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Scratching the surface: Footprint of a late Carboniferous ice sheet

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ABSTRACT

Field observations in conjunction with aerial images from an unmanned aerial vehicle were used to create the first map of a glacial unconformity underlying the late Carboniferous Dwyka Group of South Africa. Crosscutting relationships reveal that the glacial unconformity at Oorlogskloof, in which flutes, grooves, and striae were ploughed into unconsolidated sand, formed in a three-phased process charting a periodic shift in the locus of subglacial erosion. The unconformity formed by a periodically decoupled ice sheet in a probable tidewater setting. This model contrasts with earlier views that the structures simply record progressive ice-margin liftoff during transgression, and they provide unique insight into the complex temporal development of a 300 Ma subglacial environment.

INTRODUCTION

Unconformities are increasingly understood as recording complex, evolving processes during basin evolution rather than simply stasis (Davies and Shillito, 2018). Where cut into soft sediments, glacial unconformities may record the degree of basal coupling or changes in ice-flow velocity (Le Heron et al., 2005; Vesely and Assine, 2014). So-called "soft-sediment striated surfaces" are extremely common in the glaciogenic Late Ordovician (Deynoux and Ghienne, 2004; Le Heron et al., 2005; Denis et al., 2010; Girard et al., 2015; Tofaif et al., 2019) and Carboniferous–Permian (Visser, 1987, 1990; Assine et al., 2018; Dietrich and Hofmann, 2019) records alike. Although widely used to inform regional ice-sheet flow models (Ghienne et al., 2007; Le Heron, 2018; Visser, 1997), subglacial features in soft sediment are prone to later deformation and fluidization (e.g., Le Heron et al., 2005). Careful analysis is therefore required to reveal their true origin (e.g., subglacial vs. iceberg keel generated; Woodworth-Lynas and Dowdeswell, 1994; Vesely and Assine, 2014).

In the Karoo Basin of South Africa, there has been a tradition of investigation of late Paleozoic ice age (LPIA) deposits of the Dwyka Group stretching back a century (Du Toit, 1921), with groundbreaking work on paleogeographic reconstructions and facies analysis in the 1980s and 1990s (Visser, 1983, 1987, 1989, 1990, 1997; Visser and Kingsley, 1982). New insights from satellite image interpretation (Le Heron, 2018; Andrews et al., 2019) together with a new wave of field work on LPIA strata (Vorster et al., 2016; Linol et al., 2016; Belica et al., 2017; Griffis et al., 2018; Dietrich and Hofmann, 2019) have sharpened the need to understand the subglacial unconformities, and the role of ice streaming and surging behaviors. In this study, we produced the first detailed map of a LPIA glacial unconformity from Oorlogskloof, Northern Cape Province, South Africa (Fig. 1), integrating data from an unmanned aerial vehicle (UAV) and field observations.

STUDY AREA AND GEOLOGIC BACKGROUND

The Oorlogskloof area lies at the present-day western flank of the Karoo Basin of South Africa (Fig. 1). The late Carboniferous–Permian Dwyka Group was deposited by oscillating, high-latitude ice masses (Visser, 1989), with up to 800-m-thick diamictites and interglacial mudstones accumulating during up to four glacial cycles in the basin depocenter (Visser, 1997). At the northeastern flanks, diamictites accumulated in a restricted glacial valley setting (Visser and Kingsley, 1982). In the eastern Karoo Basin, a complex, condensed signature records deglaciation punctuated by short-term stillstands and minor readvances (Dietrich and Hofmann, 2019). Such basin-margin localities record glacially striated pavements of two types: (1) hard-bedrock pavements, recording the direct abrasion of LPIA ice sheets onto hard bedrock material (Du Toit, 1954; Visser and Loock, 1988; Bussert, 2010), and (2) soft-sediment pavements (e.g., Visser, 1990). The latter pavements, on which we focus herein, were first described in Oorlogskloof and surrounding area by Rust (1963).

Precisely how the sub-Dwyka unconformity was cut remains unclear. Highly complex ice flows, including trunk glaciers, ice streams, and outlet glaciers (e.g., Visser and Kingsley, 1982; Visser, 1997), have been interpreted. Deep paleovalleys, some up to 160 km long, record differing depths of incision into underlying sedimentary rocks and basement granite and gneiss (Visser and Kingsley, 1982). Across the Karoo, glaciers are thought to have coalesced from ice centers initially located to the north, east, and south (Visser, 1987, 1989). Crucially, ice-margin disintegration models are strongly influenced by interpretation of the Oorlogskloof pavement in which a phase of ice-margin liftoff culminated in collapse and proglacial sedimentation (Visser, 1990).

