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Decoding the Late Palaeozoic glaciated landscape of Namibia: A photogrammetric journey

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ABSTRACT

The geometry of unconformities carved by deep time ice sheets is often obscured and restricted by discontinuous exposure, or outcrop conditions that do not readily permit the examination of glacial unconformities (for example, steeply dipping strata). Here, we present new uncrewed aerial vehicle (UAV) data from selected outcrops across northern, central and southern Namibia to shed further light on the nature of the basal Dwyka Group unconformity. This includes the onlap relationship of basal diamictites onto the Gomatum palaeo-fjord system in northern Namibia, highly complex mapped ice flow orientations elsewhere in the northern Kaokoveld, previously undiscovered grooves along the Fish River area, and a set of subglacial grooves along the border with South Africa along the Orange River. In the latter two cases, photogrammetric methods integrating orthophotos and digital elevation models reveal the presence of subglacial grooves. Furthermore, subglacial grooves often show different orientations to striations and fabrics measured in overlying diamictites, raising fresh questions about the nature of small-scale flow variations beneath Late Palaeozoic ice sheets.

1. Introduction

An understanding of the modus, timing, and dynamics of deep time glaciers of the Late Palaeozoic Ice Age (LPIA) is vital because it provides (i) insights into how glaciation operated in the geological past and (ii) an understanding of the processes of retreat and transgression, at regional to global scales, sealed in the rock record (Dietrich et al., 2021). The LPIA is a broad interval of time in which multiple glaciations took place over Gondwana (Isbell et al., 2012; Montañez and Poulson, 2013), with an acme in southern Africa straddling the latest Carboniferous–earliest Permian (Griffis et al., 2021). In recent years, concerted efforts to improve geochronology (Griffis et al., 2019a, 2019b) have allowed the timing of the LPIA in southern Africa to be greatly improved, building on a rich tradition of research stretching back more than a century (Lomas et al., 1905; Du Toit, 1921; Sutherland, 1870; Martin, 1961; Visser, 1983, 1997). LPIA glacial deposits are recognised over wide areas of southern and central Africa (Catuneanu et al., 2005), and the record of glaciation has left a strong imprint on the modern landscape over much of the region (Dietrich et al., in review). In southern Namibia, in the Aranos and Karasburg basins, LPIA deposits belonging to the Dwyka Group blanket Cambrian sandstones and crop out over large distances (Le Heron et al., 2022a). In northern Namibia, the LPIA record takes on a different character, and deep modern-day valleys were already interpreted as relic glacial valleys 70 years ago (Martin and Schalk, 1953; Fig. 1A). LPIA sediments in these deep valleys are relatively sparse, but detailed facies analysis of locally good exposures reveals vertical transitions from subglacial diamictites, fluvial sandstones and conglomerates via marginal marine to shelf sediments, thus allowing them to be identified as palaeo-fjords (Dietrich et al., 2021). Thus, since Lomas et al. (1905) a huge amount of data has been collected that may serve to reconstruct the flow dynamics of LPIA ice masses in southern Gondwana.

At the conjugate Gondwanan margin, in South America, there has been substantial work on glacial unconformities lying directly beneath LPIA glacial deposits in recent years. There have been excellent attempts to provide an inventory of iceberg keel scour marks, soft and hard bed subglacial landforms and striated clast pavements in Brazil (e.g. Trosdtorf et al., 2005; Vesely and Assine, 2014; da Rosa et al., 2016). Others have focussed on the recognition and interpretation of roches moutonnées and streamlined surfaces both from satellite imagery and outcrops in Uruguay (Assine et al., 2018) and their subsequent

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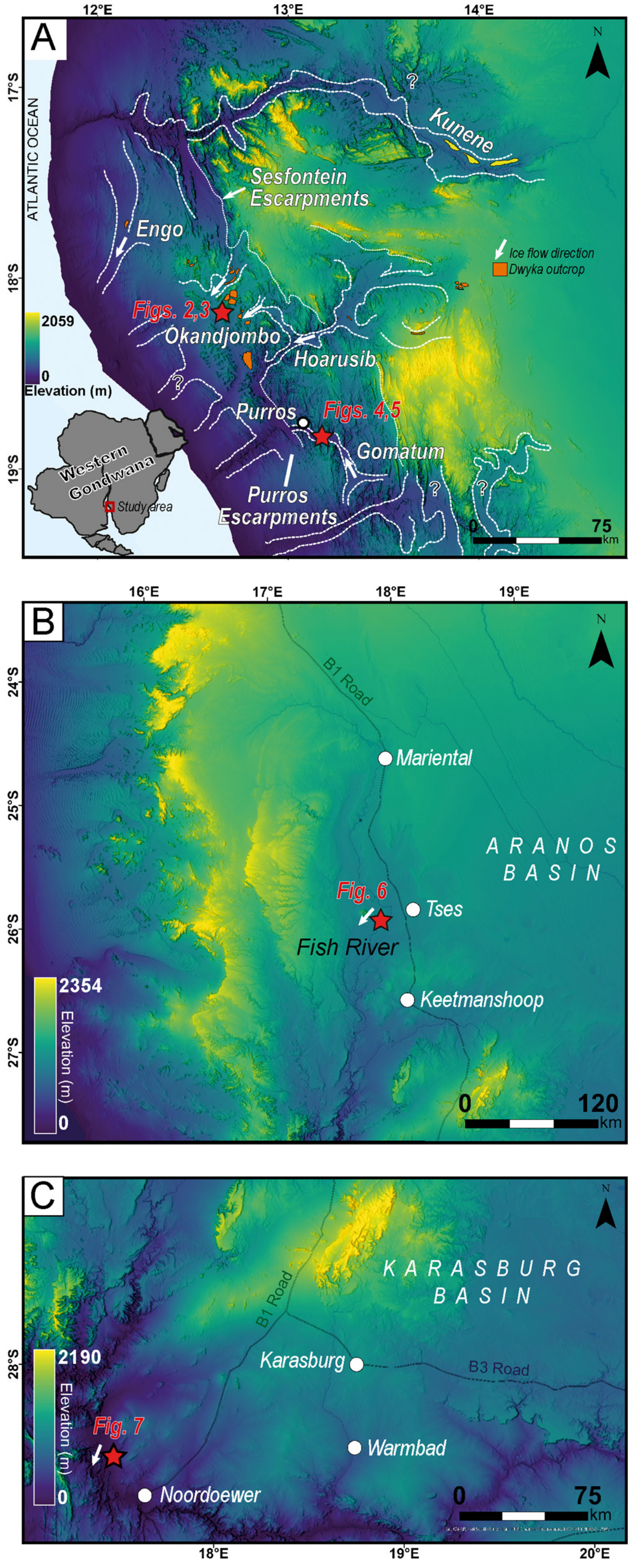

Fig. 1. Study areas in northern Namibia (map A), at the western margin of the Aranos Basin (map B), and at the SW flank of the Karasburg Basin (map C). Stippled white areas in A correspond to the modern valleys that take the course of LPIA-aged palaeovalleys and fjords (Martin and Schalk, 1953; Martin, 1981; Dietrich et al., 2021).

relevance to precise glaciological context including palaeo-ice thickness (Isbell et al., 2023; this volume). Simultaneously, work in the Paraná Basin has investigated the glacial geomorphology of the basement and discontinuities of glacial origin (Fallgatter and Paim, 2019). By comparison, systematic analyses of the distribution of glacial landforms are rare in the modern literature on southern Africa. In Namibia, published data include a bewildering mixture of palaeo-geomorphological information such as roches moutonnées and striations, clast fabrics in diamictites, and palaeocurrent data obtained from sandstone foresets (Stollhofen et al., 2000, 2008; Stratten, 1977; Visser, 1983; Werner, 2006). Thus, the question as to how each of these data types should be interpreted to aid ice mass reconstruction is important. Le Heron et al. (2022a) highlighted the issue of conflicting ice flow directions proposed by previous authors (e.g. Griffis et al., 2019a, 2019b; Stollhofen et al., 2000, 2008; Stratten, 1967, 1977; Visser, 1983; Zieger et al., 2019). Many seemingly conflicting glacier flow directions in the Dwyka Group of Namibia might be explained by the evolution of glacier flow through time, either by the evolution of a single ice mass on relatively rapid geological time scales (Boulton and Hindmarsh, 1987; Le Heron et al., 2022a) or by multiple ice masses flowing from different directions (e.g., Zieger et al., 2019). The objective of this paper is to bring fresh data on the palaeogeomorphology associated with the LPIA in Namibia to the table. Recently, the value of utilising photogrammetry together with remote sensing data interpretations (satellite images) has been emphasised as a tool to unlock the secrets of subglacial erosion in the deep time record (Le Heron et al., 2022a, 2022b). In this article, we present new photogrammetric data from an uncrewed aerial vehicle (UAV) together with ground-level photogrammetry. These data enable us to both (i) reveal previously unrecognised evidence for subglacial erosion in southern Namibia and (ii) shed new light on ice dynamics in the palaeo-fjordlands of northern Namibia.

