dark-grey quartz-plagioclase schistose metapsammites (Fig. 3c), generally massive, or locally showing graded beds, and remnants of Ta Bouma divisions. A metamorphic texture is also visible in the form of a compositional layering with quartz and plagioclase granoblastic layers alternated with mica-rich, schistose layers. In addition to quartz and plagioclase, biotite, white mica, staurolite, hornblende and, locally, garnet and kyanite can also be found. Metasiltstones and metapelites are essentially represented by micaschists with a schistose fabric defined by preferred orientation of fine-grained biotite, muscovite and minor chlorite. Metamorphic re-crystallization of garnet, staurolite and kyanite also occur in these finer intervals. Minor strings or lenses of calc-silicates mables are interlayered with the turbidites (Fig. 3d), representing remnants of impure calciturbidites. Folded and boudinaged quartz veins occur in the metapsammites and metapelites, running sub-parallel to main anisotropy.

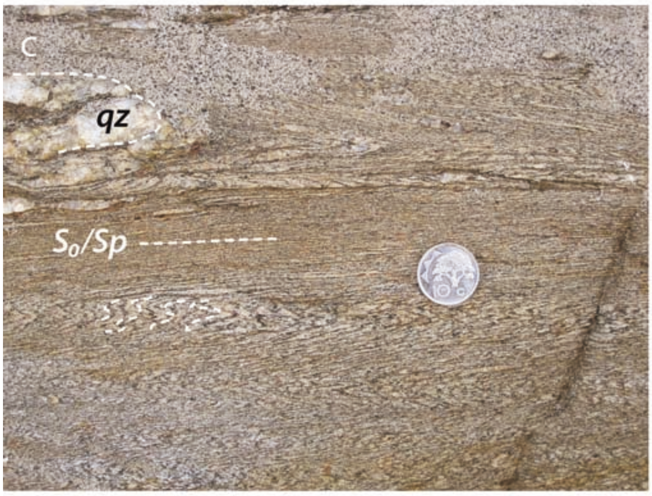


Fig. 3 - Kuiseb schists at outcrop scale. (a) general view of the metaturbidites. Bedding in picture dips to the NW. (b) close up view on turbidite strata. Bedding in picture dips to the NW. (c) psammite intervals. The attitude of the stratification (S_0)/foliation (S_p) is indicated. Isoclinal folds and intrafolial folds are also shown, as outlined by quartz (qz) vein strings. (d) calcsilicate layers (calc) along stratification (S_0)/foliation (S_p) planes.

The mafics of the Matchless Amphibolite are represented in the sections by fine-grained amphibolite and lenses of medium- to coarse-grained metagabbro (Figs. 4a, b). The amphibolites are light- to dark-green, generally massive and structureless, with horneblende, plagioclase and epidote locally recognizable at the hand sample scale. As already reported by many authors throughout the Matchless (Sawyer, 1981; Miller, 1983; Kukla and Stainstreet, 1991; Kukla, 1993), we have locally identified pillow structures at Rutile River section (Fig. 4c), with pillows surrounded by hyaloclastite. Epidote-rich veining is common in the metamafics, generally associated with quartz and calcite. Metabasalts are locally observed as dykes within the metagabbro (Fig. 4d) and, where degree of deformation is not intense, chilled margins at the metabasalts-gabbro boundaries are common. Metachert lenses tens of centimeters long have been found scattered in a highly deformed amphibolite section in the Rutile River traverse (Fig. 4e).

The metagabbro occurs mainly as lens-shaped, oblate bodies, meters to tens of meters in size (Fig. 4f). The core of the lenses are generally medium- to coarse-grained and characterized by a well-preserved primary texture now pseudomorphosed by green horneblende and plagioclase, whereas rims are frequently highly strained with consequent grain size decrease and flattening/elongation of minerals.

The measured sections are mainly upright-younging, as indicated by the majority of graded intervals in the turbidite strata. Further, indirect evidence of the normal polarity comes from the distribution of metabasalts and metagabbros in the Kuiseb River section at Niedersachsen farm. Matchless mafics alternate with the sediments of the Kuiseb schists, with different mutually crosscutting relationships: while the metagabbro bodies crop out in the structurally lower part of the section (Fig. 2), the metabasalts are intimately intercalated with the sediments in the central-upper part of the 2400 m analyzed section.

In the section at Niedersachsen farm, the metagabbro lenses are of mappable size and the distribution of each single

Fig. 4 - Matchless Anphibolite metamafics at outcrop scale. (a) fine-grained, massive metabasalt (β) with layer (S_0)-parallel foliation S_p. Basalt is in contact with psammites from the Kuiseb schists (KS). (b) metagabbro with primary texture. (c) basalt (β) pillows. (d) basaltic dyke (β) in gabbro (γ). (e) chert clast (ch) tectonically incorporated into a highly deformed metabasalt (β). (f) map-scale lenses of gabbro (γ) with evidences of tectonic incorporation within the Kuiseb schists (KS, see main text and following figures). NW in the left side of all pictures.

body is shown in Fig. 2. The metabasalts, on the contrary, frequently occur as m-thick layers tectonically alternated with the Kuiseb sediments. Consequently, we have used a specific pattern in the map to indicate a "unit" in the section characterized by the close alternation, at a scale below mappable resolution, of schists with meter-scale metabasalt layers. Similarly, in the section along Rutile River we have used a specific pattern for parts of section where the sediments are juxtaposed with thin bands of both metabasalt and metagabbro (Fig. 2b).

THE IMBRICATION OF KUISEB SEDIMENTS WITH THE MATCHLESS AMPHIBOLITE: STRUCTURAL ASPECTS AND NATURE OF CONTACTS

Similar to what is described in detail by Kukla (1992, and reference therein) for the whole Kuiseb schists in the Southern Zone, the structural geology of the two sections across the Matchless Amphibolite is characterized by folding and thrusting with intense, NW-dipping, shear-dominated transposed fabrics (Fig. 5).

The dominant structural element at outcrop scale is a planar, moderately NW-dipping schistosity, the most penetrative planar element in all rock types (Fig. 5a). Since this foliation cannot be clearly related to any of the deformational events defined by Kukla (1992) for the whole Southern Zone, and in agreement with Miller (2008), we refer, to this element to as S_p ("principal" foliation), to imply that it is a composite foliation surface resulting from shear-related transposition and sub-parallel orientation of different planar fabrics, caused by high strain.

S_p orientation is highly uniform in both sections, with schist fabric homoclinally dipping, parallel to or at a very low angle with bedding, with orientation (dip direction/dip angle) clustering around 290º-310º/30º-40º (Figs. 2, 3a, 5a). Foliation is defined by the preferential orientation of platy minerals (white mica, biotite, and chlorite), as well as, in the psammitic sections, by a compositional layering of mm-scale granoblastic layers of quartz and plagioclase alternating with phyllosilicate-rich layers. Euhedral garnet is generally found wrapped along the S_p planes. In particular, a mineralogical assemblage of garnet, quartz, biotite, chlorite, muscovite, green amphibole, staurolite, and kyanite is associated to schistosity. The S_p plane bears a mineralogical stretching lineation L_p, commonly downdip and rarely slightly oblique, with respect to the S_p dip (Figs. 2, 5b), and defined by the alignment of quartz, biotite, plagioclase, amphibole, staurolite, and kyanite. Locally, a preferred orientation of calcsilicate spindles is also visible.

Mafic units within the Matchless Amphibolite contain a foliation concordant with S_p in the schists, which is visible as a penetrative anisotropy in the fine-grained metabasalts, whereas in the gabbros it is defined by a preferred orientation of green hornblende (Fig. 5c, d).

