Report: Stratigraphic investigations of the Neoproterozoic Otavi/Swakop Group in the southern Kunene Region

P. F. HOFFMAN [1,2,*], K. G. LAMOTHE[3] & J. W. GREENMAN[3]

[1]*School of Earth & Ocean Sciences, University of Victoria, Victoria, BC V8P 5C2, Canada*
[2]*Department of Earth & Planetary Sciences, Harvard University, Cambridge, MA 01238, USA*
[3]*Department of Earth & Planetary Sciences, McGill University, QC H3A 0E8, Canada*
**Correspondence: paulfhoffman@gmail.com*
1216 Montrose Ave., Victoria, BC V8T 2K4, Canada

Abstract: As part of an ongoing investigation (since 1993) of the Otavi/Swakop Group in the southern Kunene Region, 90 stratigraphic sections were measured in 2018 in 12 areas within the Northern and Northern Margin Zones of the Damara Belt, the Southern and Eastern Zones of the Kaoko Belt, and the Otavi Mountainland of the Northern Platform. The new sections document (1) structural rotations related to rift faulting of latest Cryogenian (Marinoan) age in the Northern Zone (SE Summas Mountains), (2) early Cryogenian (Sturtian) growth faulting and subglacial trough incision in the Eastern Zone near Ondevede, (3) abrupt facies changes in the lower Rasthof Formation (Sturtian cap carbonate) in the Northern Margin Zone on the farms Aub and Rockeys, (4) stratigraphic relations between constituent formations of the Cryogenian Abenab Subgroup in the Otavi Mountainland and the Kunene Region, (5) the nature and origin of northward thickening in the Ediacaran Tsumeb Subgroup of the Eastern Zone between the Hoanib and Hoarusib rivers, and (6) the magnitudes of Ediacaran mega-karst relief, basement incision, and burial by the Welkom Subgroup (Mulden Group) in the Northern Margin Zone on farm Welkom.

Key words: Neoproterozoic; Cryogenian; Sturtian; Marinoan; Otavi Group; Swakop Group; Mulden Group; Abenab Subgroup; Tsumeb Subgroup; Welkom Subgroup.

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Introduction

This report summarizes results of stratigraphic investigations carried out between 25 May and 07 July, 2018. In addition to the work summarized here, samples were collected for detrital zircon radiometric analysis from 17 different stratigraphic units within the Otavi/Swakop and Mulden groups.

Prior results from this project are given in Hoffman & Halverson (2008), Domack & Hoffman (2011), Hoffman (2011a, b) and Hoffman *et al.* (2016, 2017). A comprehensive synthesis is scheduled for completion early in 2019.

A Marinoan angular unconformity in the Northern Zone, SE Summas Mountains (Farms Löwenfontein 84 and Macaria 390)

New sections were measured on the southeastern flank of the Summas Mountains structural dome (Fig. 1). The resulting fence diagram (Figs 2, 3) documents an angular unconformity between Tonian–Cryogenian strata (Okotjize, Orusewa, Chuos, Rasthof and Okonguarri formations) and the Ediacaran Karibib Formation, including its basal Keilberg Member. We infer from this relationship that structural tilting related to rift faulting continued in the Northern Zone until the Marinoan glaciation (650-635 Ma), several million years later than on the outer part of the Northern Platform, where rifting ceased before deposition of the Ombaatjie Formation of the Abenab Subgroup (Hoffman & Halverson, 2008; Hoffman, 2011b). The unconformity is consistent with the observed occurrence of basement-derived debris in the Marinoan Ghaub Formation in the Northern Zone, but not in the Northern Margin and Northern Platform Zones.

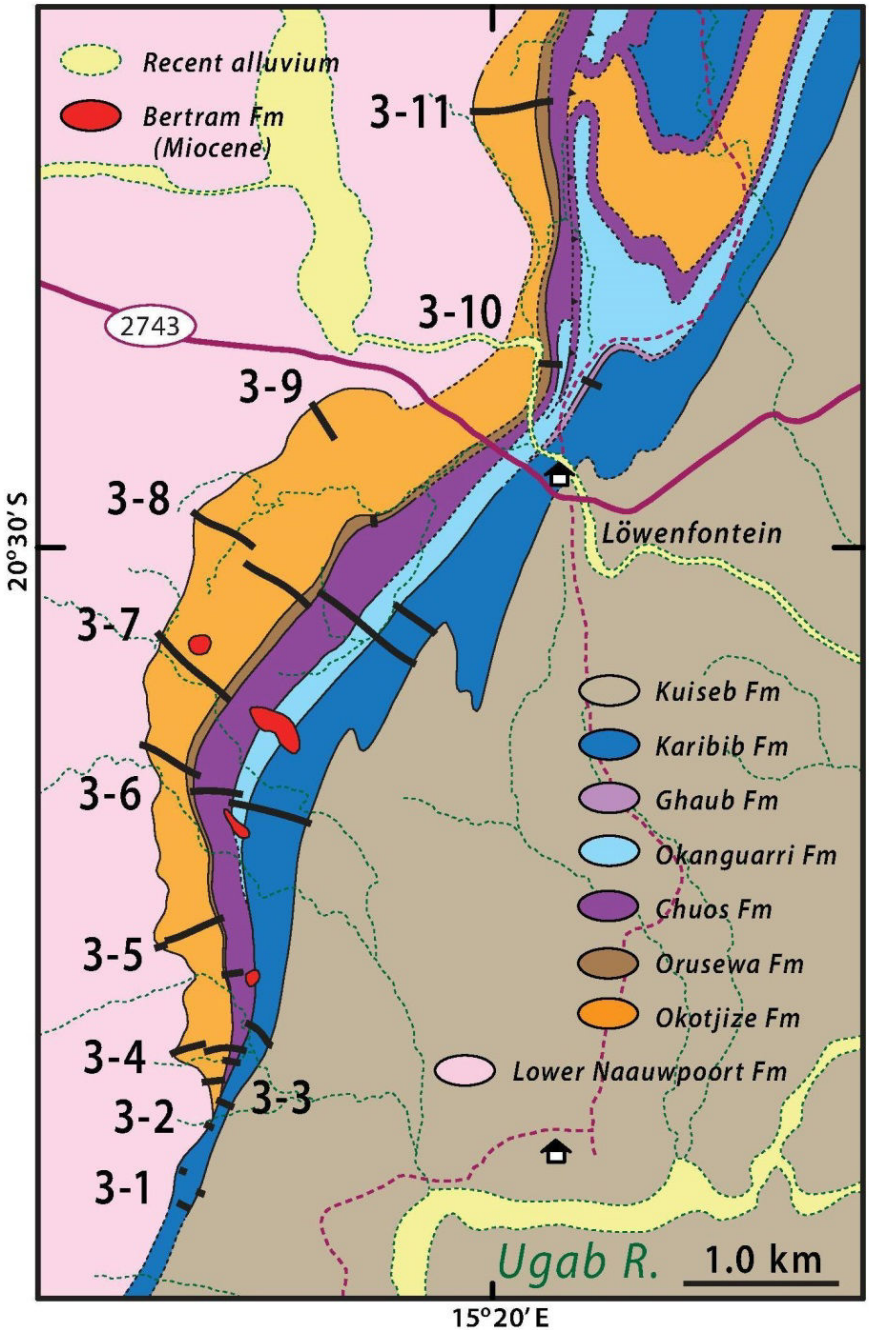

Figure 1. Location map for measured sections of the Swakop Group on the southeastern flank of the Summas Mountains structural dome in the Northern Damara Zone (modified after Miller, 1980a). Note truncation of the Cryogenian Chuos Formation and the Tonian Okotjize and Orusewa formations (Ugab Subgroup) by the Ediacaran Karibib Formation between measured sections 3-6 and 3-3.