2. Methodology

Fieldwork was conducted in the austral summer (September) of 2019. A four-week field season was split between the Kaokoland region of northern Namibia and a series of transects between Mariental and Nordoewer in southern Namibia (covering sections belonging to the Aranos and Karasburg basins) (Fig. 1). Field observations were dovetailed with photogrammetry. In terms of field measurements, the orientation of striations on clasts was measured in the basal Dwyka Group diamictite. These measurements were exclusively undertaken on the upper exposed surface of clasts. This approach was adopted because the degree of consolidation of the basal Dwyka Group diamictite inhibits excavation of the matrix around clasts and thus traditional fabric measurements (e.g. orientation of A, B and C clast axes) typical of Quaternary studies (Evans and Benn, 2021). For aerial photographs, a DJI Mavic Pro I UAV was deployed, and flown manually at various altitudes (30–150 m). This aircraft has a 1/2.3′ (CMOS) sensor capable of taking photographs of 12.35 M pixels at a focal length of 26 mm. Photos in JPEG format were taken with a maximum size of 4000 × 3000 pixels. Flying in a manual double grid mission, efforts were made to achieve 60 % overlap of photographs. In Nordoewer, owing to the potentially sensitive geographic position (international border with South Africa along the Orange River), we instead utilised a Nikon SLR camera to perform ground-level photogrammetry. For all datasets, using Agisoft Metashape Professional (Version 1.5.1 build 7618) the standard workflow was followed for image processing as follows. Photos were aligned with a tie point limit of 4000 and a key point limit of 40,000, and following manual quality control those images with a threshold quality of <0.8 were excluded. A dense point cloud was then produced, which was used to build a textured mesh. From this, a composite image (an orthophoto) was produced for each study area, and a digital elevation model (DEM) derived from the dense point cloud. The resolution of both the orthophoto and DEM is dependent on flight altitude and photo coverage. The methodology of Le Heron et al. (2019) was employed to layer orthophotos onto a DEM base map. To summarise, this process involves the calculation of a 70 % transparency algorithm followed by a multiplication algorithm to combine both data types. The resulting hybrid images have the advantage of displaying both elevation data and photographic data together, allowing the best quality geomorphological/geological interpretations to be extracted.

3. Data

3.1. Whaleback northwest of Okandjombo

3.1.1. Description

This section was first interpreted as a streamlined subglacial bedform by Martin and Schalk (1953). In simple terms, it sits between two NE–SW oriented palaeovalleys (Fig. 1A). Le Heron et al. (2022a) published a simple digital outcrop model of this locality for illustration purposes to emphasise the value of photogrammetry in general for palaeo-geomorphological research. Here, we present a hybrid orthophoto-DEM image which serves as a basemap for our interpretations (Fig. 2). The bedforms of interest are developed on paragneiss. The surface has a well-expressed polish allowing striations to be observed on some faces, and locally, a carbonate-rich muddy diamictite laps onto the structure. In terms of geomorphology, surface mapping allows the following features to be characterised (i) steep eastward-dipping bedrock slope, (ii) sculpted bedrock fracture sets, (iii) a number of nested roches moutonnées measuring 10–25 long and 5 to 50 m wide, and (iv) local striations. Measurements of the latter are collated in a rose diagram and overall demonstrate a unidirectional orientation but at the local scale show consistent bifurcation around porphyroblasts in the basement gneiss towards the west. Collectively, these features are superimposed onto a large, asymmetric bedrock structure that we name a whaleback.

In terms of ground level observation (Fig. 3), the clearly asymmetric form of the roches moutonnées is apparent, with gentle eastward-dipping stoss sides and a steep, typically irregular, lee side. P-forms (Dahl, 1965) are common, yet in low relief, and are identified by their scoop-shaped morphologies that identify with a knife sharp boundary at one side (Fig. 3). Diamictite is found locally upon the surface, and which measures no >30 cm thick, contains clasts of light grey carbonate, brown sandstone, white metaquartzite, siltstone and orange dolostone (Fig. 3B). These lithologies collectively match those expected in the Ombombo Subgroup of the Tonian succession (Miller, 2008). Clasts in the diamictites are typically rounded to subrounded, with equant geometries predominating. Immediately below the diamictites, and in numerous locations on the surface of the whaleback, striations are well developed which clearly crosscut both banding and fractures in the gneiss (Fig. 3C). Loose clasts also weather out of friable diamictites immediately east of the whaleback structure: these show excellent examples of crosscutting striations on the surface of well-rounded boulders.

3.1.2. Interpretation

The geomorphology of the bedrock northwest of Okandjombo testifies to a complex picture of subglacial abrasion aided by abundant meltwater at the ice–bed interface. When considered alone, whalebacks have been interpreted as the product of fast-flowing ice in upland areas (Evans, 1996), yet the geometry of the example herein does not aid interpretation of ice flow direction. Fortunately, the smaller-scale forms that are superimposed on it allow for reconstruction of ice flow through three independent lines of evidence. These are (i) generally unidirectional striations but with local bifurcation, (ii) swarms of roches moutonnées and (iii) p-form geometries. With regard to the first issue, and based on the rose diagram of striation orientations (Fig. 3), local ice flow direction could be interpreted as either west or east-directed but the latter interpretation is preferred owing to the bifurcation of striations around porphyroblasts in the gneiss. Supporting this interpretation is the geometry of the roches moutonnées which exhibit a gentle, eastward dipping surface (interpreted as the stoss side) and a more irregular to steep-dipping westward-dipping face (interpreted as the lee-side). The highly variable width of the roches moutonnées is interpreted as a combined product of heterogeneity in the gneiss together with local variability in ice flow direction. The p-forms indicate the presence of significant meltwater at the base of the glacier (Kor et al., 1991). Given the context and multiple lines of evidence for abrasion (striations) and meltwater (p-forms) pointing to an ice–bed interface origin for the complex geomorphology of the whaleback structure, the patchy diamictite is interpreted as a subglacial tillite. The dominance of sedimentary clasts deriving from the Ombombo Subgroup (Miller, 2008) is indicative of a local provenance for this diamictite, which on the basis of palaeo-ice flow directions derived from the geomorphological features was sourced from an outcrop to the east. Collectively, all of these observations are compatible with the regional

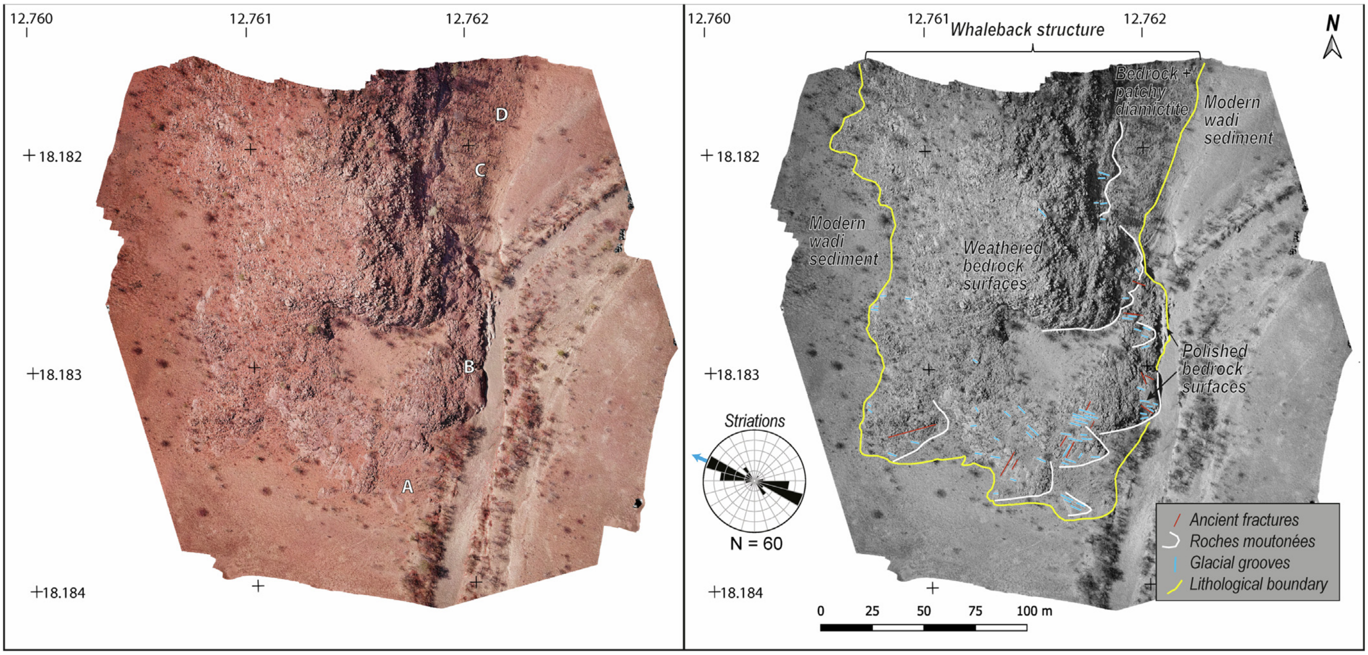

Fig. 2. Whaleback location, northern Namibia. Figure shows uninterpreted DEM-orthophoto composite on the left, and interpretation on the right. Note the wide areal extent of the whaleback structure on which the smaller scale subglacial bedforms (roches moutonnées, polished bedrock surfaces, glacial grooves/striations) are found. Letters A–D indicate the positions of features shown in Fig. 3.