METHODOLOGY

Combining traditional field work (photographs, descriptions, measurements) with UAV imagery, we mapped the unconformity beneath the Dwyka Formation in Oorlogskloof (Fig. 1) to document its geomorphology. Using a DJI Mavic Pro drone, high-resolution aerial photographs were obtained from multiple elevations (8–100 m) and stitched together in Agisoft Metashape software (www.agisoft.com). A digital elevation model (DEM) together with a mosaicked orthophoto were exported to QGIS

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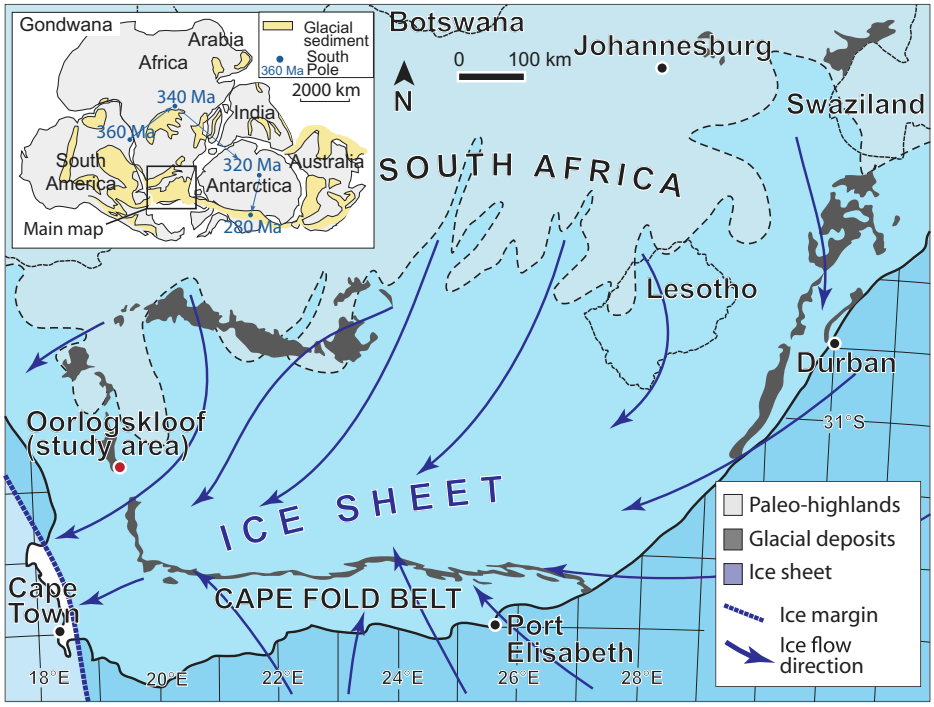

Figure 1. Paleogeographic map of South Africa during the late Paleozoic ice age, and outline of ice-sheet flow character, based on Visser (1997) and Lopez-Gamundi and Buatois (2010). Study area at Oorlogskloof is situated at the western margin of the Karoo Basin.

(www.qgis.com). Applying the methodology of Le Heron et al. (2019), a transparency algorithm was applied to the latter, allowing the two images to be combined and producing a composite aerial image. The resultant image, which served as the foundation for mapping (Fig. 2), enhances geological features that may be present on the orthophoto and absent on the DEM.

RESULTS

Description

The study section consists of medium- to coarse-grained sandstone and pebbly sandstone of the Silurian- to Devonian-aged Nardouw Subgroup (Table Mountain Group, Cape Supergroup; Thamm and Johnson, 2006), onto which series of glacially related landforms tied to the LPIA were cut. The surface dips gently east at 4°. Analysis of the composite aerial image (Fig. 2) demonstrated that the glacial landforms are spatially organized into three distinct packages (Figs. 3 and 4), and that these packages show crosscutting relationships.

