STRUCTURAL GEOLOGY OF ROBBEN ISLAND: IMPLICATIONS FOR THE TECTONIC ENVIRONMENT OF SALDANIAN DEFORMATION

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ABSTRACT
We present a detailed structural and lithologic map of Robben Island, offshore Cape Town, South Africa. Robben Island is underlain by the Tygerberg Formation, part of the Neoproterozoic to early Cambrian Malmesbury Group of the Saldania Belt. The depositional setting and structural history of the Tygerberg Formation are poorly constrained due to limited outcrop and lack of previous structural studies.

Sedimentary structures are indicative of deposition at relatively high rates in a high energy environment and we concur with previous workers that deposition occurred on turbidite fan systems in a tectonically deepening basin. By comparison with active and ancient examples, we suggest that a forearc or trench slope, supra-subduction zone basin is a possible match to the setting of the Tygerberg Formation. However, limits on preservation and insufficient age data prevent comparisons in basin geometry and deposition rates which could be used to test depositional setting with more certainty.

Northwest-southeast striking subvertical pressure solution cleavage is pervasive throughout the exposures. Upright folds, with axial planes parallel to the cleavage, plunge 10 to 15° to the northwest or southeast with approximately 20° variation in trend azimuth. The folds are limited in along-axis extent and often occur in asymmetric pairs. Subtle bedding-parallel shear zones divide folds of different plunge directions. This pattern of folds is consistent with experiments and observations of en echelon folding during distributed strain associated with oblique transpression. This finding is consistent with previous studies of parallel, slightly earlier orogenic belts to the north (Gariep and Kaoko Belts) although our observations do not allow us to distinguish whether transpressional strain was sinistral or dextral. Sinistral transpression is considered more likely given the dominantly sinistral strike-slip history on the nearby Colenso Fault and the southward migration of collision along the western margin of Africa during the late Neoproterozoic to early Cambrian.

Introduction
The Saldania Belt is one of several deformed belts of “Pan-African” age recording the closure of the Adamastor Ocean with the construction of southwestern Gondwana (Frimmel and Fölling, 2004), collectively referred to as the Brasiliano Orogeny (e.g. Cawood and Buchan, 2007, and references therein) or Adamastor Orogeny (Goscombe and Gray, 2008). In southern Africa, these belts are represented by the Kaoko Belt in Namibia, the Gariep Belt in Namibia/South Africa, and the Saldania Belt in South Africa. Dextral transpression along northwest-striking, east-ramping thrusts has been suggested for parts of the Gariep Belt (Hüblrich and Alchin, 1995), where sheath folds also suggest a strong component of shear-parallel extrusion. The Kaoko Belt displays highly oblique sinistral shortening (Goscombe et al., 2003; Goscombe and Gray, 2008). The Saldania Belt has not been subject to the same level of structural investigation, due largely to relatively poor exposure.

As noted by Rozendaal et al. (1999), the deformation of the Saldania Belt is not consistent with a “proper collisional orogeny”. The Saldania Belt is represented in the Western Cape by two terranes: the inland, slightly higher grade Swartland Terrane and the coastal Malmesbury Terrane (Figure 1; Belcher and Kisters, 2003). Belcher and Kisters (2003) gave a detailed overview of structural fabrics in the Swartland Terrane (northeast of the Colenso Fault, Figure 1) and showed that transposed fabrics therein were formed by high shear strains. Belcher (2003) suggested that a subduction trench active during the complex, multi-phase closure of
Figure 1. Regional geologic map, Cape Town area, South Africa. Redrawn from Belcher and Kisters (2003) with additional geology from Scheepers (1995). Sources for igneous ages: 1 = Scheepers and Armstrong (2002); 2 = Scheepers and Poujol (2002); 3 = Da Silva et al. (2000); 4 = Jordaan et al. (1995); 5 = Armstrong et al. (1998). Da Silva et al. (2000) also reported an age of 536 ± 5 Ma for the Robertson I-type granite (east of the map area) which is the only recent age data available for the I-type suite. Additional previous dates by Rb-Sr or Pb-Pb methods are not used in this study. Inset: study location (grey box) relative to African continent. Borders of South Africa, Namibia, Swaziland and Lesotho are shown.
the Adamastor Ocean could provide an appropriate model in which deposition of deep-marine sediments, and structures relating to high-shear strain, could be roughly co-evol and therefore a good match to his observations of the Swartland Terrane. The Colenso Fault is a poorly exposed strike-slip fault with a complex strain history comprising a reversal from sinistral to dextral motion during rapid regional exhumation at 540 Ma (Kisters et al., 2002). The Malmesbury Terrane, mostly represented by the Tygerberg Formation, has never been the subject of a similarly detailed and regionally extensive structural study.