Fig. 3. Field evidence for subglacial processes at the Whaleback locality. A: Roche moutonnée on the southernmost part of the outcrop. Ice flow from this perspective was from left to right. B: Striated contact on the eastern side of the whaleback structure. Ice flow from this perspective was from bottom right to top left. C: Diamictite plastered onto the striated surface, characterised by abundant rounded clasts. D: Fine-grained sandstone clast weathering out of the diamictite, revealing a streamlined form and multiple surface striations.

picture of a glacier flowing westward (Martin, 1981 and references therein; Dietrich et al., 2021).

3.2. Gomatum palaeo-fjord system in northern Namibia

3.2.1. Description

The Gomatum palaeovalley is one of several palaeo-fjord systems in northern Namibia, cut during the LPIA and then filled with fluvial, then shallow marine sediments, hence documenting the progressive transgression of glacial cut valleys (Dietrich et al., 2021). It has been long since known, on account of the existence of striated and polished bedrock at the palaeovalley margins, that the modern day valleys in northern Namibia are of subglacial origin (Martin and Schalk, 1953). According to Martin (1981), where “incised in resistant rocks of transverse ranges U-shaped valley forms can still be recognised”. In plan view, it is NW-oriented (Fig. 1A). Thus, our objective here is to (i) present geological maps of segments of the Gomatum palaeovalley (Fig. 4), and (ii) demonstrate the nature of the onlapping contact at the base of the Dwyka Group and its characteristics at outcrop (Fig. 5). At this locality, the contact is sharp but is typically concealed by basal Dwyka Group diamictite elsewhere in the Gomatum palaeovalley or alternatively covered by Quaternary slope sediment (see Fig. 4A). Nevertheless, in the western extremity of the palaeovalley this contact can be examined over a small area in detail. In this area, paragneiss constitutes the bedrock, and it displays excellent evidence for glacial polish directly comparable to that at the Okandjombo whaleback locality, together with p-forms and striations that crosscut gneissose banding (Fig. 5B, C). A few metres of diamictite can locally be found onlapping this surface, and where present contains numerous striated siltstone clasts (Fig. 5D). Geological mapping reveals that three stratigraphic units can be differentiated in our studied section of the Gomatum palaeovalley, namely basement, Dwyka Group and Quaternary strata (Fig. 4A). Although Quaternary alluvial fan deposits and fluvial deposits dominate the sedimentary record of the valley, several small outcrops of Dwyka Group can be observed at the southern flank of the valley (Fig. 4B). This allows the contact between the basement and the Dwyka Group to be investigated in detail. We selected one of these outcrops for detailed investigation, allowing us to present a detailed map that allows the basal Dwyka Group contact to be mapped at a high resolution onto UAV imagery. In this particular region, the lowermost Dwyka Group consists of recessive stratified diamictites bearing striated clasts, overlain by poorly exposed siltstones and sandstones and mantled by modern slope deposits. A 3D model of this same area (Fig. 5A) shows (i) the steep and irregular nature of the contact at the valley flanks and (ii) the contrast between steeply dipping basement strata and shallow-dipping deposits of the Dwyka Group directly above.

3.2.2. Interpretation

In the Gomatum palaeovalley, a thick veneer of Quaternary sediments is interpreted to explain the rarity of large subglacial bedforms in spite of excellent local evidence for striations, polished surfaces and diamictites. In modern fjords of West Greenland, thick glaciomarine basin fills are characteristic that comprise interbedded diamictons and fine-grained marine sediments (Ó Cofaigh et al., 2016). By analogy, we interpret the poorly exposed siltstones and sandstones of the Dwyka Group at the southern margin of the Gomatum palaeovalley as fjordal glaciomarine, recognising that the well-defined, crossbedded fluvial deposits observed elsewhere in the fjord system that occur above the basal diamictite (Dietrich et al., 2021) are absent at this location. To determine which interpretation is correct, further textural work including fabric analysis would be required. The absence of fluvial deposits at this level, above the basal diamictite, implies either that our study section occupied a position above the river tract prior to transgression, or alternatively that the fluvial deposits (Dietrich et al., 2021) were reworked during the transgression in the process of glaciated river valley to fjord transformation. In terms of the geomorphology of the palaeovalley that cradles the Dwyka Group, an overarching interpretation is proposed that incorporates elements of subglacial erosion via plucking and meltwater activity. At the local scale, our detailed large-scale map and the accompanying 3D model image (Figs. 4, 5) illustrate a highly irregular palaeotopography beneath the Dwyka Group that contrasts greatly with the smooth, streamlined surfaces observed at the Whaleback locality. We attribute this to the different mechanical properties of the folded basement metasediments within the Gomatum palaeovalley proper, typical of a fjord wall.

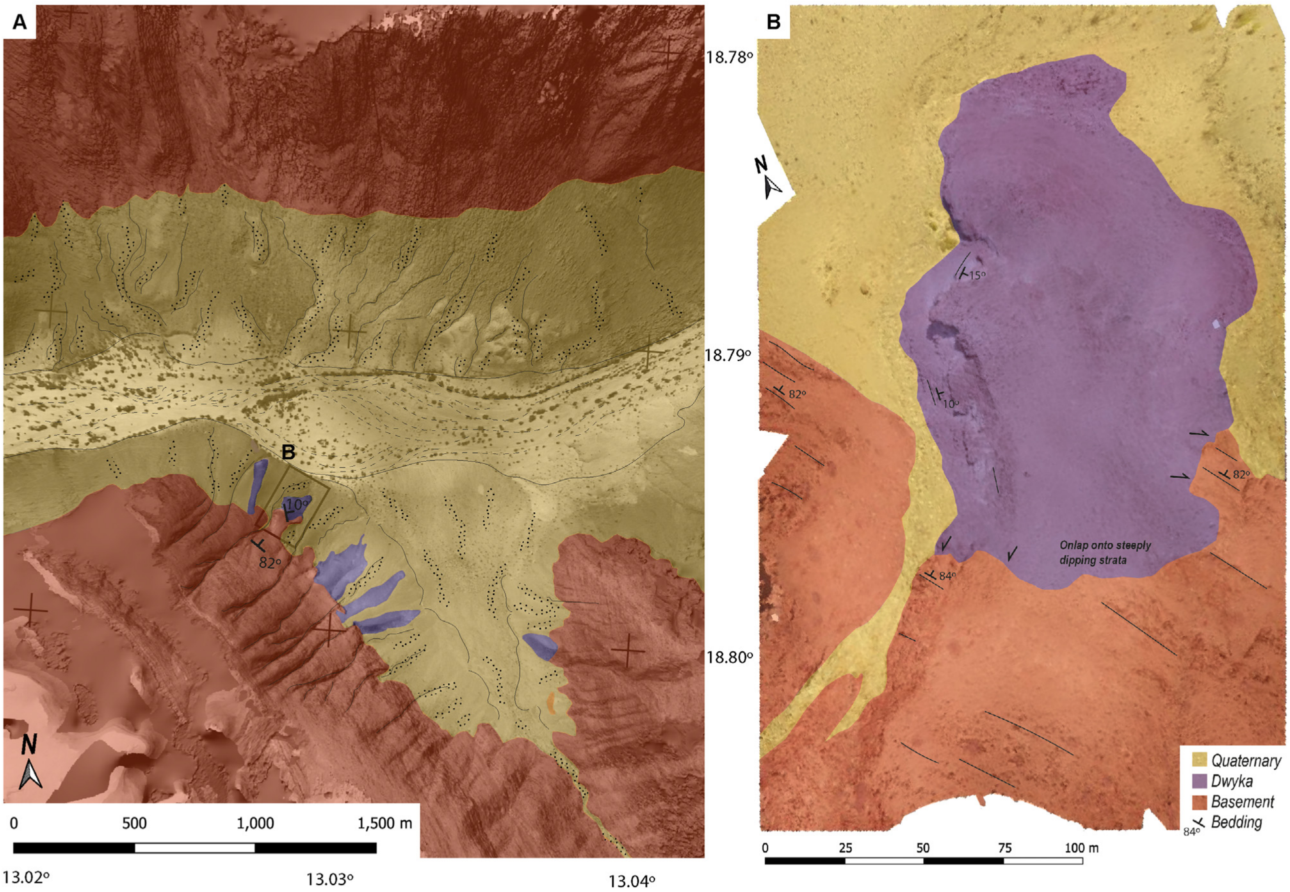

Fig. 4. A: Maps of part of the Gomatum palaeo-fjord system. Small scale geological map, produced using a hybrid DEM-Orthophoto as a base map. B: Large scale geological map, zooming into a small area in map A. Note the stratigraphic contact between the Dwyka and the underlying basement.

