NRC Research Press

ARTICLE

Early extensional detachments in a contractional orogen: coherent, map-scale, submarine slides (mass transport complexes) on the outer slope of an Ediacaran collisional foredeep, eastern Kaoko belt, Namibia[1]

Paul F. Hoffman, Eric J. Bellefroid, Benjamin W. Johnson, Malcolm S.W. Hodgskiss, Daniel P. Schrag, and Galen P. Halverson

Abstract: The existence of coherent, large-scale, submarine landslides on modern continental margins implies that their apparent rarity in ancient orogenic belts is due to non-recognition. Two map-scale, coherent, pre-orogenic, normal-sense detachment structures of Ediacaran age are present in the Kaoko belt, a well-exposed arc–continent collision zone in northwestern Namibia. The structures occur within the Otavi Group, a Neoproterozoic carbonate shelf succession. They are brittle structures, evident only through stratigraphic omissions of 400 m or more, that ramp down to the west with overall ramp angles of 1.1° and 1.3° with respect to stratigraphic horizons. The separations of matching footwall and hangingwall stratigraphic cut-offs require horizontal translations >20 km for each detachment. One of the detachments is remarkably narrow (5 km) in the up-dip direction, just one fourth of its translation. The other detachment is stratigraphically dated at the shelf–foredeep transition, when the passive margin was abortively subducted westward, in the direction of submarine sliding. Trenchward sliding on the foreslope occurred concurrently with deep karstification of the autochthonous carbonate succession to the east, presumably due to forebulge uplift and (or) conjectural basin-scale base-level fall. We expect that similar detachments exist in other orogenic belts, and failure to recognize them can lead to misinterpretations of stratigraphy, sedimentary facies, and paleogeography.

Résumé : L'existence de glissements de terrains sous-marins cohérents, à grande échelle, sur les marges continentales modernes implique que leur rareté apparente dans les anciennes ceintures orogéniques est due à une non-reconnaissance. Deux structures d'âge Édiacarien, cohérentes, à une échelle cartographiable, pré-orogène et à décollement normal, sont présentes dans la ceinture de Kaoko, une zone bien exposée de collision arc–continent dans le nord-ouest de la Namibie. Les structures sont situées à l'intérieur du Groupe d'Otavi, une suite de plateforme carbonate datant du Néoprotérozoïque. Ce sont des structures cassantes, évidentes seulement en raison de manques stratigraphiques de 400 m ou plus, qui diminuent vers l'ouest avec des angles de rampe de 1,1 ° et 1,3 ° par rapport aux horizons stratigraphiques. La séparation entre les coupes stratigraphiques correspondantes sur les épontes inférieure et supérieure exige des translations horizontales >20 km pour chaque décollement. Un des décollements est remarquablement étroit (5 km) en direction amont-pendage, soit seulement un quart de sa translation. L'autre décollement est stratigraphiquement daté à la transition plateforme-avant fosse alors que la marge passive a été coupée par une subduction vers l'ouest, dans la direction du glissement sous-marin. Un glissement sur l'avant-pente, vers la fosse, s'est produit en même temps qu'une karstification profonde de la suite carbonatée autochtone vers l'est, probablement en raison du soulèvement d'un bourrelet périphérique et (ou) d'une chute conjecturelle du niveau de base à l'échelle du bassin. Selon nous, de tels décollements similaires existent dans d'autres ceintures orogéniques et le fait de ne pas les reconnaître peut mener à des interprétations fautives de la stratigraphie, des faciès sédimentaires et de la paléogéographie. [Traduit par la Rédaction]

Introduction

Coherent, large-scale, submarine landslides exist on many modern continental margins (Dingle 1977; Bugge et al. 1987; Hampton et al. 1996; Rowan et al. 2004; Martinez et al. 2005; Masson et al. 2006; Butler and Paton 2010; Morley et al. 2011; Armandita et al. 2015). Bathymetric and (or) seismic reflection studies show them to consist of up-dip extended domains and down-dip shortened domains, characterized by breakaway- and thrust-duplexes, respectively (Fig. 1). Although stratigraphically confined, the presence of growth strata (Fig. 1A) show some examples to have developed slowly by creep. Their apparent rarity in ancient orogenic belts is more likely due to non-recognition than non-occurrence.

The discovery of the Ombonde detachment (Hoffman and Hartz 1999) in the Kaoko belt of Namibia (Fig. 2) provided an Ediacaran example for which the net displacement, paleotectonic setting, and longitudinal (i.e., slip-parallel) cross-section of the extended

Received 3 October 2015. Accepted 17 January 2016.

Paper handled by Editor Ali Polat.

P.F. Hoffman. 1216 Montrose Avenue, Victoria, BC V8T 2K4, Canada.
E.J. Bellefroid. Department of Geology and Geophysics, Yale University, New Haven, CT 06520-8109, USA.
B.W. Johnson. School of Earth and Ocean Sciences, University of Victoria, Victoria, BC V8P 5C2, Canada.
M.S.W. Hodgskiss and G.P. Halverson. Department of Earth and Planetary Sciences, McGill University, Montreal, QC H3A 0E8, Canada.
D.P. Schrag. Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA.
Corresponding author: Paul F. Hoffman (email: paulfhoffman@gmail.com).

[1]This paper is part of a special issue that honors the careers of Kevin C. Burke and John F. Dewey.

Published at www.nrcresearchpress.com/cjes on 19 January 2016.

Fig. 1. Interpretations of seismic reflection profiles (redrawn from Butler and Paton 2010; Armandita et al. 2015) showing (A) Late Cretaceous and (B) early Pliocene submarine landslides (mass transport complexes) within fine-grained terrigeous and carbonate sediments, respectively, on the passive continental margins of southwest Africa and southeast Borneo. The scale is the same for each profile and the Borneo margin is geographically "reversed" for kinematic comparison. The Namibian margin faces the South Atlantic Ocean; the Borneo margin (Paternoster Platform) faces the South Makassar Straits Basin and the West Sulawesi thrust-fold belt. The slides include extended domains characterized by normal-fault duplexes (green lines) and shortened domains by thrust duplexes (blue lines), both soled on a basal detachment (red). Note syn-slide growth strata on the Namibian margin. In the South Makassar Strait slide, the strain domains migrated down-dip over time, resulting in thrusting succeeded by cospatial normal faulting. Planform of the South Makassar slide mass (C) shows its width to be only a fraction of its maximum translation, unlike detachments of tectonic origin. The barbed line in C indicates the steep frontal ramp in B, not the toe of the detachment. [Colour online.]

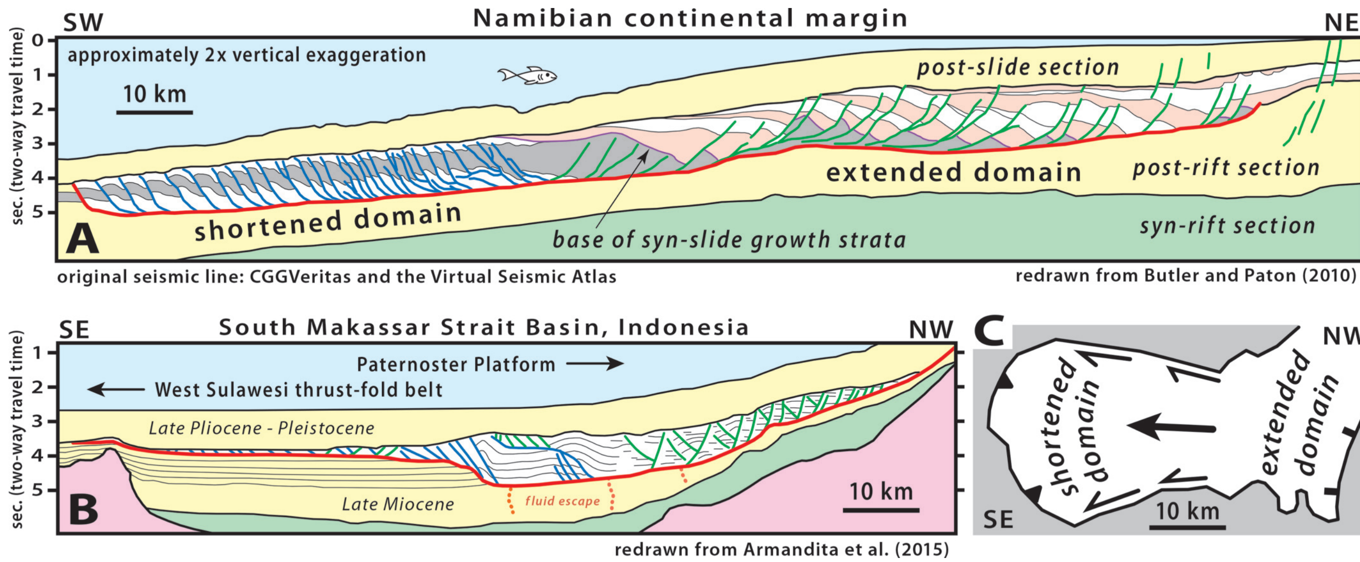
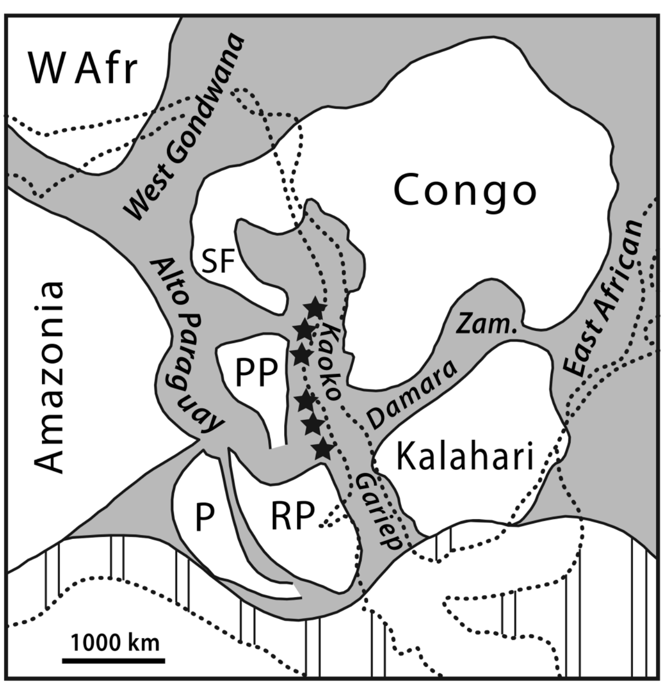


Fig. 2. Cratons (clear), Ediacaran – early Cambrian orogenic belts (shaded), and Mesozoic–Cenozoic belts (hachured) of southwest Gondwana. Dotted lines are the present shorelines of South America, southern Africa, and West Antarctica in a pre-drift reconstruction. SF, Sao Francisco; RP, Rio Plata; P, Pampean; PP, Paranápanema; Zam., Zambesi belt (modified from Fuck et al. 2008). Black stars indicate the Dom Feliciano – Ribeira magmatic arc, which collided with the Congo craton to form the Kaoko belt.

