Comment on Eyles & Januszczak (2007) Syntectonic subaqueous mass flows of the Neoproterozoic Otavi Group, Namibia: where is the evidence of global glaciation? *Basin Research,* 19, 179-198, doi: 10.1111/j.1365-2117.00319.x

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The paper by Eyles & Januszczak (2007) is welcome as it gives the observational basis for their surprising conclusion (Eyles & Januszczak, 2004a, b; Eyles, 2004) that the diamictites and associated strata of the Ghaub Formation are non-glacial in origin. The Ghaub Formation is commonly considered to represent the terminal Cryogenian (≥635 Ma) glaciation on and around the Otavi carbonate platform of northern Namibia (Hoffmann & Prave, 1996; Hoffman *et al.,* 1998; Kennedy *et al.,* 1998; Condon *et al.,* 2002; Hoffman & Schrag, 2002; Hoffmann *et al.,* 2004; Halverson *et al.,* 2005; Hoffman, 2005; Hurtgen *et al.,* 2006). In contrast, Eyles & Januszczak (2007) interpret it as a stack of subaqueous mass-flow deposits (with intercalated hemipelagic facies) of non-glacial origin, genetically related to rifting and break-up of the Congo craton. Accordingly, the Ghaub Formation has no bearing on the Neoproterozoic glacial record and provides no support for the Neoproterozoic snowball Earth hypothesis. Their conclusion is based on a study of two stratigraphic sections, one at the Fransfontein drainage gap and the other 17 km to the west near the small village of Narachaams se pos.

Their argument boils down to four interconnected points. First, the Ghaub Formation lacks key glacial indicators such as faceted, striated and bullet-shaped clasts. Second, strata above and below the Ghaub Formation are lithologically indistinguishable from the Ghaub itself, meaning that the idenitification of a glacigenic interval is entirely arbitrary. Third, the Ghaub diamictites occur strictly in base-of-slope paleoenvironments, consistent with their origin as subaqueous mass-flows. And fourth, they were deposited contemporaneously with rift faulting and continental breakup at the edge of the Congo craton, suggesting that active faulting was the trigger for mass wasting. Each of these points is contradicted by previous and ongoing studies.

Diagnostic glacial indicators

Eyles & Januszczak (2007) begin by noting that when diamictites in the Otavi Group were first reported and interpreted as glacigenic, "the absence of key glacial indicators such as striated clasts was recognized (Gevers, 1931)" and "viewed as problematic". Actually, the strata described by Gevers (1931) occur in the central zone of the Damara Belt, 235 km south of the Otavi Group. They are not even correlative with the Ghaub Formation (Hoffmann & Prave, 1996). Diamictites in the Otavi Group were first described and interpreted by le Roex (1941), who reported that "a high percentage of the pebbles show typical glacial faceting, particularly the hard quartzitic types". They also show striations (Fig. 1a), some of "indisputable glacial origin" (le Roex, 1941). He notes that striations are "much better preserved on the quartzitic than the calcareous types".

The "Otavi Tillite" (le Roex, 1941) is correlative with diamictite in the sections studied by Eyles & Januszczak (Hoffmann & Prave, 1996), but quartzitic clasts are absent in the latter. The problem is that the carbonate clasts and carbonate matrix were thoroughly welded together during middle greenschist grade metamorphism. Facets and striae might exist on every clast, or on none: it would be impossible to tell the difference because the clasts cannot be freed from their matrix. All that can be shown in cross-sections is that the clasts run the gamut from angular to smoothly rounded, a non-diagnostic characteristic of glacial tills composed of mixed englacial and subglacial debris (Agassiz, 1842). Where dolomite clasts weather in relief of more calcitic matrix, their exposed surfaces are karstic; the original surfaces are destroyed (Fig. 2b). However, faceted, striated and bullet-shaped clasts of undoubted glacial origin occur on other low-latitude continental margins of the same age (*e.g.,* Nantuo Formation, South China; Elatina Formation, South Australia; Ice Brook Formation, northwest Canada). Their matrices allow carbonate pebbles as well as other clast types to be liberated, enabling their surface morphologies to be examined (Hambrey & Harland, 1981).