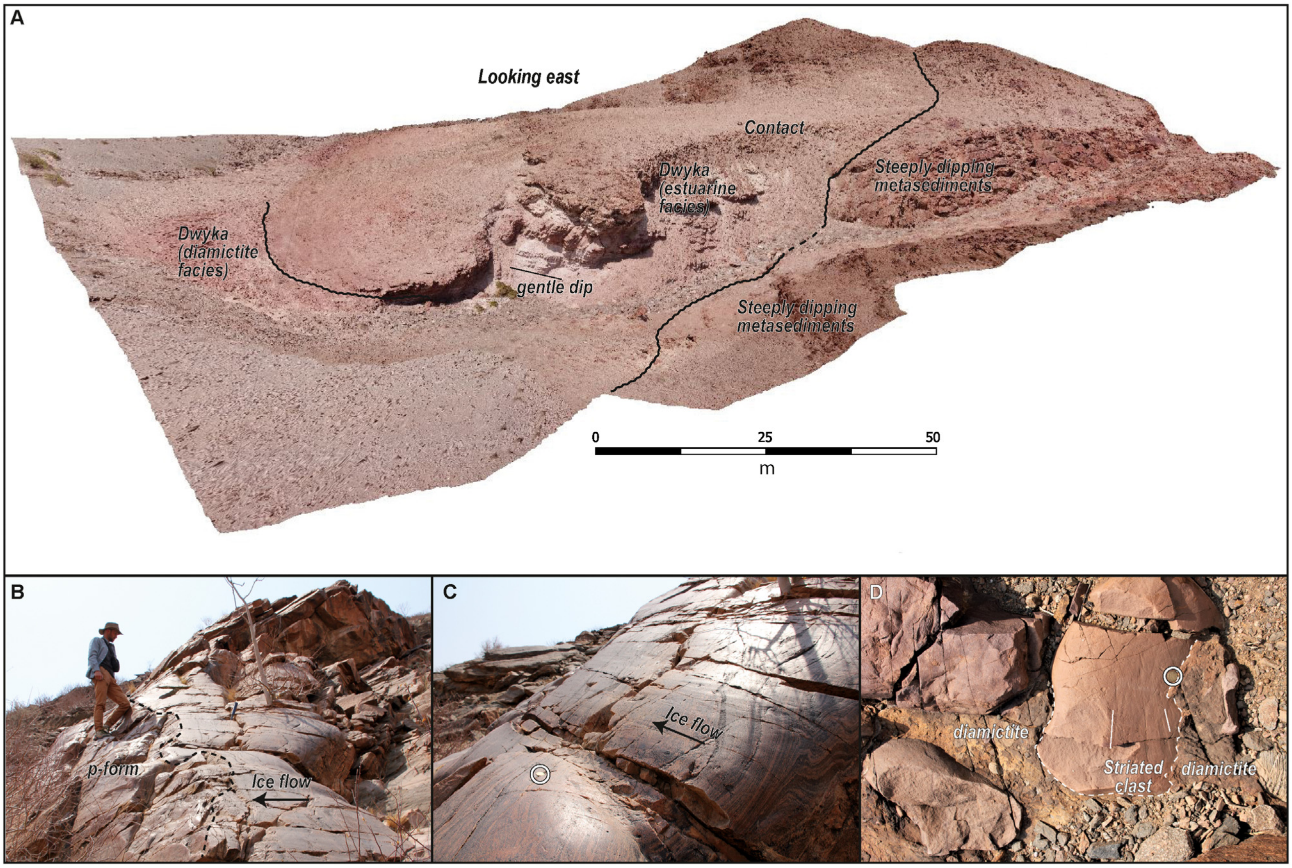

Fig. 5. The Gomatum palaeo-fjord system in northern Namibia, showing the contact between the subglacial substrate (Precambrian metasediments) and the basal Dwyka diamictite. A: Perspective view of the 3D model derived from drone data and used for geological mapping (as shown in B), emphasising the angular nature of the basal contact representing the palaeo-fjord margin. B: Detail of the sub-Dwyka polished surface at the western end of the Gomatum palaeovalley, revealing a p-form with interpreted ice flow direction also shown. C: Detail of the stoss slope of the p-form, with a coin circled for scale, revealing a glacial polish on the surface and striations crosscutting the foliations in the paragneiss bedrock. D: Relationship between a striated siltstone clast and its host diamictite directly above the surface shown in B and C. See Fig. 1 for all locations.

3.3. Fish River basal topography

3.3.1. Description

The Fish River section is characterised by a relatively low profile, tableland landscape, consisting of horizontal Cambrian sandstones at the river bank and diamictites of the Dwyka Group lying disconformably above. At this locality, the contact is well exposed together with the basal diamictites of the Dwyka Group. Previously, the orientation of striations on clasts within the diamictites was measured by Le Heron et al. (2022a), whereby a predominant NW–SE strike was apparent. We surveyed a dry, water-washed gully that exposes the upper surface of Cambrian sandstone immediately beneath the basal Dwyka Group diamictites (Fig. 6). In the gully, we recognise a series of bedrock grooves, up to 10 cm deep and 30 cm wide and spaced 0.5–1 m apart, that cut into Cambrian sandstones, and which disappear under the overlying recessive Dwyka Group diamictites. These grooves are commonly subparallel to one another, but show a range of orientations over the outcrop (Fig. 6). To our knowledge, these structures have not previously been reported from the Fish River area; they extend over at least 150 m within the gulley. These structures were not detected at ground level. We distinguish grooves from bedrock fractures in the Cambrian sandstones on the basis of crosscutting relationships.

3.3.2. Interpretation

Any interpretation of the Fish River sections must reconcile the contrasting NW–SE striation trend on clasts with the trend of bedrock grooves (Fig. 6). We interpret the bedrock grooves to have been produced by an overriding ice mass, for which two potential origins can be envisaged. In the first mechanism, the grooves could correspond to a true subglacial pavement/subglacial substrate, whereby the grooves were incised through a combination of subglacial abrasion and meltwater activity in a manner akin to the complex subglacial assemblages at Whaleback. As an alternative, the grooves were cut beneath the keel of an iceberg that periodically grounded, or alternatively beneath a partially buoyant ice shelf. In support of the second interpretation, we point to the fact that there is evidence for highly oblique grooves on this surface that are difficult to explain under an ice mass coupled to its bed. In this manner, the apparent conflict between fabric data (the striation orientations) and geomorphological data (the bedrock groove orientations) could be resolved. However, given the abundance of deformation structures locally preserved in overlying sediments which collectively point to sustained subglacial shearing (Le Heron et al., 2022a; see also Melvin, 2019 for another detailed comparison), a true subglacial origin remains the most parsimonious interpretation. Thus, the apparent conflict in orientation between subglacial grooves and striations on overlying clasts in the diamictite can be explained through en masse rotation of material in the subglacial environment. This process could likely be achieved through the development of local decollement horizons in the deforming soft bed. Such processes have been well investigated from the Late Ordovician record (for example in Niger: Denis et al., 2010). Heterogeneities in the deforming subglacial bed, for example boulders or spatially and temporal changes from cold-based to warm-based conditions, might explain this rotation mechanism. In other words, a mosaic of “sticky spots” similar to those proposed by Piotrowski et al. (2004) may adequately resolve the apparent conflict of fabric data. Thus, at Fish River, although both bedrock grooves and striation orientations on clasts in overlying diamictites originate through the action of ice, it is proposed that they need to have originated during one continuous phase of subglacial erosion.

