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PROF. DANIEL PAUL LE HERON (Orcid ID : 0000-0002-7213-5874)

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Daniel P. Le Heron[1], Christoph Kettler[1], Neil P. Griffis[2], Pierre Dietrich[3], Isabel P. Montañez[2], David A. Osleger[2], Axel Hofmann[4], Guilhem Douillet[5] and Roland Mundil[6]

[1]Institüt für Geologie, Althanstraße 14, Universität Wien, 1190 Vienna, Austria (daniel.le-heron@univie.ac.at)

[2]Earth and Physical Sciences, 2119 One Shields Avenue, University of California Davis, Davis, CA 95616, USA.

[3]Géosciences Rennes, UMR6118, Université de Rennes 1, 263 Avenue du Général Leclerc, Bâtiment 15, Campus de Beaulieu, 35042 Rennes Cedex, France.

[4]Department of Geology, University of Johannesburg, Johannesburg, South Africa.

[5]Institut für Geologie, Baltzerstrasse 1+3, 3012 Bern, Switzerland.

[6]Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, CA 94709, USA.

The expansion of ice masses across southern Africa during the Late Palaeozoic Ice Age has been known for 150 years, including the distribution of upland areas in controlling the configuration of glaciation. In

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Namibia, increasing attention has focussed on long and deep palaeovalley networks in the Kaokoland region in the north, but comparatively little work has been attempted in the topographically subdued plains of the south, in the Aranos and Karasburg basins. The desert terrain of the Aranos area exposes diamictites of the Dwyka Group discontinuously over about 300 km, extending further south to the Karasburg area at the Namibian-South African border along the Orange River. Whilst examined at a stratigraphic level, the nature of the contact between the Dwyka glacial rocks and underlying lithologies has not been systematically investigated. This paper presents the results from fieldwork in austral winter 2019, in which a highly varying basal contact is described that records the processes of growth, flow and expansion of ice masses across this part of Gondwana. At the basin margins, subglacially-produced unconformities exhibit classic glacially striated pavements on indurated bedrock. In comparison, the basal subglacial unconformity in the more basinward regions is characterised by soft-sediment striated surfaces and deformation. In the Aranos Basin, soft-sediment shear zones originated in the subglacial environment. This type of subglacial unconformity developed over well differentiated, unconsolidated, siliciclastic materials. Where ice advanced over more poorly sorted material or cannibalised pre-existing diamictites, "boulder-pavements" recognized as single clast-thick boulder-dominated intervals formed. Importantly, these boulder-pavements are enriched in clasts, which were facetted and striated in-situ by overriding ice. By integrating measurements of striation orientations, fold vergence and palaeocurrent information, former ice flow pathways can potentially be reconstructed over a wide area.

Introduction

The Dwyka Group of southern Africa preserves a world-class archive of the Late Palaeozoic Ice Age (LPIA), whose glacial record has enjoyed a rich history of research for more than a century (Sutherland, 1870; Lomas et al., 1905). Recently, important work has focussed on the geochronology of the LPIA succession, in particular regional linkages with conjugate basins in South America (Griffis et al., in press). The emerging picture of isochronous deglacial processes across the region, from South Africa to Brazil (Griffis et al., 2019a) is providing much sharper focus than that afforded by older studies that emphasised continental scale diachroneity as the LPIA record shifted across Gondwana from Bolivia via southern Africa to Australia as a result of the migration of Gondwana away from polar regions (Eyles, 1993). The LPIA was an interval of complex faunal turnover and extinction, and hence interdisciplinary earth systems approaches have been taken to shape the evolving paradigm (Montañez & Poulsen, 2013). In this, there remain key aspects where specific sedimentological, stratigraphic and geomorphological investigations play a lead role. These include accurate palaeogeographic reconstructions, including palaeotopography, whereby ice mass type, thickness and retreat patterns can be characterised. These endeavours are important, particularly as it remains the case that "the location, longevity, and geographic extent of late Palaeozoic ice centres in west-central Gondwana remain ambiguous" (Fedorchuk et al., 2019).

In spite of the rich tradition of investigation, the size of the main Karoo Basin of South Africa and neighbouring basins to the north and across southern and central Africa (Catuneanu et al., 2005), means that large regions still remain under-investigated, and hence many new insights remain possible through ongoing field investigations. In the western part of South Africa, for example, subglacially striated surfaces record a stepwise evolution at individual localities, with the potential to reveal phases of flow, decoupling and re-incision at the base of LPIA marine-terminating ice sheets (Le Heron et al., 2019). In northern Namibia (Kaokoland), deep glacial palaeovalleys first identified by Martin and Schalk (1953) have been reappraised and reinterpreted as fjords, with the palaeo-ice thickness during the melt phase estimated.

The Aranos Basin of central Namibia and the Karasburg Basin at the South Africa-Namibia border are major Dwyka diamictite depocentres located between the Kaokoland and main Karoo Basin of South Africa and have been the focus of numerous studies over the last century (Du Toit, 1921; Stratten, 1977; piot, 1983, 1987, 1997; Bangert et al., 1999; Werner, 2006; Stollhofen et al., 2000, 2008; Zieger et al., 2019). Since the turn of the century the palaeo-ice stream concept has revolutionised the approach to ancient glacial sequences, where data are integrated at all scales to characterise the former glacier bed, and thereby understand its flow character (Stokes & Clark, 2001). For the LPIA record, this has included satellite image interpretation of mega-scale glacial lineations (Le Heron, 2018; Assine et al., 2018, Andrews et al., 2019), the aerial photograph approach (Le Heron et al., 2019), outcrop description, and micromorphological analysis of thin sections (Henry, 2013). The present paper integrates new data from central and southern Namibia and the data of previous workers to (i) characterise the basal unconformity and (ii) develop a model for ice flow behaviour for these regions during the earliest phase of the Late Palaeozoic Ice Age.

Study area and geological background

Late Palaeozoic glaciogenic rocks are well documented across southern and central Africa (Rogers & Du Toit 1904; Du Toit, 1921; Linol et al., 2016). One of the largest, laterally continuous and most studied late Palaeozoic basins in Africa is the main Karoo Basin of South Africa, at the base of which the glaciogenic rocks referred to as the Dwyka Group occur (Rogers & Du Toit, 1904; Du Toit 1921; Visser 1997; Isbell et al., 2008; Dietrich & Hofmann, 2019). Karoo Basin-like sedimentation occurs in intracratonic basins, across central and southern Africa, with glacial deposits largely occurring within the Dwyka Group although some regional derivatives exist (*see* Catuneanu et al., 2005). In Namibia, Dwyka Group rocks outcrop along the entire western and southern region and in subcrop across the Kalahari Basin of Namibia and Botswana (Wilson, 1964; Miller, 2008). This study focusses on the Aranos and Karasburg subbasins of the greater Kalahari region.

The Aranos Basin and the Karasburg Basin (sometimes referred to as the Warmbad, Noerdoewer or Orange River Basin) (Figure 1A-C) can be considered co-eval to the main Karoo Basin in South Africa, which contains a record of four deglacial sequences in the centre of the basin (Visser, 1987, 1997; Grill, 1997; Isbell et al., 2008; Stolhoffen et al., 2008). In contrast to the Kaokoland in northern Namibia, which comprises an upland region deeply dissected by 300 Myr old fjords, the Aranos Basin (Figure 1B) comprises a subdued topography with the Dwyka Group resting unconformably on red Cambrian sandstones of the upper Nama Group which are hereafter referred to as “basement”. In the Aranos Basin, the Gibeon Formation, representing the basal Dwyka Group and the lowermost deglacial sequence, dips gently westward. In this region, several localities expose the basal contact with the Dwyka, including the so-called Airport Canyon south of Mariental, a set of buttes, sections at Gibeon, outcrops along the Fish River and north of Keetmanshoop (Figure 1B). In these studied sections, individual outcrops of Dwyka glaciogenic deposits do not exceed a few tens of metres in thickness, although elsewhere within the basin, glaciogenic deposits are tens to hundreds of metres thick (Martin, 1981). Recent U-Pb detrital zircon investigations (Griffis et al., in press) explore the regional-scale connections between Namibia and South America during the LPIA (Figure 1D), a connection that has been posited for a long time given the occurrence of westward-directed bedrock palaeovalleys in northern Namibia (Martin, 1981). In the Karasburg Basin, along the South Africa-Namibia border at the Orange River in the Noordoewer region the basal contact of the Dwyka Group is well exposed. There, recent study has revealed that the Dwyka Group is over a 100 m thick, and sampling of multiple ash horizons have yielded good chronostratigraphic constraints (Griffis et al., in press). The focus throughout this paper is on the basal contact between the Dwyka Group and the basement. The motivation of this study is to reveal the processes at work at the ice-bed interface to resolve the style and dynamics of LPIA in this region of Gondwana.