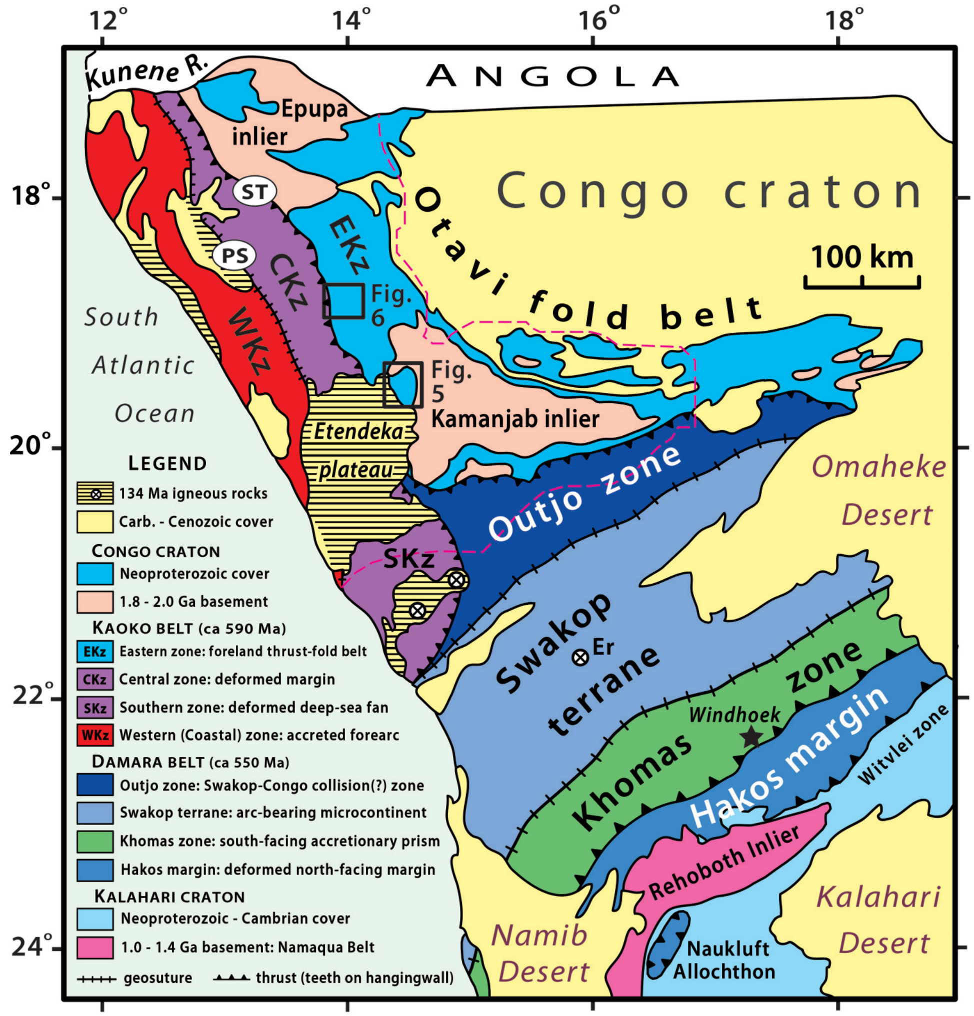


domain (Fig. 1) are well constrained by plunge projection of surface maps and stratigraphic logs (Hoffman and Hartz 1999; Hoffman and Halverson 2008). What the Ombonde detachment did not reveal was its transverse (i.e., slip-normal) dimension and an implicit shortened domain (Fig. 1) in the down-dip direction, which is obscured by post-orogenic cover. The shortened domain of a possibly analogous detachment, the "Saturn slide" (Clifford 1962, 2008), was recognized earlier within correlative strata of the adjacent Outjo zone (Fig. 3).

Here we describe a second low-angle extensional detachment in the Kaoko belt (Fig. 3). Like the Ombonde detachment, 90 km to the south, the Ombepera detachment predates orogenic shortening. It is a brittle structure within a carbonate platform succession, locally associated with a dilational breccia zone in the hangingwall, but lacking recognizeable shear fabrics. The structure is only evident through stratigraphic mapping. The average ramp angle between the detachment and stratigraphic planes is 1.3°, similar to the Ombonde detachment (1.1°). The characteristic stratigraphic omission is somewhat greater than the 395 m of missing strata across the Ombonde detachment, and the separation of stratigraphic cut-offs in the footwall and hangingwall of the Ombepera detachment imply >20 km of displacement.

The timing of the Ombonde detachment is tightly constrained. Movement postdates the entire Otavi Group carbonate shelf sequence and predates the basal foredeep clastics of the disconformably overlying Mulden Group (Fig. 4) (Hoffman and Hartz 1999). We assume contemporaneity of the two detachments based on structural homology. Like the Ombonde detachment, only the extended domain of the Ombepera detachment is exposed. Unlike the Ombonde detachment, its transverse extent is directly constrained by surface mapping. This, and mutual verification of the phenomenon, make the Ombepera detachment a structure of interest. Failure to recognize the detachment would have led to serious misinterpretations of the stratigraphy and sedimentary facies relations.

Fig. 3. Tectonic map of northwest Namibia showing elements of the Congo and Kalahari cratons, and the Kaoko and Damara orogenic belts (adapted from Hoffmann 1987). Boxes in the Eastern Kaoko zone (EKz) frame the Ombonde (Fig. 5) and Ombepera (Fig. 6) detachment areas. Dashed magenta line is the boundary of the Kunene Region. [Colour online.]



We begin by describing the basic stratigraphy of Neoproterozoic cover on the southwestern Congo craton and its relation to the Kaoko and Damara orogenic belts, in the context of centre-west Gondwana amalgamation. Next we review the salient map-scale features of the Ombonde detachment that bear on its geometry, displacement, and age. Then we describe how the Ombepera detachment came to be recognized in its type area, and how its interpretation was tested and confirmed by up-dip projection. Finally, we identify the need for additional mapping to investigate marked widening and (or) flattening of the Ombepera detachment surface in the down-dip direction.

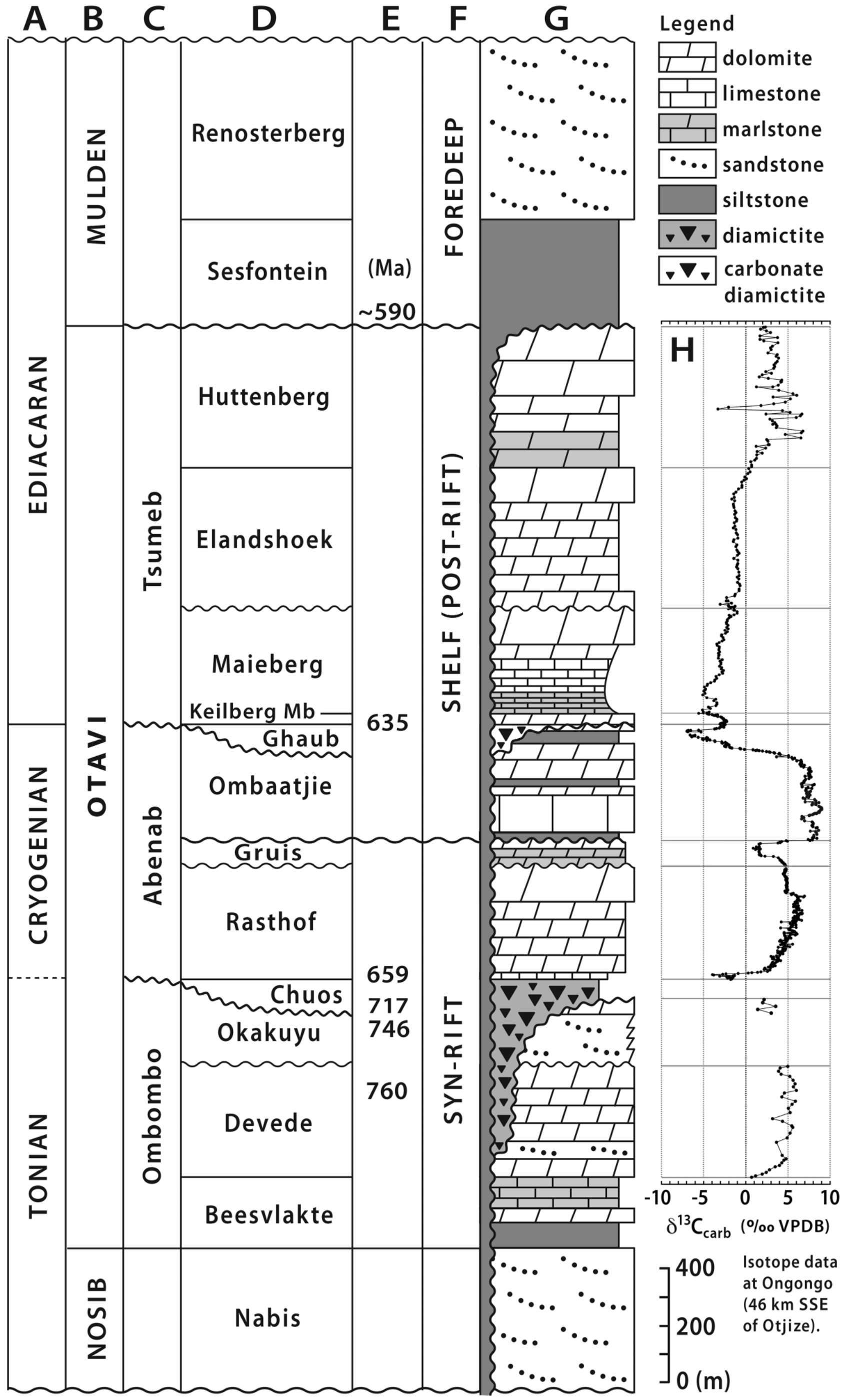
Neoproterozoic cover of the southwestern Congo craton

Paleoproterozoic crust of the present southwestern promontory of the Congo craton (Fig. 2) is blanketed by a Neoproterozoic sedimentary succession composed of three groups (Fig. 4). The basement-hugging Nosib Group (SACS 1980) consists of subfeldspathic arenite and rudite deposited on a southward-sloping alluvial braidplain. The conformably overlying Otavi Group (SACS 1980) is a 2–4 km thick carbonate shelf sequence with a well-defined shelf-break and a distally tapered southern foreslope (Hoffman and Halverson 2008). A presumed western shelf margin is occluded by the Sesfontein thrust (Fig. 3), an eastward-vergent, crustal-scale, thrust fault carrying the Central Kaoko zone, where the Otavi Group is an off-shelf facies.