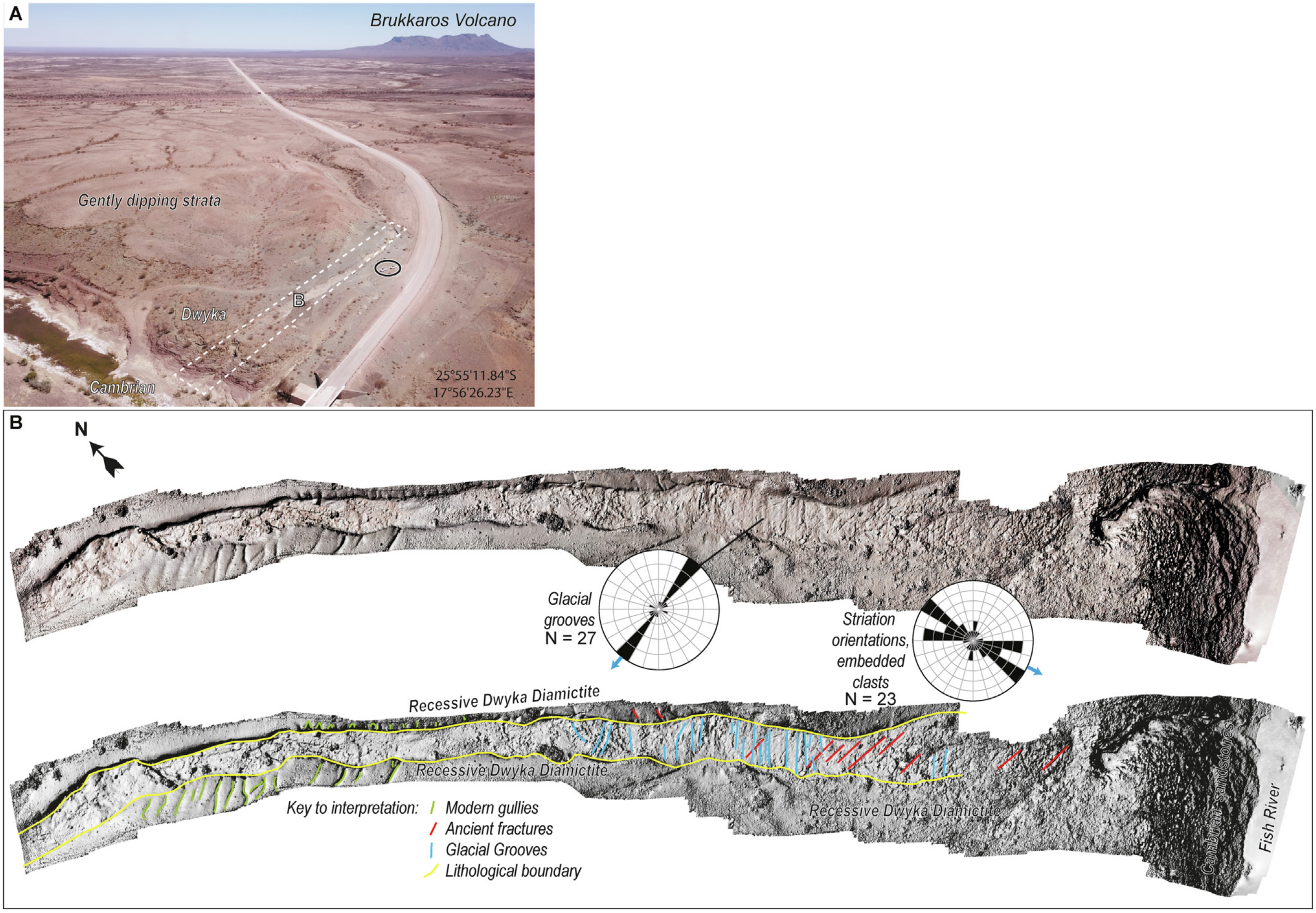

Fig. 6. The basal Dwyka palaeotopography in the vicinity of Fish River. A: Aerial view of the zone covered by detailed UAV imagery. B: Composite orthophoto-DEM image revealing the presence of bedrock grooves, interpreted as representing potential subglacial grooves. These structures are overlain by the basal Dwyka diamictite. Bedrock fractures, which are interpreted to be unrelated to the subglacial grooves, are shown in red. Note the contrasting and apparently conflicting directional data represented by the two rose diagrams: the orientation of striations measured from clast surfaces (Le Heron et al., 2022a) is almost orthogonal to the orientation of the interpreted glacial grooves.

3.4. Noordoewer

3.4.1. Description

At Noordoewer, on the Orange River at the South African border, the basal Dwyka Group section is exposed (Fig. 7A) together with an excellent contact with Cambrian sandstones. These deposits occur on both sides of the international border, but in this study only the Namibian section was examined. As summarised in Le Heron et al. (2022a), basal deposits of the Dwyka Group are characterised by dolostone-rich boulder conglomerates, and these deposits penetrate local fractures in the Cambrian sandstones. Consequently, these were suggested to record injection of subglacial materials into the substrate. The Dwyka Group onlaps and drapes the Cambrian sandstones, and is gently deformed (Fig. 7A). Owing to the high outcrop quality, an area was selected for detailed photogrammetry (Fig. 7B) from which a 3D model was built (Fig. 7C). The folding observed at outcrop is attributable to cone-in-cone structures developed within the boulder conglomerate (Fig. 7A, B). The stratigraphic interpretation of this section (Fig. 7B) shows that the boulder conglomerate is overlain by a diamictite, which is in turn capped by dropstone-bearing shale. The latter facies was previously noted to exhibit bedding planes bearing chisel-like structures interpreted to form through sea ice keels in shallow water (Le Heron et al., 2022a). In map view (Fig. 7D), we note the presence of both bedrock grooves on the surface of the boulder conglomerate that are concealed by the overlying diamictite. The long axes of the bedrock grooves (N = 32) show a consistent NE–SW orientation, whereas the long (A) axes of clasts in the overlying diamictites (N = 469) are mostly oriented NNW–SSE (Fig. 7D).

3.4.2. Interpretation

We interpret the bedrock grooves at Noordoewer as ancient structures that formed prior to the deposition of the overlying diamictite, as supported by the fact that the latter deposits conceal the grooves. This relationship is thus identical to be closely comparable to that found in the Fish River area. Le Heron et al. (2022a) proposed that the boulder conglomerate was emplaced subglacially with evidence for local sediment injection and hydrofracturing of bedrock. Therefore, these deposits were interpreted as a subglacial tillite. Taking the interpretation of the Fish River surface as precedent, we further interpret the bedrock grooves to have formed through the direct action of ice incising the freshly deposited tillite. The A-axes of the clasts in the overlying diamictite, with a well-developed NNW–SSE orientation, are interpreted to record their alignment parallel to the stress direction during the emplacement of a subaqueous debrite. We reject the possibility that this diamictite is a subglacial deposit on account of it lying directly above an undeformed shale.

4. Discussion

Compilation of all literature data from southern Namibia on palaeoflows related to LPIA glaciation, or deposition of the Dwyka Group more generally, paints a complex picture (Fig. 8). The key

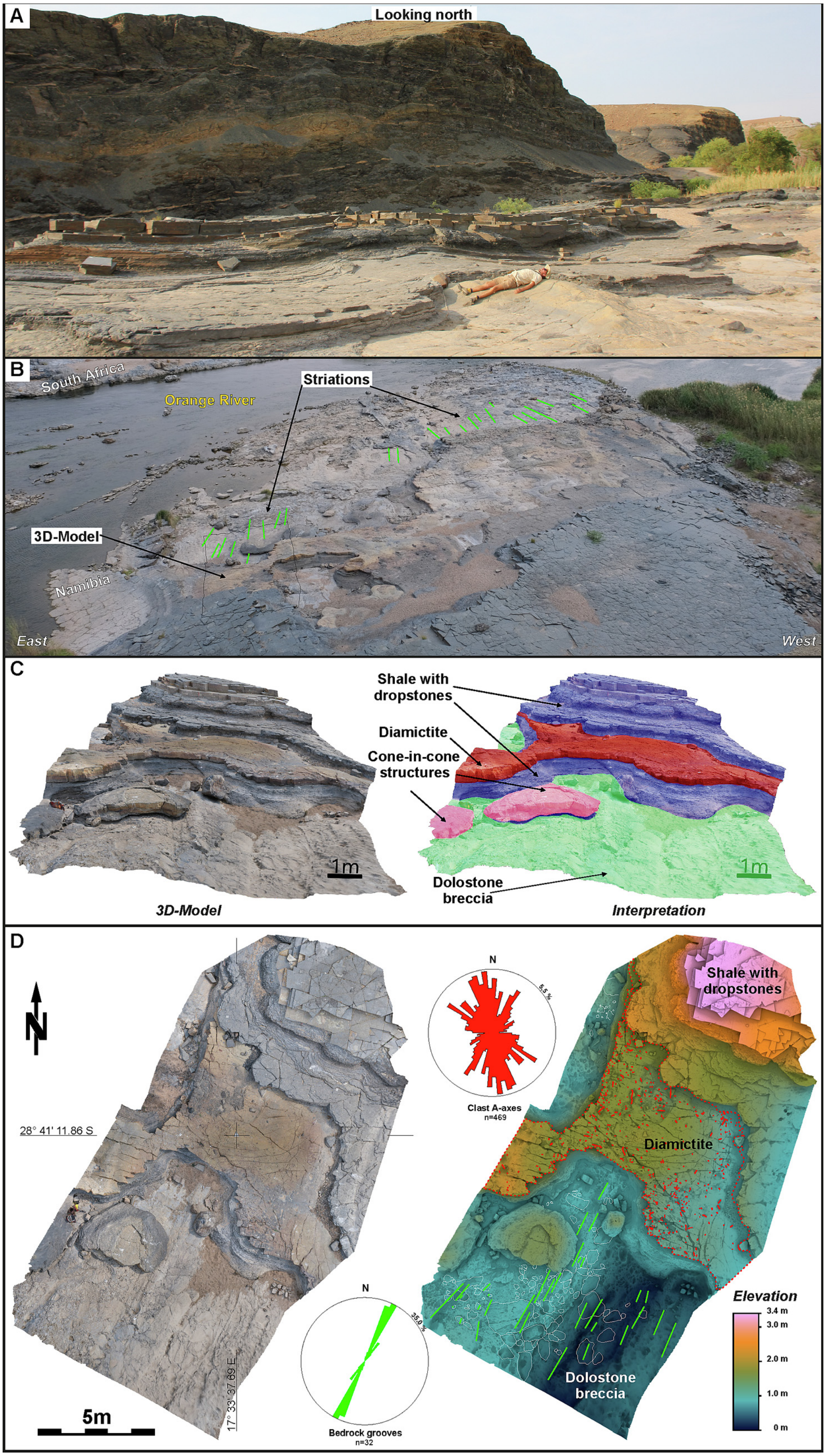

Fig. 7. The basal Dwyka palaeotopography at Nordoewer along the Orange River at the border with South Africa. A: General photograph showing the nature of the outcrop and the presence of low amplitude fold-like structures. B: Map view photomosaic constructed from ground-level photogrammetry. Note that the fold-like structures are onlapped by overlying dropstone-bearing shales (see Le Heron et al., 2022a for detailed sedimentological description) and are thus interpreted to have formed prior to the deposition of the latter deposits. Accordingly, and by direct analogy to comparable structures in a comparable context at Fish River, we interpret them as potential subglacial grooves.