DESCRIPTIONS

In this section, descriptions are given on a locality-by-locality basis as it is important to assess the spatial variations across the region in terms of the morphology of the sub-Dwyka unconformity and immediately overlying deposits. At the several localities where it was possible to measure clast striation orientations, the measurements refer to data from multiple clasts.

Airport Canyon

This section comprises a *ca* 300 m long intermittent exposure along the banks of the Fish River, immediately south of Mariental. Two logged sections from this exposure, produced 250 m apart, serve to highlight the heterogeneity of the 2-4 m thick basal Dwyka succession (Figure 2). Resting on basement, the basal Dwyka comprises lonestone-free shale overlain by deformed sandstone facies to the south (section a, Figure 2) and poorly exposed diamictite to the north (section b, Figure 2). In the southern section, the deformed sandstones are capped by undeformed sandstones: at outcrop, this manifests as a pseudo-coarsening upward profile (Figure 3A). A number of deformation features are noted within the sandstones. Flame structures occur at the contact between beds, and are developed at the decimetre-scale (Figure 3B). At a larger, metre-scale, recumbent folds occur (Figure 3C). These folded sandstones contain both the flame structures together with interference ripples on the bedding planes (Figure 3D). In addition, the folded bedding is dissected by deformation bands (Figure 3E). The lateral relationship between these sandstone facies at this section and the diamictites is unclear owing to intermittent exposure (Figure 2).

Butte

A series of basal Dwyka sandstone outcrops are exposed south of Mariental where the contact with basement is well defined. From aerial imagery captured using a DJI Mavic Pro drone, the relationship between the red-weathering Cambrian strata and the yellow-weathering Dwyka deposits is apparent (Figure 4A). The Dwyka weathers out as a series of disconnected buttes that together belong to a sinuous outcrop belt. The basal Dwyka is characterised by considerable (at least metre-scale) downcutting into the Cambrian basement (Figure 4B). The Dwyka sandstones comprise metre-scale trough cross-bedded, locally pebbly sandstones (Figure 4C). A dominant SW trend is suggested from the trough cross-beds; multistorey cut-and-fill cycles are observed, the top of which also provide evidence of climbing ripple cross-lamination at some levels (Figure 5). The degree of downward incision within the multistorey? sandstones locally exceeds 2 m (Figure 5), and the entire succession is organised into a *ca* 10 m thick fining upward motif that is interrupted by a 30 cm interval of deformed lonestone-free mudstone. The succession is capped by boulders of facetted, and locally striated, red Cambrian sandstone (inset, Figures 4B and 5).

Gibeon

The Dwyka succession at Gibeon, the locality-type of the basal Dwyka Group for the Aranos Basin (Miller, 2008), rests directly on basement, like that at Airport Canyon and Butte outcrops, forming an 8 m thick heterogeneous diamictite-dominated succession (sedimentary log, Figure 6A). The succession comprises yellow, grey and red weathering deposits that transition upwards from massive via stratified diamictites and are capped by pebble conglomerates (Figure 6 and accompanying sedimentary log). The stratified diamictites contain excellent examples of striated clasts (Figure 6C). The orientations of striations on the upper (subhorizontal) surfaces of the clasts reveal a prominent bimodal orientation, with striations oriented NNE-SSW and SNE-WSW (Figure 6B). Striations are also well developed on boulder-sized clasts that cluster at the base of the succession (Figure 6E). In between stratified diamictite horizons, delicately laminated siltstones occur (Figure 6D). The uppermost pebble conglomerates are clast-supported and dominated by equant, sub-angular clasts (Figure 6E).

Fish River

The so-called Fish River successions comprise outcrops, about 7.5 km apart, between Tses to the east and Brukkaros volcano to the west. At the studied outcrops diamictites measure a few metres thick (Figure 7A). Away from the creek beds, the 10-20 m thick Ganigobis shales are preserved. A U-Pb zircon CA-ID-TIMS age of 299.31 ±0.35 Ma is reported from the Ganigobis shales, sampled *ca* 5m above the diamictite (Griffis et al., in press). Both stratified (Figure 7B) and massive diamictite subfacies are observed, with excellent striated clasts throughout (Figure 7C). Striation orientations from the upper (subhorizontal) surfaces of clasts reveal a very weak N-S trend for the eastern section (Figure 7A), and a more clearly developed NW-SE orientation for the western section (Figure 7B).

Keetmanshoop

A roadside section in the vicinity of Keetmanshoop (Figure 8) exposes the contact between clinoform-bearing sandstone basement and basal diamictites of the Dwyka above. The morphology of the unconformity can be demonstrated in panoramic photographs, particularly with vertical exaggeration (Figure 8A) and are shown to consist of irregular undulations of approximately 2-3 m with a wavelength of about 20 m. At a finer scale, decimetre-scale undulations are also recorded (Figure 8A). The contact between the basement and the Dwyka is extremely sharp (Figure 8B). In this section, the basal deposits of the Dwyka are a maximum of 1.5 m thick and comprise pebbly, clast poor silty diamictites (Figure 8C). In a nearby outcrop, these basal diamictites encompass numerous pebbles either derived from the underlying basement or exotic lithologies. Some pebbles are conspicuously faceted and striated, and have been found deformed, forming an elongated ridge with a striated top (NNE-SSW trend).

Noordoewer

This section lies along the Orange River, with outcrops straddling the Namibian-South African border. A 100 m thick section of the Dwyka was measured in which four distinct facies can be recognised: (i) a boulder conglomerate, (ii) diamictites, with both massive and stratified variants observed, (iii) a lonestone-bearing shale facies and (iv) a lonestone-free shale facies. The boulder conglomerate (Figure 9A,B), interpreted as the lowermost "tillite" unit of the Gibeon Formation (Miller, 2008), dominates the lowest 1 m of the Dwyka; the contact between this and sandstone basement is sharp and irregular at the outcrop scale (Figure 9A). The orientation of boulder A-axes were measured and found to be of variable orientations with weak NW-SE and NE-SW trends tentatively identified (Figure 9). The first of two lonestone-bearing shale intervals, likely corresponding to the Zwartbas Formation, drapes the boulder bed, and exposes excellent examples of pebble-sized clasts below which shale laminae are warped and deformed, and above which layers are undisturbed (Figure 9C,D). Above a stratified diamictite, a second lonestone-bearing shale, a bedding plane exposes chisel-shaped incisions (Figure 9E-G). These features consist of *ca* 1 cm wide grooves with a sharp termination at one end and a tapering, gradational termination at the other. The incisions are predominantly NE-SW oriented (Figure 9). These lonestone-bearing shales pass upward into the lonestone-free shales in which two volcanic ash layers yield ages of 300.45 ±0.37 Ma and 299.41 ±0.24 Ma, 5 and 7 m above the base of the black shales (Griffis et al., in press). These ages were determined using high-resolution U-Pb zircon CA-ID-TIMS analyses (Griffis et al., in press).

INTERPRETATIONS

The consensus of previous workers is that a large, initial ice mass expanded over central and southern Namibia, with a subsequent re-advance overprinting specific areas (Visser et al., 1983; Stollhofen et al., 2000; Griffis et al., 2019b; Griffis et al., in press). In the following, the data are integrated from each of the sections described above to develop a process-based model for the earliest phases of the LPIA in central-southern Namibia. Before doing so, it is emphasised that although the data quality at the described outcrops are high, there is some uncertainty regarding lateral facies transitions both at the small scale (e.g. Airport Canyon) and at the large scale (e.g. between the sandstone facies at Butte and the other sections). These uncertainties are incorporated into the following depositional models. First, the nature of the contacts is interpreted, followed by an analysis of the facies constituting the basal Dwyka succession.