In the absence of clast morphology, the most diagnostic glacial features (aside from the overall facies association and architecture) are rafted dropstones, which occur abundantly in tongues of well-stratified debris from the base of the Ghaub Formation to its top (Condon *et al.,* 2002; Hoffman, 2005). Classic attributes of rafted dropstones are on display, including pinched and punctured substrata (Fig. 2c, f), thickened and ejected side-strata (Fig. 2g, 3c), draped or onlapping superstrata (Fig. 2c, g), and independence from bottom sediment transport events (Fig. 2c, g, h). Ejection folds (Fig. 2g; June 2002 *Terra Nova* cover photo) are small-scale analogues of the famous "overturned flap" on the rim of Meteor Crater, Arizona (Shoemaker, 1963). Eyles & Januszczak (2004a, 2007) correctly note that dropstones also occur in non-glacial settings, but the sheer density and consistency of their occurrence in the Ghaub Formation is unmatched by any non-glacial deposit. With a conservative average of one dropstone per 1000 cm^3, the uppermost stratified member alone held 50 million-million ($5x10^{13}$) dropstones, given its minimum original dimensions of 0.1x5x100 km. To reject floating ice as the source of these dropstones (Eyles & Januszczak, 2007), given their intimate intercalation with non-stratified polymictic diamictites composed of like debris (Fig. 2b), is simply unfathomable.

Pre-, syn- and post-glacial facies

The lower and upper contacts of the Ghaub Formation can be unambiguously mapped on the basis of lithology with an accuracy of centimeters along the length of the Fransfontein foreslope (Fig. 1b). The same is true of the outliers to the west (Bethanis-Toekoms and Vrede-Opdraend). The carbonate turbidite-hosted debris flows of the underlying Franni-aus Member and overlying Maieberg Formation are oligomictic and intraformational; those of the Ghaub Formation are polymictic and extraformational. Weakly- to non-stratified diamictite bodies make up 82% of the Ghaub Formation (based on 64 measured sections) but are uncommon or absent in the adjacent formations. Similarly, dropstones are profligate in the Ghaub but rare or non-existent in the Franni-aus and Maieberg. In short, the Ghaub is a true formation: it is lithologically mappable on the regional scale.

How could Eyles & Januszczak (2007) conclude that the same essential features occur within and below the Ghaub Formation? The answer is the following. At Narachaams (see their Fig. 4 and 5), they place the base of the Ghaub Formation at the base of the uppermost stratified member, which is unusually thin (2 m) in that section. At Fransfontein (their Fig. 3 and 5), everything they call Ghaub Formation lies below this same member. In other words, their "Ghaub Formation" at Fransfontein is stratigraphically equivalent to their "Abenab Subgroup" at Narachaams. Small wonder their "pre-Ghaub" and "syn-Ghaub" facies are similar; they are one and the same. I cannot explain their mistake as they were sent an advance copy of the 16th International Sedimentological Conference guidebook (Hoffman, 2002) which contains a description with columnar section and airphoto-map of the Narachaams section, where the Ghaub Formation is 54 m (not 2 m) thick. Had they descended 52 m stratigraphically they would have encountered the highly-silicified oolite debris flows (Fig. 1b, c, d) of the upper Franni-aus Member (Hoffman, 2005), indistinguishable from their Fransfontein section.