Internally, the Otavi Group consists of three subgroups (Fig. 4), divided by unconformities that underlie each of the two Cryogenian glacial–periglacial assemblages (Hoffmann and Prave 1996). The Chuos and Ghaub formations represent the prolonged Sturtian (717–659 Ma) and briefer Marinoan (ca. 645–635 Ma) glaciations, respectively. The Rasthof and Maieberg formations represent the respective postglacial cap-carbonate sequences (Hoffman and Halverson 2008).

The Tonian Ombombo Subgroup (Hoffmann and Prave 1996) consists of cyclical, shallow-marine dolomite with authigenic chert, intercalated with alluvial and deltaic clastic rocks. Clastic input resulted from intermittent uplift and erosion of northward-inclined dip-slopes, interpreted as the footwalls of spaced, south-dipping, normal faults (Hoffman and Halverson 2008). The age of the Nosib–Otavi transgression and the onset of rift faulting must be significantly older than 760 ± 1 Ma (Halverson et al. 2005), the U–Pb zircon date of a bentonite near the top of the carbonate-rich Devede Formation (Fig. 4) in the middle Ombombo Subgroup. Intermittent rift-shoulder uplift, inferred from low-angle unconformities and cannibalistic sedimentation, persisted into the Cryogenian Abenab Subgroup (SACS 1980) up to the base of the Ombaatjie Formation (Fig. 4), which marks the rift-to-shelf transition

Fig. 4. Stratigraphic column of the Neoproterozoic Damara Supergroup in the Eastern Kaoko zone Namibia (Hoffman and Halverson 2008). (A) Geologic periods, (B) Groups, (C) Subgroups, (D) Formations and Members, (E) radiometric chronology, (F) tectonic phase, (G) generalized lithology, (H) carbonate C-isotope composition in per mil relative to the VPDB (Vienna PeeDee Belemnite) standard.



(Hoffman and Halverson 2008) at an estimated 650 Ma. Thereafter, the shelf aggraded conformably and preferentially relative to the foreslope and basin in the Outjo zone (Fig. 3) until the demise of carbonate sedimentation at the top of the Ediacaran Tsumeb Subgroup (SACS 1980), the thickest and most continuous of the Otavi subgroups.

The Mulden Group (SACS 1980) paraconformably overlies the Otavi Group and forms an upward-shoaling, marine-to-nonmarine sequence of compositionally-immature clastics, culminating with crossbedded arenites (Renosterberg Formation) deposited by high-discharge southeastward-flowing rivers (Hoffman and Halverson 2008). On the southwest flank of the Kamanjab inlier (Fig. 3), paleo-outliers of Otavi Group carbonate <900 m thick are buried paraconformably by Mulden Group clastics that, at their base, were deposited directly upon the crystalline basement (Frets 1969). The karstic outliers shed dolomite-chert debris-fans and conglomerates into the more far-travelled Mulden Group detritus. Locally, the present drainages (e.g., upper Huab River at 20°06′10″S, 14°36′04″E) have re-incised Mulden-age paleovalleys (Frets 1969). The Mulden Group is interpreted as a trench–foredeep assemblage associated with abortive westward subduction of the Congo margin beneath the Dom Feliciano – Ribeira (DF–R) arc

(Fig. 2) (Oyhantçabal et al. 2009; Chemale et al. 2012). Alternatively, it was a retro-arc foreland basin developed above an east-dipping subduction zone (Goscombe and Gray 2007, 2008; Konopásek et al. 2014). In our view, the largely amagmatic development of the rifted western Congo margin (Guj 1970; Stanistreet and Charlesworth 1999; Goscombe et al. 2005; Miller 2008) is more consistent with the first alternative. There is no evidence for subduction-related magmatism in the Central Kaoko zone (see below), in contrast with the Western Kaoko zone (Fig. 3).

Kaoko belt

Neoproterozoic cover and basement of the southwestern Congo craton are deformed in an arcuate fold belt that manifests crustal shortening in the mutually perpendicular Kaoko and Damara orogenic belts (Fig. 2). In the Eastern Kaoko zone (Fig. 3), a train of tight, thin-skinned folds and subordinate thrusts formed above a décollement within the Beesvlakte Formation (Ombombo Subgroup). This thin-skinned, eastward-directed, thrust-fold belt was subsequently refolded by broader, coaxial, basement-involved structures, a relationship best observed at the northern plunge of the Kamanjab basement inlier (Fig. 3). The northward and southward plunges characteristic of Kaoko belt structures are at least in part a product of late-stage refolding as a far-field consequence of collisions in the Damara belt.

The Central Kaoko zone (CKz, Fig. 3) underwent sinistral transpression, dynamic metamorphism, and rapid exhumation at 580–570 Ma, creating a system of eastward-vergent, basement-cored, thrust nappes with northwest-plunging stretching lineations (Dürr and Dingeldey 1996; Goscombe et al. 2003*a*; Goscombe and Gray 2008). Metamorphic P–T–t paths are clockwise with limited coeval granitic magmatism (Goscombe et al. 2003*b*; Will et al. 2004; Jung et al. 2014). The CKz is juxtaposed against the Western Kaoko, or Coastal, zone (WKz), by a continuous high-grade ultramylonite zone, the Purros suture (Fig. 3), having sinistral subhorizontal shear-sense indicators (Goscombe et al. 2003*a*; Konopásek et al. 2005, 2008; Goscombe and Gray 2007). The WKz has a magmatic and metamorphic history distinct from the CKz (Goscombe et al. 2005; Goscombe and Gray 2007; Konopásek et al. 2008) and is taken to represent the leading edge of the DF–R magmatic arc of Uruguay and southern Brazil (Fig. 2), against which the Kaoko belt was juxtaposed prior to South Atlantic opening (Oyhantçabal et al. 2009, 2011; Konopásek et al. 2014). Deformation and exhumation of the CKz at 580–570 Ma (Goscombe et al. 2005; Jung et al. 2014) was broadly coeval with a transition from subduction-related to slab-failure magmatism and exhumation in the DF–R arc (Oyhantçabal et al. 2009, 2011; Faleiros et al. 2011; Tupinambá et al. 2012; Alves et al. 2013; Heilbron et al. 2013). Closure of the Adamastor paleocean, situated at this latitude between the rifted Congo margin and DF–R arc, occurred 20–30 Myr after abortive continental subduction of the opposite (eastward) polarity in the West Gondwana belt (Fig. 2) (Ganade de Araujo et al. 2014), and >10 Myr before final closure of the Brasiliano paleoocean, between the DF–R arc and the Amazonia craton (Fuck et al. 2008; Bandeira et al. 2012; McGee et al. 2015*a*, 2015*b*).

Damara belt

The Damara belt (Fig. 2) is an intact collision zone, riddled with bodies of post-collisional syenogranite, separating the Congo and Kalahari cratons. It is a compound belt with two basinal domains, the Outjo and Khomas zones (Fig. 3), divided by a central microcontinent, the southern Central Zone (Miller 2008) or Swakop terrane (Hoffmann 1987). Terminal collision in the Damara belt occurred when northward subduction within the more southerly Khomas zone led to collision around 550 Ma between the arc-bearing Swakop terrane and the north-facing passive margin (Witvlei Group) of the Kalahari craton. The fossiliferous late Ediacaran and early Cambrian Nama Group of the Kalahari craton is a compound foredeep related to collisions incurred by outward-dipping subduction in the Damara belt to the north and the Gariep belt to the west (Fig. 2).

Miller (2008) and most previous workers consider the more northerly Outjo zone to have been floored by stretched continental crust of the Congo craton, the Swakop terrane (Fig. 3) being interpreted as a horst block forming an outer basement high at the rifted continental margin. However, subduction rarely if ever initiates at a passive margin (Cloetingh et al. 1982), and we therefore favour a more complex development in which the Swakop terrane collided first with a passive Congo margin via southward subduction within the Outjo zone. The Outjo zone is coextensive with the largest-amplitude and longest-wavelength aeromagnetic anomaly trough in the country. We postulate that northward subduction in the Khomas zone initiated through subduction zone "flip" (McKenzie 1969; Suppe 1984), consequent to a Swakop–Congo collision. We suggest that the north–south shortening event recently dated by $^{40}Ar/^{39}Ar$ at ~590 Ma in the Outjo zone (Lehmann et al. 2015) is a manifestation of Swakop–Congo collision in the Damara belt, broadly synchronous with Congo – DF–R arc collision in the Kaoko belt.