S_p is axial planar to intrafolial, tight to isoclinal folds, well visible in the pelitic sections, but detectable also in the coarser-grained, psammitic intervals (Figs. 6a, b). Folds develop at the outcrop-scale as well at cm-scale, and seems to

Fig. 5 - Deformation features. (a) general view of monotonous, composite foliation S_p, dipping toward the NW. Main orientation of foliation is shown in the stereonets of Fig. 2. (b) Lp mineralogical lineation defined by preferred alignment of staurolite (black sticks sitting on top of S_0 foliation plane). (c) foliated metabasalt (β) in contact with Kuiseb Schists (KS), , with orientation of S_0/S_p plane. (d) foliated metagabbro, with orientation of S_0/S_p plane. NW in the left side of all pictures.

be related to strongly non-coaxial deformation, as suggested by asymmetric shapes, stretched fold limbs and common occurrence of isolated fold hinges (Fig. 6a, b). Folds are frequently defined by foliation-parallel quartz veins, with thickness ranging from less than 1 cm to 20 cm (Fig. 6b). Layer-parallel veins are associated with oblique veins: both sets show generally blocky morphology and only locally “crack-and-seal” growth structures, suggesting that they

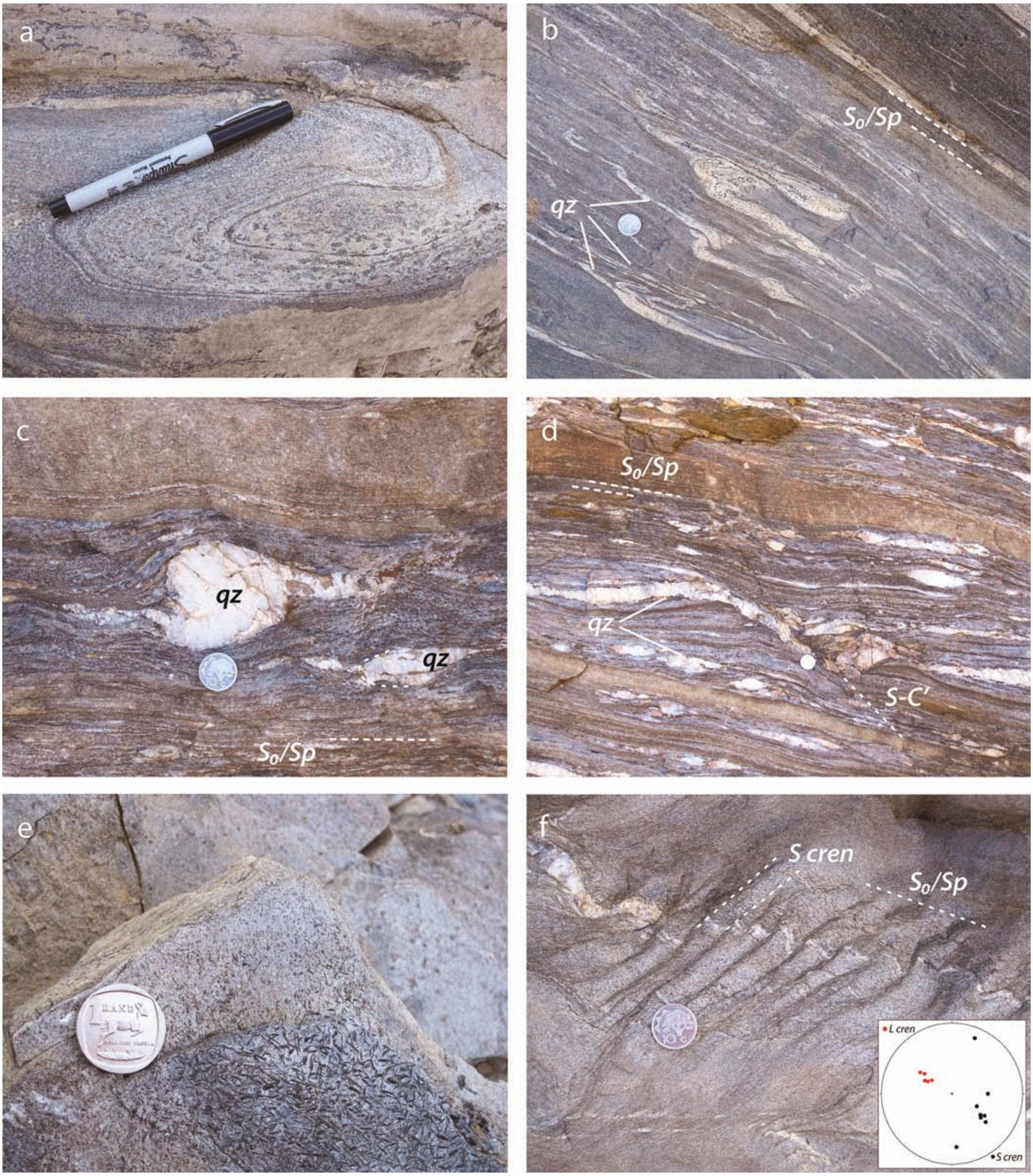


Fig. 6 - Deformation features. (a) tight to isoclinal fold in psammite interval. (b) asymmetric, shear-related folds in pelite of Kuiseb schist. Folds are outlined by foliation-parallel quartz veins (qz) that evidence asymmetry, stretched limbs, boudinage of competent layers. Asymmetry indicates top-to-SE sense of shear. Picture is oriented E-W. (c) rotated clast of quartz vein (qz) and stretched, isolated fold hinge (qz) all pointing to a top-to-SE sense of shear during deformation. (d) high strain domain in Kuiseb schists, with sub-mylonitic fabric and S-C’ structures. S_0/S_p planes dip toward the NW. (e) post-S_p, static re-crystallization of staurolite in psammitic interval of the Kuiseb Schist. (f) crenulation cleavage (Scren) deforming main, S_p foliation and a quartz vein. In the inset, the equal area, lower emisphere projection of the attitude of the crenulations surface (Scren) and lineation (Lcren) is shown. S_0/S_p planes in picture dip toward the NW.

might have developed incrementally (Fagereng et al., 2014). Quartz strings are also generally disrupted by boudinage, with boudins often asymmetric due to deformation by ductile flow, with rotation and locally shear (Fig. 6c). Quartz boudins on the S_p planes often define a rodding lineation parallel to the L_p mineral stretching lineation.

Boudin asymmetry, as well as fold asymmetry, always indicates a top-to-the-SE sense of rotation (Fig. 6b, d). Other kinematic indicators of shear are S-C structures and, locally, S-C' (Fig. 6d) structures with sense of elongation parallel to L_p lineation. All these structures point to a top to the SE sense of shear, concordant with the main structural vergence inferred for the Southern Zone, as well as for the entire belt.

The schistose fabric and the associated metamorphic mineral assemblage are overprinted by later, coarser-grained staurolite, garnet and kyanite, randomly oriented on the S_p planes and apparently static (Fig. 6e, see also Cross et al., 2015).

A later cleavage is superimposed on S_p as a steep, NE-dipping crenulation cleavage, locally axial planar to E-vergent folds (see stereonet of Fig. 6f), and spaced at the field scale over meter-distance. The distribution of the crenulation is heterogeneous throughout the sections and mainly visible in the more incompetent, mica-rich intervals.

The strain in the measured traverses is highly heterogeneous, possibly by a combination of original competent vs. incompetent ratio in the parent lithology, and degree of localization of deformation across the section (Fig. 5). Increased intensity of deformation occurs in both traverses as zones of phyllonitic or mylonitic fabric (*sensu* Passchier and Trouw, 1996) indicated by (Fig. 7a): strongly developed, regular and planar foliations that become highly penetrative in all rock types, with higher degree of transposition between S_0 and S_p, lineation and mineral elongation that are more pervasive, as well as the stretching and flattening of quartz vein boudins, that become both planar and linear fabric elements. The intensity of deformation in the section at Niedersachsen farm seems to increase from the eastern and western end of the section toward a central mylonitic zone (Fig. 2), whereas deformation is more irregularly distributed in Rutile River section.

The nature of contacts between metasediments and metamafics

Non-coaxial shear and local mylonitic fabric development are related to top-to-the-SE thrusting that is identified at map-scale by displacement, juxtaposition and structural repetition of sections of metasediments and metamafic rocks. In particular, the exceptional 3D exposure and the alternation of low- and high-strain domains across the traverses have allowed discriminating tectonic juxtaposition from primary, stratigraphic contacts between sediments and the different mafic units (Meneghini et al., 2014).

The blocks of metagabbro always show evidences of tectonic incorporation and mixing within the Kuiseb schists, as suggested by the lens shape of the meter-scale bodies (Fig. 4f) that generally show outcrop-scale necking and boudin-type terminations (Fig. 7b). The fine-grained portion of the surrounding schists usually flows around blocks, similarly to what is observed for the matrix in mylonitic rocks (Fig. 7b). Moreover, gabbro lenses have sharp contacts and extremely sheared rims with a mylonitic foliation, defined by preferred orientation of horneblende and compositional layering, and a lineation concordant with S_p and L_p in the schists (Fig. 7c). The effects of shearing gradually fade away toward the centre of the gabbro bodies that are characterized by well-preserved primary texture (Figs. 7c, 4b). As previously mentioned, the less deformed parts of gabbro bodies locally feature sets of dykes of fine-grained amphibolite cutting the coarse-grained gabbros. Similar to described elsewhere in different section through the Matchless (Miller, 1983; Kukla, 1992), well-preserved chilled margins characterize some of these dykes (Fig. 7d).

