We are eager to understand more about the setting of deposition and deformation of the Pakhuis Formation and “Fold Zone” and welcome the contribution of Blignault and Theron (2010). The presentation of this data in peer-reviewed form is a major contribution to the regional understanding of the Ordovician southern-hemisphere glaciation. However, we wish to comment on a few aspects of the sedimentology and deformation model presented by Blignault and Theron (2010). We wish to make several points with this discussion:

1. To interpret the kinematics of the “Fold Zone” deformation, it is necessary to look at the three-dimensional geometry of the structures. Two-dimensional cross sections are insufficient as multiple fold styles can produce the same appearance in cross-sectional view.

2. The three-dimensional shape of the Fold Zone features (pod folds), as described by Backeberg and Rowe (2009) and Blignault and Theron (2010), are morphologically indistinguishable from fluid expulsion structures well known from the geologic record and experiments. They are readily distinguishable from folds formed by buckling of a cohesive sedimentary layer (as suggested by Blignault and Theron, 2010), which are typically cylindrical.

3. The primary geometry of the Sneeukop Member massive sandstone/diamictite is completely unconstrained. Since it never outcrops independent of the Fold Zone deformation, it is impossible to decouple from the synformal fold structures and an integrated model of deposition and folding is viable.

4. The subaerial sediments of the Pakhuis Pass Type Locality are differentiated from the marginal- to submarine facies in the rest of the aerial extent of the Pakhuis Formation and, although these are lateral facies changes and probably roughly time equivalent, the mechanisms for soft sediment deformation must be treated separately (e.g. basal ice striated surfaces in the Pakhuis Pass section are environmentally distinct from the subaqueous Fold Zone deformation).

5. Finally, we make a few observations about the sedimentology and ice-indicating features previously reported in the Sneeukop Member of the Pakhuis Formation.

We concur with the previous researchers who identified an ice-influenced palaeoenvironment for the Pakhuis Formation, but object to the assertion of Blignault and Theron (2010) that the Fold Zone affecting the uppermost Peninsula Formation and the Sneeukop Member of the Pakhuis Formation was deformed due to loading and horizontal shearing beneath an ice sheet. We reiterate the arguments put forth in Backeberg and Rowe (2009) for reinterpreting the Fold Zone as a basin-wide sediment fluidization event affecting shallowly buried sediments. The bulk strain recorded in the Fold Zone is clearly one of compaction and vertical extrusion and very little horizontal shear strain is recorded by the folds. Therefore it is inconsistent, from a kinematic perspective, to attribute the folding to imposed horizontal shear stress from the flow of an overlying ice sheet as proposed by Blignault and Theron (2010).

The descriptions of the morphology of the folds are very consistent throughout the history of published research on the Fold Zone. Rust (1967) thoroughly documented the shape of what he called “pod folds” due to the typical doubly-plunging form of these non-cylindrical synclines. He reports a variety of shapes and scales of folds, ranging from “... small, tightly folded structures ... to medium-sized, open or steep folds ... to egg-shaped folds, of which some are of enormous dimensions.” (Rust, 1967, p. 41). He also noted the common observation of overturning, or encircling of the pod folds by plastically attenuated bedding of the Peninsula Formation and that for all but the scale of the deformation the folds look morphologically identical to ball-and-pillow soft-sediment deformation structures.

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Further documentation by Blignault (1970) substantiated these morphological observations.

**The morphology of the Fold Zone must be considered in three dimensions**

Two models have recently been suggested for the origins of the Fold Zone. Backeberg and Rowe (2009) proposed a giant load cast origin (Figure 1(a)) and Blignault and Theron (2010) proposed sub-ice sheet buckling (Figure 1(b)). The similarity of the figures in the two papers is striking, but the key distinction lies not in the cross-sectional view (Y-Z plane of Figure 1(a)), which can be similarly produced in both models, but in the map view or on two mutually perpendicular cross sections, simultaneously. The load cast interpretation of Backeberg and Rowe (2009) predicts that a cross-sectional view in any orientation would look similar, showing pod-shaped synclines separated by upward extrusions of fluidized sandstone (of different dimensions depending on the local aspect ratio of the pod folds). In contrast, the buckling model of Blignault and Theron (2010) suggests that a cross-sectional view along the fold axes would show little or no deformation (Figure 1(b)).