The basal unconformity

The basal Dwyka unconformity is interpreted as a complex, composite surface which includes elements of (i) incision and fill of bedrock channels by proglacial river deposits and (ii) shearing and deformation of subglacial and proglacial sediments. Basal facies exposed at the buttes locality is interpreted to record an unconformity cut through fluvial incision. This interpretation is supported by (i) trough cross-bedded sandstones (Figure 4C) which form the bulk of the Dwyka Group interpreted as fluvial deposits, (ii) multi-metre scale downcutting and a geometric relationship between the morphology of the incision and overlying trough cross-bedded strata, together with (iii) the organisation of individual sandstone buttes into a sinuous morphology at the landscape scale. The latter is interpreted to record a palaeovalley incision. At Gibeon, Fish River and Keetmanshoop however, subglacial shearing and deformation are observed between the basement and the Dwyka diamictites. At Keetmanshoop, however, the contact between basement and Dwyka is considered to record warm-based, subglacial erosion or groove-ploughing to explain long wavelength basin structures seen at outcrop (Figure 8), which are tentatively interpreted to record cross sections through subglacial bedforms. In particular, the elongated, striated ridge is interpreted as a drumlin formed subglacially (Ely et al., 2016). The smaller metre-scale undulations are posited to represent subglacial quarrying. The deformed (folded) boulder pavement found along the bank of the Fish River is also interpreted as subglacial striation, deformation and shearing. Among the other localities, the basal unconformity exposed at Noordoewer (Figure 9A) is also proposed to represent a combination of subglacial quarrying and subglacial sediment injection into bedrock via hydrofracturing. The sharp, locally irregular contact between the Dwyka and basement is explained as a series of either quarried or fractured bedrock weaknesses injected with subglacial sediment. It is notable that in contrast to abundant striated pavements found on the rim of the Karasburg Basin (Miller, 2008) these appear to be extremely rare at the margins of the Aranos Basin, with none recorded in this study. It is believed that only a single striated pavement has been found in the entire Aranos Basin (Heath, 1972). This is in spite of ideal outcrop conditions (very low angle dipping surfaces and abundant basement outcrops). At Airport Canyon, the contact is disconformable and consists of Dwyka shale resting on basement, but the poorly exposed nature of the contact precludes detailed interpretation.

The basal Dwyka succession

The complexity of the basal Dwyka unconformity pales in comparison to the lithofacies which are found immediately above in the Gibeon Formation. The diamictites of the Gibeon outcrop are interpreted as an assemblage of subglacial tillites (Evans et al., 2006), with multiple subglacial depositional episodes dominated by lodgement interrupted by ice-bed separation events in which stratified diamictites were deposited. The same section also records evidence for more energetic meltwater events, explaining the presence of clast-supported pebble conglomerates. The evidence for subglacial origin for the diamictites is provided by convincing preferred striation orientations on the upper surface of clasts. The bimodal trend of the striations invites the proposal that shear was applied from two separate directions. The Fish River sections also reveal complex striation orientations on clast surfaces, perhaps also suggestive of crosscutting flow orientations. In the diamictite facies, the occurrence of bedding-parallel fabrics exemplified at Gibeon is best interpreted as an assemblage of subglacial shear surfaces. Alternatively, it could be proposed that striated clasts were rotated during traction in response to changing strain rates or rheology (e.g wetting and drying) of the deforming layer. Underscoring the interpretation of ice-bed separation events in the laminites is (i) the deflection and piercing of underlying laminae, diagnosing the lonestones as dropstones, and (ii) the excellent preservation of laminae, requiring a waterlain origin. Less insight is possible for similar diamictites such as those at Keetmanshoop, yet given the context a subglacial origin for the massive, clast-poor diamictites is also possible. Further, the boulder-bearing conglomerate at Noordoewer is interpreted as a subglacial deposit. The two weak trends in terms of the clast long axes at this locality potentially indicates directions of subglacial shearing, with the long axes expected to align parallel to palaeo-ice flow. If this is the case, then the data at Noordoewer can be interpreted to record two cross-cutting flow orientations.

Both the Airport Canyon and Butte localities yield facies whose origins require special attention. The Airport Canyon assemblage is interpreted to record the build out of a small wave-dominated delta that was cannibalised by subglacial deformation during its development. In this context, basal shales are interpreted as bottomsets, the deformed sandstones belong to foresets, and the undeformed, stacked wave rippled, well sorted sandstones belong to the topsets. This interpreted succession corresponds to profile a (Figure 2); profile b (Figure 2) bears a massive diamictite in the same stratigraphic position as the deformed sandstone in profile a. In a non-glacial context, it might be possible to appeal to downslope mass wasting and slumping to explain the relationships. A mass wasting hypothesis is nevertheless stymied by the following issues. First, this does not explain the diamictites occurring at a slightly higher elevation than the laterally equivalent, deformed sandstones (Figure 2). Second, the assemblage of structures is well known from other glacial successions including the so-called Zarqa facies of the Late Ordovician in Saudi Arabia (Melvin, 2019; Tofaif et al., 2019). In that example, deformation bands crosscutting soft-sediment folds, also developed in sandstone, together with laterally equivalent diamictites, pass into laterally equivalent striated pavements. A similar interpretation for the Airport Canyon succession is proposed whereby, collectively, the deformation structures are interpreted to record strain within a subglacial substrate. The metre-scale folds were probably produced during a more ductile phase of subglacial deformation, overprinted by more brittle products i.e. the deformation bands, once deformation "locked up".

At Butte, the occurrence of stacked, multistorey trough cross-bedded sandstones characterised by erosive, pebble lined bases testify to processes of repeated cut and fill in a fluvial environment. Given the large-scale context discussed above (the infill of a palaeovalley) these deposits probably record the migration of braid bars in a generally high energy environment. The overall fining upward profile of the Butte succession implies progressive shallowing of the channel system. The presence of boulders of Cambrian red sandstones on the uppermost level replete with clast facets may imply that the Butte section was overridden during a subsequent glacial advance.

Constraints on water depth at Noordoewer?

The intercalation of three facies above the basal deposits (i.e. both massive and stratified diamictites, lonestone-bearing shale and lonestone-free shale) provide excellent insight into both process and palaeoenvironment following the emplacement of the subglacial boulder conglomerates. In contrast to the massive basal diamictites in localities such as Gibeon or Keetmanshoop, massive diamictites at Noordoewer that are intercalated with shale are interpreted as waterlain rather than subglacial (in contrast to the basal conglomerates with injectites). This interpretation was reached because of the associated well-stratified facies (both lonestone-bearing and lonestone-free shale). The deflection and warping of laminae beneath the lonestone diagnoses these as dropstones. In ancient rocks, most dropstones are interpreted to have been deposited beneath ice shelves (Lechte & Wallace, 2016) or from floating icebergs (Condon et al., 2002; Rodríguez-López et al., 2016; Le Heron et al., 2020). Numerical modelling also shows promise in terms of estimating water depth through examination of dropstone impact structures (Bronikowska et al., in press).

On account of the chisel-shaped incisions (Figure 9E-G) below one of the dropstone-bearing horizons, it is suggested that at least some of the dropstones were deposited from shorefast ice rather than by icebergs. The chisel-shaped incisions are tentatively interpreted as furrows cut by an expanding mass of shorefast ice which expanded southward during the winter. The predominant NE-SW orientation is thus proposed to reveal the direction of expansion of the ice: the sharp end of the structures is interpreted to record the point of downcutting of ice into the sea floor, with incision becoming less pronounced with distance (Figure 9). These interpretations imply that, initially at least, shallow water conditions prevailed during early Dwyka deposition. Thereafter, however, given the thickness of the succession above in the Owl Gorge region 1 km to the north, it is likely that the succession records a transition to deeper water (Griffis et al., in press) during an initial deglaciation cycle.

DISCUSSION

Development of the basal Dwyka surface: a complex, composite origin

In southern Namibia, the development of the basal unconformity beneath the Dwyka was complex and is interpreted as a combination of direct subglacial erosion of basement, deformation of subglacial sediment, the incision of bedrock through pressurised subglacial meltwater systems, and to proglacial fluvial deposition. In the following, specific reference is made to the earliest phase of glaciation to affect the region, i.e. the lowermost glacial cycle of Grill (1997) and Stollhofen et al. (2000). Since Du Toit (1921), phases of data collection on striation orientations, roches moutonnees, cross-bedding orientations and tillite fabrics (c.f. Stratten, 1977; Visser, 1983; Werner, 2006; Stollhofen et al., 2000, 2008) have painted a complex picture. Several authors (Stratten, 1967, 1977; Visser, 1983; Stolhoffen et al., 2000, 2008; Griffis et al., 2019a, 2019b; Zieger et al., 2019) have pointed to two conflicting directions of ice movements, namely the so-called Namaland ice sheet flowing from the Windhoek Highlands in the north toward the south, and the Transvaal Ice sheet that flowed from east to west. Further, some workers have proposed both southward (Namaland) and northward (Transvaal) flowing ice lobes emerging from glacial valleys over the Aranos Basin, with the relative contributing of a northward and southward flow shifting over space and time (Visser, 1987).