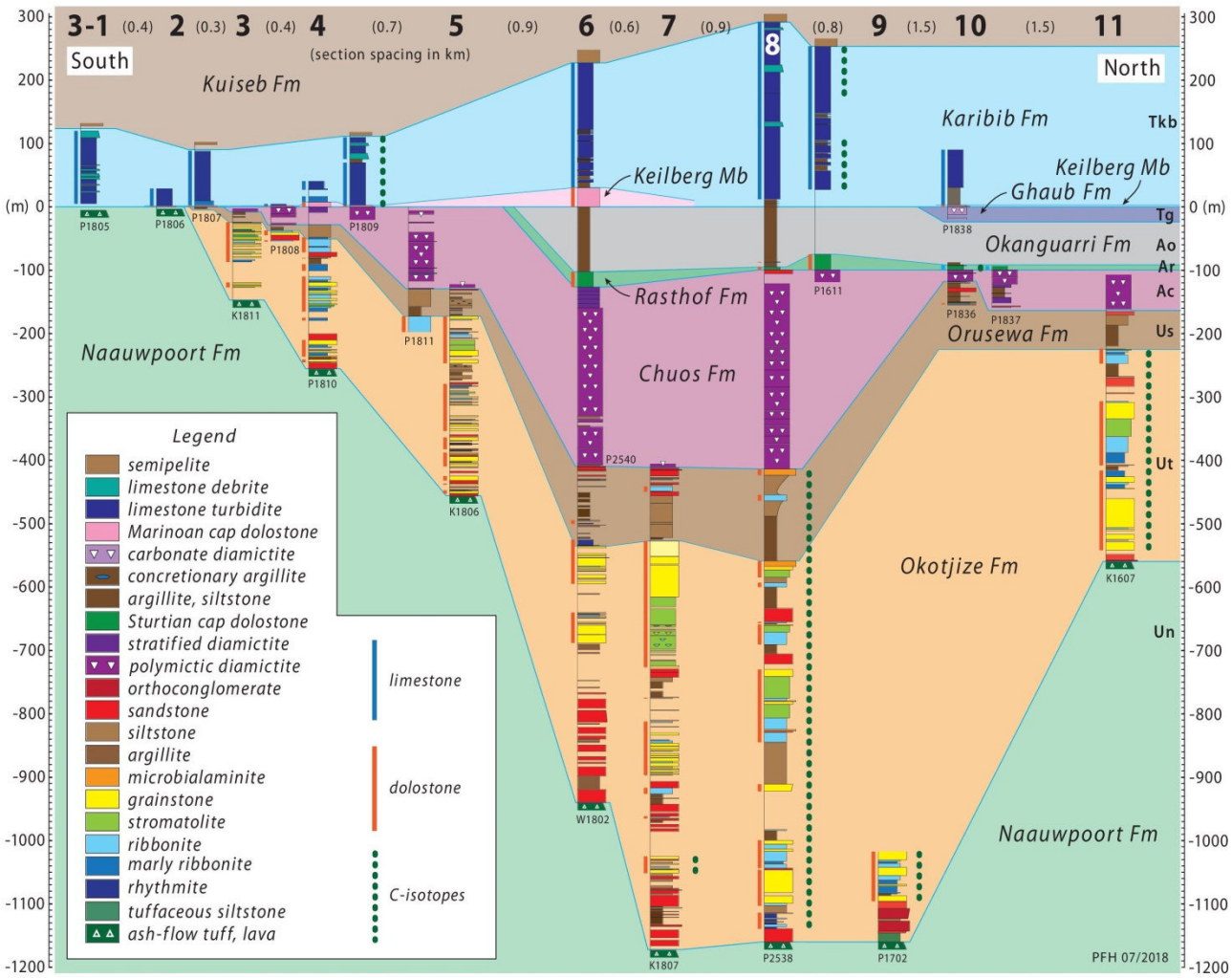

Figure 2. Fence diagram showing measured sections of the Swakop Group on the northern part of farms Macaria 390 and Löwenfontein 84 (see Fig. 1 for section locations). Note low-angle unconformity between the Ediacaran Karibib Formation and the underlying Tonian (Lower Naauwpoort, Okotjize and Orusewa formations) and Cryogenian (Chuos, Rasthof and Narachaams formations) strata. This unconformity is consistent with rifting and fault-block rotation of late Cryogenian (Marinoan) age in the Northern Damara Zone, and with the presence of basement clasts in the glacigenic Ghaub Formation in this zone (Miller, 2008).

Sturtian growth faulting in the Eastern Kaoko Zone and the subglacial bedrock trough at Omutirapo Spring

A 450-m deep palaeo-valley filled by subglacial deposits of the Sturtian Chuos Formation is incised into late Tonian shallow-marine strata of the upper Ombombo Subgroup (Devede and Okakuyu formations) at Omutirapo Spring near Ondevede (Figs 4, 5; Hoffman & Halverson, 2008; Le Heron *et al.* 2013; Hoffman *et al.*, 2017). The palaeo-valley coincides with a growth fault that cuts the Devede Formation, but not the post-glacial Rasthof Formation. Fault movement was previously inferred to be pre-Sturtian in age, ending before either the upper Devede (Hoffman & Halverson, 2008) or Okakuyu Formation (Hoffman *et al.*, 2017). The uncertainty reflected poor control on sub-Chuos Formation stratigraphic relations across the fault trace, where the Okakuyu Formation is not preserved.

In 2018, nine additional Devede and four additional Chuos formation sections in the vicinity of the growth fault (Fig. 6) were measured. The new fence diagram suggests that the last and possibly all movement on the fault is Sturtian in age. Detailed facies mapping between sections B1702 and W1807 is needed to test and investigate sedimentation in an active subglacial fault regime.

The abundance of fine-grained deposits (laminated argillite and siltstone) in the Chuos Formation within the palaeo-valley (Fig. 6) is suggestive of a glacially overdeepened (*i.e.* silled) trough in which subglacial meltwater was intermittently ponded (*e.g.* Buechi *et al.*, 2017). The lateral discontinuity of these deposits (Fig. 6) is not supportive of ice withdrawal during a postulated intra-Sturtian global interglacial stage (Le Heron *et al.*, 2013).