With this contribution we aim to document the detailed structures within the Tygerberg Formation exposed on Robben Island and compare the sedimentary facies and structures to the proposed environments of deposition and deformation.

**Geologic setting of Robben Island**

Robben Island is a World Heritage site of tremendous importance to South Africa in terms of both human and natural history. The coastline of the island (Figure 1) provides a unique opportunity to observe the structural fabrics of the Neoproterozoic to Cambrian Saldania Belt. The tectonic history of the Saldania Belt is poorly understood. The belt is composed of low-grade (low greenschist and below) metasediments of the Malmesbury Group (Hartnady et al., 1974). The depositional age is not well constrained but a few detrital zircon dates suggest that the sediments range from 750 to 560 Ma (Armstrong et al., 1998). Rozendaal et al. (1999) described the Saldania Belt rocks as marine sediments deposited in a deepening basin. The Malmesbury Group was divided by Hartnady et al. (1974) into three tectonic terranes separated by the Colenso Fault and the (inferred) Piketberg-Wellington Fault. Detailed field mapping by Belcher and Kisters (2003) revised the stratigraphy by demonstrating that the eastern terranes (Swartland and Boland Terranes of Hartnady et al. (1974)) are overlain, either structurally or unconformably, by the western Malmesbury Terrane, represented in coastal outcrops by the Tygerberg Formation. The Swartland Terrane is deformed by broad regional doubly-plunging anticlinoria, with higher metamorphic grade (up to biotite-bearing schists) in the center of the folds. Most of the Swartland Terrane is chlorite-white mica schists and psammites with strong shear fabrics transposing bedding, overprinted by horizontal shortening. The Malmesbury Terrane is dominated by fabrics suggesting significant horizontal shortening. Although the contact is nowhere exposed, Belcher and Kisters (2003) and Belcher (2003) inferred a depositional unconformity based on the strong shear fabrics of the Swartland Group which are absent from the Malmesbury Group, the presence of Swartland-derived vein quartz clasts in the Piketberg formation which forms the base of the Malmesbury Group, and the horizontal shortening which represents the latest deformation of both groups.