Package 1 exposes two distinct sets of streamlined features, namely (1) flutes, and (2) grooves and striae. Both sets of features trend east-west to ESE-WNW (270 to N285; Fig. 3; see also Visser, 1990, his figure 6). Flutes are sharp-crested, 5–20-cm-amplitude, and 50-cm-wide features. Asymmetric in transverse profile, they exhibit steep (25°–40°) northward sides and less steeply dipping (10°–25°) southward sides. Miniature grain-flow lobes occur on southward slopes, downlapping the troughs between the flutes (Fig. 3B). Striations also occur on the surfaces of the flutes (Fig. 3B). Flutes are distributed into sets of one to five that lie on a planar striated and grooved surface also characterized by smaller-scale (a few millimeters to centimeters in amplitude) flutes. The flute sets, separated by the striated and grooved surface devoid of large flutes, thus define a lin-

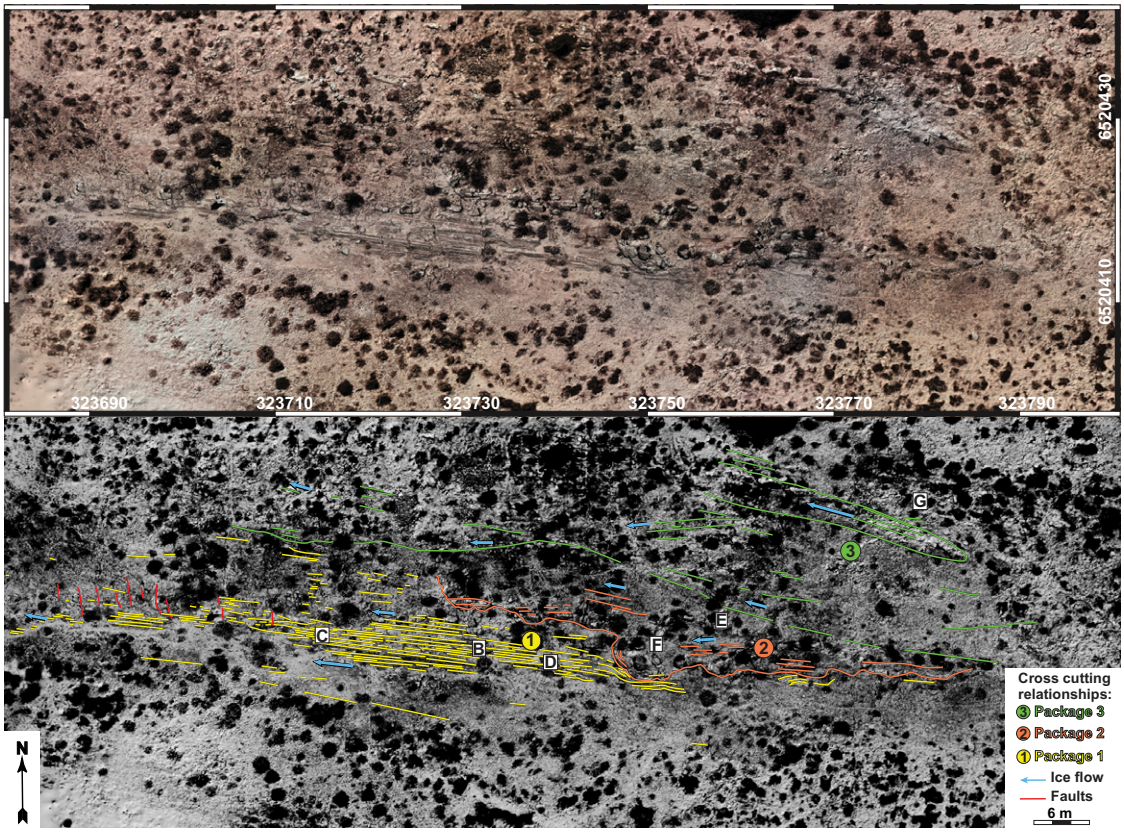

Figure 2. Composite aerial image and corresponding interpretation of Oorlogskloof glacial pavement (South Africa). Colors correspond to three different packages of subglacial bed form, which can be distinguished on the basis of slightly differing orientations at crosscutting relationships. Color-coding also corresponds to Figures 3 and 4. Locations of photos B–G shown in Figure 3 are indicated.