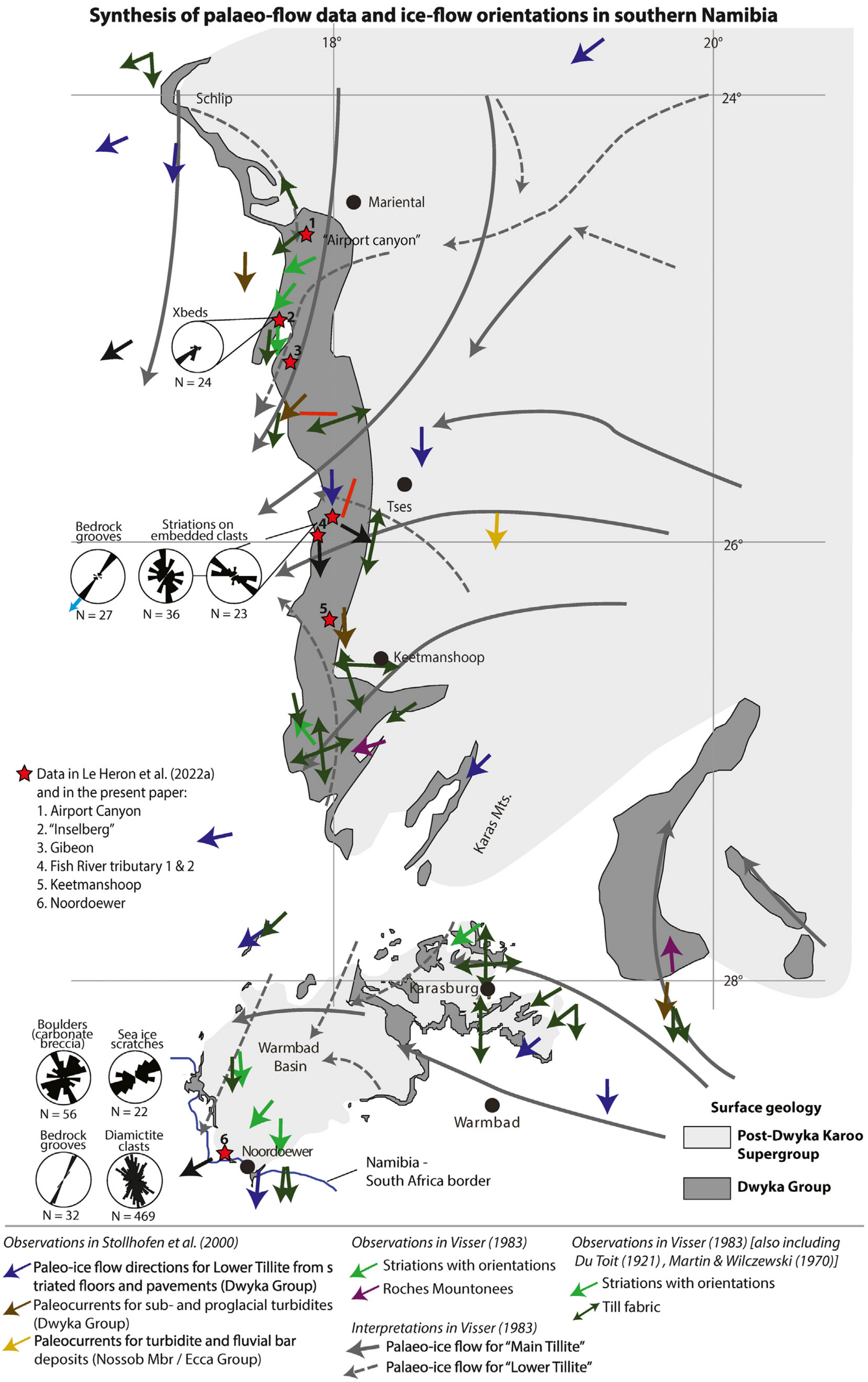

Fig. 8. Compilation of datasets and ice flow interpretation directions in southern Namibia from the literature, including our recent work (Le Heron et al., 2022a) together with the new data herein (glacial grooves in Noordoewer and Fish River). Literature compilation data from the following sources: Du Toit (1921), Martin and Wilczewski (1970), Visser (1983) and Stollhofen et al. (2000).

question, therefore, is: which line of evidence represents the most reliable palaeo-ice flow indicator? We have used the southern Namibian sections to illustrate this point owing to the wealth of data coverage in contrast to northern Namibia. The issue transcends local interpretation of the LPIA record and applies to deep-time glacial reconstructions in general. We argue that the issue of multiple advances and multiple flow directions can only be adequately resolved by relying on one data source, which should ideally derive from geomorphological phenomena (striations, p-forms, bedrock grooves, roche moutonnées, whalebacks, glacial valleys). Rather, sedimentological measurements (striations on clasts, fabric measurements etc.) should be regarded as a secondary (supporting) source given (i) the evidence that multiple intersecting striation orientations are known to exist from striation measurements in diamictites (Le Heron et al., 2022a), (ii) the rotation of sediment in the subglacial deforming bed can be expected (as argued herein from Fish River), and thus (iii) the geomorphological evidence is the most reliable source of evidence on palaeo-ice flow. Even in the Quaternary record, such as that of the Laurentide Ice Sheet, potentially conflicting ice flow orientations are common but these can often be resolved with concerted efforts to improve geochronology with cosmogenic nuclide dating (Rice et al., 2019). This option is not available in Palaeozoic studies, and hence a different approach is required.

We therefore promote this as a best practice in the deep time record, an approach already embraced in studies of the LPIA in Brazil. There, da Rosa et al. (2016) recognised striated pavements, ice keel scour marks, and features classified as subglacial landforms both on soft beds (flutes) as well as on rigid substrates (roches moutonnées) in São Paulo and Santa Caterina states. These workers also concluded that the roches moutonnées were the best indicators of palaeo-ice flow direction not least because ice keel scour marks record the passage of drifting ice. In the southern Namibia data, the Nordoewer sections (Fig. 8) offer no less than four independent datasets that could be used to inform palaeocurrent interpretations. Herein, we have revealed the presence of bedrock grooves beneath the Dwyka and have presented clast orientation data for a diamictite interval (Fig. 7). Both of these contrast with chisel-like structures that Le Heron et al. (2022a) interpreted through the action of sea ice. Drifting blocks of sea ice are known to collide with each other when they are blown by the wind, forming pressure ridges, and these may develop significant relief that scour the sea floor to a depth of about 50 m (Héquette et al., 1995), as well as the orientation of boulders in the basal carbonate breccia (Fig. 8). Of all of these, for the reasons highlighted above, the bedrock grooves are regarded as the most reliable, and whose mapping has been possible using photogrammetric methods.

Mapping of the whaleback structure northwest of Okandjombo has revealed a hierarchy of subglacial bedforms of different scales. Of these, the whaleback structure is the largest, hosting superimposed roches moutonnées, onto which p-forms and striations are superimposed. The superimposition of these structures allows questions to be raised about subglacial conditions. For the southern part of the Parana Basin in Uruguay, Isbell et al. (2023) were able to offer a first order reconstruction of ice thickness, using the logic that whalebacks typically evolve under significant depths of ice in the interior of an ice sheet. Their presence records warm-based conditions but high confining pressures (Sugden et al., 2005), which inhibit asymmetrical development (i.e. no clearly differentiated stoss and lee slopes). They contrasted this with the presence of roches moutonnées, argued to form under ice of reduced thickness and typically towards the margins of ice sheets, thus using these spatial relationships to build up a palaeo-glaciological reconstruction for the LPIA of Uruguay. Applying this approach to the Okandjombo structures, it could be argued that the geomorphology also represents a time-transgressive evolution of the subglacial environment whereby (i) the whaleback structure formed under greatest ice thickness followed by (ii) the roches moutonnées, p-forms and striations evolving subsequently in concert with thinning ice cover.