Significance of the Otavi–Mulden group transition

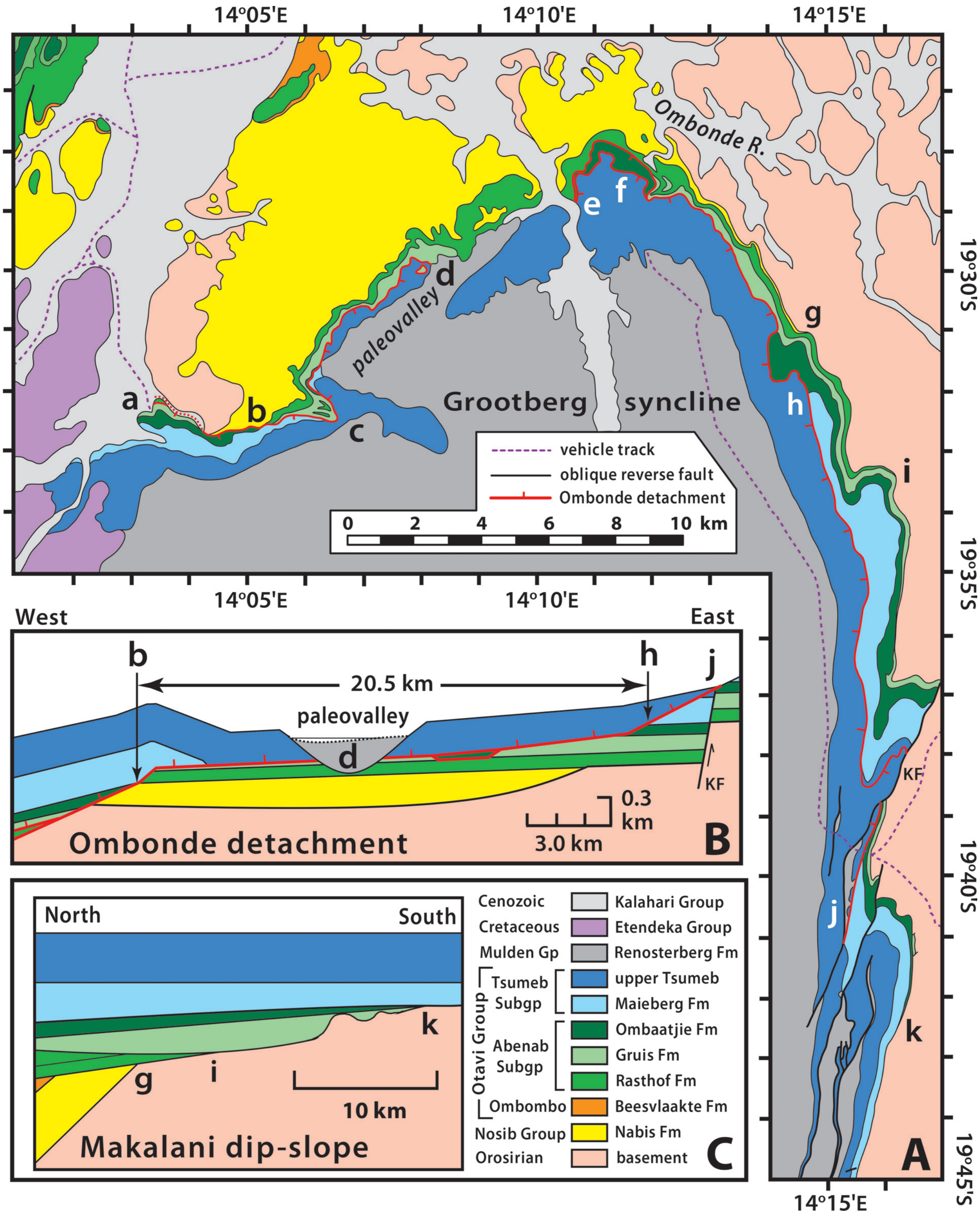
Assuming the Kaoko belt is an arc–continent collision zone, the Otavi–Mulden group transition (Fig. 4) records the passage of the upper Otavi Group carbonate shelf margin over the outer forebulge of a west-dipping subduction zone and its descent on the outer slope of the trench. Diachronous (southward-younging) closure of the Adamastor paleocean and growth of the resulting collisional orogen (Stanistreet et al. 1991) complies with paleocurrent evidence for southeastward directed fluvial sediment transport (Renosterberg Formation) on the Congo foreland (Hoffman and Halverson 2008). Rapid exhumation of the Kaoko belt at 580–570 Ma (Goscombe et al. 2005; Jung et al. 2014) implies an age of ~585 Ma or older for the shelf-to-foredeep transition in the southern Kunene Region (Fig. 3).

Ombonde detachment

The Ombonde detachment (Hoffman and Hartz 1999) is exposed for a strike length of 51 km (22 km east–west) in the south-plunging Grootberg syncline (Fig. 5), a basement-involved structure in the autochthonous foreland of the Kaoko belt. The east limb of the syncline is steeply-dipping (50°–70°), but the west limb is gentler and crests in a broad anticline before disappearing beneath Early Cretaceous traps (Etendeka Group). Paleogeographically, the Otavi Group is situated on the Makalani dip-slope (Fig. 5C), where rift-shoulder uplift and erosion caused progressive southward truncation of the Ombombo Subgroup, the Nosib Group, and the Rasthof and Gruis formations. The Gruis Formation undergoes a remarkable facies change, from peri-littoral carbonate cycles in the north to alluvial fanglomerate of exclusive basement derivation 20 km to the south. Where intersected by the Ombonde detachment, the Gruis Formation is a rheologically weak facies characterized by marlstone and fine-grained clastic rocks. Other rheologically weak units are limestones of the lower Rasthof, lower Ombaatjie, and lower Maieberg formations, while strong units are dolomites of the upper Rasthof, upper Ombaatjie, upper Maieberg, and Elandshoek–Hüttenberg (upper Tsumeb) formations. The Mulden Group is represented by compositionally immature sandstone with metre-scale crossbedding, locally with a basal chert-dolomite conglomerate containing clasts of Elandshoek Formation stromatolite.

The Ombonde detachment was first identified in 1994 by Tony Prave and Dawn Sumner on the east limb of the syncline (location h, Fig. 5A) by virtue of the fact that ~400 m of well-known strata (Ombaatjie and Maieberg formations) are missing across a brittle, bedding-parallel, mappable, fault surface. The fault was subsequently

Fig. 5. (A) Geologic map of the Grootberg syncline (location, Fig. 3). Red line is the Ombonde detachment (ticks on hangingwall), a brittle, low-angle, normal-sense detachment that ramps stratigraphically downward from east to west and omits ~400 m of stratigraphic section at any location (Hoffman and Hartz 1999). (B) Unfolded west–east cross-section showing ramp-flat geometry of the detachment (red line), matching footwall and hangingwall cutoffs (e.g., arrows b and h, keyed to locations on map), and paleovalley (d) filled by dolomite-chert conglomerate (basal Renosterberg Formation) that is incised across the detachment. Minimum age of the detachment is the sub-Renosterberg paleovalley (d). Its maximum age is the top of the Tsumeb Subgroup at location i. (C) Unfolded north–south cross-section before the detachment showing stratigraphic truncation of the basal Nabis Formation (g), basal Rasthof Formation (i), and basal Gruis Formation (k). Truncations are related to episodic uplift and down-to-the-north rotation of the Makalani dip-slope, the footwall of an inferred south-dipping, syn-rift, normal fault, older and unrelated to the Ombonde detachment. [Colour online.]



mapped throughout the syncline, revealing a ramp-flat-ramp geometry (Fig. 5B) that cuts down-section westward from the lower Elandshoek Formation to granitic basement in the footwall, and from the upper Hüttenberg Formation to the Rasthof Formation in the hangingwall. The detachment is commonly a single fault, but a 2.5 km long extensional horse occurs at the exposed keel of the syncline (f, Fig. 5A) and smaller horses occur elsewhere. Fault-related vein systems are uncommon, but stratigraphic cut-offs (Fig. 5B) provide essential constraints on the fault-plane geometry and net slip.

The western ramp is exposed over the crest of the broad anticline (a–c, Fig. 5A). The fault ramps down-section westward from the lower Elandshoek to the Rasthof Formation in the hangingwall, and from the Gruis Formation to the basement in the footwall. The hangingwall cut-off of the topmost Maieberg Formation is exposed on both limbs of a second-order anticlinal crossfold (c, Fig. 5A), across which the projected cut-off strikes 357°, implying a dip direction of 267° at that location. A dip direction between 260° and 280° is required by the distribution of cut-offs throughout the syncline in order for the detachment to ramp continuously down-section in one direction. It is noteworthy that the hangingwall is not structurally extended in the panel that parallels the inferred slip direction (a–c, Fig. 5A).

Stratigraphic cut-offs in the hangingwall of the western ramp (a–c, Fig. 5A) are matched by cut-offs in the footwall of the eastern ramp (h–j, Fig. 5A). The horizontal separations of the corresponding cut-offs are 16.0, 16.4, and 17.3 km for the top of the Gruis, Ombaatjie, and Maieberg formations, respectively. Corrected for an estimated 25% synclinal shortening, the respective horizontal separations are 20.0, 20.5, and 21.6 km (Fig. 5B). Because stratigraphic thicknesses are known from measured sections (Hoffman and Halverson 2008), ramp angles between the detachment surface and stratigraphic horizons can be calculated. The ramp angle averaged through the Rasthof Formation in the footwall is 14°, while the respective ramp angles through the Ombaatjie and Maieberg formations are 10° and 9° in the hangingwall, and 8° and 9.5° in the footwall. The uncorrected footwall ramp angle averaged through the entire Abenab Subgroup (395 m thick), including the long flat within the Gruis Formation, is a mere 1.3°, or 1.1° corrected for synclinal shortening. Compaction is slight in most Otavi Group carbonates; only in limestone (Fig. 4) are stylolites common. If post-detachment compaction were 20%, at a maximum, the overall ramp angle would increase by 0.2°.

The age of the Ombonde detachment is tightly constrained. High on the eastern ramp, the detachment carries uppermost Otavi Group in the hangingwall onto upper Maieberg Formation in the footwall (j, Fig. 5A). Fault slip must therefore post-date the entire Otavi Group. The critical minimum age constraint comes from basal Mulden Group (Renosterberg Formation) paleovalleys, the largest of which is located on the west limb of the syncline near the axial trace (d–e, Fig. 5A). This paleovalley trends northeast–southwest and is filled by crudely bedded chert-dolomite conglomerate that dips ~20° toward the southeast, structurally conformable with the underlying Otavi Group. Stromatolite clasts derived from the upper Tsumeb Subgroup are prominent in the conglomerate, the structural attitude of which precludes a Karoo (Carboniferous to Early Cretaceous) or younger age. On the east wall of the paleovalley, the conglomerate forms a buttress unconformity against the hangingwall of the detachment. The axial drainage of the syncline covers the contact between the paleovalley and the detachment (e, Fig. 5A). On the west wall of the paleovalley, the basal conglomerate bevels the detachment without disturbance and variably abuts the Elandshoek Formation of the hangingwall and both the Gruis and Rasthof formations of the footwall (d, Fig. 5A). Close to where the paleovalley truncates the detachment, a small window in the hangingwall exposes the Gruis Formation of the footwall. Erosional incision and truncation of the detachment fault by the basal Mulden Group conglomerate (Fig. 5B), which is conformably overlain by sandstone of the Renosterberg Formation, demonstrate that the detachment must be pre-Mulden, as well as post-Otavi, in age.

High on the eastern ramp, a set of small paleogullies at the base of the Mulden Group incises the uppermost Otavi Group in the hangingwall of the detachment (j, Fig. 5A). The floors of these paleogullies reach the footwall Maieberg Formation. The paleogullies confirm a post-Otavi, pre-Mulden group age for the detachment.