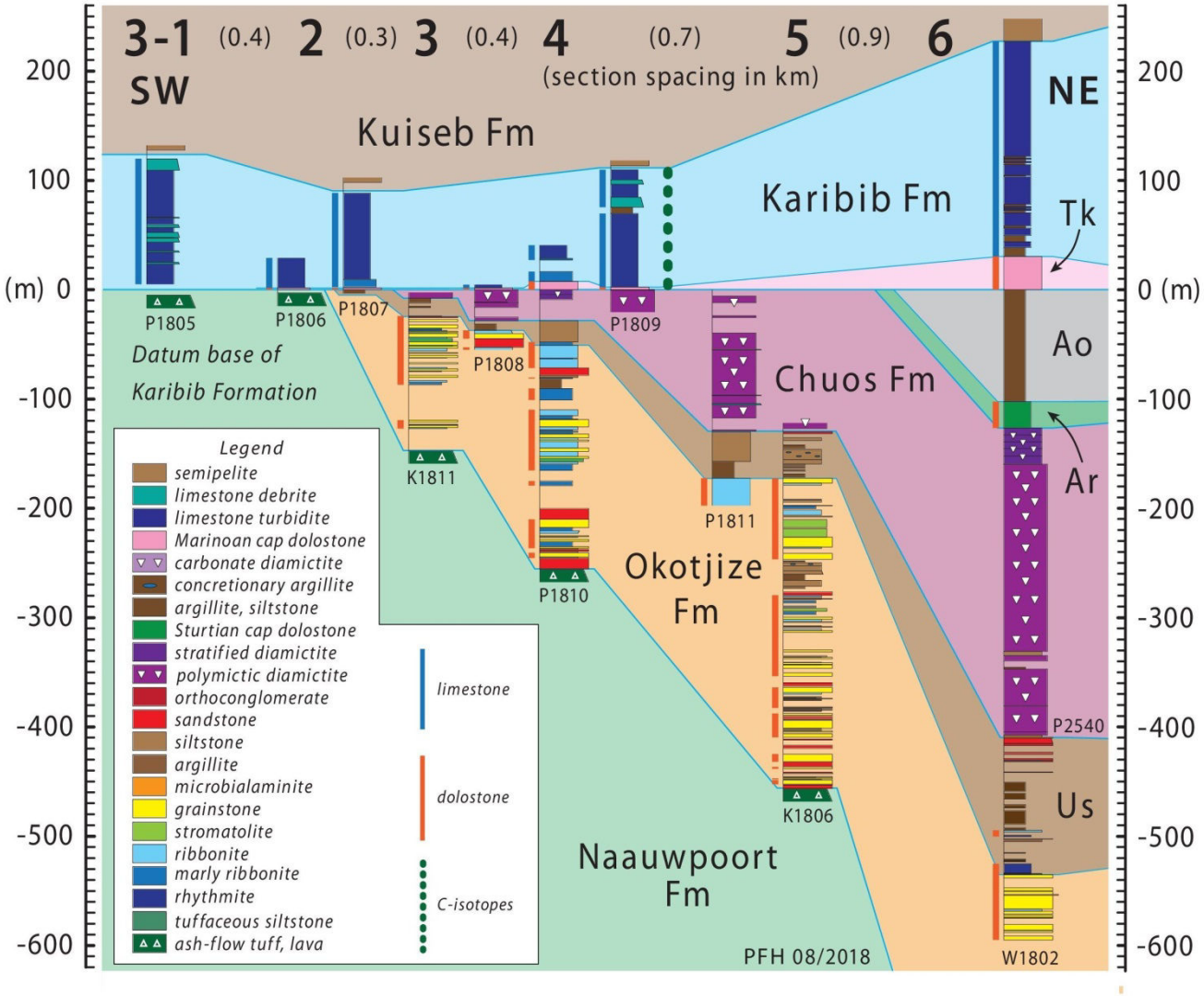

Figure 3. Expanded fence diagram showing low-angle unconformity beneath the Karibib Formation (including basal Keilberg Member) between sections 3-1 and 3-6. Note progressive top-down truncation of pre-Ediacaran units from northeast to southwest, consistent with structural rotation and erosional bevelling, as distinct from depositional onlap.

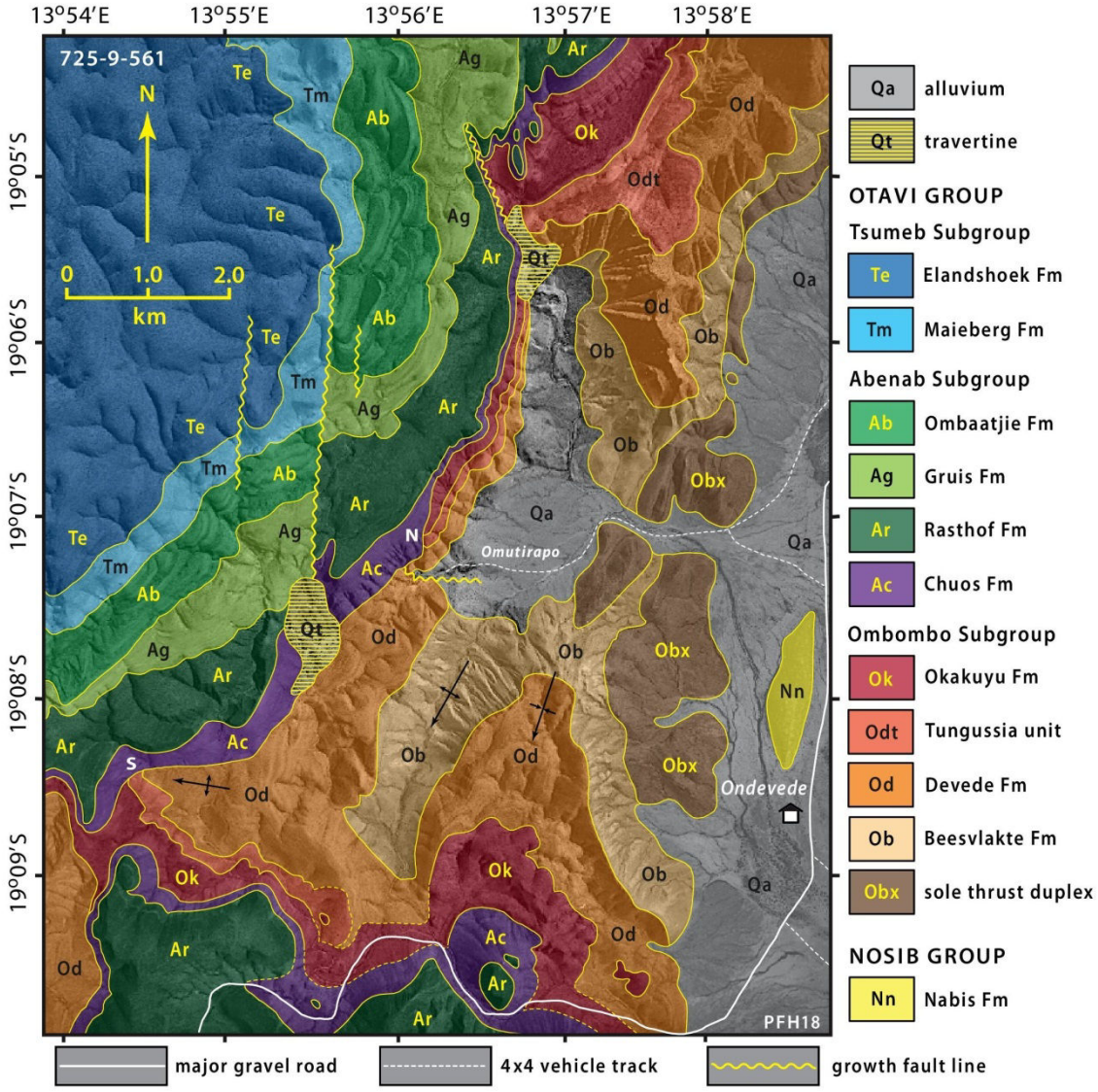

Figure 4. Geology of the Carboniferous glacial cirque and Quaternary travertine springs localized by Neoproterozoic growth faults in the Otavi Group northwest of Ondevede. A palaeo-valley filled by Sturtian subglacial deposits (Chuos Formation) is incised into late Tonian carbonates and clastics of the Ombombo Subgroup. **N** marks the north wall of the palaeo-valley near the former village of Omutirapo and **S** marks the south wall. The area is ideally suited for a geological field school and is now easily accessible due to the graded road through Ondevede linking Warmquelle and Omarumba. Base map is aerial photo 725-9-561.

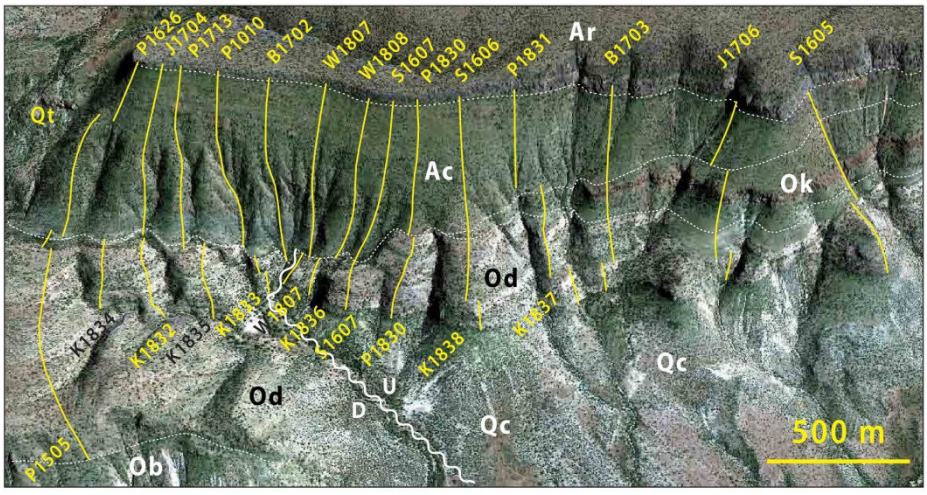

Figure 5. Inclined satellite (Google Earth) view looking westward at the northern wall of the Sturtian age palaeo-valley at Omutirapo. Units: **Ob**-Beesvlakte Fm; **Od**-Devede Fm; **Ok**-Okakuyu Fm; **Ac**-Chuos Fm; **Ar**-Rasthof Fm; **Qc**-Quaternary calcrete; **Qt**-Quaternary travertine. Note growth fault (D-downside, U-upside) in the foreground. Locations of measured sections (Fig. 6) are shown.