The data presented here suggest that support for the "Namaland ice sheet" as well as the "Transvaal ice sheet" can be found within a single deposit implying that these fabric orientations must have developed in a single phase. This applies to multiple localities where two ice flow orientations can be interpreted from the same basal Dwyka succession, namely at Gibeon, the Fish River sections, and at Noordoewer. These seemingly conflicting flow orientations are best interpreted as evolving in one, time-transgressive phase of deformation in the subglacial environment. Through this process, the direction of shear in the subglacial environment switched over time from N-S to E-W, or vice versa, recording the local flow conditions such as the development of bedrock obstacles or stick-slip behaviour in the deforming bed (Boulton & Hindmarsh, 1987). Translation of part of the subglacial bed must account for this, in a manner similar to the mosaic concepts of deforming spots proposed by Piotrowski et al. (2004). Note that a complex, evolving subglacial environment appears to conflict with the model of Zieger et al. (2019) developed from detrital zircon work, who envisaged two separate flow orientations: a southward ice flow in an early phase (lower Gibeon Formation) and a westward flow in a later phase (upper Gibeon Formation).

Reappraising regional ice flow and ice sheet reconstructions

At the scale of Gondwana, if emphasis is placed on detrital zircon provenance, a very simple picture has emerged: Craddock et al. (2019) interpret two westward flowing ice caps. The northern ice cap- named the Dwyka ice cap- connected Namibia to south-eastern Brazil, whereas the southern Ellsworth ice cap was proposed to nourish Uruguay and eastern Argentina with glacial sediments (Griffis et al., 2019b; Craddock et al., 2019; Fedorchuk et al., 2020; Zieger et al., 2019).

At a slightly smaller scale, based on new data together with a swathe of data from previous authors, Dietrich et al. (2019) presented a regional reconstruction (their figure 10) which showed both south-west (Aranos Basin) and south and west (Karasburg Basin) flows inferred from striated pavements. Paradoxically, the Kalahari-Karoo Basin (to the east) was depicted as an "ice-influenced sea" where iceberg and ice shelf sedimentation prevailed. Therefore, the palaeoglaciological connection between the upland areas and both the Aranos and Karasburg basins requires further investigation.

Consideration of the palaeoglaciology of central and southern Namibia during the LPIA cannot be undertaken without giving detailed attention to South America, where a number of important papers have been published in the past six years. Traditionally, attention has focussed on the connection between an ice mass considered to be centred on the Windhoek Highlands of Namibia (i.e. north of the Aranos Basin) and the conjugate Paraná Basin of Brazil. There, predominantly NNW-SSE oriented striations mostly cut into Devonian sandstone in Paraná State or in bedrock to the states in the south, together with p-forms carved into Neoproterozoic granites, have been interpreted to indicate a NNW directed ice flow (Rocha-Campos et al., 2008). This regional flow pattern is approximately 180 degrees to that interpreted in the Aranos Basin regional NNW-SSE trend, yet is supported by recent fieldwork and satellite image interpretation that convincingly demonstrates a suite of polished, streamlined and asymmetrical structures developed on granite in Uruguay (Assine et al., 2018). In Brazil, the record of striation is not only preserved on hard bedrock but also on soft sediment where some structures are interpreted as ice keel turbates (Vesely & Assine, 2014). At a regional scale, including in Namibia, it is vital to separate those structures and features that are produced subglacially from those produced from floating ice.

At the south-eastern margin of the Paraná Basin on the Rio Grande do Sul Shield, Fedorchuk et al. (2019) reinterpreted palaeovalleys with supposed fjord fills as non-glacial lacustrine to estuarine deposits. In that study, however, core did not penetrate the base of the palaeovalley precluding its context with basement to be evaluated. It also proposed that rather than the eastern part of the Paraná Basin being "fed" by ice lobes centred on Namibia, ice lobes from Uruguay delivered sediment to the north. Nevertheless, based on a provenance study the following year (Fedorchuk et al., 2020) it was acknowledged that although Uruguayan sediment sources could be recognised in the Paraná Basin, glaciers derived from the highlands of Namibia continued to be a valid interpretation. In contrast, investigation of the fill to the east-west oriented Mariana Pimentel palaeovalley at the southern margin of the Paraná Basin reveals a record dominated by rhythmites, interpreted as varves and associated with dropstones in core (Tedesco et al., 2020). Thus, apparent distance from the supposed ice centres in Namibia does not have an obvious bearing on whether palaeovalley fill contains glacial facies or not. At the larger scale, this emphasises the complexity of the basal LPIA phases. Indeed, basins with thick glaciomarine sequences (e.g. the Rio Bianco Basin, Argentina: 1.4 km thick) favour rather nuanced interpretations for earlier phases of the LPIA, with climate phases hierarchically organised with glacial advance, retreat and non-glacial intervals (Ezpeleta et al., 2020).

New investigations in the Kaokoland in northern Namibia have reinforced earlier studies, where compelling evidence for deep palaeovalley incision has long been known (Martin, 1981). There, in conjunction with the glacial geomorphology (roches moutonnees, striated bedrock etc), the upward facies transitions from subglacial through nearshore to deeper marine diagnose a wide-network of palaeo-fjords: the first pre-Pleistocene fjord landsystems positively identified in the pre-Cenozoic record. The palaeogeographic and palaeoglaciological context is vital because modern fjord systems are major carbon sinks, the burial of which has a positive feedback effect on ongoing cold climate cycles, and this is also expected to have had a major impact on the LPIA climate dynamic. These processes compound the complexity of LPIA glacial cycles that are envisaged, including the role of equilibrium line altitude as Gondwana (Isbell et al., 2012).

Conclusions

Reappraisal of the basal Dwyka surface at several locations at the margins of the Aranos and Karasberg basins in Namibia reveal that a complex suite of processes was responsible for the generation of the basal unconformity. Analysis of a number of outcrops at the western margin of the Aranos Basin allows us to recognise the products of subglacial erosion, subglacial shearing of unconsolidated sediments, together with channelisation and palaeovalley development compatible with a fluvial genesis. The basal LPIA unconformity in southern Namibia must therefore be viewed as a patchwork mosaic that evolved from these processes. Re-examination of diamictites and conglomerates immediately above this unconformity paints an increasingly complex picture. Evidence for both N-S and E-W ice flow can be found within these deposits: these orientations have traditionally been associated with the products of ice sheets coming from these directions. Instead, however, it is proposed that these orientations simply reflect shearing of sediment beneath the LPIA ice masses.

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Figure captions

Figure 1: A series of maps placing the study in context. A-C Study areas of the Dwyka Group in southern Namibia, compiled from Martin (1981), Visser (1983), Bangert et al. (1999) and Geiger (1999). D: Simplified regional-scale geological map emphasising the connections between Namibia and South America during the LPIA. Slightly modified from Griffis et al. (in press).

Figure 2: The Mariental "Airport Canyon" sections at approximately 24°39'42.90"S 17°55'51.30"E. Profile (a) exhibits a spectacular suite of soft sediment deformation. These include convolute bedding, deformation bands in wave rippled sandstone, complex thrust geometries and recumbent folds. Profile b. lacks all these facies, but a pebbly diamictite is present. The profiles are bracketed by presumed Lower Palaeozoic sandstone with nodules beneath and young (presumed Pleistocene-Recent) river terrace gravels on top. The assemblage of deformation structures compares closely to subglacial facies described elsewhere (Melvin 2019). Profile (b) lacks these characteristics, and preserves a massive diamictite in place of the sandstone facies at (a). Note that owing to scree-covered sections the nature of the lateral relationship between (a) and (b) is uncertain at that stratigraphic level.

Figure 3: Lithofacies from the Airport Canyon section, profile (a). Photographs as follows: (A) Overall profile view. (B) Soft-sediment injection structure. (C) Recumbently folded wave rippled sandstones, traversed by deformation bands. (D) Ladderback ripples. (E) Deformation bands. Collectively, the deformation structures are interpreted to record strain within a subglacial substrate, i.e. within the deforming bed (Evans et al., 2006).