Hoffman and Hartz (1999) inferred that the Ombonde detachment formed as a submarine slide on the outer slope of a trench that became a collisional foredeep when the descending plate passed from oceanic to continental as the Congo margin was abortively subducted at ~590 Ma. They postulated that coherent sliding of the low-angle detachment was facilitated by pore-fluid overpressure, resulting from a Messinian-type sea-level fall in the foredeep. As evidence for base-level fall, they cited deep karstic erosion beneath the Mulden Group in the southwest of the Otavi platform, incision of the conglomerate-filled paleovalley across the detachment, and the fluvial paleoenvironment of the Mulden Group (Renosterberg Formation) in the area of the detachment.

One troubling fact regarding the Ombonde detachment emerged only over time. After its nature and age were established by mapping in 1996, seventeen field seasons elapsed before another example of the phenomenon was found in the Kaoko belt. Such structures should not occur singly.

Ombepera detachment

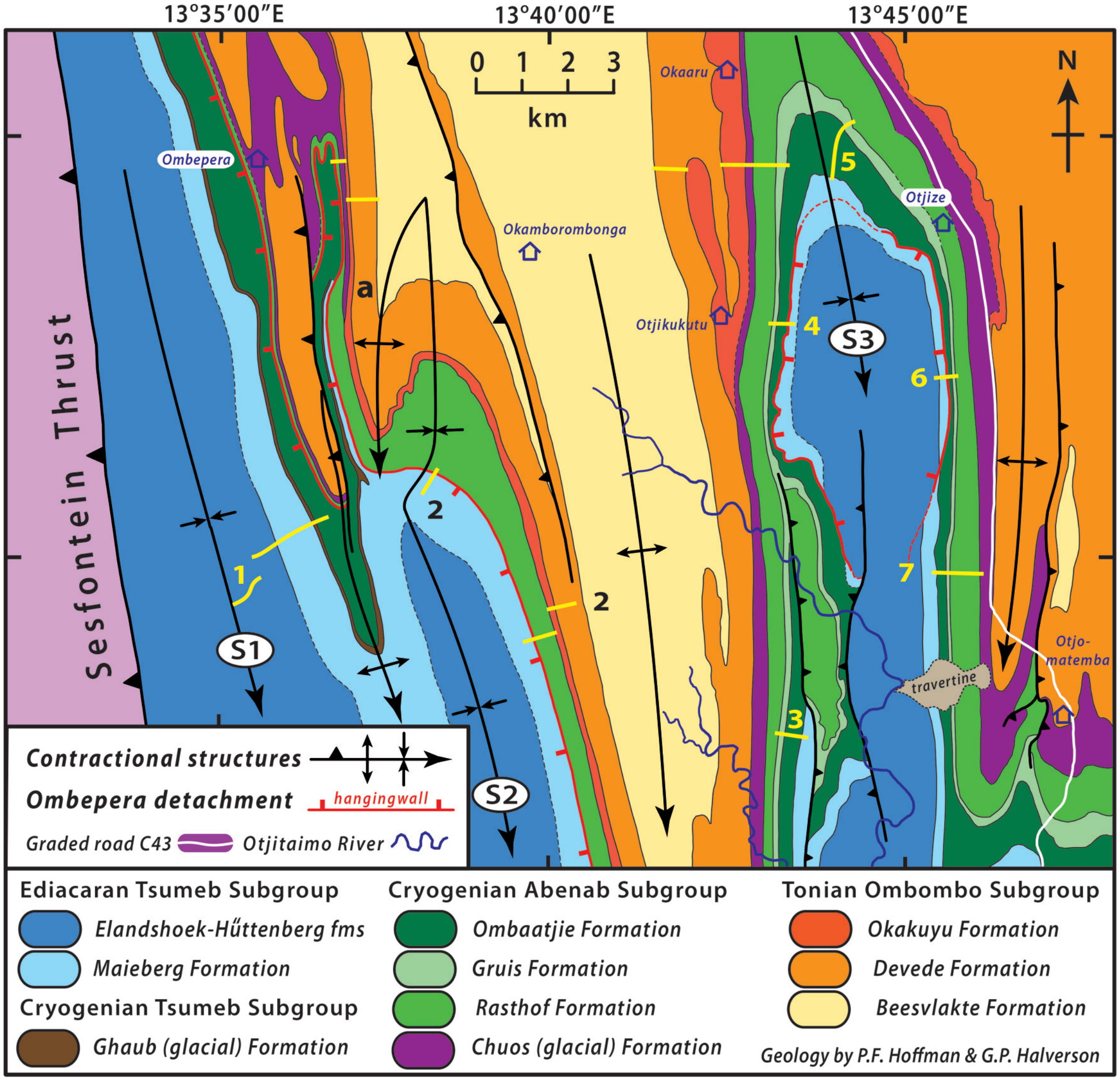
Ninety kilometres to the northwest of the Grootberg syncline, the internal part of the thin-skinned Eastern Kaoko zone includes a train of three synclines (S1–S3, Fig. 6). Reconnaissance mapping and stratigraphic logging identified a problem in the central syncline. The distinctive "cap dolostone" of the younger Cryogenian (Marinoan) glaciation, the normally ever-present Keilberg Member at the base of the Maieberg Formation (Fig. 4), could not be found. In contrast, the cap dolomite was easily recognized in the eastern and western synclines, in the latter atop glacigenic carbonate diamictite of the Ghaub Formation. The conundrum of the central syncline (S2, Fig. 6) remained unresolved until the area was revisited in the last week of the 2014 field season.

Measuring the entire succession in the central syncline prompted a postulate (Fig. 7) that the Gruis, Ombaatjie, and lower Maieberg formations are missing across a cryptic, normal-sense detachment that predates folding and thrusting, analogous to the Ombonde detachment. The postulate was corroborated by carbon-isotope chemostratigraphy. Strata directly overlying the Rasthof Formation are isotopically depleted, $\delta^{13}C$ = −2‰ to −5‰ VPDB (section 2, Fig. 7). This is incompatible with the Gruis and Ombaatjie formations, which are characteristically enriched ($\delta^{13}C$ = +1‰ to +8‰ VPDB), but it is consistent with the Maieberg Formation (Fig. 4H).

In the western syncline (S1, Fig. 6), the upper Ombaatjie, Ghaub, and lower Maieberg formations, including the cap dolostone, appear on the hangingwall of the inferred detachment (section 1, Fig. 7), consistent with westward stratigraphic downcutting analogous to the Ombonde detachment. The estimated thickness of missing strata, 450–700 m, implies a steeper ramp angle and (or) larger displacement compared with the Ombonde detachment.

In 2015, we tested a prediction of the detachment hypothesis: an up-ramp extension of the detachment in the eastern syncline, near the village of Otjize (Fig. 6). On air photos and satellite imagery (Fig. 8), a channel-like salient of Tsumeb Subgroup dolostone, ~5.0 km wide in a north–south direction, is seen to cut out much of the underlying, strongly-cyclical, Ombaatjie Formation. This is evident on both limbs of the syncline. Alternative interpretations of the channel-like structure can be discriminated on the ground. If the structure was a (Ghaub) glacial-age paleovalley (Fig. 8A), the

Fig. 6. Geologic map of a part of the eastern Kaoko belt (location, Fig. 3), showing the Ombepera detachment (red line with ticks on the hangingwall) exposed in three synclines (S1–S3). Numbered lines indicate measured stratigraphic sections displayed graphically in Figs. 7 and 9. The detachment widens (north–south direction) from the eastern syncline to the central and western synclines. The Ombaatjie Formation (dark green) in the hangingwall of the western syncline restores palinspastically to the east of the same formation in the footwall of the eastern syncline. Abrupt thinning of the Rasthof Formation at location a is tentatively interpreted as a lateral ramp. [Colour online.]



cap dolostone would occur in the channel axis as well as outside the channel. Up to 85 m of Ghaub-age local relief is known elsewhere on the carbonate shelf (Halverson et al. 2002; Hoffman 2011) and more than 400 m occurs at the southern shelf break on Fransfontein Ridge (Hoffman et al. 2014). In those areas, the thickness of the Maieberg Formation as a whole reciprocates with relief on the Ghaub glacial surface (Fig. 8A). Alternatively, if the structure is a post-Otavi Group detachment (Fig. 8B), the cap dolostone (Keilberg Member) would be missing in the channel, and both the footwall and hangingwall should contain strata younger than their equivalents in the central syncline. This is because an Ombonde-type detachment should ramp up-section in an eastward direction (Fig. 5B).

Figure 9 compares measured sections through the upper Abenab and lower Tsumeb subgroups in the eastern syncline. Sections 4 and 6 are from the axial part of the channel-like structure on opposite limbs of the syncline (Fig. 6). Sections 3 and 7 are from south of the structure on opposite limbs, and section 5 is from north of the structure in the synclinal hinge zone (Fig. 6). The cap dolostone (Keilberg Member) does not occur within the confines of the channel-like structure (Fig. 8), where dolostone grainstone of the upper Maieberg Formation is in fault contact with marly limestone of the lower Ombaatjie Formation. Missing are ~215 m of the upper Ombaatjie Formation, and between 215 and 350 m of the lower Maieberg and Ghaub formations. The total missing interval, 430–565 m, compares favourably in thickness with that in the central and western synclines, 450–700 m.

There is no discernible difference in stratigraphic level of the missing interval across the eastern syncline (sections 4 and 6, Fig. 9). Footwall and hangingwall stratigraphies in the eastern syncline are compared with those in the central and western synclines in a longitudinal section of the detachment along the axial zone (Fig. 7). An unfaulted section from east of the detachment is included for comparison (section 8, Fig. 7). From east to west, the detachment ramps down-section from the lower Ombaatjie to the lower Rasthof formation in the footwall, and from the upper Maieberg to the upper Ombaatjie formation in the hangingwall. Like the Ombonde detachment, the Ombepera detachment ramps down-section westward, which is therefore the inferred direction of normal-sense displacement. The hypothesized Ombepera

Fig. 7. Axial (west–east) section of the Ombepera detachment (red line), with graphic logs of measured sections of the Ombombo, Abenab, and lower Tsumeb subgroups (section 1–6 locations, Fig. 6; section 8 located 57 km due east of section 6). The detachment ramps stratigraphically downward from east to west in both the hangingwall and footwall, and 430–700 m of strata are omitted across the detachment in each section. Inset in section 2 shows depleted C-isotope values in the hangingwall, diagnostic of the Maieberg Formation (Fig. 4H). Keilberg Member cut-off in the hangingwall at magenta x corresponds to footwall cut-off at magenta y. Ghaub–Keilberg diamictite-cap dolostone interval is missing in sections 2, 4, and 6. Field notebook section numbers given alongside columns. [Colour online.]