Elsewhere, concerted efforts have been made over the last 15 years to investigate the glacial geomorphology associated with the LPIA in different parts of Gondwana recognising the unique perspective into ice dynamics. In this context, the paper by Bussert (2010) focussing on the glacial landsurface in Ethiopia can be regarded as a benchmark contribution, where care was taken to differentiate a variety of complex subglacial bedforms (with increasing scale: striae, grooves, crescentic gouges and lunate fractures, chatter marks, Muschelbrüche, roches moutonnées, whalebacks and rock drumlins, rock basins and troughs). Orientations of these structures were also measured wherever possible and incorporated into a synoptic model that also accounted for the influence of heterogeneity (orientation of foliation/folds) in the subglacial substrate. This work did not incorporate aerial photographs but was a major step forward, not least because previous work had only reported striations and roches moutonnées (Beyth, 1972), as opposed to the full range of structures which were used to interpret a palaeo-landscape sculpted largely by abrasion and secondarily by quarrying, with a wet-based and initially thick continental ice sheet or lobe proposed (Bussert, 2010). The photogrammetric approach holds much promise for these study sites: as demonstrated here in Namibia, in addition to excellent evidence that can be observed at ground level, a bird's eye view reveals previously unrecognised grooves and bedforms whose interpretation throws clearer light on ice dynamics and the temporal evolution of the subglacial environment. Le Heron et al. (2022b) proposed that UAV photogrammetry plays a role in bridging traditional ground level interpretations with satellite image interpretation. The spectacular LPIA subglacial landscape at the southern part of the Parana Basin in Uruguay, as described by Assine et al. (2018) would benefit from this approach. It is also possible that a photogrammetric approach would yield still greater detail on palaeo-fjord geomorphology of mid-Carboniferous age in central Argentina: Valdez Buso et al. (2021) presented high quality DEMs and cross-valley profiles to a resolution of 12.5 m from ALOS-PALSAR (satellite) data. Producing profiles across three palaeovalleys, they also identified a “possible drumlin”, which owing to the arid conditions and excellent outcrop conditions would lend these landforms to furthering the testing of this hypothesis via photogrammetry.

In summary, a photogrammetric approach incorporating both UAV data collection and ground-based data collection sheds new light on various aspects of the glacial geomorphology of the LPIA in Namibia. This has included aspects of the genesis of complex subglacial bedforms of different orders of magnitudes, resolving crosscutting relationships, and some recommendations for resolving the apparent conflict (Stratten, 1977) between ice flow indicators based on geomorphological data and sedimentological data. In particular, it has generated critical new data with which palaeo-ice flow directions can be determined, providing geomorphological data of high confidence that would not otherwise be available with traditional sedimentological fieldwork techniques. We recommend that the geomorphological data should be used in preference, wherever possible, for ice flow reconstructions, even if the ice flow direction that is measured represents a local flow direction. This is because shear in the subglacial deforming bed, where present, may rotate clast fabrics *en masse* to produce a shear fabric that appears to be inconsistent with the geomorphological evidence. Obviously, in the absence of geomorphological data, the sedimentological fabrics could then be used *in lieu*, with the caveat that these are a less reliable ice flow proxy.

5. Conclusions

In this study, we have shown that photogrammetric data, including data derived from a UAV together with a camera at ground level, permit new understanding into the behaviour of LPIA glaciers through detailed insight into the character of the former subglacial substrate. These insights include: (i) illuminating the geometry of the margins of a palaeo-fjord (Gomatum), (ii) the relationship between roches moutonnées, p-forms, striations and the host whaleback structure (Okandjombo), (iii) the relationship between subglacial grooves and overlying diamictites (Fish River) and (iv) the demonstration that subglacial grooves occur on top of basal diamictite (Noordoewer, Orange River). Building on the tradition of focussed palaeo-geomorphological work in the LPIA record in South America (Da Rosa et al., 2016; Assine et al., 2018; Fallgatter and Paim, 2019; Isbell et al., 2023), we recommend that existing palaeo-ice flow reconstructions should be reappraised in the case of the southern Namibia sections. This is because of the issue of apparently conflicting ice flow reconstructions coming from different authors, meaning that the precise nature of the proxy (cross-bedding, striations, clast fabrics) should be critically appraised in each case. We recommend that the geomorphological datasets (bedrock striations, grooves, and other subglacial landforms) should be used in preference to sedimentological proxies for this reason.

CRediT authorship contribution statement

D.P. Le Heron: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Writing – original draft, Writing – review & editing. **C. Kettler:** Investigation, Methodology, Visualization. **P. Dietrich:** Funding acquisition, Investigation. **N. Griffis:** Investigation. **I.P. Montañez:** Investigation. **R. Wohlschlägl:** Investigation, Visualization.

Data availability

None of the options in the drop down list apply. This is field geology, the data are contained within

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Assine, M.L., de Santa Ana, H., Veroslavsky, G., Vesely, F.F., 2018. Exhumed subglacial landscape in Uruguay: erosional landforms, depositional environments, and paleo-ice flow in the context of the late Paleozoic Gondwanan glaciation. Sedimentary Geology 369, 1–12.

Beyth, M., 1972. To the Geology of Central-western Tigre. Rheinische Friedrichs-Wilhelms-Universität Bonn, Bonn (Dissertation).

Boulton, G.S., Hindmarsh, R.C.A., 1987. Sediment deformation beneath glaciers: rheology and sedimentological consequences. Journal of Geophysical Research 92 (B9), 9059–9082.

Bussert, R., 2010. Exhumed erosional landforms of the Late Palaeozoic glaciation in northern Ethiopia: indicators of ice-flow direction, palaeolandscape and regional ice dynamics. Gondwana Research 18, 356–369.

Catuneanu, O., Wopfner, H., Eriksson, P.G., Cairncross, B., Rubidge, B.S., Smith, R.M.H., Hancox, P.J., 2005. The Karoo basins of south-central Africa. Journal of African Earth Sciences 43, 211–253.

Da Rosa, E.L.M., Vesely, F.F., França, A.N., 2016. A review on late Paleozoic ice-related erosional landforms in the Paraná Basin: origin and paleogeographical implications. Brazilian Journal of Geology 46, 147–166. https://doi.org/10.1590/2317-4889201620160050.

Dahl, R., 1965. Plastically sculptured detail forms on rock surfaces in northern Nordland, Norway. Geografiska Annaler. Series A, Physical Geography 47, 83–140. https://doi.org/10.1080/04353676.1965.11879716.

Denis, M., Guiraud, M., Konaté, M., Buoncristiani, J.F., 2010. Subglacial deformation and water-pressure cycles as a key for understanding ice stream dynamics: evidence from the Late Ordovician succession of the Djado Basin (Niger). International Journal of Earth Sciences 99, 1399–1425.

Dietrich, P., Griffis, N.P., Le Heron, D.P., Montañez, I.P., Kettler, C., Robin, C., Guillocheau, F., 2021. Fjord network in Namibia: a snapshot into the dynamics of the Late Paleozoic glaciation. Geology 49, 1521–1526. https://doi.org/10.1130/G49067.1.

Dietrich, P., Guillocheau, F., Douillet, G., Griffis, N.P., Le Heron, D.P., Montañez, I.P., Barrier, L., Robin, C., Kettler, C., Hofmann, A., in review. The ancestral landscapes of southern African cratons: the legacy of glacial erosion.

Du Toit, A.L., 1921. The Carboniferous glaciation of South Africa. South African Journal of Geology 24, 188–227.

Evans, I.S., 1996. Abraded rock landforms (whalebacks) developed under ice streams in mountain areas. Annals of Glaciology 22, 9–16.

Evans, D.J.A., Benn, D.I., 2021. A Practical Guide to the Study of Glacial Sediments. Second edition. Quaternary Research Association (373 pp.).

Fallgatter, C., Paim, P.S.G., 2019. On the origin of the Itararé Group basal nonconformity and its implications for the Late Paleozoic glaciation in the Paraná Basin, Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology 531, 108225.

Griffis, N.P., Montañez, I.P., Mundil, R., Richey, R., Isbell, J., Fedorchuk, N., Linol, B., Iannuzzi, R., Vesely, F., Mottin, T., da Rosa, E., Keller, B., Yin, Q.-Z., 2019a. Coupled stratigraphic and U–Pb zircon age constraints on the late Paleozoic icehouse-to-greenhouse turnover in south-central Gondwana. Geology 47, 1146–1150.

Griffis, N.P., Montañez, I.P., Fedorchuk, N., Isbell, J., Mundil, R., Vesely, F., Weinshultz, L., Iannuzzi, R., Gulbranson, E., Taboada, A., Pagani, A., Sanborn, M.E., Huyskens, M., Wimpenny, J., Linol, B., Yin, Q.Z., 2019b. Isotopes to ice: constraining provenance of glacial deposits and ice centers in west-central Gondwana. Palaeogeography, Palaeoclimatology, Palaeoecology 531, 108745.

Griffis, N.P., Montañez, I.P., Mundil, R., Le Heron, D.P., Dietrich, P., Kettler, C., Linol, B., Mottin, T., Vesely, F., Iannuzzi, R., Huyskens, M., Yin, Q.-Z., 2021. High-latitude ice and climate control on sediment supply across the late Carboniferous and early Permian of SW Gondwana. GSA Bulletin 133, 2113–2124. https://doi.org/10.1130/B35852.1.