Figure 4: (A) Aerial image revealing the relationship between pebbly sandstone inselbergs of the basal Dwyka and underlying Cambrian sandstones. (B) Outcrop level view of the Cambrian-Dwyka contact, with inset photograph showing large boulder of Cambrian sandstone sitting at the top of the Butte. (C) Stacked sets of pebbly, trough cross-bedded sandstone (note lens cap for scale, circled) Interpreted as a fluvial channel system cut into basement, probably recording initial downcutting and incision into the surface prior to glacial advance. Outcrop at 25° 4'49.20"S 17°44'13.40"E

Figure 5: Logged section through the basal Dwyka succession at the inselberg, showing characteristic stacked pebbly sandstones arranged into fining up intervals. Rose diagram shows a well-developed south-westward palaeocurrent dispersal.

Figure 6: The basal Dwyka at Gibeon. The logged section shows the dominance of massive diamictites at the base, stratified diamictites in the middle, and pebbly conglomerates at the top. The numbered intervals to the left of the log correspond to each of the beds shown in photograph (A), i.e. an interval showing the full transition from massive via stratified diamictite, capped by pebbly conglomerate. (B) Detailed view of the massive to stratified diamictite, with photograph taken approximately 8 m along strike from photograph A. Note the excellent 3D exposure of clasts. Striations on their upper surface were measured (N=30): on the rose diagram, a strong NW-SE orientation is observed, with a secondary W-E orientation. (C) Detail of striations on the upper surface of an embedded sandstone clast. (D) Detail of virtually clast-free, delicately stratified interval. (F) Clast-supported conglomerate at the top of the succession.

Figure 7: The basal Dwyka at the Fish River sections. (A) Simple sedimentary log showing a predominantly stratified diamictite and a weak N-S trend of striation orientations on the upper surface of clasts. (B) Typical view of stratified muddy diamictite in the Fish River Tributary region. Note lens cap for scale. (C) Example of a striated clast: throughout this study, orientation measurements were only taken from similar sub-horizontal surfaces, and not from the side of the clast. Note lens cap for scale. (D) Aerial view of the relationship between Cambrian basement and Dwyka. Clast orientations from the basal diamictite record a more prominent NW-SE trend in this locality.

Figure 8: Nature of the basal Dwyka unconformity and basal diamictites in a road cut near Keetmanshoop. (A) Photomosaic of the road cut together with a vertically exaggerated version to emphasise topography at the base of the Dwyka. This topography consists of long wavelength (*ca* 20-30) undulations, with smaller metre-scale to decimetre-scale undulations superimposed. (B) close up photograph (position shown in A) of the sharp nature of the contact, also exhibiting well developed clinoforms in the Cambrian strata. (C) Detail of massive, basal diamictite at the contact (see (A) for position of photograph, lens cap for scale).

Figure 9: Nature of the basal Dwyka contact and its relationship with underlying Cambrian sandstones at Noordoewer, along the Orange River on the border with South Africa. The Dwyka crops out on both sides of the border. Sedimentary log shows the position of each of the photographs and features alongside. (A) Lens cap for scale sits on Cambrian sandstone, with the Dwyka sitting irregularly upon it. The basal Dwyka occupies fractures and fissures defining a highly irregular contact. (B) Series of elongated boulders immediately above the basal contact, with lens cap circles for scale. The orientation of these is shown on the rose diagram to the right of the log. (C) Dropstones in shales approximately 1.5 m above the basal contact. (D) Dropstone in stratified muddy diamictite. (E), (F) and (G) correspond to three views of chisel shaped incisions found along bedding planes in lonestone-bearing shales. Each of the photographs shows

the structures on the upper surface of the beds. The orientation of these features is shown (“bedding plane scour marks”) to the right of the log.