The exceptional preservation of delicate structures in the less deformed sections of the traverse allowed detection of primary stratigraphic relationships between metabasalts and the Kuiseb schists, in the form of intrusive contacts of metabasalts layers crosscutting the sediment bedding at a low angle (Fig. 7e, Meneghini et al., 2014). Both hanging wall and footwall boundaries of amphibolite layers cut bedding at a low angle (Fig. 7e). Moreover, the top contact of the metabasalts layers commonly displays undulations of various wavelengths, resembling in morphology (but on a much smaller scale) the sheet intrusion into poorly consolidated host rock described by Schofield et al. (2010; 2012). These observations, coupled with the occurrence of delicate interfingering of amphibolite and sediments (Fig. 7e), and of xenoliths of metasediments in metamafic layers (Fig. 7f), all point to that these are primary intrusive features and not the result of erosion.

The mutual relationships between amphibolites and Kuiseb sediments, exceptionally well preserved in low strain domains, become less detectable where mylonitic fabric dominates. Here amphibolite layers are stretched and flattened together with sediment layers and the nature of contacts (tectonic, intrusive, or by interlayering) might be misinterpreted because of transposition of planar fabrics and extreme flattening of structures (Fig. 7a).

THE KHOMAS BASIN FROM OPENING TO SUBDUCTION AND ACCRETION

The proposed evolution of the area, reconstructed by Meneghini et al. (2014) on the basis of the stratigraphic and structural analyses of the two traverses, and of the data of Kukla (1992; 1993) on another parallel section across the Matchless Amphibolite, is represented in Fig. 8. The figure illustrate the evolutionary stages from the deposition of the turdibitic fan deposits to the deformation and imbrication of the turbidites and the upper portion of the Khomas ophiolites, through the interaction between sediments and basaltic flows. This sequence of events is compared to those documented from turbidite-dominated Meso-Cenozoic convergent margins.

The ophiolite section: the rifting and spreading phases

The extensive degree of transposition prevents us from reconstructing an original stratigraphy, but strain partitioning around the competent metamafic rocks of the Matchless Amphibolite belt preserves original textures that document the common presence of massive and pillow basalts, and gabbros, with less common, dispersed ultramafic bodies, sheeted dykes, and rare lenses of metalimestones and metacherts. These rock types, the tholeiitic affinity of the Matchless metabasites Kukla (1992), and the system of sulfide mineralization hosted in the metamafics (Breitkopf and Maiden, 1988; Preussinger, 1990; Pirajno and Jacob, 1991; Killick, 2000; Steven et al., 2014), typical of oceanic lithosphere, allow favouring the interpretation of the Matchless

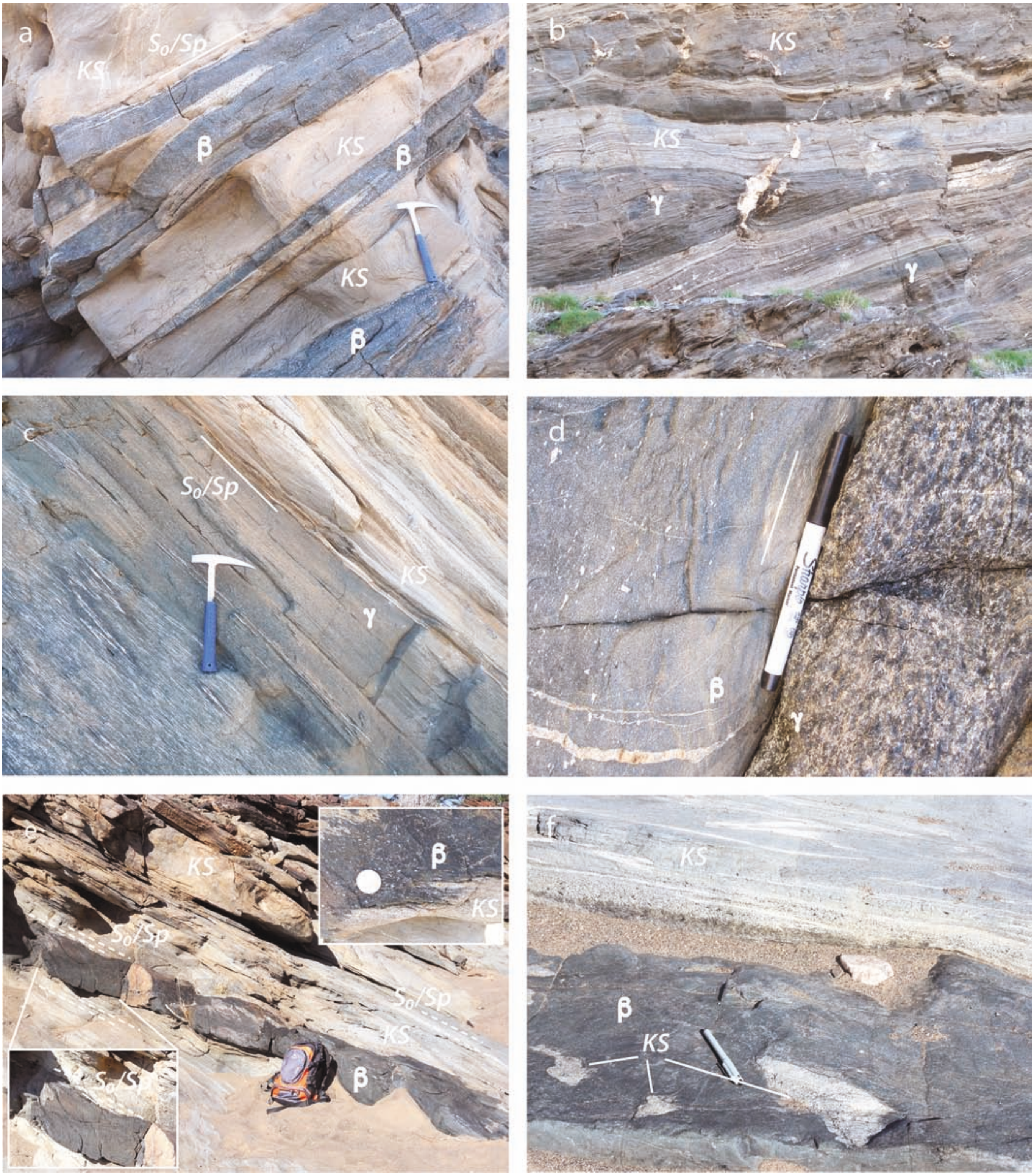


Fig. 7 - Strain partitioning and contact relationships between sediments and mafics. (a) high strain zones in the studied traverses show highly transposed, mylonitic fabric and dense tectonic alternation of extremely deformed metaturbidites (KS) and metabasalt (β) layers. All original relationships between layers are obliterated in these sections. S_0/S_p planes dip toward the NW. (b) boudin-type terminations of map-scale lenses of gabbro (γ) incorporated tectonically into the Kuiseb schists (KS). (c) the boundary between gabbro (γ) lenses and metasediments (KS), is typically characterized by foliated and deformed rims that grades progressively to the gabbro core, often preserving primary, isotropic texture. S_0/S_p planes dip toward the NW. (d) metabasalt dyke (β) with chilled margin at contact with gabbro (γ). (e) primary, sill-like intrusion of basalt layer (β) into metasediments (KS). Basalt (β) layer cuts at a very-low angle the S_0/S_p planes and shows undulating top and bottom boundaries (lower-left inset), suggesting intrusive rather than erosional contacts (see similarities with sheet intrusion into poorly consolidated host rock described by Schofield et al., 2010; 2012). Upper right inset shows delicate interfingering between sediment and basalt. S_0/S_p planes in picture dip toward the NW. (f) xenoliths of metasediments (KS) in basalt layer (β). The basalt layer is the same as in Fig. 7e with picture taken along-bedding from that photo.