Paleoenvironmental setting

The sections studied by Eyles & Januszczak (2007) are indeed situated on the distal foreslope of the Otavi carbonate platform (Henry *et al.,* 1990; Hoffman, 1999, 2002, 2005; Halverson *et al.,* 2002, 2005). Their interpretation of the Ghaub Formation as a stack of submarine mass flows is seemingly consistent with this setting, but it does not take into account the evidence for massive base-level fall in the unit (Franni-aus Member) directly below the Ghaub Formation (Hoffman, 1999, 2005; Hoffman & Halverson, in press) and massive base-level rise in the unit (Keilberg Member cap dolostone) directly above it (Hoffman *et al.,* 2007; Hoffman & Halverson, in press). In the latter, low-angle cross-lamination and giant wave ripples in peloidal dolostone prove that the distal foroeslope was above storm wave base at the glacial-deglacial transition. Of the total mass of the Ghaub Formation, >98% is confined to a laterally continuous prism (Fig. 4) situated on the distal foreslope, at estimated paleodepths >0.5 km below the rim of the platform (Hoffman, 2005; Hoffman *et al.,* 2007), yet the facies associations and stratal architecture of that prism (Condon *et al.,* 2002; Domack & Hoffman, 2003; Hoffman, 2005) closely resemble ice grounding-zone wedges found on continental shelves and upper slopes (at high latitudes) in the Quaternary (Alley *et al.,* 1989; Boulton, 1990; King *et al.,* 1991; King, 1993; Powell & Domack, 1995). The prism is dominated by tongues of weakly- to non-stratified polymictic (carbonate) diamictite (Fig. 2b), both ice-proximal (Fig. 3a) and ice-contact diamictites (Fig. 3b, c), and they are separated and enveloped by thinner units of well-stratified diamictite, composed of plume fallout (Fig. 2c), contourites (Fig. 2e), turbidites (Fig. 2c), debris flows (Fig. 2d), sand and gravel fans (Fig. 2h), and ice-rafted debris (Fig. 2c, d, f, g), in variable proportions. An alternative to the interpretation of Eyles & Januszczak (2007) is that the distal-slope setting of the main Ghaub prism reflects the quasi-stable location of the ice grounding line during the glacial period (Hoffman, 2005). The implied glacioeustatic change of ≥0.5 km is consistent with the volume of grounded ice simulated in climate models of either the snowball or slushball Earth (Donnadieu *et al.,* 2003; Peltier *et al.,* 2004; Pollard & Kasting, 2004). It is equivalent to an average ice thickness of ≥1.0 km on all continents, and is more than twice the glacioeustatic fluctuation implied in the original sub-hemispheric Ice Age of Schimper and Agassiz (Maclaren, 1842).

In this alternative scenario (Hoffman, 2005), the Otavi platform was above sea-level but beneath an ice sheet for most of the Ghaub glaciation. Consequently, the raised outer rim of the platform and the upper foreslope are all but devoid of glacial deposits (Fig. 4), but discontinuous lenticles of carbonate diamictite, possibly lodgement tillites, are widespread across the inner platform (Fig. 2a). Up to 60 m of diamictite with granitic and quartzitic as well as carbonate clasts (le Roex, 1941; Hoffmann & Prave, 1996) are preserved ~20 km inboard of the platform edge (Smit, 1962) in the Otavi Mountains (Fig. 1a). Curiously, Eyles & Januszczak (2004a, b, 2007) make no mention of these epi-platform deposits. They are underlain and overlain by shallow-water carbonate facies (Ombaatjie Formation and Keilberg Member, respectively), and could not have been emplaced as submarine mass-flows.

Role for rift faulting?

Le Roex (1941) argued that the quartzitic and granitic clasts in his diamictite could not be locally derived (*e.g.,* through faulting) because the diamictite is separated from quartzite and granitic basement in the Otavi Mountains by 100s of meters of shallow-water (stromatolitic and oolitic) carbonate strata forming a conformable stratigraphic succession. He concluded that the clasts must have been transported from distant sources, where quartzite and granitic basement were exposed in Ghaub time.

Halverson *et al.* (2002) greatly strengthened le Roex's (1941) argument with detailed isotopic chemostratigraphy of the upper Ombaatjie Formation. They documented a steep decline in δ^{13}C from +5‰ or higher down to –5‰ in the final pair of depositional cycles (parasequences) at 17 locations distributed from the edge of the platform far into its interior. This isotopic shift has been correlated globally and is named the Trezona anomaly after the formation in South Australia where it was first encountered (Halverson *et al.,* 2002, 2005). Plotting all the sections using the interpolated 0‰ cross-over as a datum provides a quantitative basis for reconstructing the palaeotopography of the erosion surface on the platform beneath the Ghaub diamictite, or beneath the Keilberg Member where the Ghaub is absent (Halverson *et al.,* 2002; Hoffman *et al.,* 2007). There is up to 80 m of local relief on the erosion surface but no evidence of uplift or back-rotation of the outer platform. If a basinward-dipping normal fault was active at the edge of the platform (Eyles & Januszczak, 2007), uplift and back-rotation would occur as an isostatic response to tectonic unloading of the footwall. The resulting unconformities as well as cannibalistic clastic deposits on the back-rotated dip-slopes are precisely the criteria successfully used to determine the location and timing of rift faulting in the lower Otavi Group, prior to the Ombaatjie Formation (Soffer, 1998; Hoffman, 1999; Halverson *et al.,* 2002; Hoffman & Halverson, 2007). But there is no shred of evidence of such activity at the time of the Ghaub Formation. The edge of the platform preserves more upper Ombaatjie strata than does the interior, not less, and over the platform as a whole the upper Ombaatjie cycles and the Keilberg Member are parallel. This is a very sensitive test because even a small angular rotation of a rift "shoulder" of modest dimensions will result in significant stratigraphic truncation in a shallow marine environment. None is observed. The history of rift faulting on the proto-platform has been known for many years to have ended before the Ombaatjie Formation was deposited, millions of years before the Ghaub glaciation (Hoffman *et al.,* 1998; Hoffman, 1999, 2002; Halverson *et al.,* 2002). Eyles & Januszczak (2004a, 2007) simply ignore these inconvenient truths.