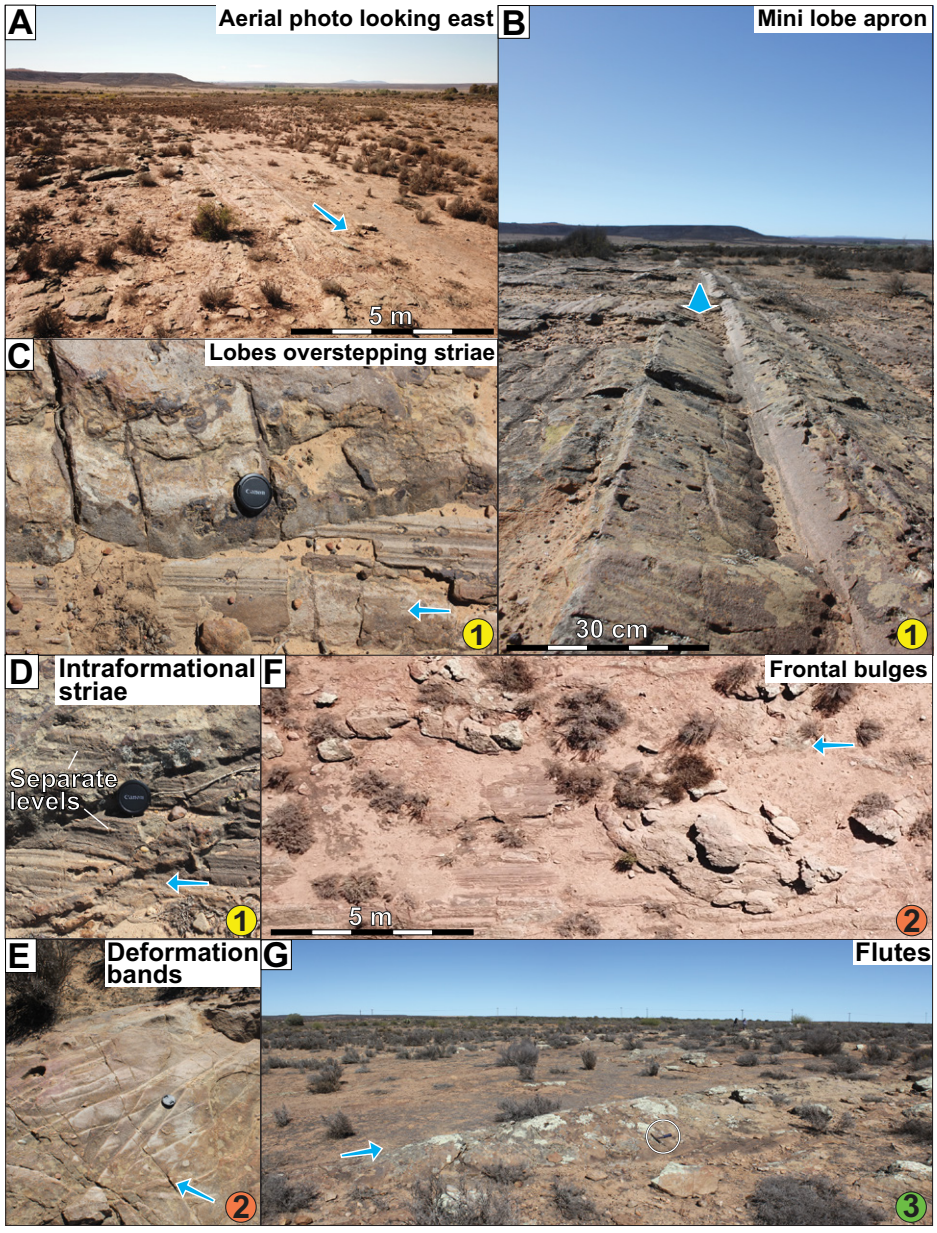

Figure 3. Photographs of Oorlogskloof glacial pavement (South Africa), with interpreted direction of ice advance shown by the blue arrow in each case. Text is color-coded to correspond to three discrete landform packages (numbers in colored circles) mapped in Figure 2. (A) General overview provided by an oblique aerial photograph looking westward. (B) Close-up image of the minilobe apron developed on landform package 1. (C) Detail of minilobes overstepping/downlapping onto striae in package 1. (D) Evidence for intraformational striated surfaces in package 1. (E) Centimeter-scale deformation bands (normal faults with millimeter- to centimeter-scale throws interpreted to form through compaction of unlithified sand) in package 2. (F) Development of frontal bulges in package 2, deflecting and warping the landforms in package 1. (G) Example of well-defined isolated flute in package 3. Note that locations of all features shown in photos B–G are shown in Figure 2.

eation pattern at a larger wavelength (1–3 m). Intraformational striations also occur, which are defined as those that occur beneath the present-day land surface at multiple stratigraphic levels (Fig. 3D).