Héquette, A., Desrosiers, M., Barnes, P.W., 1995. Sea ice scouring on the inner shelf of the southeastern Canadian Beaufort Sea. Marine Geology 128, 201–219.

Isbell, J.L., Henry, L.C., Gulbranson, E.L., Limarino, C.O., Fraiser, M.L., Koch, Z.J., Ciccioli, P.L., Dineen, A.A., 2012. Glacial paradoxes during the late Paleozoic ice age: evaluating the equilibrium line altitude as a control on glaciation. Gondwana Research 22, 1–19.

Isbell, J.L., Fedorchuk, N.D., Rosa, E.L.M., Goso, C., Alonso-Muruaga, P.J., 2023. Reassessing a glacial landscape developed during terminal glaciation of the Late Paleozoic Ice Age in Uruguay. Sedimentary Geology 451, 106399.

Kor, P.S.G., Shaw, J., Sharpe, D.R., 1991. Erosion of bedrock by subglacial meltwater, Georgian Bay, Ontario: a regional view. Canadian Journal of Earth Sciences 28, 623–642. https://doi.org/10.1139/e91054.

Le Heron, D.P., Vandyk, T.M., Kuang, H., Liu, Y., Chen, X., Wang, Y., Yang, Z., Scharfenberg, L., Davies, B., Shields, G., 2019. Bird's-eye view of an Ediacaran subglacial landscape. Geology 47, 705–709. https://doi.org/10.1130/G46285.1.

Le Heron, D.P., Kettler, C., Griffis, N.P., Dietrich, P., Montanez, I.P., Osleger, D.A., Hofmann, A., Douillet, G., Mundhil, R., 2022a. The Late Palaeozoic Ice Age unconformity in southern Namibia viewed as a patchwork mosaic. The Depositional Record 8, 419–435. https://doi.org/10.1002/dep2.163.

Le Heron, D.P., Busfield, M.E., Chen, X., Corkeron, M., Davies, B.J., Dietrich, P., Ghienne, J.-F., Kettler, C., Scharfenberg, L., Vandyk, T.M., Wohlschlägl, R., 2022b. New perspectives on glacial geomorphology in Earth's deep time record. Frontiers in Earth Science 10, 870359. https://doi.org/10.3389/feart.2022.870359.

Lomas, J., Molengraaff, G.N., Penck, A., Hobson, B., Beck, P.R., Anderson, W., Coleman, A.P., Katzenstein, F.G., Davis, W.M., 1905. Permian glaciation in South Africa. Science 22 (563), 475.

Martin, H., 1961. The hypothesis of continental drift in the light of recent advances of geological knowledge in Brazil and in South West Africa. A. L. du Toit, Memorial Lectures, No. 7, Geological Society of South Africa vol. 64, p. 47.

Martin, H., 1981. The Late Paleozoic Dwyka Group of the South Kalahari Basin in Namibia and Botswana and the subglacial valleys of the Kaokoveld in Namibia. In: Hambrey, M.J., Harland, W.B. (Eds.), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, New York, NY, pp. 61–66.

Martin, H., Schalk, K., 1953. Gletscherschliffe an der Wand eines U-Tales im Nördlichen Kaokofeld, Südwestafrika. Geologische Rundschau 46, 571–575.

Martin, H., Wilczewski, N., 1970. Palaeoecology, conditions of deposition and the palaeogeography of the marine dwyka beds of South West Africa. In: Haughton, S.H. (Ed.), Proceedings Papers of the 2nd Gondwana Symposium, Pretoria, pp. 225–232.

Melvin, J., 2019. Zarqa megafacies: widespread subglacial deformation in the Sarah formation of Saudi Arabia and implications for the sequence stratigraphy of the Hirnantian glaciation. In: Le Heron, D.P., Hogan, K.A., Phillips, E.R., Huuse, M., Busfield, M.E., Graham, A.G.C. (Eds.), Glaciated Margins: The Sedimentary and Geophysical Archive. Geological Society, London, Special Publications vol. 475, pp. 53–80.

Miller, R.M.G., 2008. The Geology of Namibia, Volume III: Upper Palaeozoic to Cenozoic. Ministry of Mines and Energy, Geological Survey, Windhoek, Namibia 0869767348.

Montañez, I.P., Poulson, C.J., 2013. The late Paleozoic ice age: an evolving paradigm. Annual Review of Earth and Planetary Sciences 41, 629–656.

Ó Cofaigh, C., Hogan, K.A., Dowdeswell, J.A., Strueff, K., 2016. Stratified glacimarine basin-fills in West Greenland fjords. In: Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K., Hogan, K.A. (Eds.), Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient. Geological Society of London Memoirs vol. 46, pp. 99–100.

Piotrowski, J.A., Larsen, N.K., Junge, F.W., 2004. Reflections on soft subglacial beds as a mosaic of deforming and stable spots. Quaternary Science Reviews 23, 993–1000.

Rice, J.M., Ross, M., Paulen, R.C., Kelley, S.E., Briner, J.P., Neudorf, C.M., Lian, O.B., 2019. Refining the ice flow chronology and subglacial dynamics across the migrating Labrador Divide of the Laurentide Ice Sheet with age constraints on deglaciation. Journal of Quaternary Science 34, 519–535.

Stollhofen, H., Stanistreet, I.G., Bangert, B., Grill, H., 2000. Tuffs, tectonism and glacially related sea-level changes, Carboniferous–Permian, southern Namibia. Palaeogeography, Palaeoclimatology, Palaeoecology 161, 127–150.

Stollhofen, H., Werner, M., Stanistreet, I.G., Armstrong, R.A., 2008. Single-zircon U–Pb dating of Carboniferous–Permian tuffs, Namibia, and the intercontinental deglaciation cycle framework. In: Fielding, C.R., Frank, T.D., Isbell, J.L. (Eds.), Resolving the Late Paleozoic Ice Age in Time and Space. Geological Society of America Special Paper vol. 441, pp. 83–96.

Stratten, T., 1967. A preliminary report on a directional study of the Dwyka Tillites in the Karroo Basin of South Africa. Gondwana Stratigraphy, IUGS Symposium Buenos Aires. UNESCO, pp. 741–761.

Stratten, T., 1977. Conflicting directions of Dwyka ice flow in the Western Cape Province and southern south west Africa. Geological Society of South Africa Transactions 80, 79–86.

Sugden, D.E., Balco, G., Cowdery, S.G., Stone, J.O., Sass III, L.C., 2005. Selective glacial erosion and weathering zones in the coastal mountains of Marie Byrd Land, Antarctica. Geomorphology 67, 317–334.

Sutherland, P.C., 1870. Notes on an ancient boulder-clay of Natal. Quarterly Journal of the Geological Society of London 26, 514–517.

Trosdtorf, I., Rocha-Campos, A.C., dos Santos, P.R., Tomio, A., 2005. Origin of late Paleozoic, multiple, glacially striated surfaces in northern Paraná Basin (Brazil): some implications for the dynamics of the Paraná glacial lobe. Sedimentary Geology 181, 59–71. https://doi.org/10.1016/j.sedgeo.2005.07.006.

Valdez Buso, V., Milana, J.P., DiPasquo, M., Espinoza Aburto, J., 2021. The glacial paleovalley of Vichigasta: paleogeomorphological and sedimentological evidence for a large continental ice-sheet for the mid-Carboniferous over central Argentina. Journal of South American Earth Sciences 106, 103066. https://doi.org/10.1016/j.jsames.2020.103066.

Vesely, F.F., Assine, M.L., 2014. Ice-keel scour marks in the geological record: evidence from Carboniferous soft-sediment striated surfaces in the Paraná Basin, southern Brazil. Journal of Sedimentary Research 84, 26–39. https://doi.org/10.2110/jsr.2014.4.

Visser, J.N.J., 1983. An analysis of the Permo-Carboniferous glaciation in the marine Kalahari Basin, southern Africa. Palaeogeography, Palaeoclimatology, Palaeoecology 44, 295–315.

Visser, J.N.J., 1997. Deglaciation sequences in the Permo-Carboniferous Karoo and Kalahari basins of southern Africa: a tool in the analysis of cyclic glaciomarine basin fills. Sedimentology 44, 507–521.

Werner, M., 2006. The Stratigraphy, Sedimentology, and Age of the Late Palaeozoic Mesosaurus Inland Sea, SW Gondwana — New Implications From Studies on Sediments and Altered Pyroclastic Layers of the Dwyka and Ecca Group (Lower Karoo Supergroup) in Southern Namibia. University of Würzburg, Würzburg (PhD thesis, 425 pp.).

Zieger, J., Rothe, J., Hofmann, M., Gärtner, A., Linnemann, U., 2019. The Permo-Carboniferous Dwyka Group of the Aranos Basin (Namibia) — how detrital zircons help understanding sedimentary recycling during a major glaciation. Journal of African Earth Sciences 158, 103555.