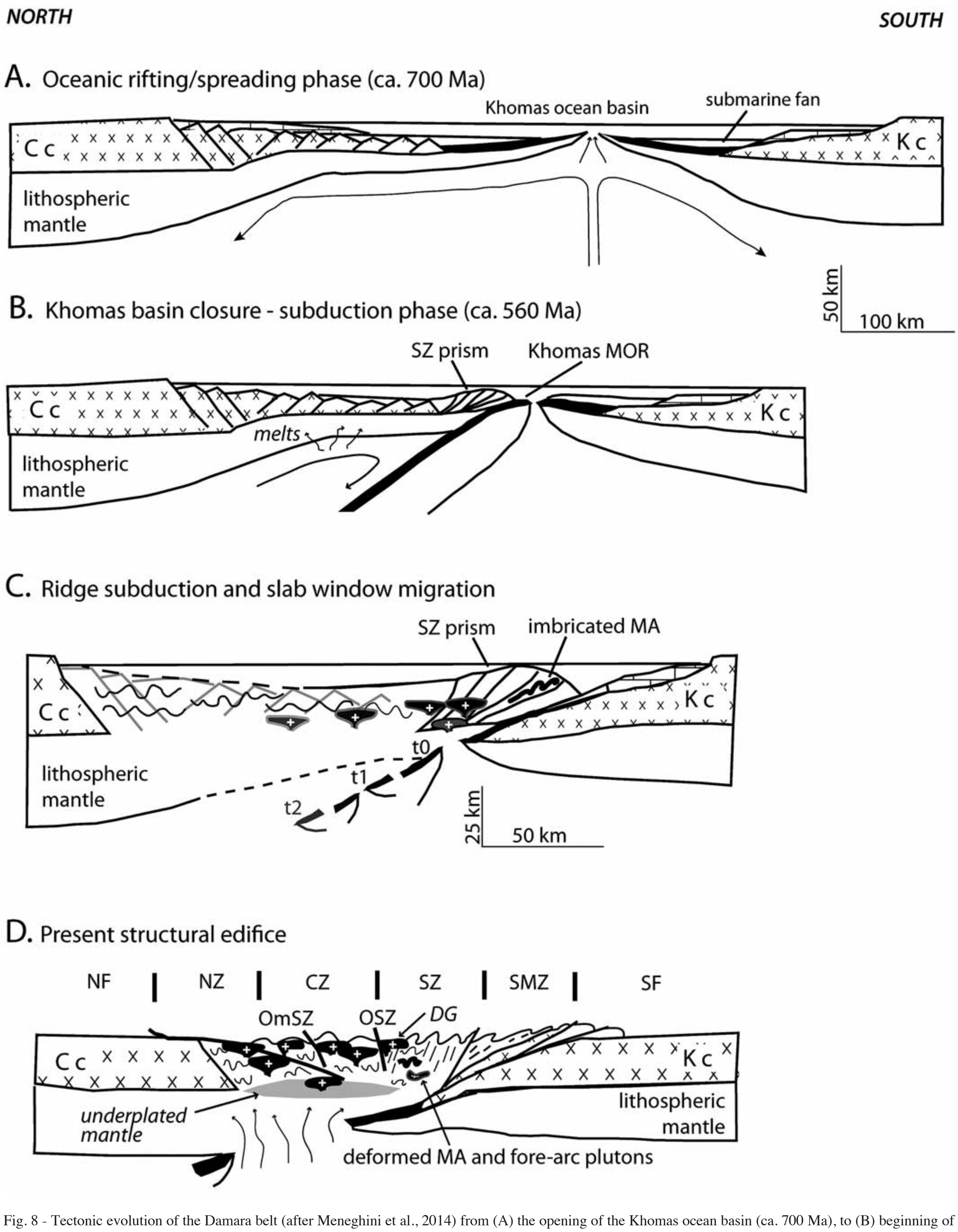


Fig. 8 - Tectonic evolution of the Damara belt (after Meneghini et al., 2014) from (A) the opening of the Khomas ocean basin (ca. 700 Ma), to (B) beginning of subduction and ocean consumption, up to (C) ridge subduction and migration of the relative slab window at depth, with associated magmatic evidence in the forearc region (migration is exemplified for hypothetic three time steps t_0, t_1 and t_2, as in Meneghini et al., 2014). (D) the Damara structural unit stack at present. Key: Cc - Congo craton; Kc - Kalahari craton; NF - Northern Foreland; NZ - Northern Zone; CZ - Central Zone; SZ - Southern Zone; SMZ - Southern Margin Zone; - SF - Southern Foreland; OmSZ - Omaruru Shear Zone; OSZ - Okahandia Shear Zone; MA - Matchless Amphibolite; DG - Donkehoek Granite.

Amphibolite as the deformed remnant of an ophiolite section. This section is representative of the oceanic lithosphere of the small Khomas ocean basin, opened between the Congo and Kalahari cratons (Barnes and Sawyer, 1980; Kasch, 1983). Therefore, we favour this interpretation instead of the alternative hypothesis of an intracratonic, ensialic origin of the Matchless mafics, proposed by Martin and Porada (1977). Gray et al. (2007), referring to the unusual length, lateral continuity and style of deformation of the Matchless, stressed some similarities with the Dun Mountain ophiolite of the Rangitatan orogeny of New Zealand.

The sedimentary section: from spreading to convergence

The Khomas schists comprise the metamorphic equivalents of graywackes, often graded, siltites and pelites that are organized in turbiditic sequences of different thickness and various sandstone to pelite ratios. Kukla (1992)'s detailed litostratigraphic and sedimentological analyses of the Kuiseb schists recognized different facies organized in characteristic sequences and comprising thick-bedded strata with massive, graded, parallel- and cross-stratified psammite layers, thin-bedded and thin-laminated psammite and metasiltstone strata, thick- to thin-bedded pelite layers (facies D and G of Mutti and Ricci Lucchi, 1975), metacarbonate and graphite schists facies. Kukla interpreted the observed distribution and organization of facies, and the uniform longitudinal paleocurrent distribution, as representative of middle-fan and outer fan deposits part of an elongate submarine fan extending in the north and centre of the Khomas Through. In the same study, the author described facies associations in the southern part of the Southern Zone, interpreted as pelagic and hemipelagic basin-plain deposits, possibly representing the sedimentary cover of the ophiolitic sequence now preserved in the Matchless Amphibolite.

Although our traverses did not extend far enough south to confirm the occurrence of basinal deposits, we interpret the studied schists as representative of turbidite deposits within a submarine fan, in accordance with Kukla (1992).

The geochemical data of Kukla (1992), in accordance with a similar study by Phillips et al. (1989) in the Windhoek area, suggest an active continental margin, such as an oceanic trench, as the tectonic setting of deposition for the Kuiseb greywakes (see Table 3.3, Fig. 3.17 and Appendix I.A of Kukla, 1992). Moreover, despite different metamorphic grades and conditions, and various degrees of structural repetition, the sedimentology of the Kuiseb metasediments show strong similarities with some of the best known trench- and subduction-related Meso-Cenozoic turbidite complexes: the Otago Schist belt in New Zealand (Gray and Foster 2004; Gray et al., 2006); the Kodiak and Chugach units of the Kodiak Island accretionary complex of Alaska (Byrne, 1982; Fisher and Byrne, 1987; Byrne and Fisher, 1990), the Internal Ligurian Units of the Northern Apennines (Marroni et al., 2004; Meneghini et al., 2009); the Shimanto Belt of Japan (Kimura, 1994; Hashimoto and Kimura, 1999).

Therefore the Kuiseb schists formed by turbidity currents in trench-related elongated submarine fans during subduction of the Khomas oceanic crust. According to what observed in the above-mentioned turbidite-dominated margins (Meneghini et al., 2009), and to the comparative study of Gray et al. (2006), the continentally-derived sediment input in the Kuiseb was probably large, and certainly significantly greater than the pelagic input.

The ridge-trench interaction

Metamorphic massive basalts show intrusive relationships with the trench turbidites of the Kuiseb schists by developing sill-like structures (Pollard and Johnson, 1973; Schofield et al., 2012). The geometry and morphology of the intrusive contacts and the delicate interfingering with metasediments, indicate that basaltic lava was able to flow in the same basin of deposition of turbidites while the deposits from turbidite currents were unlithified or only poorly lithified, according to the strong similarities with what described in sill structures related to non-brittle magma emplacement mechanisms (Pollard et al., 1975; Schofield et al., 2010; 2012). Following Meneghini et al. (2014), this can be interpreted as the evidence of the ridge being close to and approaching the trench, so that lava would flow from the ridge axis up to the close trench. In fact, similar structures have been extensively described in Meso-Cenozoic ridge-trench encounters such as North America (Kusky and Young, 1999; Groome et al., 2003; Sisson et al., 2003) and southern Chile (Forsythe and Nelson, 1985; Lagabrielle et al., 1994), or documented in active margins like the Woodlark Ridge/Solomon Trench (Taylor and Exon, 1987), the Chile Ridge/Chile Trench (Forsythe and Nelson, 1985; Cande et al., 1987) and the Juan de Fuca Ridge/Oregon Margin (Wilson et al., 1988) encounters. In particular, the ophiolitic units of Alaska, such as that of the Resurrection Peninsula, are described by Bradley et al. (2003) as typically characterized by off-axis igneous activity in the form of basaltic flow interbedded with flysch sequences and not associated with sheeted dike complexes. Similar evidences of near-trench off-axis magmatism have been reported in the ophiolitic complex of the Taitao Peninsula of the Chilean coast (Lagabrielle et al., 1994).