Package 2 (Fig. 2) is notable for frontal bulges (Fig. 3F), which are arcuate piles of sandstone in which the margins deflect, contort, and warp the striae and flutes of package 1 (Fig. 2). A dispersion tail is sometimes observed in the downstream continuation of some of the frontal bulges. Conjugate deformation bands (Fossen et al., 2007) surround the bulges (Fig. 3E).

Package 3 consists of large-scale flutes up to 10 m long, one of which has a well-defined eastern apex. The amplitude of these streamlined features is meter scale. The southern margin of package 3 crosscuts packages 1 and 2 obliquely (Fig. 2). While flutes, grooves, and frontal bulges generally trend east-west in each of the packages, those in package 3 are somewhat sinuous (Fig. 3G).

Interpretation

Unlike many other subglacial unconformities of the Karoo Basin, which typically occur as hard bedrock scratches onto crystalline basement beneath the Dwyka Formation (Visser and Loock, 1988), all deformation in the Oorlogskloof locality is well established to be soft sediment in nature, as evidenced by fluting and bulging (see also Visser, 1990), either as subglacial material emplaced during the formation of the subglacial features or, alternatively, as reworking of the still unlithified underlying Nardouw Subgroup. The preservation of the Oorlogskloof assemblage was previously argued to result from "separation of the glacier sole from the substrate during a sudden rise in sea-level" (Visser, 1990, p. 231). Based on crosscutting relationships, we argue that this complexity is attributable to a lateral shift in the locus of erosion in the subglacial environment (Fig. 4). The three laterally superposed bedform packages record subglacial incision and fluting (package 1), temporary separation of the basal ice from its bed (package 2), and renewed coupling and fluting (package 3; Fig. 4). The frontal bulge deformation structures in package 2 are comparable to terminal berms at the leading edge of iceberg keel scour marks (e.g., Woodworth-Lynas and Dowdeswell, 1994; Vesely and Assine, 2014) and provide affirmative evidence of ice advance to the west. Nevertheless, we attribute these structures to temporary liftoff of the ice margin from the sediment surface to explain the third, crosscutting set of structures (package 3). The presence of conjugate deformation bands testifies to the application of a vertical load, compacting and distorting the sediment.

The soft-sediment striated surface was largely generated at the ice-sediment interface, with some evidence for intrasediment shearing and soft-sediment striation (Sutcliffe et al., 2000; Deynoux and Ghienne, 2004; Le Heron et al., 2005; Trosdtorf et al., 2005). The steepness of the flutes exceeded the angle of repose, and during local decoupling of the ice from its bed, grain-flow lobes were shed into the adjacent grooves. The asymmetric profiles of the flutes, in tandem with the development of mini-grain-flow lobes down one side only, are also compatible with the progressive lateral shift in the locus of subglacial erosion toward the north of the study site as the striated surface evolved. At modern ice grounding lines in Antarctica, tidal activity results in periodic liftoff of the ice margin from the seafloor during the rising tide, which then touches back down on the bed as the tide recedes (Domack and Harris, 1998; Domack et al., 1999). Thus, we appeal to a dynamic, buoyant ice margin to explain the present-day arrangement of structures (Fig. 4).