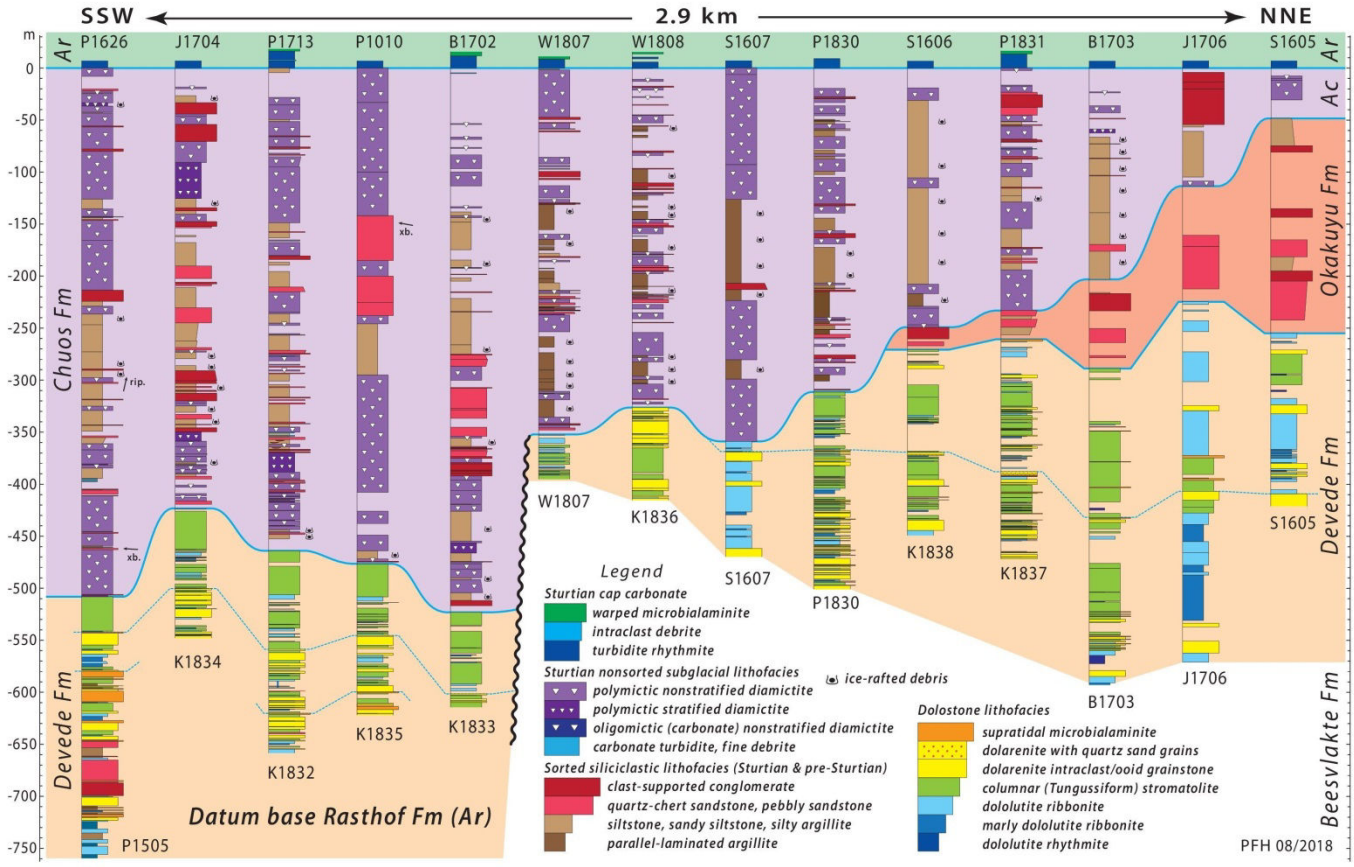

Figure 6. Fence diagram showing measured sections of the glacigenic Chuos Formation in relation to those of the late Tonian Ombombo Subgroup (Beesvklakte, Devede and Okakuyu formations; see Fig. 5 for section locations). Note down-cutting of the sub-Chuos glacial erosion surface relative to the Ombombo Subgroup, and their reciprocal thickness changes. Datum is the base of the Rasthof Formation postglacial cap carbonate. The growth fault between sections B1702 and W1807 appears to be syn-Chuos in age, not pre-Chuos as earlier inferred (Hoffman & Halverson, 2008; Hoffman *et al.* 2017) when fewer Devede sections had been measured.

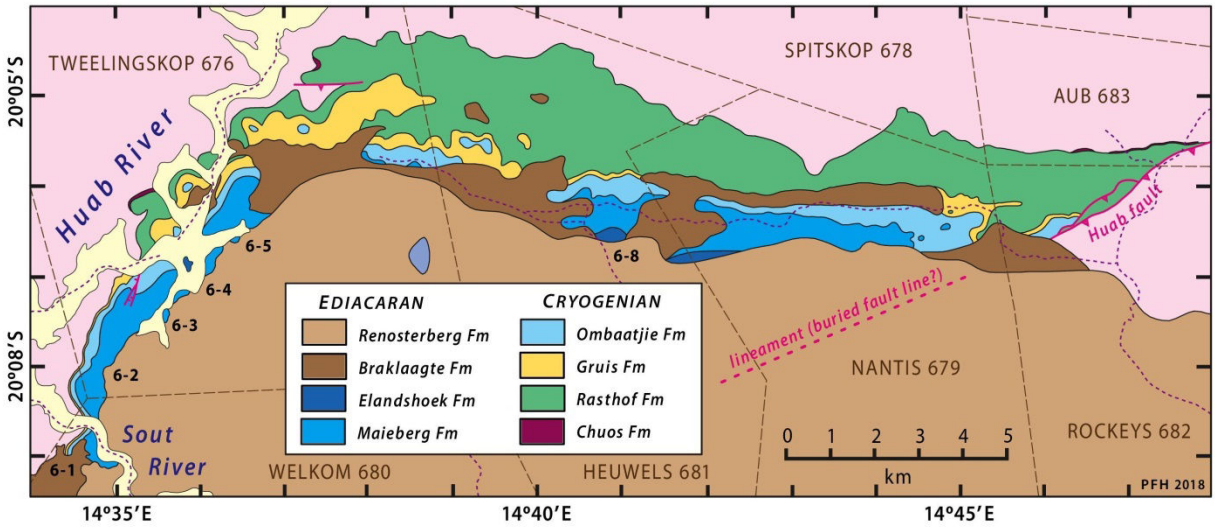

Figure 7. Geology of the Otavi Group palaeo-outlier on the northern limb of the Achas Syncline. Area coloured pink underlain by Orosirian basement of the Kamanjab inlier. Numbers 6-1, etc. indicate locations of columnar sections in Fig. 9.