Another strikingly similar feature between the Southern Zone of the Damara and other complexes for which the subduction of a ridge has been invoked (Bradley et al., 2003), is the occurrence of extensive, massive sulfide deposits, with gold mineralization, hosted by the Kuiseb schists all along the 350 km strike length of the Matchless Amphibolite (Breitkopf and Maiden, 1988; Preussinger, 1990; Pirajno and Jacob, 1991; Steven et al., 2014; Meneghini et al., 2014).

Subduction and accretion

The evolution of deformation described in the two studied localities (and in Kukla's contributions) is similar to what is typically observed in coherent units from the Northern Apennines and Corsica, the high-grade units of the Franciscan Complex, the Kodiak Complex of Alaska and the Shimanto Belt of Japan (Jayko and Blake, 1989; Kimura, 1994; Meneghini et al., 2009; Marroni et al., 2010). Therefore, both in the studied area and in Meso-Cenozoic accretionary complexes, deformation fabrics actually develop through progressive phases of folding and thrusting, associated with metamorphic re-crystallization. Prior to imbrication, layer-parallel veining (fluid-saturated conditions) and boudinage (layer-parallel extension) typically accompany the early stages of deformation in Meso-Cenozoic analogues: despite a different metamorphic grade and the extent of high-strain domains in the two studied localities, the same sets of veins, with same geometry, have been described for the Kuiseb schists. A similar distribution of quartz mineralization and deformation has been described in the Southern Marginal Zone of the same belt by Fagereng et al. (2014).

The multiphase folding and thrusting in "younger" prisms is classically interpreted as related to the transfer of thick sections of the lower plate to the base of the prism, by the process of underplating (Fisher and Byrne, 1987; 1992; Moore and Sample, 1986; Moore, 1989). Similarly, we favor the interpretation by Kukla and Stainstreet (1991) of the whole Southern Zone as developed during multiple events of accretion of trench deposits and fragments of Khomas oceanic crust and its sedimentary cover, at the front of the Congo craton during convergence between the Congo and Kalahari cratons. In this view, the Matchless Amphibolite can be considered as representative of the ophiolitic suture of the Damara orogeny.

Moreover, the tectonic incorporation and mixing of blocks of gabbros within the Kuiseb schists, the lens shape of blocks and the "flow" of metapelites around them, strongly resemble the structure of accretion-related map-scale mélanges as described in various exhumed accretionary complexes (Wakabayashi, 1992; Jeanbourquin, 2000; Rojay, 2013; Goncuoglu et al., 2014). The various styles of accretion (folding and thrusting of thick units without disruption vs. accretion via mélange formation), have been related to the availability of thick sections of sediments on the lower plate when entering the subduction system (Kusky et al., 1997; Sample and Reid, 2003; Clift and Vannucchi, 2004; Meneghini et al., 2009): subduction of slabs with a thin veneer of sedimentary cover generally leads to the formation of mélanges, whereas subduction of thickly-sedimented slabs results in large-scale accretion of relatively coherent packages, separated by thin and sharp zones of shearing. While in the last case sediments are mostly preserved, with occasional basalts as the only component of the subducted ophiolitic section, in the first case basalts and gabbros can be as equally preserved as the sedimentary section in the accreted material. Depending on the variation of boundary conditions with time, the same complex can grow through both accretion processes. In the case of the Southern Zone prism the strain distribution across the measured sections, with mappable lenses of gabbro concentrated in the high-strain, mélange-like portions of the section, suggest a possible evolution of the Damara prism through accretion of slices of lower plate tapered with a variable sediment thickness, with alternating events of accretion of thick volumes of sediments and episodic scraping off of ophiolitic sequences/topographic relief.

UNIQUE CONDITIONS FOR THE WELL-PRESERVED PRECAMBRIAN RIDGE SYSTEM OF THE MATCHLESS BELT

We have extensively shown how the Southern Zone can be well framed in the context of plate tectonics as part of the accretionary prism of a subduction system (Miller, 1983; Gray et al., 2008), and stressed that the entire Damara orogen is known for showing characteristics that are not easily explained in a collisional geodynamic evolution of subduction (Miller, 1983; 2008; Jung and Mezger, 2003; Jung et al., 2005). In Meneghini et al. (2014) we have shown how these peculiarities can be reconciled in a ridge subduction model with opening and migration of a slab window: the Matchless suture zone well preserve the thermometamorphic imprint (Cross et al., 2015). Both these recent studies highlight the uniqueness of this accretionary complex that, despite its age and complexity, preserves both the structural and metamorphic evidence of accretion of different MOR lithotypes during ridge subduction, which is the natural fate of ocean closure, but is only rarely documented in literature. Rare is also the regional preservation of the Matchless Amphibolite that crops out for a length of ca. 350 km along strike, at approximately the same structural level throughout the Southern Zone. We will here list likely circumstances that might have determined the preservation of a ridge system in an ancient belt.

"Soft" collision

On a map- and regional- scale, the Southern Zone prism appears as almost perfectly intact, with convergence-related geometry and vergence. In addition, the petrologic study by Cross et al. (2015) on samples from the same traverse on the Rutile River, reveals that the subduction-related deformation is associated a with two-stage prograde metamorphic history that is perfectly preserved and not reworked by a collision event. All this, together with the already mentioned evidence that the Damara orogen never underwent any significant crustal thickening, suggests that collision in the Damara was not pervasive, if not aborted. A soft collision is the first, straightforward condition for an almost perfect preservation of accretionary deformation in the Southern Zone.

Small and young ocean basin

The Khomas Sea was a small basin with short life, with subduction and rifting considered to have been separated by ca. 80 Ma (Stainstreet et al., 1991). Therefore it can be considered as tapered by a young and fairly "warm" oceanic crust. The age of the descending lithosphere, which controls its thermal structure, thickness and density, and the subduction of anomalously low-density oceanic lithosphere, such as that of ridges, aseismic ridges, oceanic plateaus etc., are considered as key factors determining a low angle dip of the subducting slab (Cross and Pilger, 1982). Therefore, the Khomas oceanic crust subducted under the Congo craton along a relatively "shallow" subduction thrust interface.

Subduction of the ridge sub-parallel to the trench

Kusky et al. (1997), Kusky and Young (1999) and Bradley et al. (2003) all listed a series of hallmarks for ridge subduction in Southern Alaska and observed that many of these events are diachronous along strike. In line with the models of ridge subduction of Thorkelson (1996) they interpreted this diachronic distribution, and the strong strike-slip component of deformation, as the evidence of a ridge subducting the trench at a high angle, and migrating progressively with time along the trench. Along these lines, we propose that the ridge entered the subduction zone nearly parallel to trench (Fig. 9), so that it was driven more or less at once into the subduction system, based on the followings: the along strike continuity of the Matchless Amphibolite, the lack of a strike-slip component to deformation, and the lack of diachronous along strike arc magmatic activity in the Damara.

A ridge entering a convergent system must offer quite some resistance to subduction, especially if > 350 km of ridge entered at once into the system. In addition, a ridge entering a trench implies subduction of a rough topography, with topographic lows and highs that would further contribute to impede subduction. Nevertheless, the previously exposed lines of evidence testify to a complete subduction of the ridge, with decapitation of topographic highs and accretion of deeper portion of the ophiolitic sequence and closure of the Khomas Ocean, up to a continental collision,