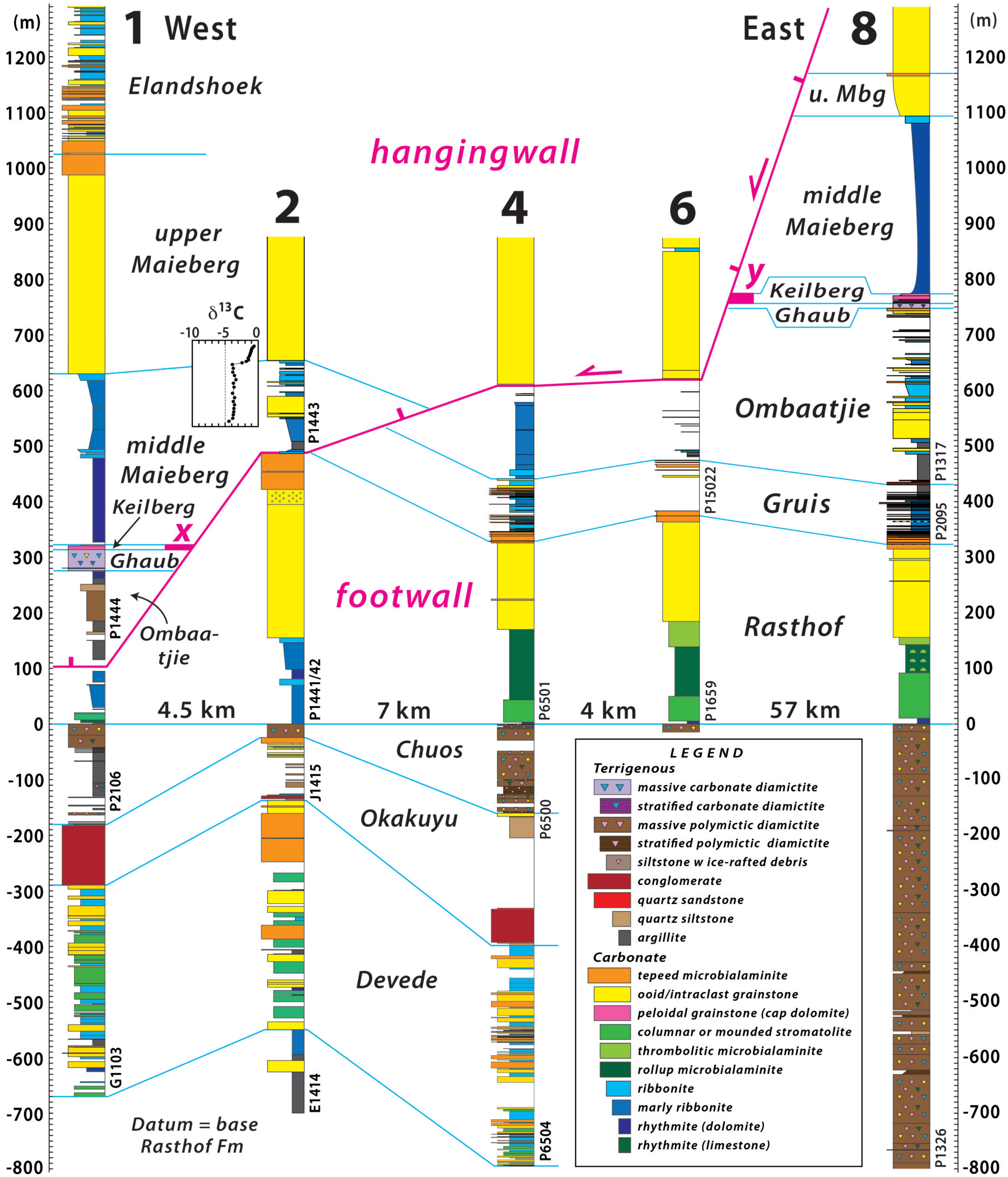
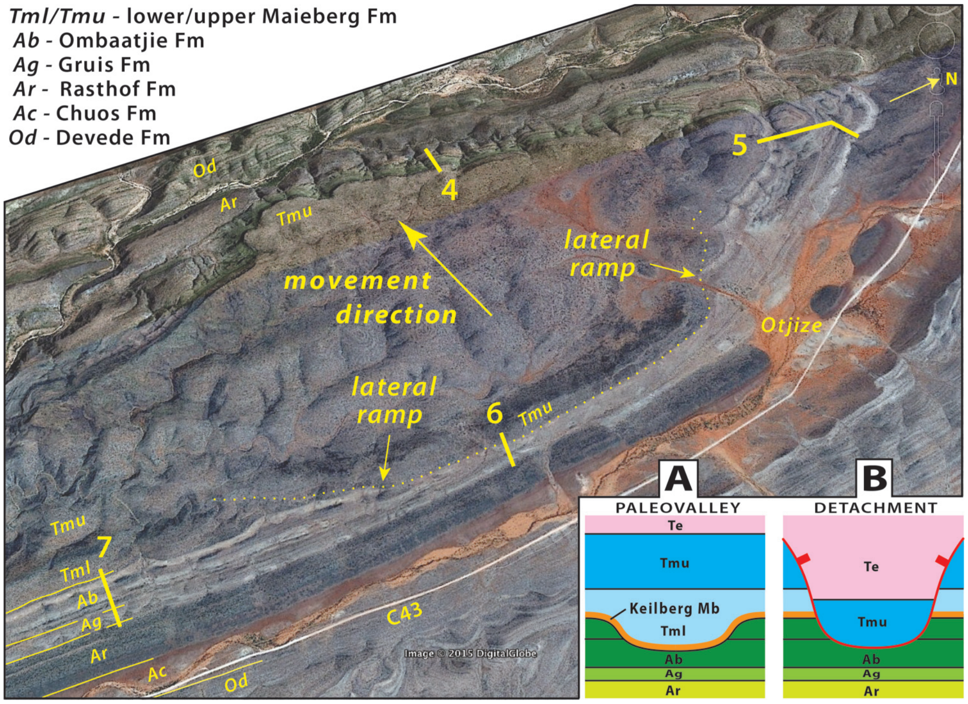


Fig. 8. Oblique satellite image (GoogleEarth) looking northwestward at the eastern syncline near the village of Otjize (Fig. 6). The light-dotted line is the Ombepera detachment where it cuts out the lower Maieberg and upper Ombaatjie formations. Measured sections are numbered as in Figs. 7 and 9. Insets A and B show downcuttings of different origin: (A) Ghaub glacial-age paleovalley and (B) post-Maieberg extensional detachment. Observed truncation of the lower Maieberg Formation including its basal Keilberg Member favours interpretation B. [Colour online.]



detachment is validated by its predicted up-ramp extension in the eastern syncline.

We cannot determine the magnitude of displacement from the separation of matching stratigraphic cut-offs, because the footwall and hangingwall have no exposed cut-offs in common (Fig. 7). However, we can calculate a ramp angle of 2.0°, uncorrected for tectonic shortening, given the stratigraphic climbs of ~516 and ~528 m in the footwall and hangingwall, respectively (Fig. 7), over a horizontal distance in the dip direction of 15 km. Corrected for an estimated 40% shortening due to folding and thrusting, the original ramp angle was 1.3°, slightly steeper than the Ombonde detachment (1.1°). As the footwall and hangingwall of the three synclines have no stratigraphic cut-offs in common, the tectonically corrected distance of 25 km between the four sections (Fig. 6) is a minimum bound on the magnitude of displacement of the Ombepera detachment. Inescapably, strata in the hangingwall of the western syncline restore palinspastically to the east of footwall strata in the eastern syncline (Fig. 7).

Discussion and remaining problems

Arc–continent collisions have been a common process for billions of years (Brown and Ryan 2011); therefore, early extensional detachments of the type described here should occur in other orogenic belts, regardless of whether sharp base-level fall is essential to their origin. Moreover, most examples on existing margins occur on passive margins, so incipient subduction is not required for their development. Yet to our knowledge, few coherent map-scale extensional detachments (mass transport complexes) have been described from paleomargins in ancient orogenic belts.

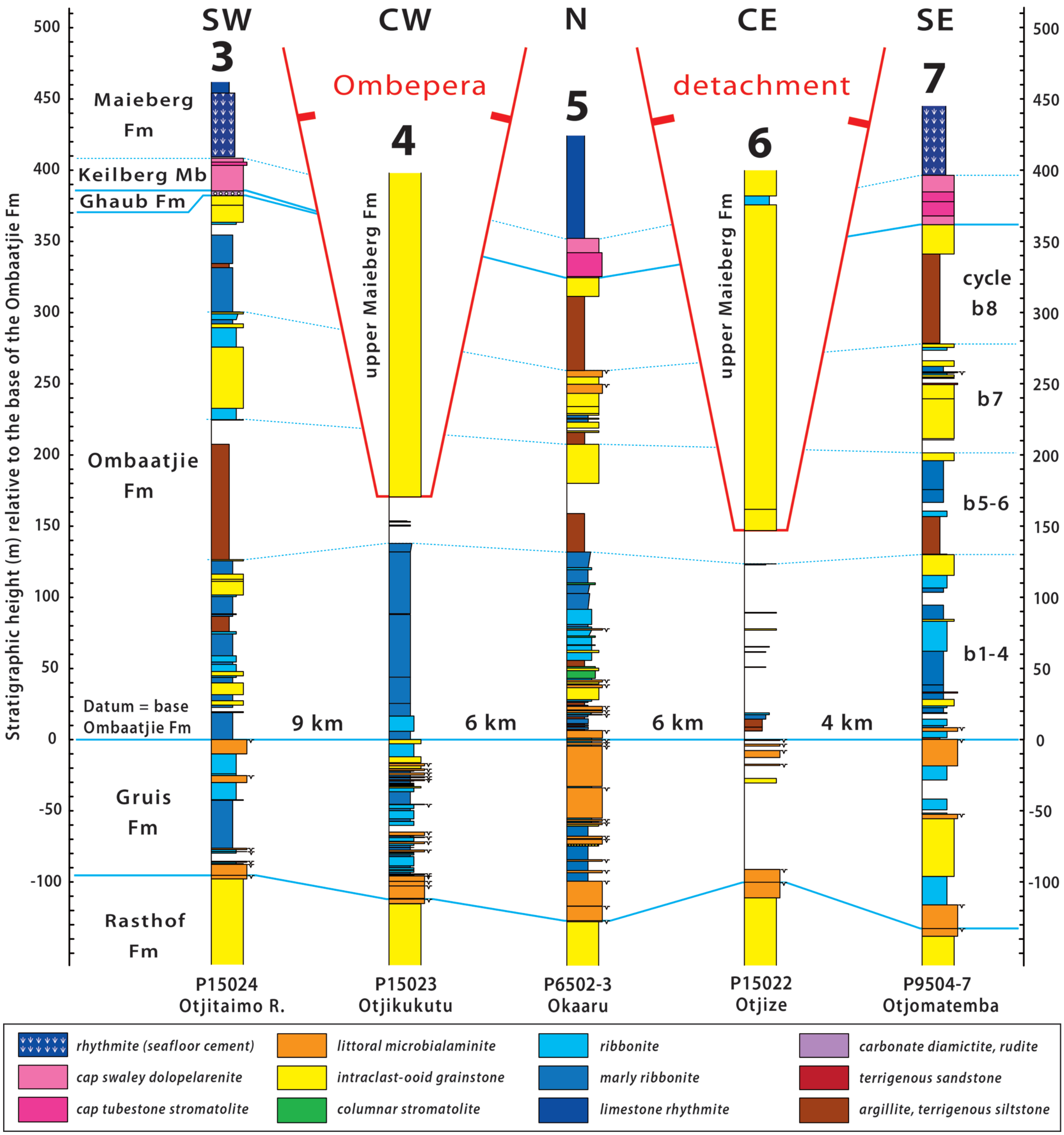
Failure to recognize the Ombepera detachment could have led to serious errors in the interpretation of shelf development. The anomalously thin and argillaceous Abenab Subgroup of the western syncline (Fig. 7) could have been interpreted as evidence for a western shelf margin, although no such margin is apparent in the Ombombo or Tsumeb subgroups in the same area. According to the detachment hypothesis, the Ombaatjie Formation is thin in the western syncline because it is truncated from below. Its more terrigenous character, relative to footwall sections in the eastern syncline, relates to its more inboard, not outboard, palinspastically location on the shelf.