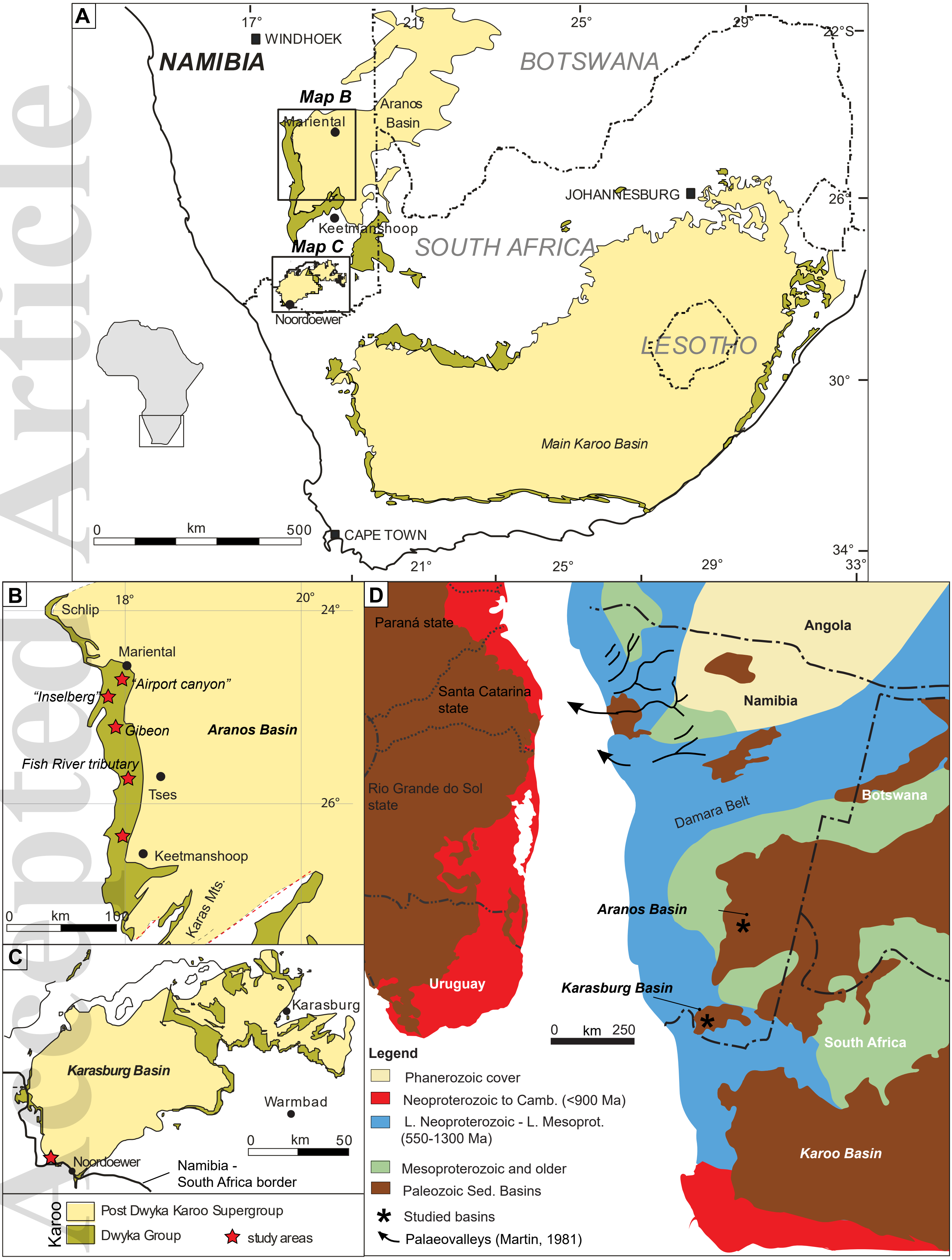
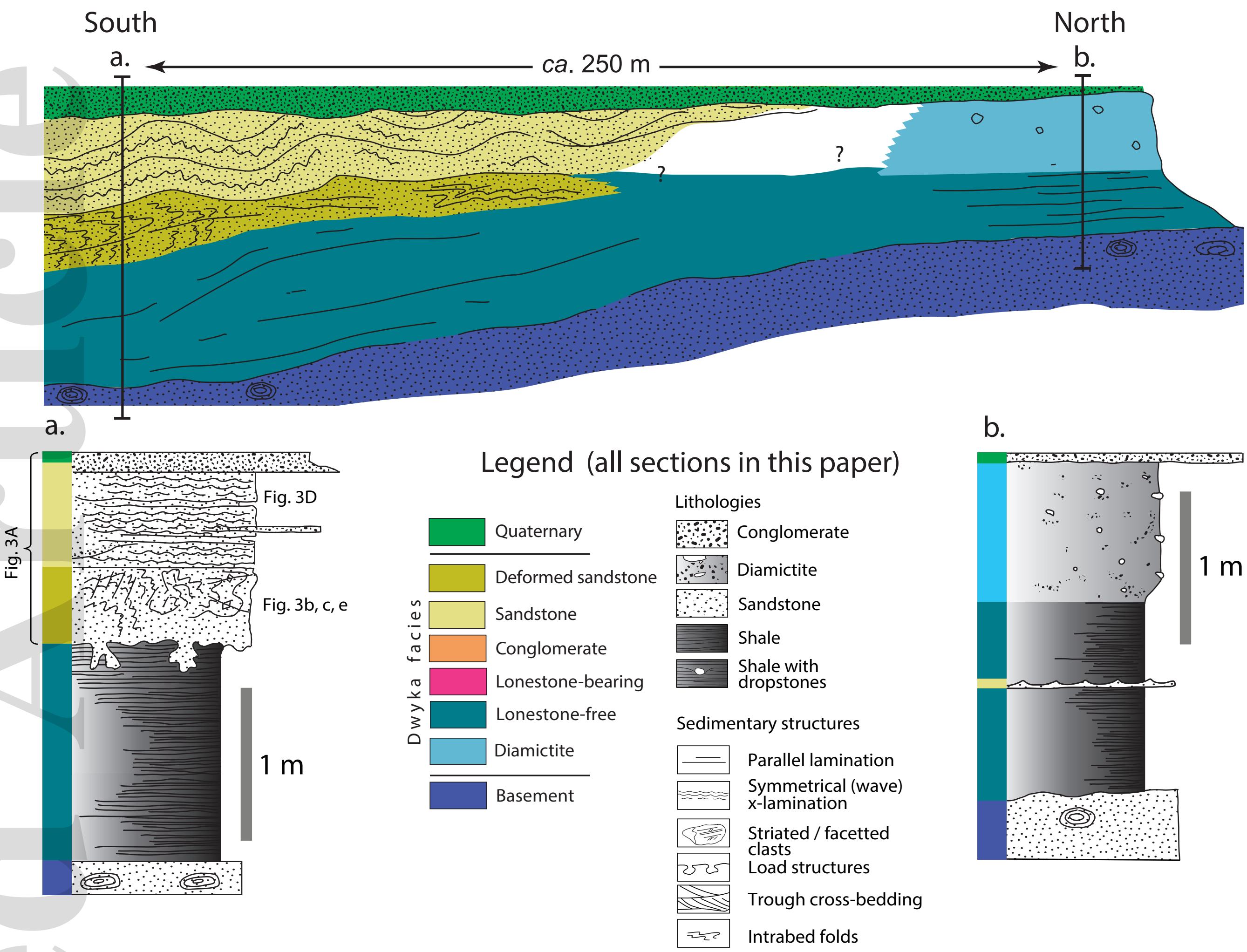
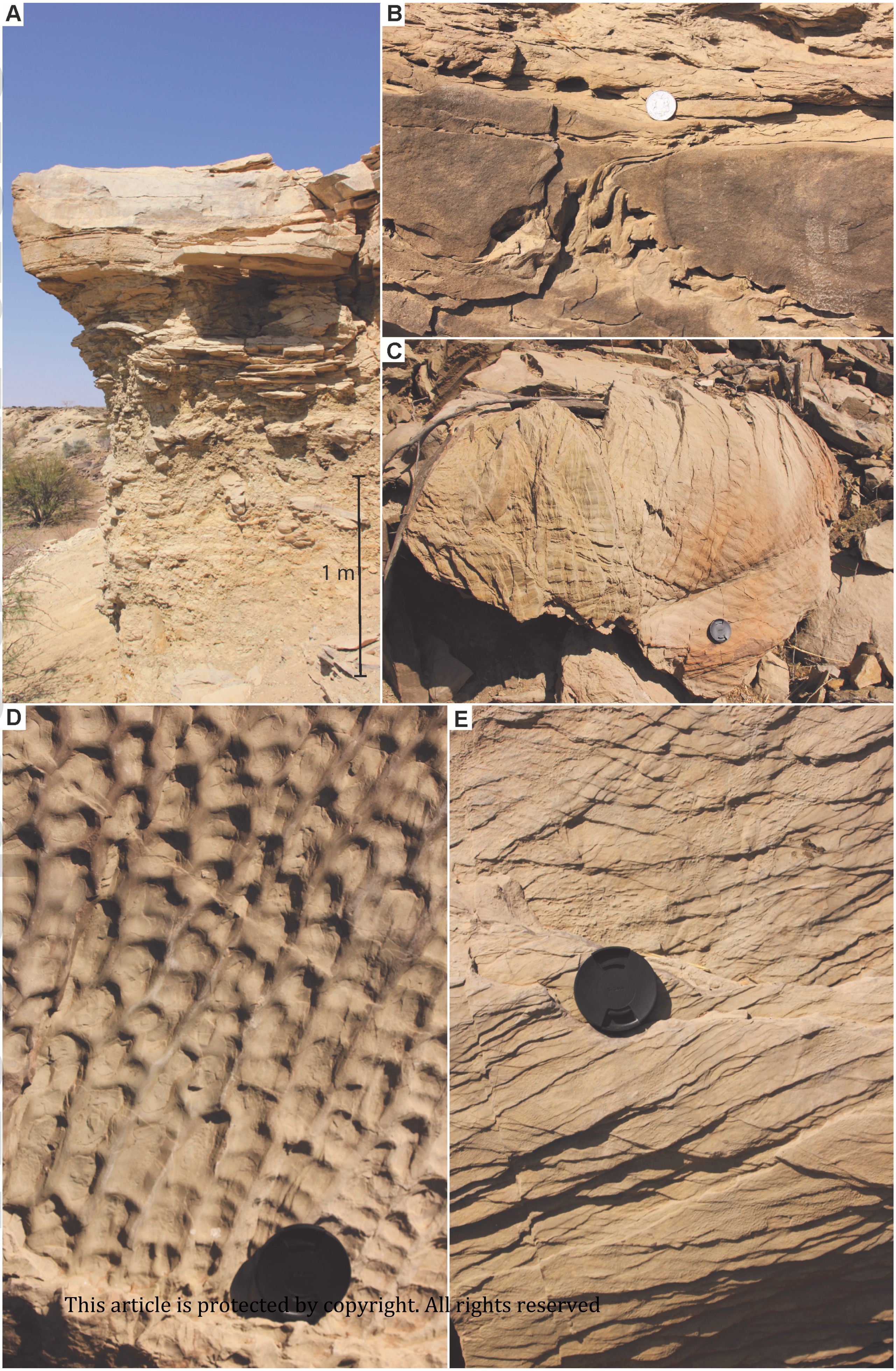

A
17°
WINDHOEK
NAMIBIA
21°
25°
29°
22°S
BOTSWANA
Map B
Aranos
Basin
Mariental
JOHANNESBURG
26°
Keetmanshoop
Map C
SOUTH AFRICA
Noordoewer
LESOTHO
30°
Main Karoo Basin
0
km
500
CAPE TOWN
34°
21°
25°
29°
33°
B
Schlip
18°
20°
24°
Mariental
"Airport canyon"
"Inselberg"
Gibeon
Aranos Basin
Fish River tributary
Tses
26°
Keetmanshoop
Karas Mts.
0
km
100
C
Karasburg
Karasburg Basin
Warmbad
0
km
50
Noordoewer
Namibia -
South Africa border
Karoo
Post Dwyka Karoo Supergroup
Dwyka Group
study areas
D
Paraná state
Santa Catarina
state
Rio Grande do Sol
state
Uruguay
Angola
Namibia
Damara Belt
Botswana
Aranos Basin
Karasburg Basin
0
km
250
South Africa
Karoo Basin
Legend
Phanerozoic cover
Neoproterozoic to Camb. (<900 Ma)
L. Neoproterozoic - L. Mesoprot.
(550-1300 Ma)
Mesoproterozoic and older
Paleozoic Sed. Basins
Studied basins
Palaeovalleys (Martin, 1981)