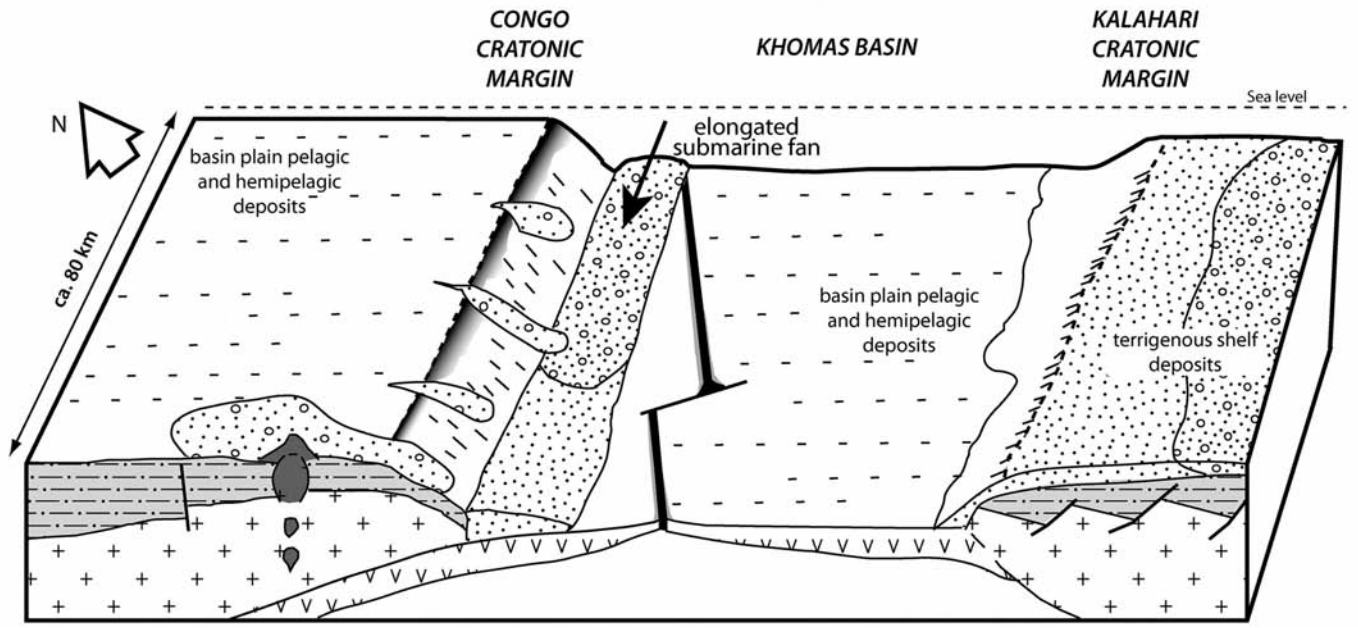


Fig. 9 - 3-D cartoon showing ridge sub-parallel to the trench and channeling elongate fan systems into the trench area.

even if soft or aborted. In fact, the subduction of young lithosphere with positive buoyancy and the high heat flow around the ridge are believed to play together to enhance crust-mantle decoupling and favoring imbrication of subducting oceanic crust along a shallow subduction plate interface (van den Beukel and Wortel, 1992; Cloos, 1993). In particular the thermal and mechanical modelling of van den Beukel (1990) and van den Beukel and Wortel (1992) predicts that the interaction of a spreading centre and a subduction zone can lead to the breakup of the descending young oceanic plate and accretion of elongated sheets of oceanic sections to the accretionary wedge. Moreover, these models suggest that detachment of sheets of oceanic lithosphere in the upper part of a subduction zones becomes more likely if the age of the subducting plate decreases, and, in addition, that the subduction of gradually younger oceanic lithosphere is accompanied by a decrease in the strength of the descending slab. The Khomas basin matches the criteria of a young subducting oceanic lower plate, thus making the Damara belt a good example of ophiolite emplacement during ridge-trench interaction following these models.

A big, sediment-dominated prism

The impressive thickening of the turbiditic complex preserved in the Southern Zone and its sedimentological features indicate a subduction system with a high sedimentary input. The ridge approaching sub-parallel the trench would enhance the thickness of the sedimentary pile to be subducted by contributing to the development of a strongly confined trench depocentre, channelling elongated submarine fans into a confined basin (Fig. 9): the stratigraphical and sedimentological characteristics of the Kuised elongate fan (Kukla, 1992) seems to support this hypotesis. We then propose that subduction of the ridge and decapitation of the upper part of the ophiolitic sequence to be preserved into the accretionary wedge, was aided by an extremely thick turbiditic trench sequence. These sediments may have nullified the rugged topography by filling in topographic lows, thus assisting the slicing up and subduction of a ridge that would otherwise have offered quite some resistance to subduction (Figs. 8 and 9).

In summary, we suggest that the combination of (i) a shallow subduction of young, buoyant oceanic lithosphere, (ii) a sub-parallel subduction, with the ridge over a length of > 350 km long, trench-parallel ridge driven more or less at once into the prism, and (iii) a sediment-dominated system, must have prepared the case for strong non-coaxial deformation and high shear stresses at the prism front, contributing to prism thickening and the slicing up of the ridge (Lallemand et al., 1992). Broad accretionary prisms and sediment-rich trenches are typically described in active subduction of spreading ridges nearly parallel to the trench, such as the Chile Ridge-Chile Trench and Juan de Fuca Ridge/Oregon Margin examples (Cande and Leslie, 1986; Wilson, 1988; Cloos, 1993); and imbrication of flow and pillow basalts within turbidites are described in the exhumed portions of some of these margins (Forsythe and Nelson, 1985; Lagabrielle et al., 2010). Similarly, we propose that scraping off and imbrication of thick sections of the ridge occurred during subduction, so that not just pillow basalts, but also gabbros were incorporated and preserved into the prisms.

As a corollary, ridge subduction, and the consequent slab-break off of a young oceanic plate, that was relatively warm and buoyant anyway, might have helped the collision event to be particularly soft, by basically annulling the slab pull and the Kalahari Craton entrance into the system. In fact, although a "warm" prism with higher grade than many others developed, it still preserves most of the subduction kinematics, such as downdip lineations and top-to-SE shear deformation, and some sedimentary structures, such as graded intervals in turdibite sequence and various way up indicators, suggesting that the prism never underwent successive refolding beyond recognition (see also Cross et al., 2015).

CONCLUSIONS

– The sequence of events that characterizes the geodynamic evolution of the Damara belt can be interpreted in terms of convergence, subduction and development of an accretionary prism, whose characteristics are strikingly similar to those documented from turbidite-dominated, younger Meso-Cenozoic convergent margins.

– The Matchless Amphibolite ophiolitic slivers were emplaced in the accretionary wedge during ridge subduction that occurred with the ridge subducting sub-parallel to the trench.

– The unusual geometry and along strike continuity of the Matchless Amphibolite, the preservation of this ophiolitic suture and the record of a ridge-trench encounter were possible thanks to the combination of (i) shallow subduction of young, buoyant oceanic lithosphere, (ii) subduction of the ridge sub-parallel to the trench, and (iii) a sediment-dominated system, with an extremely thick turbiditic trench sequence. These factors might have determined an aborted or very mild collision, allowing the subduction-related structures to be preserved and not obliterated by collision-related deformation.

ACKNOWLEDGEMENTS

We are thankful to the editors of Ofioliti, and to reviewers L. Federico and C. Göncüoğlu for their constructive reviews that substantially improved the quality of the manuscript. FM work was supported by a Claude Leon Foundation postdoctoral fellowship at Stellenbosch University (South Africa).

REFERENCES

Barnes S. and Sawyer E., 1980. An alternative model for the Damara mobile belt: ocean crust subduction and continental convergence. Precam. Res., 13: 297-336.

Belcher R.W. and Kisters A.F.M., 2003. Lithostratigraphic correlations in the western branch of the Pan-African Saldania belt, South Africa: the Malmesbury Group revisited. S. Afr. J. Geol., 106: 327-342.

Byrne T., 1982. Structural evolution of coherent terranes in the Ghost Rocks Formation, Kodiak Island, Alaska. In: J.K. Leggett (Ed.), Trench forearc geology. Geol. Soc London Spec. Publ.. 10: 229-242.

Byrne T. and Fisher D., 1990. Evidence of a weak and overpressured décollement beneath sediment-dominated accretionary prisms. J. Geophys. Res., 95: 9081-9097.

Bradley D., Kusky T., Haeussler P., Goldfarb R., Miller M., Dumoulin J., Nelson S.W. and Karl S., 2003. Geologic signature of early Tertiary ridgesubduction in Alaska. In: V.B. Sisson et al. (Eds.), Geology of a transpressional orogeny developed during ridge-trench interaction along the North Pacific margin: Geol. Soc. Am. Spec. Paper, 371: 19-49, doi:10.1130/0-8137-2371-X.19.

Breitkopf J.H. and Maiden K.J., 1988. Tectonic setting of the Matchless Belt pyritic copper deposits, Namibia. Econ. Geol., 83: 710-723.

Cande S.C. and Leslie R.B., 1986. Late Cenozoic tectonics of the Southern Chile Trench. J. Geophys. Res., 91: 471-496.

Cande S.C, Leslie R.B, Parra J.C. and Hobart M., 1987. Interaction between the Chile Ridge and Chile trench: Geophysical and geothermal evidence. J. Geophys. Res., 92: 495-520.

Clemens J., Buick I.S., Kisters A.K.M. and Frei D., 2017. Petrogenesis of the granitic Donkerhuk batholith in the Damara Belt of Namibia: protracted syntectonic, short-range, crustal magma transfer. Contrib. Mineral. Petrol., 172:50, doi: 10.1007/s00410-017-1370-0, published online.