The Saldania Belt is intruded by the Neoproterozoic to Cambrian Cape Granite Suite (Figure 1). Complicating structural interpretations, these units were later involved in the Carboniferous-Permian Cape Orogeny (Frimmel et al., 2001). The Cape Granites are spatially separated into a seaward belt of locally tectonised S-type granites and a landward belt of undeformed I-type granites (Scheepers, 1995). Available dates are suggestive of a southward-younging trend in the S-type granites although the resolution of the ages is not sufficient to confirm this trend (Figure 1). Post-tectonic A-type granites and ignimbrites occur in both terranes (Scheepers, 1995). The granites and their intrusive contacts appear to be undeformed during the Cape Orogeny, and they clearly crosscut pre-existing folds and foliations in the Saldania Belt meta-sediments although the resolution of the ages is not sufficient to confirm this trend (Figure 1). Post-tectonic A-type granites and ignimbrites occur in both terranes (Scheepers, 1995). The granites and their intrusive contacts appear to be undeformed during the Cape Orogeny, and they clearly crosscut pre-existing folds and foliations in the Saldania Belt meta-sediments although the resolution of the ages is not sufficient to confirm this trend (Figure 1). Post-tectonic A-type granites and ignimbrites occur in both terranes (Scheepers, 1995). The granites and their intrusive contacts appear to be undeformed during the Cape Orogeny, and they clearly crosscut pre-existing folds and foliations in the Saldania Belt meta-sediments although the resolution of the ages is not sufficient to confirm this trend (Figure 1). Post-tectonic A-type granites and ignimbrites occur in both terranes (Scheepers, 1995). The granites and their intrusive contacts appear to be undeformed during the Cape Orogeny, and they clearly crosscut pre-existing folds and foliations in the Saldania Belt meta-sediments although the resolution of the ages is not sufficient to confirm this trend (Figure 1). Post-tectonic A-type granites and ignimbrites occur in both terranes (Scheepers, 1995). The granites and their intrusive contacts appear to be undeformed during the Cape Orogeny, and they clearly crosscut pre-existing folds and foliations in the Saldania Belt meta-sediments although the resolution of the ages is not sufficient to confirm this trend (Figure 1). Post-tectonic A-type granites and ignimbrites occur in both terranes (Scheepers, 1995). The granites and their intrusive contacts appear to be undeformed during the Cape Orogeny, and they clearly crosscut pre-existing folds and foliations in the Saldania Belt meta-sediments although the resolution of the ages is not sufficient to confirm this trend (Figure 1). Post-tectonic A-type granites and ignimbrites occur in both terranes (Scheepers, 1995). The granites and their intrusive contacts appear to be undeformed during the Cape Orogeny, and they clearly crosscut pre-existing folds and foliations in the Saldania Belt meta-sediments although the resolution of the ages is not sufficient to confirm this trend (Figure 1). Post-tectonic A-type granites and ignimbrites occur in both terranes (Scheepers, 1995). The granites and their intrusive contacts appear to be undeformed during the Cape Orogeny, and they clearly crosscut pre-existing folds and foliations in the Saldania Belt meta-sediments although the resolution of the ages is not sufficient to confirm this trend (Figure 1). Post-tectonic A-type granites and ignimbrites occur in both terranes (Scheepers, 1995).
Sandstones

The sandstones of the Tygerberg Formation outcrop on the east and west-northwestern coasts of Robben Island (Figure 2). They are tan to light grey in colour, corresponding to slight changes in composition, although they tend to discolour into a darker brown with weathering. In general, the Tygerberg Formation sandstone is medium to coarse grained. Bedding thickness is typically in the range of 10 to 30 cm but reaches 50 cm locally in the northwest corner of the island. Orthogonal joints cut the sandstones in three major orientations: north to south, east to west and northwest to southeast (Figure 3A). Grey-green reduction stains may be observed on the surfaces of these sandstones and are concentrated along the joint surfaces. Spheroidal weathering between joint surfaces is a characteristic feature of the outcrop appearance (Figure 3A). Where bedding and cleavage are sub-

Figure 2. Generalized lithologic map of the rock type distributions and major structures within the Tygerberg Formation on Robben Island. Locations of field photos in Figures 3, 4 and 6 are indicated.
parallel and cleavage is closely spaced, the sandstones may take on a slaty appearance but bedding structures are still very well preserved. Parallel lamination and trough cross-bedding are common. Discrete intervals of convolute bedding (also reported by Nakashole, 2004) are locally present and sometimes deformed by widely-spaced pressure solution cleavage (Figure 3B). In general, pressure solution cleavage in the sandstones is weaker and more widely spaced than in the more pelitic units of the Tygerberg Formation. The spacing and orientation of cleavage planes varies with bedding thickness and with slight, often gradational variations in grain size and clay content (Figure 3C). Sand-filled burrows were reported by Nakashole (2004), suggesting active bioturbation in these facies, although this study did not confirm these observations.