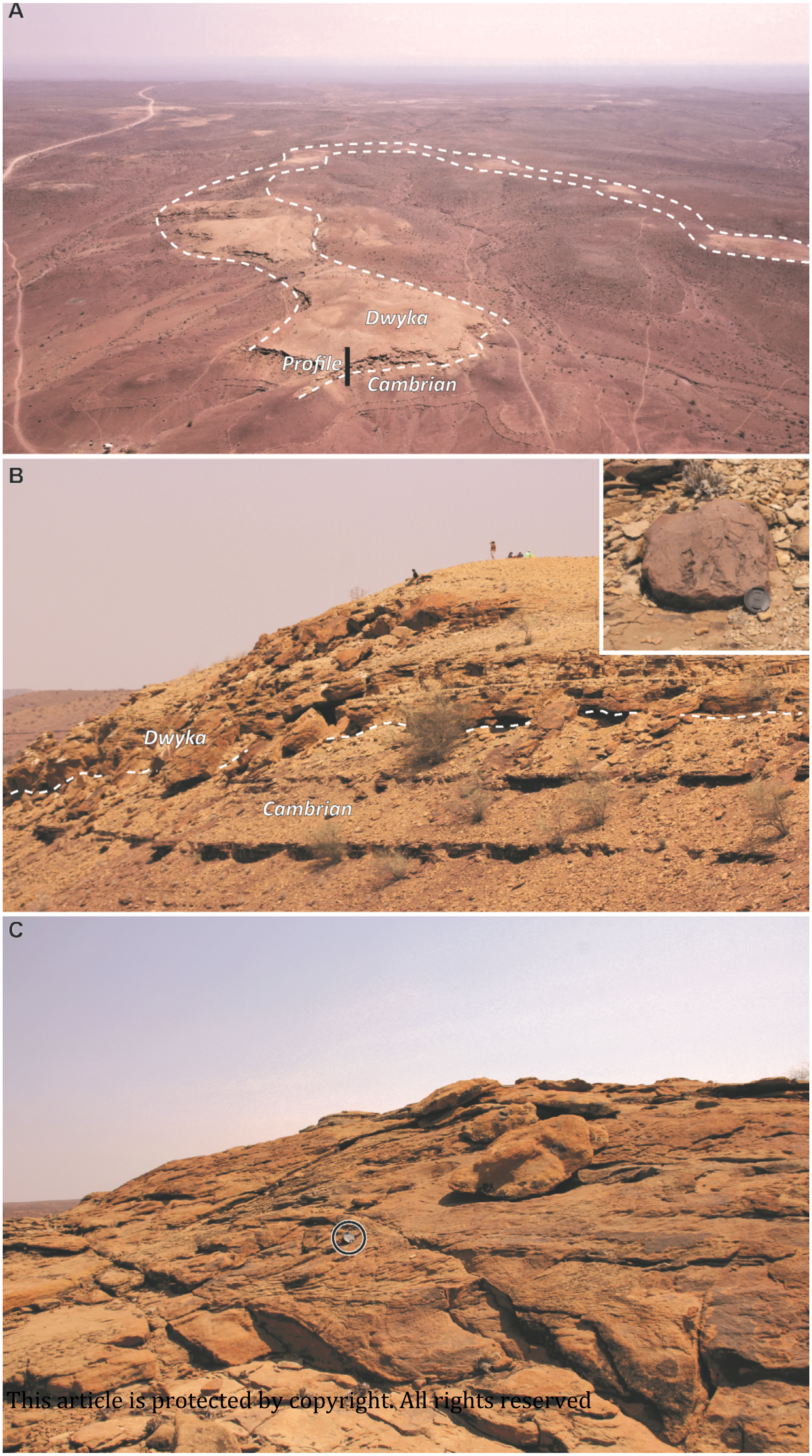
Figure 1



South
North
a.
ca. 250 m
b.
?
?
a.
Fig. 3A
Fig. 3D
Fig. 3b, c, e
1 m
Legend (all sections in this paper)
Quaternary
Deformed sandstone
Sandstone
Conglomerate
Lonestone-bearing
Lonestone-free
Diamictite
Basement
Dwyka facies
Lithologies
Conglomerate
Diamictite
Sandstone
Shale
Shale with dropstones
Sedimentary structures
Parallel lamination
Symmetrical (wave) x-lamination
Striated / facetted clasts
Load structures
Trough cross-bedding
Intrabed folds
b.
1 m

Figure 2


A
B
C
D
E
1 m


A
Dwyka
Profile
Cambrian
B
Dwyka
Cambrian
C

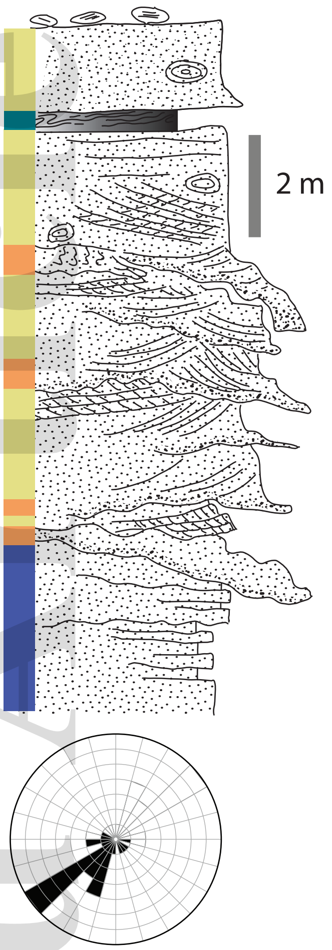
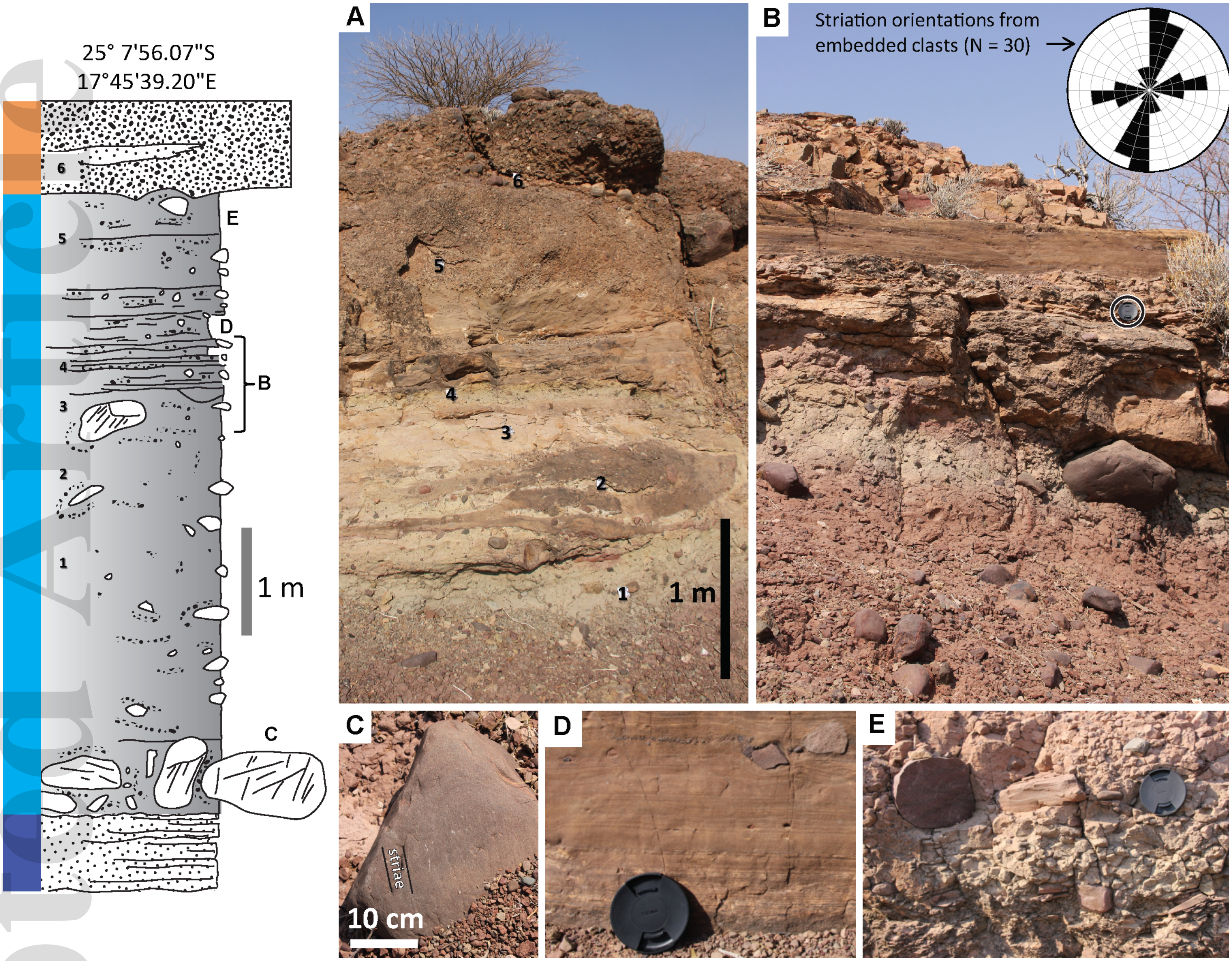