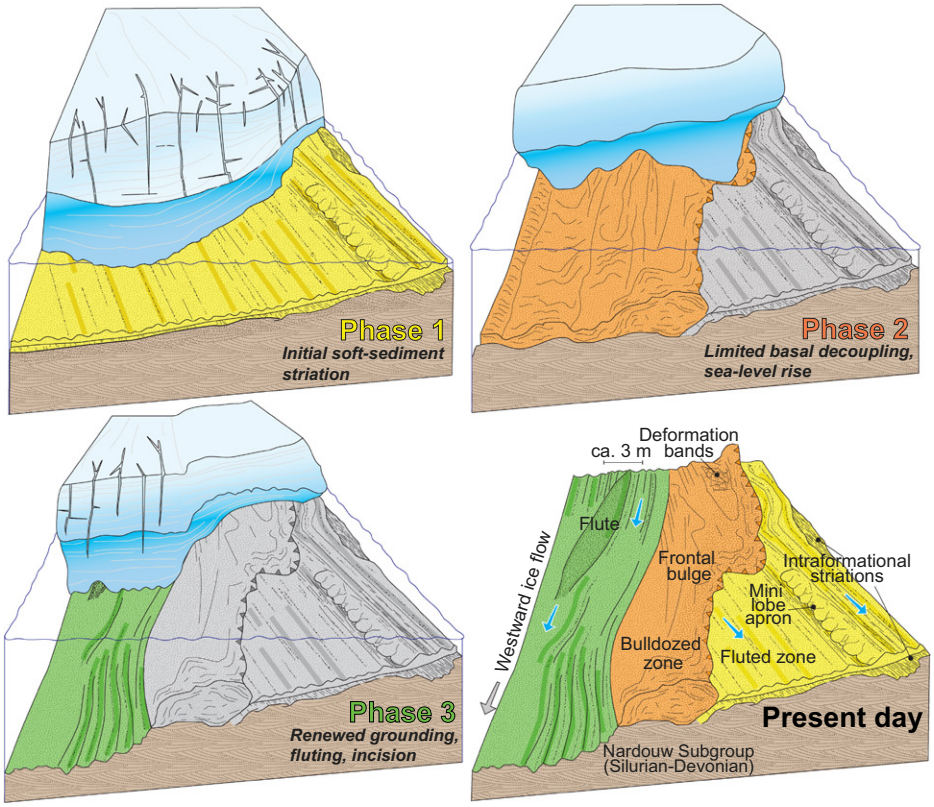

Figure 4. Series of schematic models showing the progressive development of each landform package on the Oorlogskloof (South Africa) surface. Each landform package is allied to a corresponding phase of incision, as the locus of incision migrated from right to left on the diagram (toward the north in Fig. 2). Colors correspond to three landform packages in Figure 2. The final result, with three crosscutting landform packages produced through subglacial shearing and fluting separated by a buoyancy phase (phase 2), is shown in present-day situation.

DISCUSSION AND CONCLUSION

Outcrop-scale analysis of the Oorlogskloof surface revealed that (1) the locus of erosion shifted laterally in the subglacial environment, (2) crosscutting relationships reveal that the unconformity is much more complex than previously thought, and (3) these relationships can be explained though basal liftoff and regrounding. Collectively, this analysis provides significant new insight into the degree of coupling between the Dwyka ice mass and its bed, challenging earlier views of a simple retreat and progressive basal liftoff prior to deposition of subaqueous diamictites (Visser, 1990), because renewed grounding is required to explain the youngest suite of structures. We speculate that this would have been best accomplished by cyclic, potentially tidally influenced grounding in a marginal marine setting. We emphasize that the entire assemblage in Oorlogskloof can be interpreted as an evolving subglacial setting during a single advance-retreat cycle.

Previous planform models envisaged a large ice sheet feeding trunk ice streams that flowed westward to South America (Visser, 1989, 1997). The assemblage of structures described herein is closely comparable to those described from the Late Ordovician of North Africa, which are typically associated with paleo–ice stream tracks (Moreau et al., 2005). Interestingly, structures of different orders of magnitude appear to be geometrically identical and thus self-similar (cf. Deynoux and Ghienne, 2004; Trotsdorf et al., 2005; Le Heron, 2018). In southern Africa, LPIA subglacial structures are also well developed on hard-bedrock substrates, particularly on the eastern flank of the Karoo Basin, together with putative megascale glacial lineations interpreted to result from paleo–ice stream tracks in northern Namibia (Andrews et al., 2019). The spatial relationships between hard-bedrock and soft-sediment striated pavements remain poorly established, although it is speculated that the former are "basin marginal," whereas the latter are "intrabasinal" in terms of paleogeographic significance. Collectively, detailed analysis of these unconformities has much to reveal about the styles and mechanisms of LPIA ice flow across the Karoo Basin and neighboring areas. Tools such as detrital zircon analysis (Craddock et al., 2019) allow sediment transport distances of up to thousands of kilometers to be posited for the Dwyka diamictites, but mapping and unconformity analysis are essential to reveal ice dynamics in detail.

Reevaluation of glacial unconformities from an aerial perspective is one step toward revealing the "missing link" between full glacial and deglacial conditions in deep time. This is because the laterally superposed sets of structures, charting the evolution of the subglacial environment, preserve vital information. Often, this information is missing, e.g., where transgressive deposits blanket glacial deposits, with extensive reworking suspected. However, reevaluation of comparable subglacial unconformities in other basins where a similar range of structures is recognized (e.g., the Sarah Formation of Saudi Arabia; Tofaif et al., 2019) may reveal critical steps in the evolving subglacial environment during retreat that have been hitherto overlooked. Reappraisal of similar surfaces of different ages with the approach adopted herein may help crack long-standing enigmas, such as whether they developed subglacially or through the grounding of drifting icebergs (Dowdeswell et al., 2016).

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