The sandstones are similar to Facies A of Von Veh (1982), who interpreted the mechanism of deposition as fluidization, grain flow or high density turbidity currents. The frequency of convolute bedding horizons suggests high rates of deposition and burial.

**Interbedded shales and greywacke/siltstones**

The siltstones of the Tygerberg Formation are darker in colour than the sandstones and contain metamorphic chlorite and diagenetic or metamorphic pyrite (Mbangula, 2004; Nakashole, 2004). The greywacke grain fraction contains sub-rounded to angular lithic,
Figure 4. Features of dark grey slates. (A) Combined ripples in dark grey slates, Jan van Riebeeck Quarry. (B) Rip-up clasts of light-coloured siltstone in fine dark grey slates, Jan van Riebeeck Quarry. Clasts are weakly oriented with long axis approximately horizontal across photograph. Median axis is approximately up-down. Clasts are highly flattened perpendicular to cleavage in the third dimension. (C) Fine-scale planar lamination and convolute slump textures in dark grey slates, Jan van Riebeeck Quarry. Diameter of pen is 12 mm. (D) Pressure solution cleavage in dark grey slates, Jan van Riebeeck Quarry. Left edge of photo is annotated to show scoured bedding surfaces (sub horizontal, solid white lines) and pressure solution cleavage (dashed white lines). Gradations within each bed correspond to changes in orientation and spacing of cleavage creating anastomosing geometries. General regions of closely and broadly spaced cleavage (relatively speaking) are indicated. Repetitive graded beds result in closely spaced cleavage transitioning toward increasing spacing upsection. Bedding is upright as shown by the subtle crossbedding. (E) Anastomosing slaty cleavage seen intersecting the plan of the bedding surface, Jan van Riebeeck Quarry. Pen is 12 mm in diameter and points toward the northwest. Dashed white lines on left side of photo annotate cleavage-beding intersection lines showing gently wavy, anastomosing geometry. (F) Stereonet plot of axial planar pressure solution cleavages from all across Robben Island (n=107). Mean cleavage plane shown, circle around mean pole indicates 95% confidence cone.
Figure 5. Structural map of the Tygerberg Formation outcropping on Robben Island. Aerial photography acquired in 2008 generously provided by Chief Directorate: National Geospatial Information (DMC job 5318C 2008 1274). Inset (A) Cleavage fanning in meso-scale cylindrical fold. Stereonet shows X-diagram solution for fold axis from bedding measurements. Star symbol = fold axis (15/122). Inset (B) Adjacent but oppositely plunging folds separated by cryptic, bedding-parallel wrench surface. Bedding is continuous from each axis out to the wrench fault, the position of which is restricted to a 1.5 m-wide limb-parallel zone with minor bedding deflection and no noticeable brittle damage zone on either side. Wreck of the 60 m Sea Challenger for scale. (C) Stereonet plot of meso-scale fold axes across Robben Island (n=18). Each fold axis was calculated using a minimum of 4 bedding attitudes representing both limbs, although spatially detailed data has been omitted from the map (Figure 5) for clarity. (D) Block diagram shows the sense of rotation on a typical Mode II fault on the west coast of Robben Island.
feldspar and quartz grains in a clay-rich matrix. Typically, the silstones are interbedded with greywackes and slight cleavage refraction is observed across lithologic contacts. These silstone/greywacke intervals are 1 to 20 cm thick, separated by thin shale beds. Differential erosion of the shale beds is common along the coastline, resulting in excellent bedding plane exposures in the axial region of 10’s of metres-scale folds (Figure 3D). These strata are similar to Facies B defined by Von Veh (1982), who interpreted them as deposited by turbidity currents in a “proximal” setting.