Figure 5



dep2_163_f6.tif

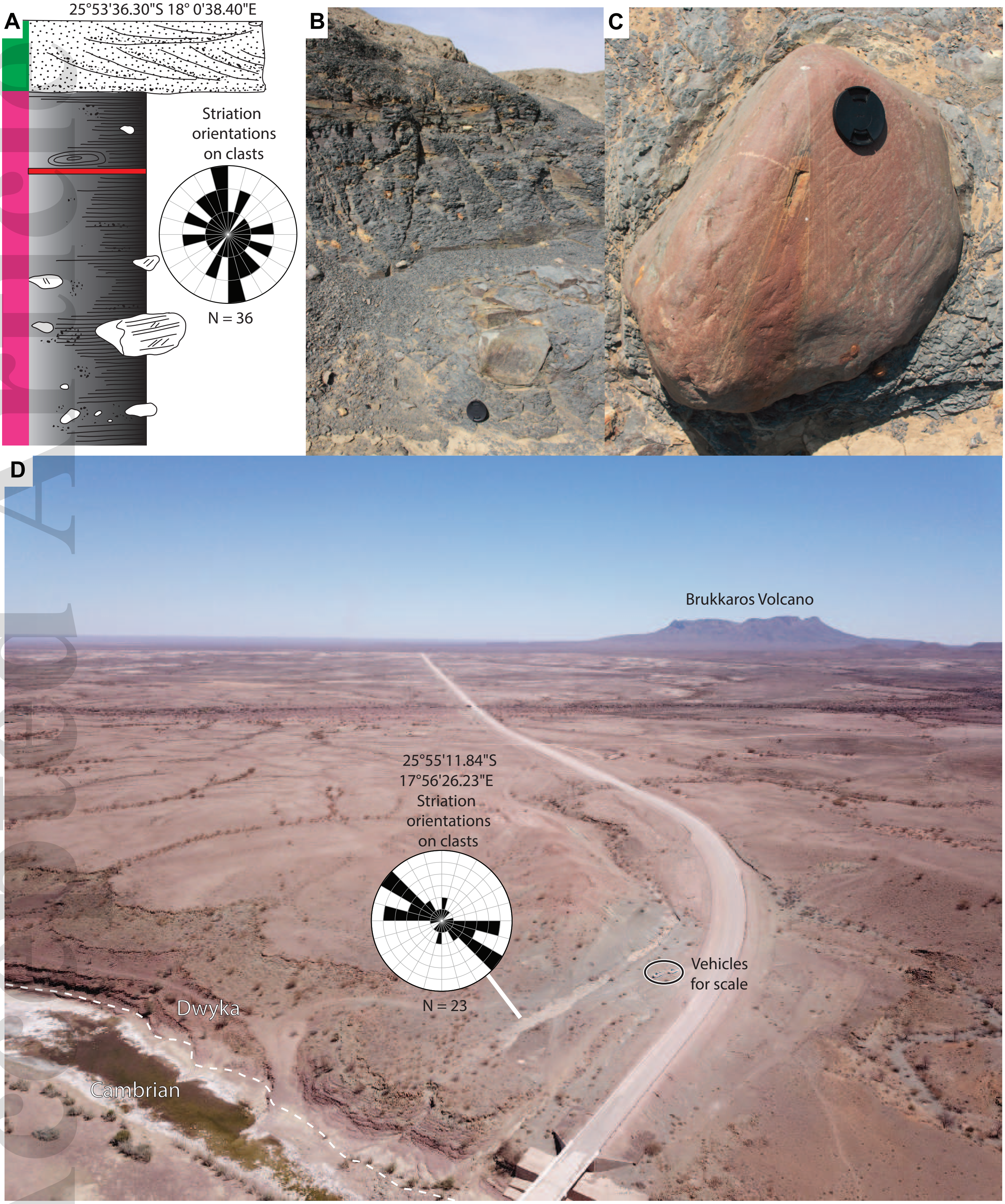
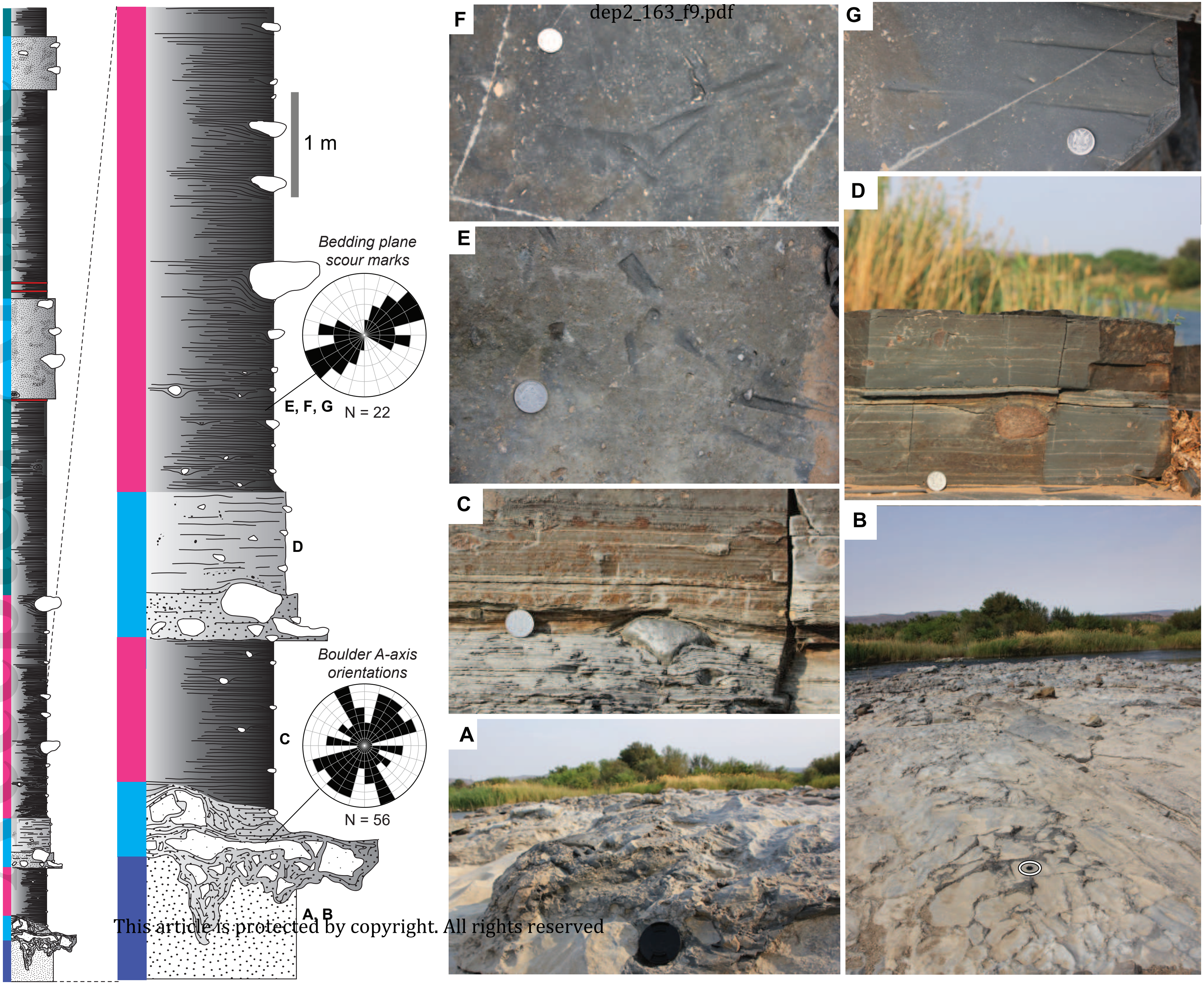

A
25°53'36.30"S 18° 0'38.40"E
Striation
orientations
on clasts
N = 36
B
C
D
Brukkaros Volcano
25°55'11.84"S
17°56'26.23"E
Striation
orientations
on clasts
N = 23
Vehicles
for scale
Dwyka
Cambrian

Figure 7

dep2_163_f8.tiff


1 m
Bedding plane scour marks
E, F, G
N = 22
D
Boulder A-axis orientations
C
N = 56
A, B
F
G
E
D
C
B
A