Abrupt facies change in the lower Rasthof Formation in the upper Huab River area (farms Rockeys 682 and Aub 683) of the Northern Margin Zone

Stratigraphic reconnaissance (Hoffman & Halverson, 2008) indicated that a major facies change exists in the lower Rasthof Formation between the central and eastern parts of the palaeo-outlier of Otavi Group preserved on the north limb of the Achas Syncline east of the upper Huab River (Fig. 7; Frets, 1969). Shallow-water carbonate facies in the central area give way to deep-water argillaceous facies hosting carbonate turbidites at the faulted eastern end of the Rasthof belt (Fig. 8). In the eastern part of the facies change eight parallel sections of the lower Rasthof Formation were measured over a strike length of 3.0 km (Fig. 9). Our sections confirm a major facies change in the lower 300 m of Rasthof strata, where argillaceous facies hosting carbonate turbidites pass laterally into westward-thickening carbonate debrites and intraclast conglomerate. Mounded microbialite and void-filling dolospar cement is increasingly abundant westwards in the lower 100 m of the formation, which conformably overlies a few metres of glacigenic Chuos Formation diamictite above a glaciated basement unconformity.

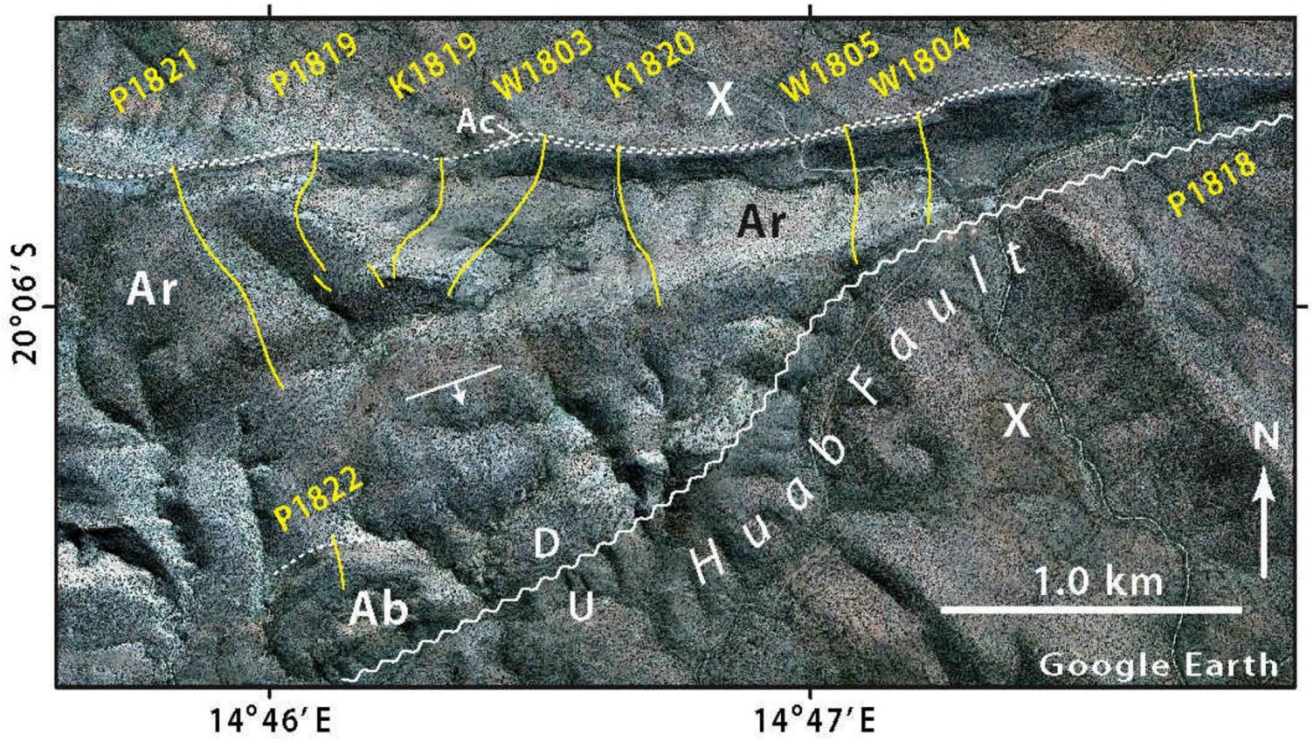

Figure 8. Vertical satellite (Google Earth) view of the eastern termination of the Otavi Group palaeo-outlier on the northern limb of the Achas Syncline (Frets, 1969: farms Rockeys 682 and Aub 683) (Fig. 7) at the southern edge of the Otavi carbonate platform. Measured sections (K- KGL; P-PFH; W-JWG) document part of a rapid facies change in the lower and middle Rasthof Formation. Strata dip toward the south-southeast. Units: X - Orosirian basement complex; Ac - Chuos Formation; Ar - Rasthof Formation; Ab - Ombaatjie Formation.

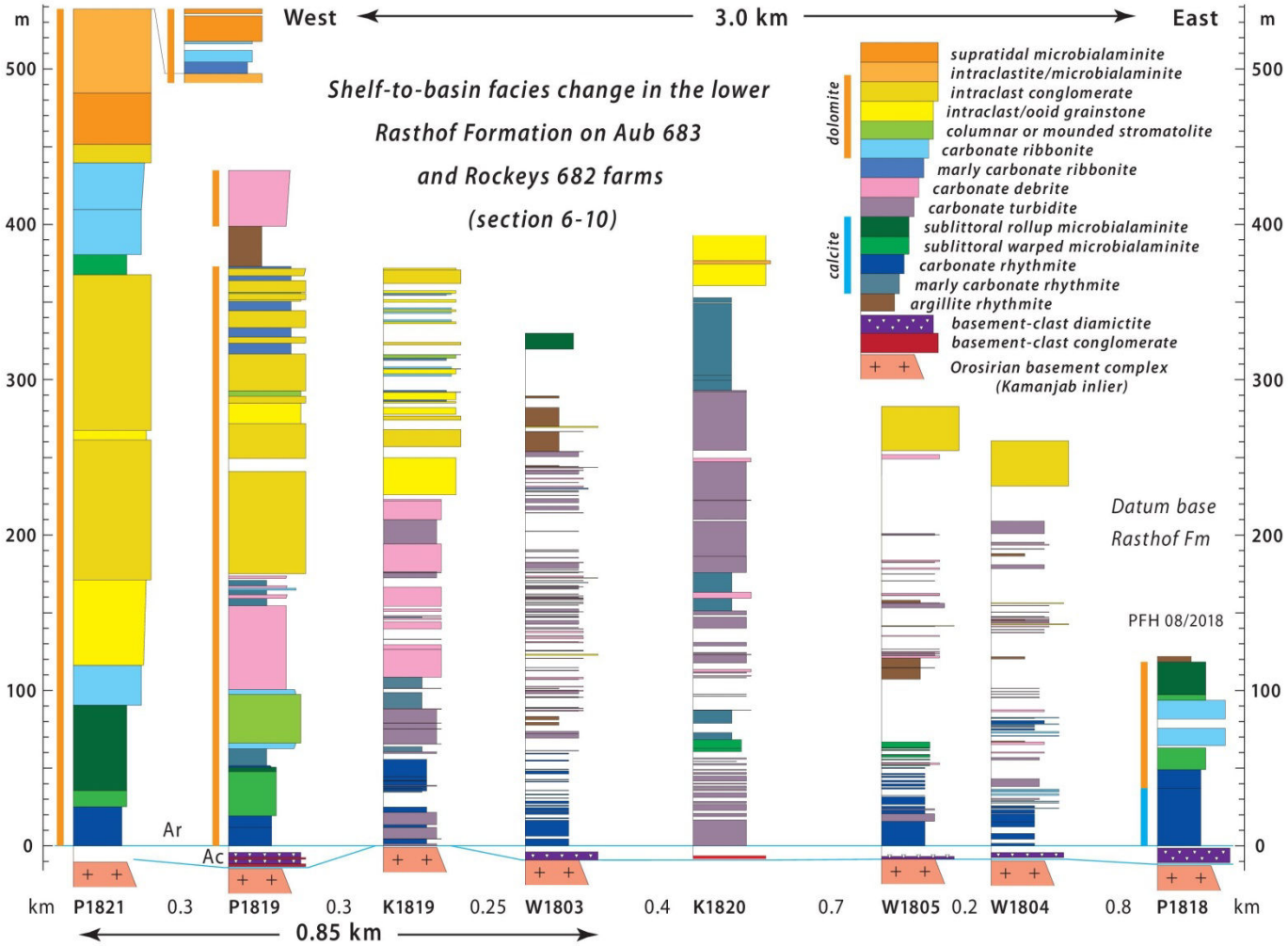

Figure 9. Fence diagram documenting part of an eastward-deepening facies change in the Rasthof Formation postglacial cap-carbonate sequence. Shoreface carbonate sands and gravels grade laterally into argillite-hosted carbonate debrites and turbidites over 0.85 km along strike.