Clift P. and Vannucchi P., 2004. Controls on tectonic accretion versus erosion in subduction zones: implications for the origin and recycling of the continental crust. Rev. Geophys., 42: RG2001, doi: 10.1029/2003RG000127.

Cloos M., 1993. Lithospheric buoyancy and collisional orogenesis: subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts. Geol. Soc. Am. Bull., 105: 715-737.

Cross T.A. and Pilger R.H., 1982. Controls of subduction geometry, location of magmatic arcs, and tectonics of arc and back-arc regions. Geol. Soc. Am. Bull., 93: 545-562.

Cross C.B., Diener J.F.A. and Fagereng A., 2015. Metamorphic imprint of accretion and ridge subduction in the Pan-African Damara Belt, Namibia. J. Metam. Geol., 33: 633-648.

Dilek Y. and Robinson P.T., 2003. Ophiolites in the Earth history: Introduction. In: Y. Dilek and P.T. Robinson (Eds.), Ophiolites in the Earth history. Geol. Soc. London Spec. Publ., 218: 1-8.

Fagereng Å., Hillary G.W. and Diener J.F., 2014, Brittle-viscous deformation, slow slip, and tremor. Geophis. Res. Lett., 41: 4159-4167.

Fisher D.M. and Byrne T., 1987. Structural evolution of underthrust sediments, Kodiak Islands, Alaska. Tectonics, 6: 775-793.

Fisher D.M. and Byrne T., 1992. Strain variations in an ancient accretionary complex: implications for forearc evolution. Tectonics, 11: 330-347.

Forsythe R. and Nelson E., 1985. Geological manifestations of ridge collision: evidence from the Golfo de Penas-Taitao Basin, Southern Chile. Tectonics, 4: 477-495.

Goscombe B., Hand M. and Gray D., 2003. Structure of the Kaoko Belt, Namibia: progressive evolution of a classic transpressional orogen. J. Struct. Geol., 25: 1049-1081.

Gray D.R. and Foster D.A., 2004. ^{40}Ar/^{39}Ar thermochronologic constraints on deformation, metamorphism and cooling/exhumation of a Mesozoiic accretionary wedge, Otago Schist, New Zealand. Tectoniphysics, 385: 181-210.

Gray D.R., Foster D.A., Goscombe B.D., Passchier C.W. and Trouw R.A.J., 2006. ^{40}Ar/^{39}Ar thermochronology of the Pan-African Damara orogen, Namibia, with implications for tectonothermal and geodynamic evolution. Prec. Res., 150: 49-72.

Gray D.R., Foster D.A., Maas R., Spaggiari C.V., Gregory R.T., Goscombe B.D. and Hoffmann K.H. 2007. Continental growth and recycling by accretion of deformed turbidite fans and remnant ocean basins: examples from Neoproterozoic and Phanerozoic orogens. In: R.D. Jr., Hatcher, M.P. Carlson, J.H. Mcbride and N.J.R. Martinez Catala' (Eds.), The 4D framework of continental crust. Geol. Soc. Am. Mem., doi: 10.1130/2007.1200(05).

Gray D.R., Foster D.A., Meert J.G., Goscombe B.D., Armstrong R., Trouw R.A.J. and Passchier C.W., 2008. A Damara orogen perspective on the assembly of southwestern Gondwana. In: R.J. Pankhurst et al. (Eds.), West Gondwana: Pre-Cenozoic correlations across the South Atlantic region. Geol. Soc. London Spec. Publ. 294: 257-278, doi: 10.1144/SP294.14.

Groome W.G., Thorkelson D.J., Friedman R.M., Mortensen J.K., Massey N.W.D., Marshall D.D. and Layer P.W., 2003. Magmatic and tectonic history of the Leech River Complex, Vancouver Island, British Columbia: Evidence for ridge-trench intersection and accretion of the Crescent Terrane. In: V.B. Sisson et al. (Eds.), Geology of a transpressional orogeny developed during ridge-trench interaction along the North Pacific margin: Geol. Soc. Am. Spec. Paper 371: 327-353, doi: 10.1130/0-8137-2371-X.327.

Göncüoglu M.C., Marroni M., Pandolfi L., Ellero A., Ottria, G. Catanzariti R., Tekin U.K. and Sayit K. 2014. The Arkot Dağ Mélange in Araç area, central Turkey: Evidence of its origin within the geodynamic evolution of the Intra-Pontide suture zone. J. Asian Earth Sci., 85: 117-139.

Hashimoto Y. and Kimura G., 1999. Underplating process from mélange formation to duplexing: example from the Cretaceous Shimanto Belt, Kii Peninsula, southwest Japan. Tectonics, 18: 92-107.

Jayko A.S. and Blake M.C. Jr., 1989. Deformation of the Eastern Franciscan Belt, northern California. J. Struct. Geol., 11: 375-390.

Jeanbourquin P., 2000. Chronology of deformation of a Franciscan mélange near San Francisco (California, U.S.A.). Ecl. Geol. Helv., 93: 363-378.

Jung S. and Mezger K., 2003. Petrology of basement dominated terrains: I. Regional metamorphic T-t path from U-Pb monazite and Sm-Nd garnet chronology (Central Damara orogen, Namibia). Chem. Geol., 198: 223-247.

Jung S., Mezger K. and Hoernes S., 2001. Trace element and isotopic (Sr, Nd, Pb, O) arguments for a mid-crustal origin of Pan-African garnet-bearing S-type granites from the Damara Orogen (Namibia). Precam. Res., 110: 325-355.

Jung S., Hoernes S. and Mezger K., 2002. Synorogenic melting of mafic lower crust: constraints from geochronology, petrology and Sr, Nd, Pb and O isotope geochemistry of quartz diorites (Damara Orogen, Namibia). Contrib. Miner. Petr., 143: 551-566.

Jung S., Hoernes S. and Hoffer E., 2005. Petrogenesis of cogenetic nepheline and quartz syenites and granites (northern Damara Orogen, Namibia) - Enriched mantle vs. contamination. J. Geol., 113: 651-672, doi: 10.1086/467475

Jung S., Hoernes S., Masberg P. and Hoffer E., 1999. The petrogenesis of some migmatites and granites (Central Damara Orogen, Namibia): evidence for disequilibrium melting, wallrock contamination and crystal fractionation. J. Petr., 40: 1241-1269.

Kasch K.W., 1981. The structural geology, metamorphic petrology and tectonothermal evolution of the southern Damara Belt around Omitara, South West Africa/Namibia. Chamber Mines Precam. Res. Unit Bull., 27: 333-342.

Kasch K.W., 1983. Continental collision, suture progradation and thermal relaxation: a plate tectonic model for the Damara orogen in central Namibia. In: R. McG. Miller (Ed.), Evolution of the Damara orogen of South West Africa/Namibia. Geol. Soc. South Africa Spec. Publ., 11: 73-80.

Killick A.M., 2000. The Matchless Belt and associated sulphide mineral deposits, Damar orogen, Namibia. In: R. McG. Miller (Ed.), Henno Martin Commemorative Volume. Comm. Geol. Survey Namibia, 12: 197-209.

Kimura G., 1994. The latest Cretaceous-early Paleogene rapid growth of accretionary complex and exhumation of high-pressure series metamorphic rocks in northwestern Pacific margin. J. Geoph. Res., 99: 22147-22164.

Kisters A.F.M., Jordaan L.S. and Neumaier K. 2004. Thrust-related dome structures in the Karibib district and the origin of orthogonal fabric domains in the south Central Zone of the Pan-African Damara belt, Namibia. Precam. Res., 133: 283-303.

Kukla C., 1992. Tectonics and sedimentation of a Late Proterozoic Damaran convergent continental margin, Khomas Hochland, Central Namibia. Comm. Geol. Surv. Namibia Mem., 12: 1-95.

Kukla C. 1993. Strontium isotope heterogeneities in amphibolite facies, banded metasediments - A case study from the Late Proterozoic Kuiseb Formation of the southern Damara orogen, Central Namibia. Comm. Geol. Surv. Namibia Mem., 15: 1-139.

Kukla P.A. and Stanistreet I.G., 1991. Record of the Damaran Khomas Hochland accretionary prism in central Namibia: Refutation of an "ensialic" origin of a Late Proterozoic orogenic belt. Geology, 19: 473-476.

Kusky T.M. and Young C.P., 1999. Emplacement of the Resurrection Peninsula ophiolite in the southern Alaska forearc during a ridge-trench encounter. J. Geophys. Res., 104: 29025-29054, doi: 10.1029/1999JB900265.

Kusky T.M., Bradley D.C., Haeussler P.J. and Karl S., 1997. Controls on accretion of flysch and mélange belts at convergent margins: evidence from the Chugach Bay thrust and Iceworm mélange, Chugach accretionary wedge, Alaska. Tectonics, 16: 855-878.