For the record, Eyles & Januszczak (2007) give me credit for two important papers (Hoffmann & Prave, 1996; Hoffmann *et al.,* 2004) supporting a glacial interpretation in which I had no involvement. The senior author of both papers is K.-H. (Charlie) Hoffmann of the Geological Survey of Namibia. The glacial interpretation of the Ghaub Formations is therefore not one that I alone support, but is shared by three sedimentary geologists intimately familiar with the Otavi Group (Hoffmann, Hoffman and Prave) as well as ones who have worked extensively on Quaternary glacial sediments (Douglas Benn and Eugene Domack). Eyles & Januszczak (2007) also gratuitously criticize Hoffman & Schrag (2000) for labelling carbonate turbidites as "varves" (the word does not appear in our paper). In fact, we would be very surprised if true (annual) varves did exist because seasonality is weak at low latitudes in non-monsoonal settings, where we believe the Otavi Group was deposited.

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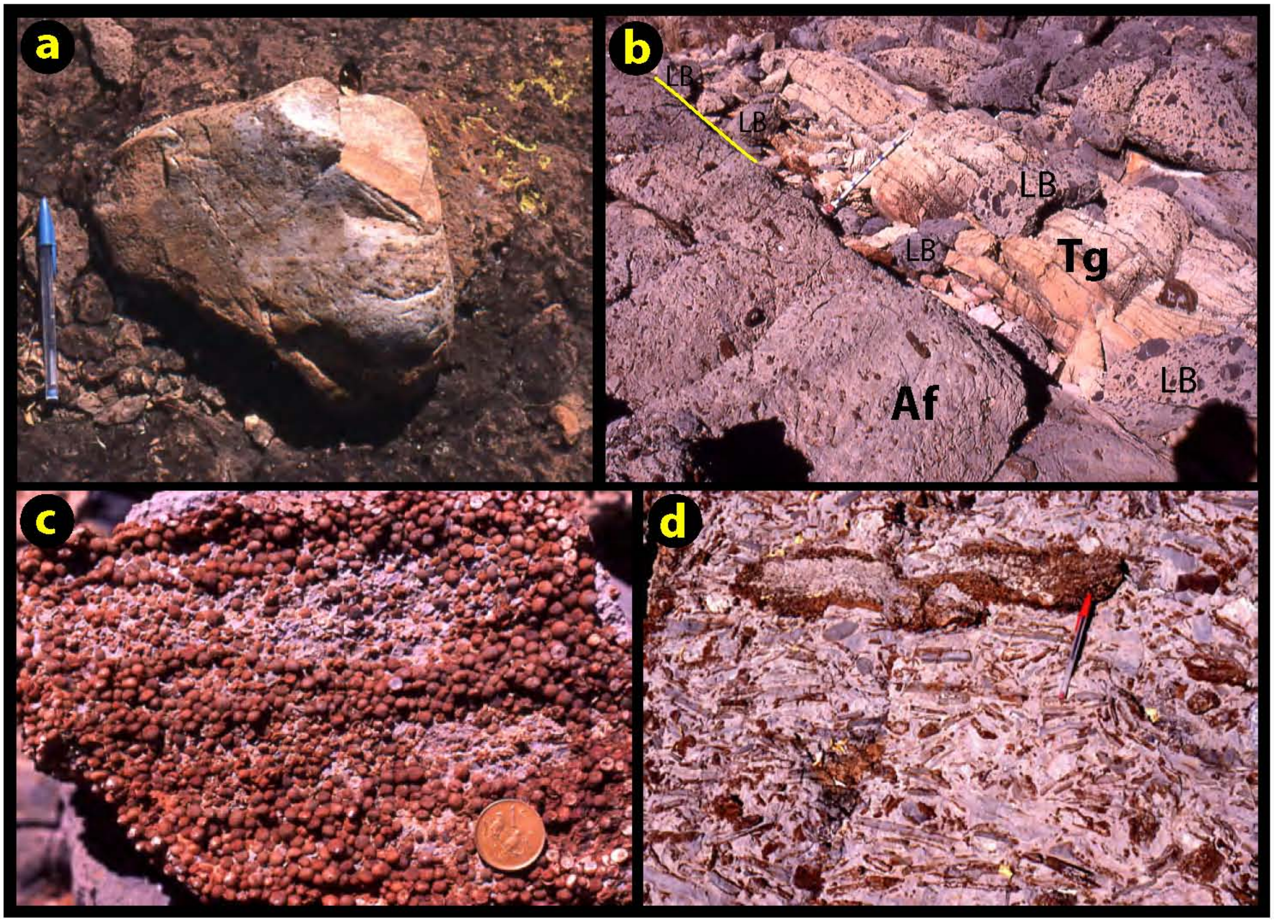
Figure captions