Stratigraphic correlations within the Cryogenian Abenab Subgroup between the Kunene Region and the Otavi Mountainland

Correlations between the Kunene Region and the Otavi Mountainland (OML) are hindered by a general lack of measured sections in the OML and by disjunctive petrography-based descriptive schemes appropriate for drill-core logging (OML) and bedform-based schemes for logging outcrop.

To shed light on correlations between the two areas for non-glacial carbonates of the Cryogenian Abenab Subgroup, an outcrop section of the Berg Aukas, Gauss and Auros formations on farm Nosib 682 southeast of Tsumeb (base and top of section at 19°25.85'S, 17°48.23'E and 19°25.18'S, 17°48.14'E, respectively) was measured. Comparison between this section and a representative section in the Eastern Kaoko Zone (near Otjomatemba, base and top at 18°50.86'S, 13°45.44'E and 18°50.83'S, 13°44.88'E, respectively) suggests the correlations indicated in Figure 10. Accordingly, the Rasthof, Gruis and Ombaatjie formations of the Kunene Region (Hedberg, 1979; Hoffman & Halverson, 2008) are correlative only in aggregate with the Berg Aukas, Gauss and Auros formations in the OML. The suggested correlations (Fig. 10) may be testable by carbon isotope profiling in the OML.

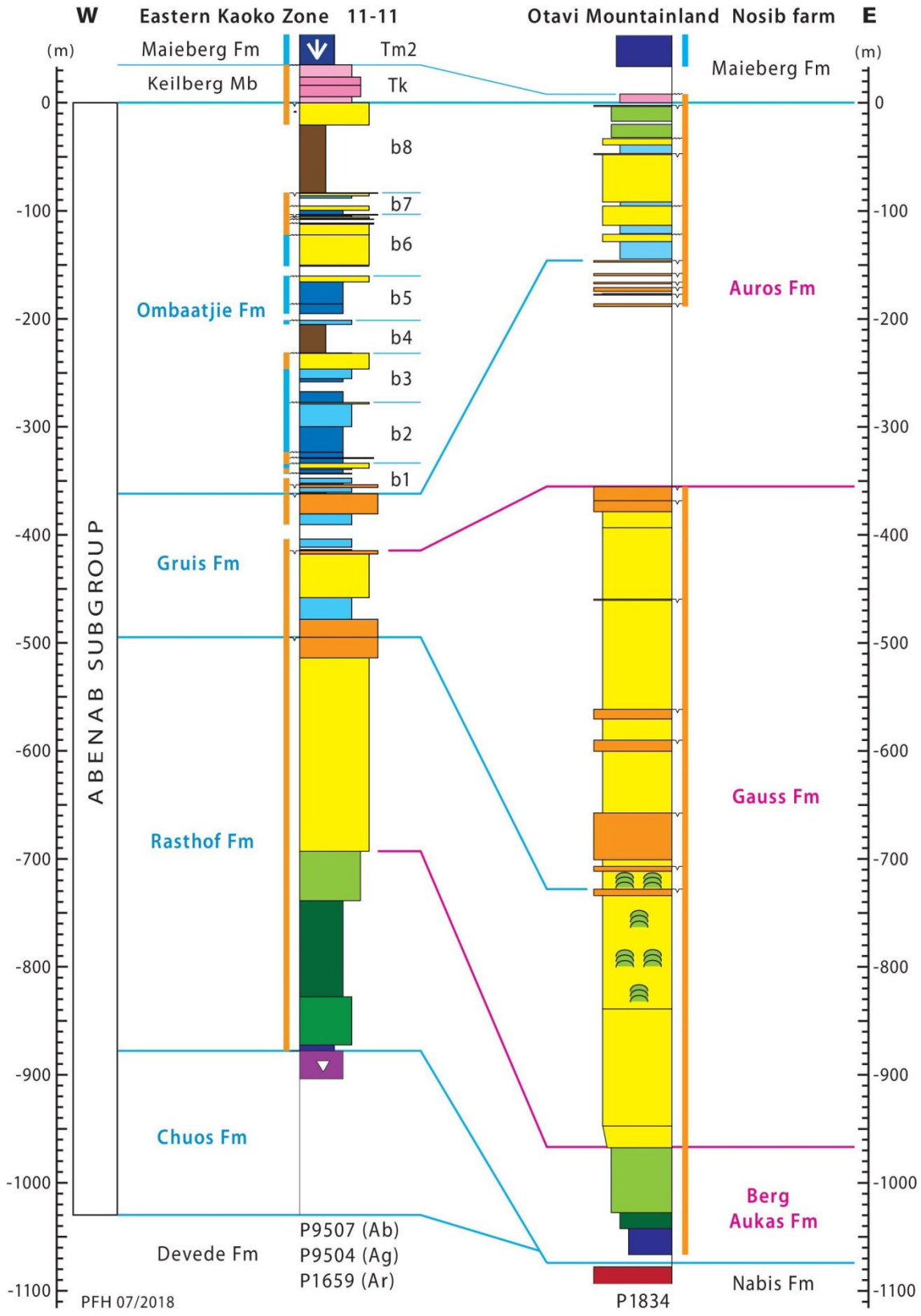

Figure 10. Comparison of representative measured sections and suggested stratigraphic correlations, subject to chemostratigraphic testing, between the Eastern Kaoko Zone and the Otavi Mountainland. West-East stratigraphic comparisons within the Otavi Fold Belt are inhibited by the lack of measured surface sections in the Otavi Mountainland and the difficulty of macrofacies recognition in drill cores.