Lagabrielle Y., Le Moigne J., Maury R.C., Cotton J. and Bourgois J., 1994, Volcanic record of the subduction of an active spreading ridge, Taitao Peninsula (southern Chile). Geology, 22: 515-518.

Lallemand S.E., Malavieille J. and Calassou S., 1992. Effects of oceanic ridge subduction on accretionary wedges: experimental modelling and marine observations. Tectonics, 11: 1301-1313.

Longridge L., Gibson R.L., Kinnaird J.A. and Armstrong R.A., 2011. Constraining the timing of deformation in the southwestern Central Zone of the Damara Belt, Namibia. Geol. Soc. London Spec. Publ., 357: 107-135.

Marroni M., Pandolfi L. and Meneghini F., 2004. From accretion to exhumation in a fossil accretionary wedge: a case history from Gottero Unit (Northern Apennines, Italy). Geodin. Acta, 17: 41-53.

Marroni, M., Meneghini, F. and Pandolfi, L., 2010. Anatomy of the Ligure-Piemontese subduction system: evidence from Late Cretaceous-Middle Eocene convergent margin deposits in the Northern Apennines, Italy. Int. Geol. Rev., 23: 1-33.

Martin H., 1983, Overview of the geosynclinal, structural and metamorphic development of the intracontinental branch of the Damara orogeny. In: H. Martin and F.W. Eder (Eds.), Intracontinental fold belts. Springer-Verlag, Berlin, p. 473-502.

Martin H. and Porada H., 1977. The intracratonic branch of the Damara orogen in southwest Africa I. Discussion of geodynamic models. Precam. Res., 5: 311-338.

Meneghini F., Marroni M., Moore J.C., Pandolfi L. and Rowe C.D., 2009. The processes of underthrusting and underplating in the geologic record: structural diversity between the Franciscan Complex (California), the Kodiak Complex (Alaska) and the Internal Ligurian Units (Italy). Geol. J., 44: 126-152.

Meneghini F., Kisters A.F.M., Buick I.S. and Fagereng Å., 2014. Fingerprints of late Neoproterozoic ridge subduction in the Pan-African Damara Belt, Namibia. Geology, 42: 903-906.

Miller R. McG. (Ed.), 1983. Evolution of the Damara orogen of South West Africa/Namibia. Geol. Soc. S. Africa Spec. Publ., 11, 515 pp.

Miller R. McG., 2008. The geology of Namibia, Vol. 2: Neoproterozoic to Lower Paleocene. Geol. Survey Namibia, Windhoek. Namibia.

Moore J.C., 1989. Tectonics and hydrogeology of accretionary prisms: role of the décollement zone. J. Struct. Geol., 11: 95-106.

Moore J.C. and Sample J.C., 1986. Mechanisms of accretion at sediment-dominated subduction zones: consequences for the stratigraphic record and the accretionary prism hydrogeology. Mem. Soc. Geol. It., 31: 107-118.

Moore J.C. and Silver E., 1987. Continental margin tectonics: Submarine accretionary prisms. Tectonophysics, 25: 1305-1312.

Mutti E. and Ricci Lucchi F., 1975. Turbidite facies and facies associations. In: E. Mutti et al. (Eds.), Examples of turbidite facies and associations of facies fro selected formations of the Northern Apennines. Fiel Trip Guidebook A-11, 9th IAS Congress, Nice, p. 21-36.

Passchier C.W. and Trouw R.A.J., 1996. Microtectonics. Springer-Verlag, Berlin, 289 pp.

Phillips G.N., Groves D.I. and Reed K., 1989. Geochemical evolution of the Kuiseb schists, Windhoek, Namibia. Comm. Geol. Surv. Namibia, 5: 19-30.

Pearce J.A., Lippard S.J. and Roberts S., 1984. Characteristics and tectonic significance of suprasubduction zone ophiolites. In: B.P. Kokelaar and M.F. Howells (Eds.), Marginal basin geology. Geol. Soc. London Spec. Publ., 16: 77-94.

Pirajno F. and Jacob R.E., 1991. Gold mineralisation in the intracontinental branch of the Damara orogen, Namibia: A preliminary survey. J. Afr. Earth Sci., 13: 305-311.

Pollard D.D. and Johnson A.M., 1973. Mechanics of growth of some laccolith intrusions in the Henry Mountains, Utah. Part II. Tectonophysics, 18: 311-354.

Pollard D.D., Muller O.H. and Dockstader D.R., 1975. Form and growth of fingered sheet intrusions. Geol. Soc. Am. Bull., 86: 351-363.

Porada H., 1989. Pan-African rifting and orogenesis in southern to equatorial Africa and eastern Brazil. Precam. Res., 44: 103-136.

Preussinger H., 1990. Host-rock geology of the metamorphosed massive sulfide deposits at Gorob in the Pan-African Damara Orogen, Namibia. J. Afr. Earth Sci., 10: 717-732.

Rojay B., 2013. Tectonic evolution of the Cretaceous Ankara ophiolitic mélange during the Late Cretaceous to pre-Miocene interval in Central Anatolia, Turk. J. Geodyn., 65: 66-81.

Rowe C.D., Backeberg N.R., van Rensburg T., Maclennan S.A., Faber C., Curtis C. and Viglietti P.A., 2010. Structural geology of Robben Island: implications for the tectonic environment of Saldanian deformation. S. Afr. J. Geol., 113: 57-72.

Sample J.C. and Reid M., 2003. Large-scale, latest Cretaceous uplift along the northeast Pacific Rim: evidence from sediment volume, sandstone petrography and Nd isotope signatures of the Kodiak Formation, Kodiak Islands, Alaska. In: V.B. Sisson et al. (Eds.), Geology of a transpressional orogeny developed during ridge-trench interaction along the North Pacific margin: Geol. Soc. Am. Spec. Paper, 371: 51-70.

Sawyer E.W., 1981. Damaran structural and metamorphic geology of an area southeast of Walvis Bay, SW Africa/Namibia. South West Africa Geol. Surv. Mem. 7, 94 pp.

Shreve R. L. and Cloos M., 1986. Dynamics of sediment subduction, melange formation, and prism accretion. J. Geophys. Res., 91: 10229-10245.

Schofield N.J., Stevenson C.T. and Reston T., 2010. Magma fingers and host rock fluidization in the emplacement of sills. Geology, 38: 63-66.

Schofield N.J., Brown D.J., Mage C. and Stevenson C.T, 2012. Sill morphology and comparison of brittle and non-brittle emplacement mechanisms. J Geol. Soc. London, 169: 127-141.

Sisson V.B., Pavlis T.L., Roeske S.M. and Thorkelson D.J., 2003. Introduction: An overview of ridge-trench interactions in modern and ancient settings. In: V.B. Sisson et al. (Eds.), Geology of a transpressional orogeny developed during ridge-trench interaction along the North Pacific margin: Geol. Soc. Am. Spec. Paper, 371: 1-18, doi: 10.1130/0-8137-2371-X.1.

Stainstreet I.G., Kukla P.A. and Henry G., 1991. Sedimentary basinal sequences to a Late Precambrian Wilson cycle: the Damara orogen and Nama foreland, Namibia. J. Afr. Earth Sci., 13: 141-156.

Steven N., Wulff K., Kisters A.F.M., Eglington B. and Miller J., 2014. Implication of high-precision Re-Os molybdenite dating of the Navachab orogenic gold deposit. Geochem. Explor., Environ., Analysis, 15: 125-130.

Taylor B. and Exon N.F., 1987. An investigation of ridge subduction in theWoodlark-Solomons region: Introduction and overview. In: B. Taylor and N. Exon (Eds.), Marine geology, geophysics, and geochemistry of the Woodlark Basin-Solomon Islands. Circum-Pacific Council for Energy and Miner. Res. Earth Sci. Series, 7: 1-24.

Thorkelson, D.J., 1996. Subduction of diverging plates and the principles of slab window formation. Tectonophysics, 255: 47-63.

van den Beukel J. and Wortel R., 1992. Ridge-trench interaction: a possible mechanism for ofiolite emplacement. Ofioliti, 17: 141-154.

van den Beukel J., 1990. Breakup of young oceanic lithosphere in the upper part of a subduction zone: Implications fro the emplacement ofophiolites. Tectonics, 9: 825-844.

Wakabayashi J., 1992. Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California. J. Geol., 100: 19-40.

Wilson D.S., 1988. Tectonic history of the Juan de Fuca Ridge over the last 40 million years. J. Geophys. Res., 91: 10259-10269.

Received, January 21, 2017
Accepted, May 16, 2017