Fig. 1. Ghaub Formation and underlying glacioeustatic low-stand wedge (Franni-aus Member): **(a)** Faceted and striated quartzite clast in diamictite ("Otavi Tillite" of le Roex, 1941) of the Ghaub Formation (Hoffmann & Prave, 1996) on Keilberg-743 farm, Otavi Mountainland. **(b)** Sharp erosive contact between oolite-clast debris flow of the Franni-aus Member (Af) and stratified grading to non-stratified, limestone-clast diamictites of the Ghaub Formation (Tg). Loose blocks (LB) of non-stratified diamictite are out-of-place. (**c**) Silicified coarse-grained oolite clast in debris flow of the Franni-aus Member low-stand wedge. **(d)** Oligomictic intraformational debris flow in the upper Franni-aus Member. Pen cap rests on a partially-silicified clast of coarse-grained oolite. The oolite originally formed in the surf zone on the foreslope and was redeposited gravitationally while partially lithified as sea-level fell due to buildup of ice sheets at higher paleolatitudes (Hoffman, 2005).

Fig. 2. Glacial and proglacial facies of the Ghaub Formation: **(a)** Thin diamictite (lodgement tillite?) and breccia of the Ghaub Formation (Tg) on the inner platform of the Otavi Group, sandwiched between peritidal dolostone of the Ombaatjie Formation (Ab) and swaley cross-bedded dolostone of the Keilberg Member (Tk). **(b)** Weakly-stratified, polymictic, extraformational diamictite near Fransfontein gap containing dolomite (tan) and limestone (grey) clasts. **(c)** Well-stratified carbonate diamictite consisting of parallel-laminated plume fallout (tan), sandy turbidites (grey) and ice-rafted debris (IRD). Note that IRD occurs only in fallout, not in turbidites, reflecting different sedimentation rates. **(d)** Graded carbonate-clast debris flow. **(e)** Starved ripple (arrow) resulting from westward-directed contour current associated with plume fallout holding IRD and turbidite (pen), uppermost member. **(f)** Dropstone of laterally-linked hemispheroidal stromatolite characteristic of the uppermost member, which represents the terminal collapse of the ice sheet on the Otavi platform. **(g)** Recumbent syncline-anticline (arrow) ejected by the impact of a dropstone of oolitic limestone, basal well-stratified unit. Note deformation of underlying strata and onlap of overlying strata. **(h)** South-directed climbing ripples in fine-grained carbonate sandstone with IRD (arrow).

Fig. 3. Diamictite types in the Ghaub Formation: **(a)** Upward gradation from plume fallout (tan) with IRD and turbidites (grey) into non-stratified, limestone-clast, 'rain-out' diamictite. Gradational contact suggests diamictite deposition proximal to but seaward of an ice grounding line. **(b)** Lenticular "silt-stringer" (tan) draping an erosion surface within a body non-stratified, limestone-clast diamictite. **(c)** Rotated and sheared-off "silt-stringers" (tan) in limestone-clast diamictite. The delicately-laminated "silt-stringers" are interpreted to have been deposited in quiescent subglacial meltwater cavities during times of ice stagnation. They were later rotated and sheared-off (arrow) by recurrent glacial flowage (Domack & Hoffman, 2003). They are one of the features indicative of grounded ice on the distal foreslope (>5 km seaward of the slope break) of the Otavi platform.