**Dark grey slates**

Dark grey fine-grained slates outcrop on the southern tip and northwestern corner of the island and were quarried at Jan van Riebeek Quarry in the south and Bangatir Quarry in the north (Figure 2). Delicate sedimentary and soft-sediment deformation features are common, including combined ripples and bidirectional cross-bedding (Figure 4A), sinusoidal ripple lamination, graded bedding, formsets of ripple-drift cross laminations, regular cross laminations, light grey rip-up clasts (Figure 4B), and delicate soft-sediment deformation structures (e.g. Figure 4C). The slates have gently anastomosing cleavage, which refracts slightly across bedding when cutting at a high angle (Figure 4D). The cleavage-bedding intersections as viewed on the bedding surface (Figure 4E) are also anastomosing and variable in spacing.

This lithology is consistent with Facies D of Von Veh (1982), who also noted very fine laminations alternating between dark (clay rich) and light (silt rich) as well as the delicate sedimentary structures characteristic of fluid escape processes.

**Dolerite dyke**

A single dolerite dyke occurs on Robben Island. The dyke is similar in lithology and orientation to the local Cretaceous (132 ± 5 Ma) False Bay dyke swarm (Reid et al., 1991). The dyke is tabular and trends east-southeast to north-northwest across the south coast of the island, crosscutting bedding and cleavage in the Tygerberg Formation. It is preferentially eroded and the contacts are not exposed. Although the dolerite does not outcrop in situ, it is abundant in boulders and cobbles within a tabular zone approximately 20 m thick (Figure 2).

**Summary**

The sedimentary units on Robben Island are dominated by turbiditic sequences (similar to the Sea Point exposures, Von Veh (1982)) and all the representative lithologies show evidence of rhythmic normal grading. Coarse sediments dominate most sections and the sediments are chemically immature. Sole marks and rip up clasts (Figure 4B) testify to high rates of sediment flow and deposition. The rate of deposition often exceeded the rate of static dewatering, as demonstrated by symmetric dewatering structures such as convolute bedding, load casts and flame structures which are present in all facies. Fine horizontal laminations are also common in all facies (Figure 4D.) Locally, bidirectional ripples and cross-bedding suggest multi-directional currents were active during deposition. Massive muddy olistostromal beds were observed at Sea Point (Von Veh, 1982), and ~8 km north of Robben Island at Silverstroomstrand (C. Rowe et al., unpublished data).

Conclusive evidence of bioturbation is rare, although sand-filled burrows were described by Nakashole (2004). The lack of fossils in the Tygerberg Formation limits the precision of palaeo-environmental interpretations. In the modern world, shallow marine environments are characterised by intense bioturbation and biological reworking. Nakashole (2004) relied on the rarity of bioturbation fabrics to prefer deep water turbidite origin over a shallower water tempestite or contourite setting for the Tygerberg Formation. However, an age constraint on the Tygerberg Formation is given by the intrusion of the Cape Granite Suite.

The nearest intrusion to Robben Island is the Peninsula Pluton cropping out at Sea Point (540 ± 4 Ma, Armstrong et al. (1998)). Globally, the widespread appearance of burrowing behaviours which contribute to bioturbation is known as the “substrate revolution” (Bottjer et al., 2000). This stratigraphic event is recorded in Cambrian shallow marine sediments worldwide. Therefore, the paucity of bioturbation in the Tygerberg Formation is not considered an indication of deep water, and the depth remains unconstrained.

**Structural features**

The structural features exposed at Robben Island are dominated by: strong vertical northwest-southeast pressure solution cleavage, asymmetric meso-scale folds, cryptic bedding-parallel shear zones (sometimes bearing quartz-cemented breccia), and east-west vertical joints and quartz veins (Figure 5).