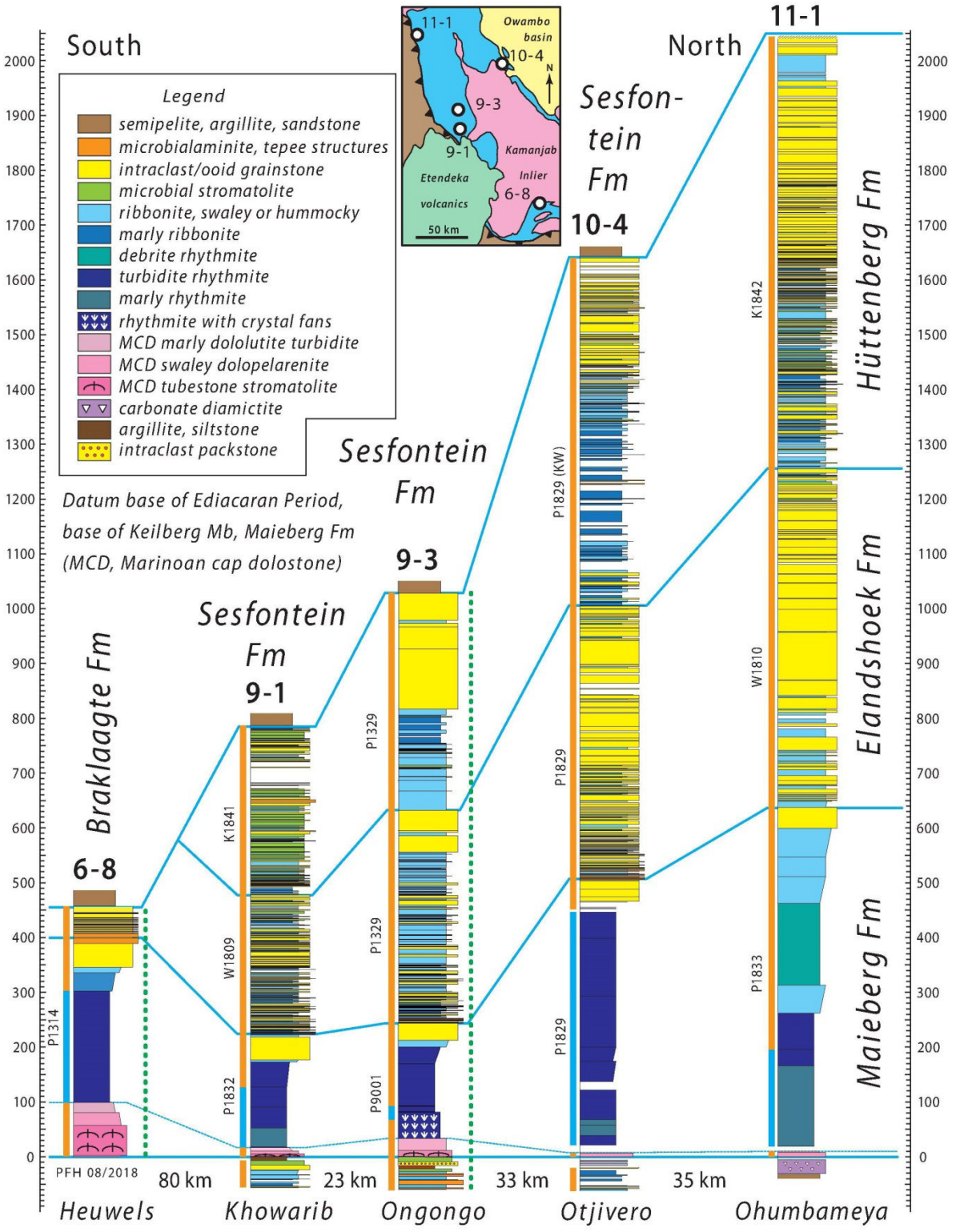

Figure 11. South-North fence diagram of the Ediacaran Tsumeb Subgroup (Otavi Group) in the western part of the Northern Platform. Inset map gives section locations (open circles). Covariation in thickness of the Maieberg, Elandshoek and Hüttenberg formations north of the Etendeka Plateau proves that northward thickening reflects variable subsidence, not variable sub-Mulden (Sesfontein Formation) erosion.

Northward thickening of the early Ediacaran Tsumeb Subgroup

Reconnaissance stratigraphy indicates northward thickening of the early Ediacaran Tsumeb Subgroup in the Eastern Kaoko Zone (Hedberg, 1979; Hoffman & Halverson, 2008), but the degree to which accumulation rate vs erosional truncation controlled the thickening is unclear.

Three new detailed sections of the entire Tsumeb Subgroup were measured near Khowarib (~780 m thick), Otjivero (~1640 m) and Ohumbameya (~2050 m) covering a meridional distance of 91 km (Fig. 11). Adding previously measured sections from farms Ongongo (~1020 m) and Heuwels (~455 m; Fig. 7) increases this distance to 171 km (Fig. 11).

Northward thickening between Khowarib and Ohumbameya should relate to variable subsidence since all three formations—Maieberg, Elandshoek and Hüttenberg—thicken sympathetically. In contrast, thinning between Khowarib and Heuwels is related to erosional truncation beneath the Mulden Group (Braklaagte Formation) since the Maieberg Formation actually thickens, while the Elandshoek and Hüttenberg formations are partly or totally missing, respectively (Fig. 11).

All three formations also thicken eastward between the Kunene Region and the OML, where their aggregate maximum thickness may exceed 3.8 km (Miller, 2008).

Sub-Mulden Group mega-karst landscape and basement incision in the lower Sout River area (farm Welkom 680)

A 30-km-long palaeo-outlier of Otavi Group carbonate is exposed on the northern limb of the Achas Syncline (Frets, 1969) separating the Kamanjab and Welwitschia basement inliers (Fig. 7). The eastern end of the palaeo-outlier is faulted (Fig. 8), but its western end is truncated by an erosional unconformity beneath the Welkom Subgroup (Braklaagte and Renosterberg formations) of the Ediacaran Mulden Group (Fig. 12). As mapped by Frets (1969), the Otavi Group is truncated beneath fluvial sandstone of the Renosterberg Formation (Frets' unit MnQ). However, Miller (2008, p. 13-224) describes a Mulden-age palaeo-valley incised into the basement complex in the same area that is filled by subaqueously-deposited, tabular-bedded, silt-stone and fine-grained sandstone of the Braklaagte Formation (Frets' unit Mn). Dolostone-clast debrite and conglomerate occurs on the northern side of the palaeo-valley proximal to the Otavi Group palaeo-outlier.

At section P1824 (Fig. 12), the Braklaagte Formation is incised ≥300 m below the sub-Otavi Group basement surface (Fig. 13). Metre-scale blocks of Keilberg Member cap dolostone in the basal breccia in the same section (P1824) are lodged ≥400 m stratigraphically *below* their source horizon (Fig. 13), which is therefore a minimum magnitude of palaeo-relief on the sub-Braklaagte disconformity surface. South of section P1824, the base of the Braklaagte is a basement-derived roundstone conglomerate (Fig. 12). If this conglomerate marks the original palaeo-valley axis, then the magnitude of basement incision likely exceeds 300 m.

Bedding attitudes (n=22) where the Otavi and Mulden groups meet suggest that the Abenab Subgroup was tilted 17° to the southeast when the Braklaagte Formation was deposited. This angular relation could be related to deformation associated with the Huab Fault (Frets, 1969), which projects in the subsurface towards the Sout River, and on which displacement on farm Rockeys 682 postdates the Abenab Group but predates the Braklaagte Formation (Fig. 7).