The anticlinorium between the western and central synclines includes a west-facing panel in which the apparent thickness of the Rasthof Formation attenuates northward from 350 to 96 m in a strike distance of just 4.4 km (location a, Fig. 6). In the absence of structural disturbance, the attenuation would imply a north-facing shelf margin of upper Rasthof age. In light of the detachment hypothesis, the attenuation could represent instead a lateral footwall ramp. Closely spaced measured sections imply top-down truncation, consistent with a footwall ramp having an average ramp angle of 3.3°. On the other hand, the detachment could merely track the Rasthof–Gruis formation rheological boundary across a primary shelf margin. In this case, sedimentary facies should be distinct from those in the shelf interior.

The lateral ramps bounding the Ombepera detachment are just ~5.0 km apart at the base of the Tsumeb Subgroup in the footwall of the eastern syncline (Fig. 8). The narrowness of the detachment recalls the South Makassar Strait mass transport complex (Fig. 1C) and other submarine landslides (Martinez et al. 2005; Masson et al. 2006; Armandita et al. 2015). Narrowness may help to account for their infrequent recognition on ancient continental margins, including the belated recognition of a second detachment in the Kaoko belt.

However, reconnaissance mapping and air-photo interpretation have not revealed any lateral ramp above the Rasthof Formation for 20 km southward or 40 km northward of the detachment axis in the central and western synclines. Additional mapping is required to investigate the possibility that channel-like lateral ramps develop preferentially where the detachment surface intersects specific stratigraphic intervals.

Fig. 9. Transverse (north–south) sections of the Ombepera detachment (red line) on both limbs of the Otjize syncline (S3 in Fig. 6), with graphic logs of measured stratigraphic sections (locations, Fig. 6) of the upper Abenab and lower Tsumeb subgroups (Fig. 4). The upper Ombaatjie and lower Maieberg formations are missing in the axial zone of the detachment (sections 4 and 6), compared with sections to the north (section 5) and south (sections 3 and 7) of the detachment. [Colour online.]



Conclusions

A second map-scale, coherent, very-low-angle, detachment structure of Ediacaran age has been found in the Kaoko belt of northwestern Namibia. Like the previously described Ombonde detachment, the Ombepera detachment is a brittle structure that predates orogenic shortening, ramps downward stratigraphically to the west, and underwent normal-sense displacement of substantial magnitude (>20 km). The detachment is surprisingly narrow (5 km north–south), 25% of its displacement, at the level of the Cryogenian–Ediacaran boundary. By analogy with the Ombonde detachment, the stratigraphic age of which is tightly constrained, we interpret the Ombepera structure as the extended domain of a coherent submarine slide (mass transport complex), mobilized on the outer slope of a trench–foredeep basin during incipient collision between the Congo craton and the Dom Feliciano – Ribeira arc. Accordingly, the average ramp angle of 1.3° for the Ombepera detachment, relative to the host stratigraphy, would have been augmented at the time of failure by a few degrees of incline related to lithospheric flexure. We expect that submarine slides of this type should occur in other orogenic belts regardless of age. Failure to recognize them can lead to misinterpretation of sedimentary facies and stratigraphic relations.

Acknowledgements

P.F.H. first met John Dewey in April 1971 at a Canadian (then Alberta) Society of Petroleum Geology short course on "The New Global Tectonics" at Banff (Alberta), presented by Dewey and the late William R. Dickinson. He met Kevin Burke a few months later at a night club in downtown Toronto. Together, they convinced him that, in tectonics, the present is the key to past. Field work was authorized by the Geological Survey of Namibia and supported in 2010–2014 by the Earth System Evolution Project of the Canadian Institute for Advanced Research (CIFAR). Roy McG. Miller drew our attention to Tom Clifford's Saturn slide. We thank Stephen T. Johnston, Francis A. Macdonald, and William A. Thomas for thoughtful comments on the manuscript; and Andrew Hynes and John W.F. Waldron for constructive reviews. Ali Polat invited the paper.

References

Alves, A., Janasi, V.A., Neto, M.C.C., Heaman, L., and Simonetti, A. 2013. U–Pb geochronology of the granite magmatism in the Embu Terrane: Implications for the evolution of the Central Ribeira Belt, SE Brazil. Precambrian Research, **230**: 1–12. doi:10.1016/j.precamres.2013.01.018.

Armandita, C., Morley, C.K., and Rowell, P. 2015. Origin, structural geometry, and development of a giant coherent slide: The South Makassar Strait mass transport complex. Geosphere, **11**: 376–403. doi:10.1130/GES01077.1.

Bandeira, J., McGee, B., Nogueira, A.C.R., Collins, A.S., and Trindade, R. 2012. Sedimentological and provenance response to Cambrian closure of the Clymene ocean: The upper Alto Paraguai Group, Paraguay belt, Brazil. Gondwana Research, **21**: 323–340. doi:10.1016/j.gr.2011.04.006.

Brown, D., and Ryan, P.D. (*Editors*). 2011. Arc-Continent Collision. Springer-Verlag, Heidelberg (Germany), 493 p.

Bugge, T., Befring, S., Belderson, R.H., Eidvin, T., Jansen, E., Kenyon, N.H., et al. 1987. A giant three-stage submarine slide off Norway. Geo-Marine Letters, **7**: 191–198. doi:10.1007/BF02242771.

Butler, R.W.H., and Paton, D.A. 2010. Evaluating lateral compaction in deepwater fold and thrust belts: How much are we missing from "nature's sandbox"? GSA Today, **20**: 4–10. doi:10.1130/GSATG77A.1.

Chemale, F., Jr., Mallmann, G., Bitencourt, M.F., and Kawashita, K. 2012. Time constraints on magmatism along the Major Gercino Shear Zone, southern Brazil: Implications for West Gondwana reconstruction. Gondwana Research, **22**: 184–199. doi:10.1016/j.gr.2011.08.018.

Clifford, T.N. 1962. Notes on nappes in the Otavi facies of northern South West Africa. University of Leeds (United Kingdom), Research Institute of African Geology, 6th Annual Report, pp. 44–45.

Clifford, T.N. 2008. The geology of the Neoproterozoic Swakop–Otavi transition zone in the Outjo District, northern Damara Orogen, Namibia. South African Journal of Geology, **111**: 117–140 and maps 1–3. doi:10.2113/gssajg.111.1.117.

Cloetingh, S.A.P.L., Wortel, M.J.R., and Vlaar, N.J. 1982. Evolution of passive continental margins and initiation of subduction zones. Nature, **297**: 139–142. doi:10.1038/297139a0.

Dingle, R.V. 1977. The anatomy of a large submarine slump on a sheared continental margin (SE Africa). Journal of the Geological Society, London, **134**: 293–310. doi:10.1144/gsjgs.134.3.0293.

Dürr, S.B., and Dingeldey, D.P. 1996. The Kaoko belt (Namibia): Part of a late Neoproterozoic continental-scale strike-slip system. Geology, **24**: 503–506. doi:10.1130/0091-7613(1996)024<0503:TKBNPO>2.3.CO;2.

Faleiros, F.M., Campanha, G.A.C., Martins, L., Vlach, S.R.F., and Vasconcelos, P.M. 2011. Ediacaran high-pressure collision metamorphism and tectonics of the southern Ribeira Belt (SE Brazil): Evidence for terrane accretion and dispersion during Gondwana assembly. Precambrian Research, **189**: 263–291. doi:10.1016/j.precamres.2011.07.013.

Frets, D.C. 1969. Geology and structure of the Huab-Welwitschia area, South West Africa. University of Cape Town (South Africa), Precambrian Research Unit, Bulletin 5, 235 p.

Fuck, R.A., Brito, Neves, B.B., and Schobbenhaus, C. 2008. Rodinia descendants in South America. Precambrian Research, **160**: 108–126. doi:10.1016/j.precamres.2007.04.018.

Ganade de Araujo, C.E., Rubatto, D., Hermann, J., Cordani, U.G., Caby, R., and Basei, M.A.S. 2014. Ediacaran 2,500-km-long synchronous deep continental subduction in the West Gondwana Orogen. Nature Communications, **5**: 5198, 1–8. doi:10.1038/ncomms6198. PMID:25319269.

Goscombe, B.D., and Gray, D.R. 2007. The Coastal Terrane of the Kaoko Belt, Namibia: Outboard arc-terrane and tectonic significance. Precambrian Research, **155**: 139–158. doi:10.1016/j.precamres.2007.01.008.