In plan view, the load cast model predicts closed elliptical or bean-shaped closed rings of bedding planes with limited long-axis extent of each individual fold, while the buckling model predicts axial trace exposures perpendicular to the flow of ice with an essentially unlimited long axis. Certain patterns of cuspite upwellings separating lobate basins or doubly plunging synforms is expected in the load cast model. The buckling model, if strictly defined, would predict symmetry between anticlines and synclines. With sufficient field observations, it should be easy to distinguish between the two geometric models.

Finally, we wish to point out that the strain model presented in Blignault and Theron (2010, Figure 22) is not internally consistent. In the first (top) diagram, the authors suggest horizontal shortening in the direction of “compressional ice flow”, but the intrusion of sandstone from below in planar dykes perpendicular to this orientation actually suggests extension parallel to their “z” axis. They describe maximum extension “x” parallel to the fold axis. This is not consistent with the top diagram, which shows no strain parallel to “x”, nor is it consistent with the bottom diagram, an apparent cross-sectional view, in which the “x” axis is sub-vertical and perpendicular to the “fold axis”, parallel to the direction of flow of the fluidized sand. This diagram is actually consistent with our bottom diagram, showing predominantly vertical flow.

**Documented three-dimensional shape of Fold Zone features resembles load casts, not folds formed by buckling.**

**The third dimension as seen in plan view**

Steep-walled Kloofs present cross-sectional views through the entire thickness of the Fold Zone throughout the north to south trending mountain ranges...
Figure 2. (a) Sedimentary fluid escape structures (asymmetric load casts and deflected flame structures) in turbidite sandstones of the Pigeon Point Formation, central California, United States of America. Sketch of photo is included in lower right corner. Photo courtesy of Dr Katherine Snell. (b) Experimental load structures formed by unconsolidated sediment fluidization (Owen, 1996, Figure 7). Compare to cross-sections across the Fold Zone at (c) De Trap (Blignault and Theron, 2010, Figure 10) and (d) De Balie (Backeberg and Rowe, 2009, Figure 3).
north of Cape Town. These cross-sections can be compared to the cross-sectional view of known load cast structures (Figure 2(a) to 2(d)). Figure 2(a) shows sand-in-sand load casts and flame structures typical of those found world-wide in bedded sediments, while Figure 2(b) shows load casts formed experimentally by the fluidization of unconsolidated sediments (Owen, 1996). Two examples of Fold Zone structures are shown here for comparison: Figure 2(c) from Blignault and Theron (2010) and 2(d) from Backeberg and Rowe (2009). Morphologically, all four examples share common attributes, especially the cuspate-lobate shape, upward antiformal deflection of the bedding of the lower, fluidized layer which decays in intensity downsection to coherent bedding, and concentric deformation of the sandstone beds within the load cast. Regardless of the overall stress regime responsible for the folding, the proximal process must have included significant contributions from both flexural slip and plastic flow to establish the final fold shape. In Figure 2(a), the core of the loadcasts is unstratified, unsorted coarse sandstone containing tabular intraclasts of fine-grained sandstone. The alignment of the intraclasts is concentric to the edge of the load cast, demonstrating the deformation and viscous attenuation of the sandstone bed as it sagged into the underlying fluidized sediment. This creates a steep clast axis plunge distribution, with a roughly radial

Figure 3. (a) Sedimentary fluid escape structures (asymmetric load casts seen from below the deformed bed, in plan view) in turbidite sandstones of the Laingsburg Formation, near Laingsburg, Western Cape, compared to plan view of pod folds at De Balie (Backeberg and Rowe, 2009, Figure 2) and at De Trap (Blignault and Theron, 2010, Figure 8).
distribution of bearing of clast axes (with no preferred bearing, similar to the “steeply dipping macrofabric” described by Blignault and Theron (2010, Figure 4)).