**Pressure Solution Cleavage**

All outcrops of Tygerberg Formation on Robben Island are crosscut by strong pressure solution cleavage. The cleavage in the clay-rich lithologies is planar and parallel on a regional scale (Figure 4F) but in sandier lithologies the cleavage shows distinct local fanning around fold axes (Figure 5A). As described above, the pressure solution cleavage is locally anastomosing and refracts gently through graded beds. In general, cleavage is axial planar to the major folds and bedding parallel between fold axes. On the scale of the whole island, the cleavage is very well aligned (Figure 4F) with the mean cleavage plane oriented 330/86NE (axial planar to the upright folds.)

**Folds**

The structure of Robben Island is dominated by northwesterly and southeasterly plunging folds, which
often occur in anticline-syncline pairs (Figure 5). The half-wavelength of the folds is typically 40 ± 10m. Axial planes are upright and parallel to the regional pressure solution cleavage. The shape of fold hinges varies, with concentric folds occurring in sandier sections (e.g. Figure 3D) and increasingly similar fold morphologies observed in shalier units (e.g. Figure 4A). Asymmetry of anticline-syncline pairs generally suggests northeast vergence. Parasitic folding at scales below the meso-scale folds was only observed in one location. The folds are open to closed with interlimb angles ranging between 35 to 75°.

The eighteen mapped meso-scale folds on Robben Island are coaxial with the regional tectonic fabrics and plunge 5 to 20° in either direction (Figure 5C). The fold axes cluster in either orientation but do not define a continuous distribution in plunge angle. Folds are cylindrical and doubly-plunging folds were not observed on the island. This could be attributed to limited along-trend exposure, however, one would expect that random exposure of doubly plunging folds would produce an array of fold axes around a central mean value. Our data clearly form two discrete clusters at 10 to 15° plunge. The clusters trend in opposite directions although there is considerable scatter in trend direction. It was not possible to trace fold axes across Robben Island where they might be covered by Holocene sediments, suggesting that axial traces may not be continuous on the km-scale. This distinctive pattern will be further discussed below.

In more than one location, oppositely plunging folds are closely associated, apparently sharing roughly parallel limbs (e.g. Figure 5B). The transition zone between the two anticline axes in Figure 5B does not show a gradual rotation of bedding as would be expected if a syncline separated the antclinal hinges. Limb orientation is maintained at relatively constant curvature from both folds, up to a zone approximately 1.5m wide where bedding is not exposed. These observations suggest that the unexposed zone represents a cryptic wrench fault along bedding separating the shared limbs. A similar scissor is observed farther south on the west coast of the island (Figure 5D.)

**Faults and shear zones, quartz-cemented breccias**

The majority of faults are inferred from poorly exposed narrow zones across which bedding and/or cleavage change orientation sharply (e.g. Figure 5B described above). Although direct indications of shear sense are rare, the bedding orientation discontinuities require significant rotation along the faults. A few small faults showed quartz slickenfibres but in most cases the direction of shear is inferred from drag folding of bedding. In all cases these indicate oblique slip.

Rarely, quartz-cemented breccias are found in these zones (Figure 6A), most commonly in sandstone units although they are inferred in other lithologies by the presence of quartz-cemented breccia boulders observed in float. The breccias have a chaotic fabric and quartz veins around them are deformed (flattened and boudinaged) along the pressure solution cleavage, suggesting that these breccias are pre-to syn-shortening. Stretching direction recorded by the boudinage of these early quartz veins is parallel to the strike of the pressure solution cleavage.

At the southern end of the island, an intensely deformed breccia zone cemented by quartz indicates the presence of a brittle shear zone (Figure 6B). A tight anticline is asymmetrical toward the southwest, suggesting southwest vergence. This anticline structurally overlies an intensely veined shear zone and is interpreted as a drag fold in the hanging wall of a southwest-vergent, bedding-parallel thrust fault. This unique exposure suggests an association between the early quartz-cemented breccias and shortening by brittle faulting.