Goscombe, B.D., and Gray, D.R. 2008. Structure and strain variation at mid-crustal levels in a transpressional orogen: A review of Kaoko Belt structure and the character of West Gondwana amalgamation and dispersal. Gondwana Research, **13**: 45–85. doi:10.1016/j.gr.2007.07.002.

Goscombe, B., Hand, M., and Gray, D. 2003*a*. Structure of the Kaoko Belt, Namibia: progressive evolution of a classic transpressional orogen. Journal of Structural Geology, **25**: 1049–1081. doi:10.1016/S0191-8141(02)00150-5.

Goscombe, B., Hand, M., Gray, D., and Mawby, J. 2003*b*. The metamorphic architecture of a transpressional orogen: the Kaoko Belt, Namibia. Journal of Petrology, **44**: 679–711. doi:10.1093/petrology/44.4.679.

Goscombe, B., Gray, D., Armstrong, R., Foster, D.A., and Vogl, J. 2005. Event geochronology of the Pan-African Kaoko Belt, Namibia. Precambrian Research, **140**: 103.e1–103.e41. doi:10.1016/j.precamres.2005.07.003.

Guj, P. 1970. The Damara mobile belt in the south-western Kaokoveld, South West Africa. University of Cape Town (South Africa), Precambrian Research Unit, Bulletin 8, 168 p.

Halverson, G.P., Hoffman, P.F., and Schrag, D.P. 2002. A major perturbation of the carbon cycle before the Ghaub glaciation (Neoproterozoic) in Namibia: Prelude to snowball Earth? Geochemistry, Geophysics, Geosystems, **3**(6): 1–24. doi:10.1029/2001GC000244.

Halverson, G.P., Hoffman, P.F., Schrag, D.P., Maloof, A.C., and Rice, A.H.N. 2005. Toward a Neoproterozoic composite carbon-isotope record. Geological Society of America Bulletin, **117**: 1181–1207. doi:10.1130/B25630.1.

Hampton, M.A., Lee, H.J., and Locat, J. 1996. Submarine landslides. Reviews of Geophysics, **34**: 33–59. doi:10.1029/95RG03287.

Heilbron, M., Tupinambá, M., Valeriano, C.M., Armstrong, R., Siva, L.G.E., Melo, R.S., et al. 2013. The Serra da Bolívia complex: The record of a new Neoproterozoic arc-related unit at Ribeira belt. Precambrian Research, **238**: 158–175. doi:10.1016/j.precamres.2012.09.014.

Hoffman, P.F. 2011. Strange bedfellows: glacial diamictite and cap carbonate from the Marinoan (635 Ma) glaciation in Namibia. Sedimentology, **58**: 57–119. doi:10.1111/j.1365-3091.2010.01206.x.

Hoffman, P.F., and Halverson, G.P. 2008. Otavi Group of the western Northern Platform, the Eastern Kaoko Zone and the western Northern Margin Zone. *In* The Geology of Namibia, Volume 2, Neoproterozoic to Lower Palaeozoic. *Edited by* R.McG. Miller. Geological Survey of Namibia, Windhoek, pp. 13-69–13-135.

Hoffman, P.F., and Hartz, E.H. 1999. Large, coherent, submarine landslide associated with Pan-African foreland flexure. Geology, **27**: 687–690. doi:10.1130/0091-7613(1999)027<0687:LCSLAW>2.3.CO;2.

Hoffman, P.F., Bellefroid, E., Hodgin, E.B., Johnson, B.W., Kunzmann, M., Sansjofre, P., et al. 2014. A Cryogenian-early Ediacaran carbonate shelf break dominated by glacial paleotopography, Fransfontein Ridge, Kunene Region, Namibia. Geological Society of America, 2014 Annual Meeting Abstracts, Paper 130-2.

Hoffmann, K.-H. 1987. Application of tectonostratigraphic terrane analysis in the Damara Province of central and northern Namibia. *In* Abstract Volume, A.L. Du Toit Golden Jubilee Conference on Tectonostratigraphic Terrane Analysis. Royal Society and Geological Society of South Africa, Cape Town. pp. 25–27.

Hoffmann, K.-H., and Prave, A.R. 1996. A preliminary note on a revised subdivision and regional correlation of the Otavi Group based on glacigenic diamictites and associated cap dolostones. Communications of the Geological Survey of Namibia, **11**: 77–82.

Jung, S., Brandt, S., Nebel, O., Hellebrand, E., Seth, B., and Jung, C. 2014. The P–T–t paths of high-grade gneisses, Kaoko Belt, Namibia: Constraints from mineral data, U–Pb allanite and monazite and Sm–Nd/Lu–Hf garnet ages and garnet ion probe data. Gondwana Research, **25**: 775–796. doi:10.1016/j.gr.2013.05.017.

Konopásek, J., Kröner, S., Kitt, S.L., Passchier, C.W., and Kröner, A. 2005. Oblique collision and evolution of large-scale transcurrent shear zones in the Kaoko Belt, NW Namibia. Precambrian Research, **136**: 139–157. doi:10.1016/j.precamres.2004.10.005.

Konopásek, J., Košler, J., Tajčmanová, L., Ulirch, S., and Kitt, S. 2008. Neoproterozoic igneous complex emplaced along major tectonic boundary in the Kaoko Belt (NW Namibia): ion probe and LA-ICP-MS dating of magmatic and metamorphic zircons. Journal of the Geological Society, London, **165**: 153–165. doi:10.1144/0016-76492006-192.

Konopásek, J., Košler, J., Sláma, J., and Janoušek, V. 2014. Timing and sources of pre-collisional Neoproterozoic sedimentation along the SW margin of the Congo craton (Kaoko Belt, NW Namibia). Gondwana Research, **26**: 386–401. doi:10.1016/j.gr.2013.06.021.

Lehmann, J., Saalmann, K., Naydenov, K.V., Milani, L., Belyanin, G.A., Zwingmann, H., et al. 2015. Structural and geochronological constraints on the Pan-African tectonic evolution of the northern Damara Belt, Namibia. Tectonics. doi:10.1002/2015TC003899.

Martinez, J.F., Cartwright, J., and Hall, B. 2005. 3D seismic interpretation of slump complexes: examples from the continental margin of Israel. Basin Research, **17**: 83–108. doi:10.1111/j.1365-2117.2005.00255.x.

Masson, D.G., Harbitz, C.B., Wynn, R.B., Pedersen, G., and Løvholt, F. 2006. Submarine landslides: processes, triggers and hazard prediction. Philosophical Transactions of the Royal Society, A: Mathematical, Physical and Engineering Sciences, **364**: 2009–2039. doi:10.1098/rsta.2006.1810.

McGee, B., Collins, A.S., Trindade, R.I.F., and Jourdan, F. 2015*a*. Investigating mid-Ediacaran glaciation and final Gondwana amalgamation using coupled sedimentology and $^{40}Ar/^{39}Ar$ detrital muscovite provenance from the Paraguay Belt, Brazil. Sedimentology, **62**: 130–154. doi:10.111/sed.12143.

McGee, B., Collins, A.S., Trindade, R.I.F., and Payne, J. 2015*b*. Age and provenance of the Cryogenian to Cambrian passive margin to foreland basin sequence of the northern Paraguay Belt, Brazil. Geological Society of America Bulletin, **127**: 76–86. doi:10.1130/B30842.1.

McKenzie, D.P. 1969. Speculations on the consequences and causes of plate motions. Geophysical Journal International, **18**: 1–32. doi:10.1111/j.1365-246X.1969.tb00259.x.

Miller, R.McG. 2008. The Geology of Namibia, Volume 2, Neoproterozoic to Lower Palaeozoic. Geological Survey of Namibia, Windhoek.

Morley, C.K., King, R., Hillis, R., Tingay, M., and Backe, G. 2011. Deepwater fold and thrust belt classification, tectonics, structure and hydrocarbon prospectivity: A review. Earth-Science Reviews, **104**: 41–91. doi:10.1016/j.earscirev.2010.09.010.

Oyhantçabal, P., Siegesmund, S., Wemmer, K., Presnyakov, S., and Layer, P. 2009. Geochronological constraints on the evolution of the southern Dom Feliciano Belt (Uruguay). Journal of the Geological Society, London, **166**: 1075–1084. doi:10.1144/0016-76492008-122.

Oyhantçabal, P., Siegesmund, S., Wemmer, K., and Passchier, C.W. 2011. The transpressional connection between Dom Feliciano and Kaoko Belts at 580-550 Ma. International Journal of Earth Sciences (Geologische Rundschau), **100**: 379–390. doi:10.1007/s50031-010-0577-3.

Rowan, M.G., Peel, F.J., and Vendeville, B.C. 2004. Gravity-driven fold belts on passive margins. *In* Thrust Tectonics and Hydrocarbon Systems. *Edited by* K.R. McClay. American Association of Petroleum Geologists, Memoir 82, pp. 157–182.

SACS (South African Committee for Stratigraphy). 1980. Damara sequence. *In* Stratigraphy of South Africa, Part 1. *Edited by* L.E. Kent. Handbook of the Geological Survey of South Africa, **8**: 415–438.

Stanistreet, I.G., and Charlesworth, E.G. 1999. Damaran basement-cored fold nappes incorporating pre-collisional basins, Kaoko Belt, Namibia, and controls on Mesozoic supercontinental breakup. University of Witwatersrand (South Africa), Economic Geology Research Unit, Information Circular 332, 14 p.

Stanistreet, I.G., Kukla, P.A., and Henry, G. 1991. Sedimentary basinal responses to a late Precambrian Wilson cycle: The Damara orogen and Nama foreland, Namibia. Journal of African Earth Sciences (and the Middle East), **13**: 141–156. doi:10.1016/0899-5362(91)90048-4.

Suppe, J. 1984. Kinematics of arc-continent collision, flipping of subduction, and back-arc spreading near Taiwan. Geological Society of China, Memoir 6, pp. 21–33.

Tupinambá, M., Heilbron, M., Valeriano, C., Júnior, R.P., Dios, F.B., Machado, N., et al. 2012. Juvenile contribution of the Neoproterozoic Rio Negro Magmatic Arc (Ribeira Belt, Brazil): Implications for Western Gondwana amalgamation. Gondwana Research, **21**: 422–438. doi:10.1016/j.gr.2011.05.012.

Will, T.M., Okrusch, M., and Gruner, B.B. 2004. Barrovian and Buchan type metamorphism in the Pan-African Kaoko belt, Namibia: implications for its geotectonic position within the framework of Western Gondwana. South African Journal of Geology, **107**: 431–454. doi:10.2113/107.3.431.