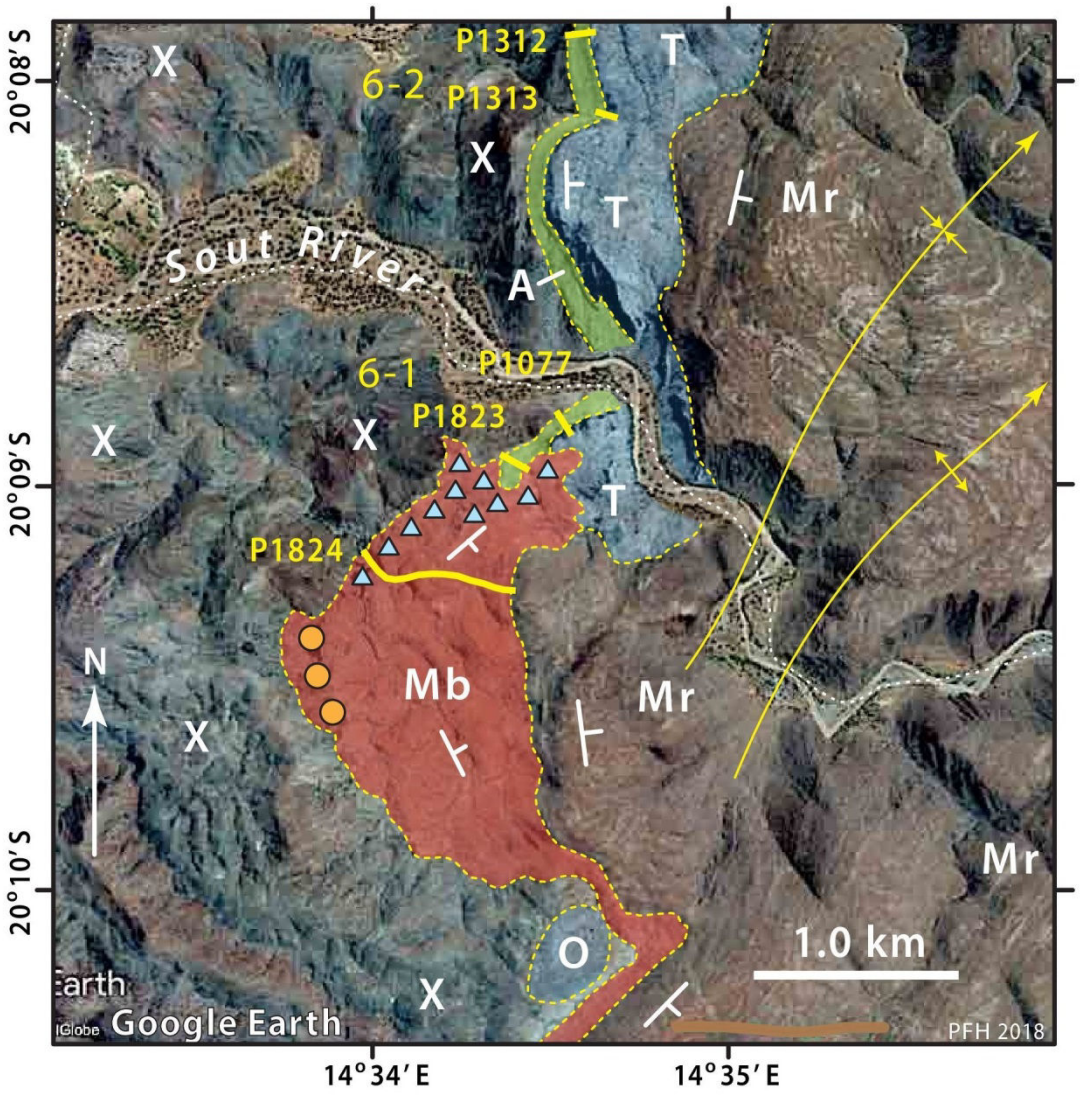

Figure 12. Meeting of the (A) Abenab (green) and (T) Tsumeb (blue) subgroups with the (Mb) Braklaagte Formation (red) of the lower Welkom Subgroup (Mulden Group) near the lower Sout River (2 km upstream from its junction with the upper Huab River). Other units: X - Orosirian Huab gneiss complex; Mr - Renosterberg Formation (upper Welkom Subgroup); O - undivided Otavi Group. Blue triangles indicate carbonate-clast (Otavi-derived) talus, debrite and conglomerate. Orange circles indicate basement-derived roundstone conglomerate.

Mega-karstic erosion between the Tsumeb and Welkom subgroups was broadly contemporaneous with submarine mass slides in the Ombonde Syncline (Hoffman & Hartz, 1999) and, with weaker age constraints, in the Northern Damara (Clifford, 2008) and Eastern Kaoko (Hoffman *et al.*, 2016) Zones. Large-amplitude lithospheric flexure and/or base-level changes are inferred. The former may relate to flexure of a thermally-young plate—rift cessation at ~650 Ma and arc-continent collision at ~590 Ma—at the cusp between converging Damara and Kaoko orogens.

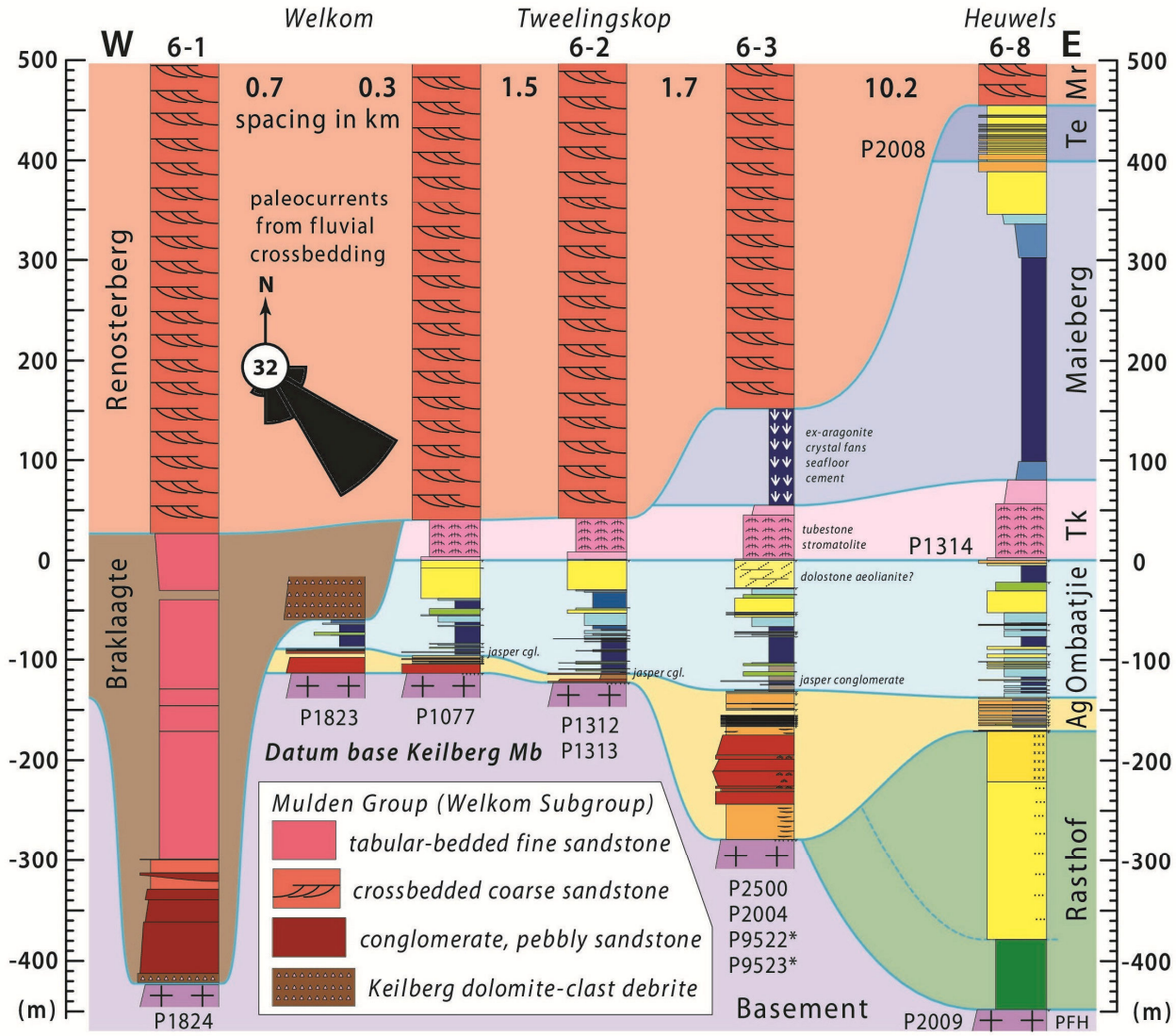

Figure 13. Fence diagram showing stratigraphic relations at the western termination of the Otavi Group palaeo-outlier on the northern limb of the Achas Syncline near the junction of the Sout and upper Huab rivers (farm Welkom 680). The Ediacaran Tsumeb Subgroup is erosionally truncated beneath fluvial sandstone of the paraconformable Renosterberg Formation (upper Mulden Group). Conformably underlying the Renosterberg, finer-grained sandstone, conglomerate and carbonate-clast debrite of the Braklaagte Formation (lower Mulden Group) fill a palaeo-valley incised through an attenuated Abenab Subgroup and ≥0.3 km of Orosirian basement rock. Basal carbonate megaclast debrite (Soutrivier Member) in section 6-01 (P1824) are rich in Keilberg-derived tubestone stromatolite blocks, which fell 0.4 km into the basement-walled 'inner gorge' from their source at the lip of the palaeo-valley. The western side of the Braklaagte palaeo-valley is marked by basement-derived roundstone conglomerate. These stratigraphic relations and facies were first described by Miller (2008, p. 13-224). Attenuation of the Abenab Subgroup is related to structural rotation and depositional onlap of the Huab ridge dip-slope (Hoffman & Halverson, 2008).

Acknowledgements

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