For comparison in plan view, we present Figure 3(a), which shows the underside of a sandstone bed in the Laingsburg Formation, near Laingsburg, Western Cape. The bed was subject to soft sediment deformation and the load casts which formed along the base of the sandstone bed are exposed while the softer mudstone layer which formed the complimentary flame structures is now eroded away. This exposure allows us to look at the plan view morphology of a bedding plane deformed by load casts, keeping in mind that this is the underside of the bed.

A first order observation is that the individual load casts are locally consistent in amplitude and curvature, but quite variable in terms of their long axis dimension. Although the short axis is similar across the image (a bit larger than the finger for scale at the left side), a few of the individual load casts are equidimensional but most are elongate with aspect ratios of about 2 to 5. We can also determine that the long axis of the load casts in this image are generally trending in the current direction (based on the orientation of the large ripples on which the load casts are superposed) but note that there is considerable scatter in orientation.

Backeberg and Rowe (2009) present the results of detailed mapping of a bedding-plane surface exposure of the top of the Fold Zone at De Balie (Backeberg, 2008). The map surface is curved as it outcrops in the hinge and western limb of a large-scale Cape Fold anticline (Figure 3(b)). The map shows several pod folds consisting of elliptical or bean-shaped bodies of Sneeukop massive sandstone, surrounded by concentric steeply-dipping to overturned beds of cross-bedded Peninsula Formation sandstone. Linear ridges of massive sandstone intervene; in our model we consider these to be mega-flame structures or upward extrusions of sand derived from a fluidized layer below the pod folds (Backeberg and Rowe, 2009). The pod folds vary from equidimensional to elongate and the ridges between them are discontinuous and sinuous.

The map pattern at De Trap presented by Blignault and Theron (2010, Figure 8) (Figure 3(c)) is very similar to our map at De Balie. The map, adapted from Blignault (1970), shows doubly-plunging non-cylindrical fold axes anastomosing around equidimensional to elongate pods of the Sneeukop Member.

**Structure and kinematic models**

The doubly-plunging shape of the synformal pod folds indicates three-dimensional strain, which is not accommodated in a simple two-dimensional buckle-folding model, as shown by Blignault and Theron (2010). The authors discuss the presence of flutes and striations on the stratigraphic surfaces of the deposits, and present these as evidence of ice flow direction. However, Backeberg (2008) reported radial striations on the folded stratigraphic contacts in pod folds at De Balie. These are clearly related to flexural slip in folding of semi-elastic (therefore likely frozen or partially consolidated) sediments and their orientation reflects local shear tractions during deformation, clearly not the regional transport direction of a palaeo-ice flow. Blignault and Theron (2010) do not distinguish between local and regional control on striations. Likewise, the shortening estimations of Blignault (1981) utilize techniques which assume elastic (non-attenuated) bedding lengths for restorability. These techniques over-estimate shortening by unconstrained degrees of error when applied to layers where plastic attenuation is already well documented (see Rust, 1967).

As reported by Carreras et al. (2005), folds formed during shear strain show distinctive morphological characteristics including rotation of the axial plane toward the plane of shear, increasing asymmetry, and with high enough shear strain, flattening into sheath folds with the long axes pointing in the direction of viscous flow. No folds of this morphology have been described by any previous work on the Fold Zone.

Folds and deformation features formed by fluidization of unconsolidated sediments are thoroughly documented in the literature (e.g. Owen, 1996; Rowe, 1975; Moss and Howells, 1996; Moernaut et al., 2009). Owen (1996) described the formation of laboratory produced and natural load structures in sand-sand interfaces and noted that “fluidization developed locally within the lower layer and that deformation driven by water escape was superimposed forming water-escape cusps”. These “water-escape cusps” disrupt the antiformal hinges between load structures (a common observation in the Fold Zone pod folds throughout all previous studies (e.g. Rust, 1967; Blignault, 1970; Backeberg and Rowe, 2009; Blignault and Theron, 2010). Moernaut et al. (2009) describe large-scale pod-shaped sedimentary structures in lake sediments, detected by disruption of the seismic horizons, formed by expulsion of fluidized sediments from the subsurface. These fluidization structures produce similar plan view geometry (Moernaut et al., 2009, Figure 9) to that of the Fold Zone (Figure 3(c) and Figure 3(b)). Moernaut et al. (2009) interpret their origin as catastrophic fluidization, triggered either by volcanic debris flows entering the lakes or by local or far-field seismic shaking.