**Joints and fibrous/blocky extensional quartz veins**

Quartz veins were observed throughout the strata at Robben Island and crosscut the pressure solution cleavage and folds (Figure 6C). Veins are concentrated in the sandstone-dominated units and do not have any apparent association with fold hinges or faults. They generally strike east-west and dip steeply south, although there is quite a bit of scatter in the orientations (Figure 6D). The veins are generally blocky but locally aligned euhedral fibrous crystals are present. They plunge gently to the north-northwest, suggesting gradual oblique opening for the veins (Figure 6F). The veins are roughly parallel to the tabular Cretaceous-age False Bay dykes (only one on Robben Island; Figure 2).

These veins are therefore kinematically consistent with, and most likely associated with, Cretaceous extensional rifting coincident with the intrusion of the False Bay dykes (Reid et al., 1991).

**Environment of deposition and deformation**

The depositional environment of the Tygerberg Formation is not well constrained by previous studies, although two general themes exist in the literature: Rozendaal et al. (1999) suggest a deepening ocean/continental margin setting, and Von Veh (1982) suggests intercalation of proximal and distal distributary fans. The significant volume of turbidites implies a dynamically deepening depocentre, while the sedimentary structures imply high energy.

One possible match to these environmental conditions, and the stratigraphic relationship to the more deformed Swartland terrane, is the setting of a forearc or trench slope basin overlying an active subduction zone. Depositional basins often develop in the forearc region of a subduction margin due to high sediment supply from the nearby volcanic arc, and the topographic basins created by the intricate processes of compression and extension in accretionary wedges. These may be separated or continuous with depositional basins on the trench slope, which share many characteristics with forearc basins but may be distinguishable by their deeper water and steeper slope, expressed in finer
overall grain size and increased relative importance of gravity slides. Both basin geometries are predicted by Coulomb models for wedge evolution, especially models incorporating erosion (where appropriate) and thermo-mechanical evolution of the wedge sediments (e.g. Fuller et al., 2006; Kimura et al., 2007).

Lithofacies of forearc and trench slope basins

Several recent and modern examples of forearc and trench slope basins are presented for comparison to the Tygerberg Formation. Our examples range from the landward edge of the forearc basin (the Pliocene Quinault Formation, Cascadia (Campbell et al., 2006)), broad forearc settings (the modern Kumano Basin, Japan (Park et al., 2002; Moore et al., 2009) and the Cretaceous Great Valley Sequence, California (Ingersoll, 1979)), outer forearc basin (the Mio-Pliocene Awa Group, Japan (Tokuhashi, 1989)), trench slope (Cretaceous Matanuska Formation, Alaska, USA, (Trop, 2008), and trench slope-trench (the Eocene Sitkalidak Formation, Alaska, USA (Moore and Allwardt, 1980)). All the examples are dominated by turbidite fans which overlap laterally and through vertical section. They are all relatively long, narrow basins which unconformably overlie higher

Figure 6. Occurrence of quartz veins and breccia cements on Robben Island. (A) Intrafolial quartz-cemented breccia extended along pressure solution fabric. Length of pen = 14cm. (B) Hanging wall asymmetric fold pair adjacent to small southwesterly-vergent quartz-cemented brecciated thrust zone. (C) Late transtensional quartz veins crosscut pressure solution fabrics. Aligned fibres and C-axes of subhedral crystals show direction of vein opening (black arrows), which is consistent across different vein orientations (D) Stereonet plot of late transtensional tabular quartz veins from all across Robben Island (n=37). Extension direction as recorded by orientation of quartz fibres shown with black squares.
grade, more deformed meta-greywackes and shales, comprising accretionary wedges. They share the characteristic palaeocurrent patterns with two maxima parallel and perpendicular to the basin axis, representing sediment flow into the basin and along the axis. Large-scale slumping and slope collapse deposits are prominent in all the examples, particularly in the trench slope settings. Lithologically, coarse sands and conglomerates dominate the landward forearc basin (Campbell et al., 2006), transitioning to finer silts and shale in the trench slope to trench deposits (e.g. Moore and Allwardt, 1980; Trop, 2008). Some of the basins contain regionally continuous tuff beds: airfall deposits from the nearby arc (Great Valley, Kumano: Ingersoll, 1979; Moore et al., 2009), while the others do not but may have a significant volcaniclastic component in the sandstones. Water depth indicators in the mid-forearc basin, where they are reported, are generally bathyal (~200 to 2000m) (Awa Group, Great Valley, Kumano: Tokuhashi, 1989; Ingersoll, 1979; Park et al., 2002). Several examples show evidence of tectonic deepening of the basin by localized normal faulting either pre- or syn-depositionally (Kumano, Awa, Matanuska: Park et al., 2002; Tokuhashi, 1989; Trop, 2008).