Fig. 4. Stratigraphic-paleobathymetric reconstruction of the Otavi platform and foreslope, showing location of the Ghaub diamictite prism, the underlying low-stand wedge (Franni-aus Member) and overlying transgressive cap dolostone (Keilberg Member). Eyles & Januszczak (2007) interpret the Ghaub prism as a toe-of-slope stack of mass-flows; Domack & Hoffman (2003) and Hoffman (2005) interpret it as an ice grounding-zone prism associated with large-amplitude glacioeustatic fall (Hoffman *et al.*, 2007).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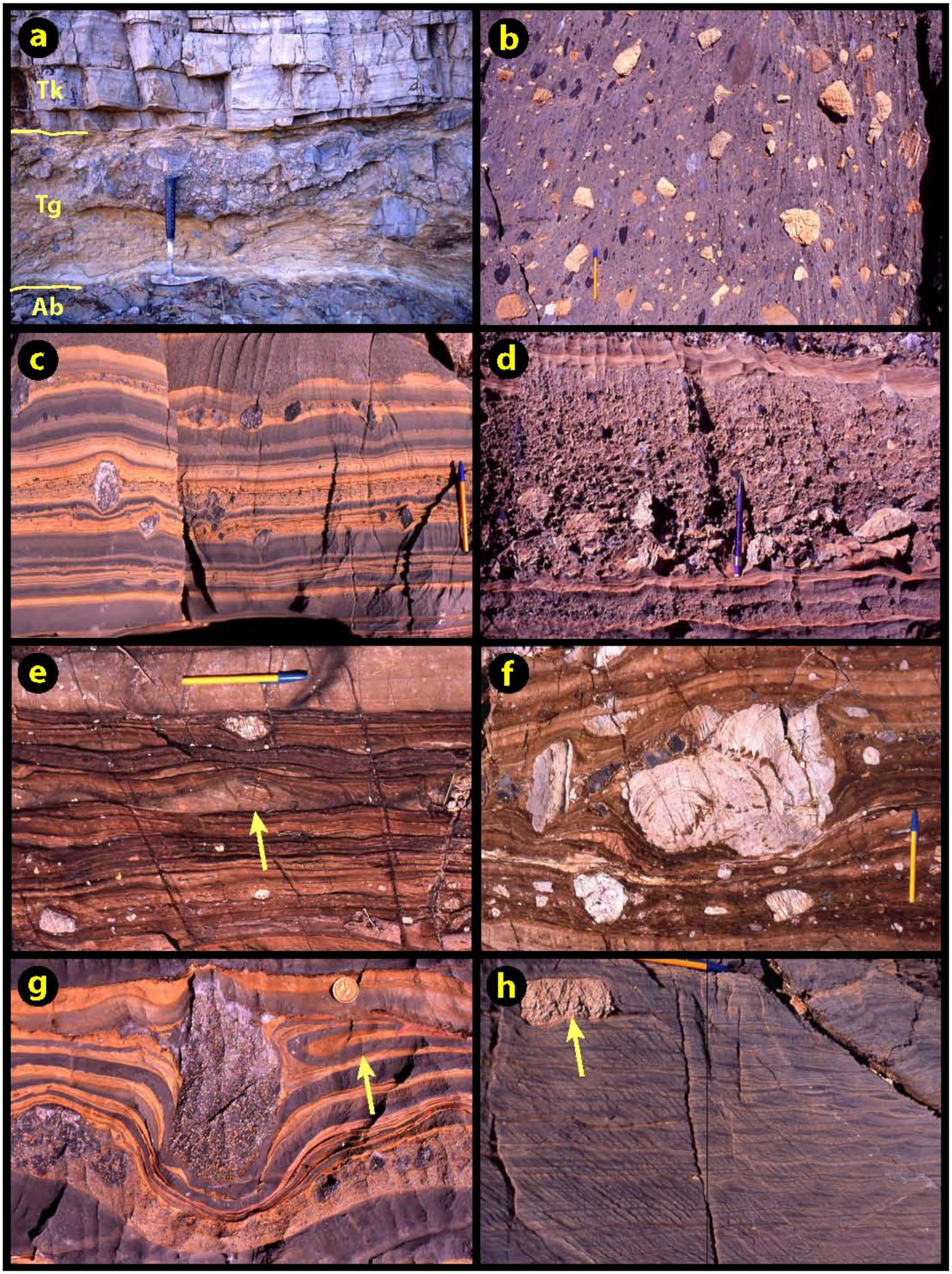
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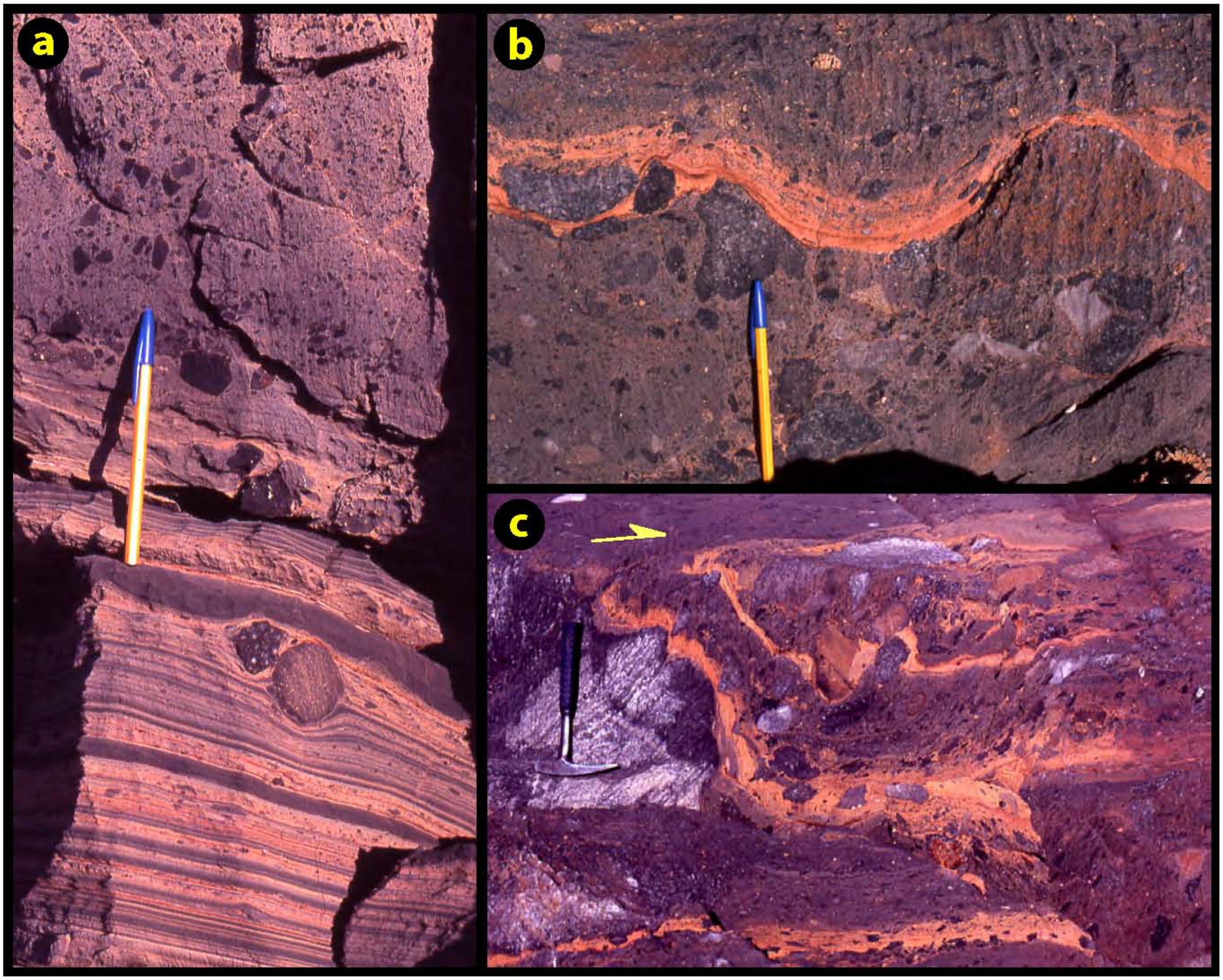
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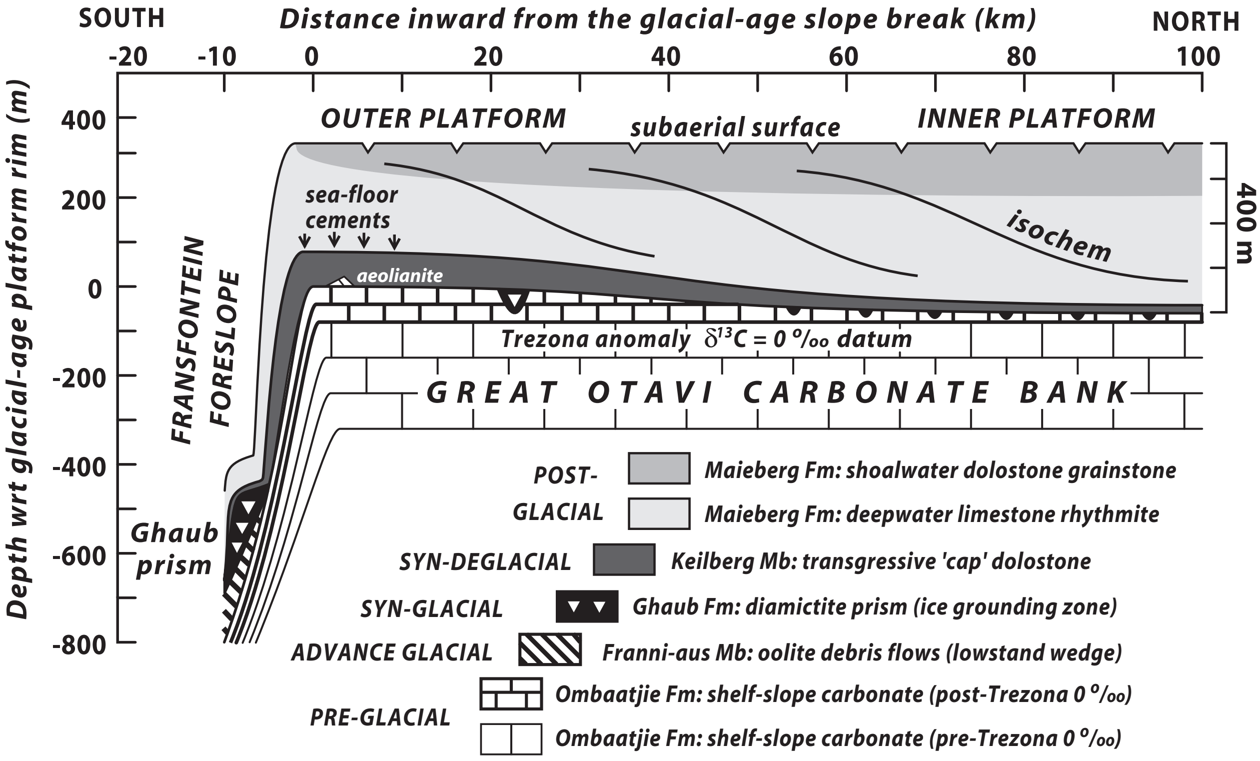
SOUTH
Distance inward from the glacial-age slope break (km)
NORTH
-20
-10
0
20
40
60
80
100
Depth wrt glacial-age platform rim (m)
400
200
0
-200
-400
-600
-800
OUTER PLATFORM
subaerial surface
INNER PLATFORM
sea-floor cements
isochem
400 m
aeolianite
FRANSFONTEIN FORESLOPE
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Ghaub prism
POST-GLACIAL
Maieberg Fm: shoalwater dolostone grainstone
Maieberg Fm: deepwater limestone rhythmite
SYN-DEGLACIAL
Keilberg Mb: transgressive 'cap' dolostone
SYN-GLACIAL
Ghaub Fm: diamictite prism (ice grounding zone)
ADVANCE GLACIAL
Franni-aus Mb: oolite debris flows (lowstand wedge)
PRE-GLACIAL
Ombaatjie Fm: shelf-slope carbonate (post-Trezona 0 ‰)
Ombaatjie Fm: shelf-slope carbonate (pre-Trezona 0 ‰)