**Original geometry of the Sneeukop Member is unconstrained**

Blignault and Theron (2010) state that “Prior to the onset of folding, the Sneeukop Diamictite was probably a sheet-like deposit of about 6 m in thickness.” No data is presented to support this key assertion, but the initial geometry of the Sneeukop Diamictite is crucial to the interpretation of strain accommodated by the folding (as explicitly discussed by Backeberg and Rowe, 2009). Everywhere that the Sneeukop diamictite member is observed, it occurs in pods and irregular basinal bodies within the synformal cores of folded Peninsula strata,
and is cut on the upper surface by a regional unconformity (e.g. Blignault and Theron, 2010). In our opinion, it is not possible from any of the currently available observations to determine the initial geometry of the Sneeukop Member, and the variable thickness of the Fold Zone (as reported by Blignault and Theron, 2010) implies regional heterogeneities across the study area. However, Blignault and Theron (2010)'s interpretation of buckling folds depends critically on this unsupported statement.

Lateral facies changes suggest subaerial deposition in Pakhuis Pass; subaqueous deposition and deformation further south

As discussed by Backeberg and Rowe (2009), and consistent with the reports by previous workers (e.g. Rust, 1967; Blignault, 1970), the sedimentary facies present in the glacial to glaciomarine Pakhuis Formation vary laterally over the outcrop area. In the Type Section in Pakhuis Pass, there is compelling evidence for terrestrial to shallow marine deposition. The conglomeritic sandstones display fluvial sedimentary structures and locally imbricated and well-sorted clasts. This contrasts to the Sneeukop member through most of the outcrop area to the south of Pakhuis Pass, which is a "diamictite" or unbedded massive sandstone with random pebbles. In fact, our observations show that the Sneeukop sandstone is extraordinarily similar to the Peninsula sandstone. Figure 4, for comparison, shows photomicrographs of typical samples of Peninsula and Sneeukop sandstones, and the Dwyka Group glaciomarine diamictite. The Peninsula Formation sandstone is primarily composed of ~0.5 mm rounded to angular quartz grains with an increased clay matrix fraction, which may have acted to inhibit overgrowth cement by armoring the quartz grains during diagenesis. Both samples were collected at De Balie.

The Sneeukop Member sandstone is also composed of ~0.5 mm rounded to angular quartz grains with an increased clay matrix fraction, which may have acted to inhibit overgrowth cement by armoring the quartz grains during diagenesis. Both samples were collected at De Balie.

For comparison, we also show a local example of a true glaciomarine diamictite from the Dwyka Group (Laingsburg, Western Cape). The Dwyka example is a matrix-dominated, matrix-supported rock with very angular and immature clasts. The matrix is a very fine silt, derived from glacially produced rock flour. Clasts of diverse rocks representing the large catchment area of an ice sheet are matrix supported, and variable in size and transport distance from their source areas. The development of large volume of clay-sized grains of quartz and feldspar is a peculiar characteristic of glacial erosion, present today in sub-ice sheet and glacial outwash settings. Evans and Pudsey (2002) define the characteristics of sub-ice sheet and proximal glaciomarine sedimentary facies in the modern depositional environments of the Antarctic Peninsula. All the facies observed in these environments are mud-dominated and contain significant tectosilicate rock flour (Evans and Pudsey, 2002, Figure 3), which is a signature of ice erosion, and has been found in the "post-glacial" Soom Shale (Gabbott et al., 2010). This grain fraction is rare or essentially absent in the Sneeukop Member, suggesting that very little of the source area was actively eroded by ice. Rather, the dominant grain similarity to the underlying Peninsula sandstone seems to imply that the Sneeukop member was derived from the same source area, or from the semi-consolidated Peninsula sand itself. This similarity was also noted by Rust (1981), who attributed the

Figure 4. Thin section comparison of Peninsula Formation (Left), Sneeukop Member (Centre) and Dwyka diamictite (right). Top vs bottom rows are ppl vs xpl views respectively.
Sneukkop sediments to originate from water-worn beach sediments that were sourced by the migrating ice sheet. We assert that proximal sedimentary source and limited subsequent reworking, are consistent with submarine debris flow origins. The current geometry is more consistent with debris flow lobes or fans spreading out, subaqueously, over the partially consolidated Peninsula sand, than it is with the in situ deformation of a planar, continuous bed of foreign, far transported glacial sediment.

A number of unsubstantiated assertions respecting the palaeoenvironment are presented by Blignault and Theron (2010). For example, the authors state that: “A temperate thermal environment is inferred from:
1. subglacial meltwater drainage features; and
2. Basal erosion implying decoupling of the ice-bed interface.” We argue that
a. neither of these features imply a temperate thermal environment, as both features are present under modern polar ice sheets where melting may occur at high pressure and low temperature or during drainage through ice-sheet plumbing systems; and
b. basal erosion requires slip at the ice bed, a condition that conflicts with the authors’ assertion of shear stress translation to 10s to 100 metres depth in the bed.

The non-systematic thickness (as reported by Blignault and Theron, 2010, Figure 6) and the non-continuous occurrence of the Fold Zone (“...zone of deformation changes to a zone of non-deformation within 300m...”; Blignault and Theron, 2010, p.340) argues against consistent deformation beneath a regional ice stream.

Features in the Sneukkop Member, Pakhuis Formation, which give direct evidence of ice processes

Many of the descriptions provided by Blignault and Theron (2010) used to support the subglacial setting of the Fold Zone development, such as striated, faceted and polished pebbles (Blignault, 1970), suggest to the reader that these observations are plentiful. We do not disregard the presence of faceted and striated pebbles in the diamictite; however, no typical “ice-striated” pebbles were found at De Balie during our study (Backeberg, 2008; Backeberg and Rowe, 2009).

In other localities many striated clasts are not found on ice-bed surfaces, and could be reworked clasts or ventifacts, and many examples we have found are bull quartz pebbles with a weak pressure solution cleavage that leads them to cleave in flat planes/pseudofacets. This feature explains known observations of parallel facets: Rust (1967): “...the erratics are frequently faceted on opposite sides and then look like flattened buns.” We invite readers to test the existence of a pre-existing cleavage in the quartz pebbles by smashing them with a hammer to see the facet-parallel fracture.

While the Ordovician palaeo-environment of the Cape Basin was certainly cold and potentially ice-influenced, our observations do not support previous reports of an ice sheet in this region, and we believe that previously published observations are also better explained by our model than by a model of a regional ice sheet. As the Pakhuis Formation has provided the only data point for connecting the abundant evidence of major glaciation in North Africa across to the southern part of the continent (e.g. Young et al., 2004; van Staden et al., 2010; Sutcliffe et al., 2000), the palaeoenvironmental interpretation is of global importance.

Concluding remarks

We hold that the data presented by Blignault and Theron (2010) is not only consistent with the data presented by Backeberg and Rowe (2009), but it is also more fully explained by a model of the Fold Zone as a large load-cast horizon (as originally hypothesized as ball and pillow structures by Rust, 1981, and expanded by Backeberg and Rowe (2009)). We regret that Blignault and Theron (2010) chose not to discuss the comparison between their interpretations and our previously published model, and hope that with this discussion we can initiate further conversation to elucidate the history of the globally unique Fold Zone, which is a crucial point for palaeo-climatic interpretations of the Ordovician glaciation.

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