In terms of the basin geometry, the Kumano Basin sediments outline the irregular topography created by the extension of the wedge landward of the outer rise of the accretionary wedge, and even lap seaward over the outer rise into the trench slope basin (Moore et al., 2009). Moore and Allwardt (1980) distinguished two structural zones in the Sikikalidak Formation: the seaward edge of the basin was sheared and then horizontally shortened, while the landward part of the basin shows upright folds and axial planar cleavage, with no evidence of shearing or substantial intraformational faulting.

**Comparison to the Tygerberg Formation**

Several of the diagnostic features indicating relatively high-energy, episodic deposition for the forearc and trench slope basins described above were also observed on Robben Island and reported elsewhere in the Tygerberg Formation. The dominance of turbidites and occurrence of olistostromes and slump features suggest deposition by periodic high-volume events. The combined ripples (Figure 4A) require multi-directional flow, the rip-up clasts (Figure 4B) suggest transient high-velocity flow conditions, and the abundant convolute bedding (Figure 3B) and dewatering structures (Figure 4C) present in all facies suggest high rates of deposition. Hummocky cross stratification in massive sandstone beds was not observed on Robben Island, but has been recorded in the Tygerberg Formation at Sea Point (Von Veh, 1982) and at Grotto Bay about 10 km north (C. Rowe et al., unpublished data). Scoured bedding contacts were not observed in the Tygerberg Formation on Robben Island although they have been reported elsewhere (Von Veh, 1982). Von Veh (1982) also reported varying but generally bimodal current directions for the Tygerberg Formation turbidites at the Sea Point Contact, consistent with the other examples.

Based on the multi-directional current indicators, frequent coarse sands, rip-up clasts and abundant dewatering structures, we concur with the interpretation by previous researchers that the Tygerberg Formation was deposited in a deepening basin (Rozendaal et al., 1999) by migrating distributary channels on coalescing fans (Von Veh, 1982). Although there is yet insufficient data to uniquely determine the depositional setting of the Tygerberg Formation, we note the similarities to forearc and trench slope basins in which large volumes of chemically immature marine sediment are deposited, dominantly as turbidites building distributary fans, with tectonic basin deepening acting to generally maintain consistent water depth. As pointed out by Cawood et al. (2009), forearc basins are dominated by lithic greywacke-shales as the primary source is an arc, but backarc basins are more quartzose as they also receive sediment from the landward continent. In addition, the closure of a back-arc basin is associated with high geotherms while the closure of a fore-arc basin remains cold (Cawood et al., 2009). The unconformable relationship to the Swartland terrane described by Belcher and Kisters (2003) and Von Veh (1982) is consistent with the relationship between a flat-lying forearc basin and the underthrust sediments of the accretionary wedge.

**Implications of fold orientation distribution**

Models of folding in transpressional systems predict parallel fold axes which rotate with material lines toward the shear direction during increasing strain. This paradigm treats fold axes as features which, once formed, rotate as passive markers during increasing shear. These folds are typically shown as symmetrical and upright horizontal or gently doubly-plunging, with parallel trends (e.g. Davis and Reynolds, 1996; Sanderson and Marchini, 1984; Krantz, 1995, and references therein). In this paradigm, the long axis of the strain ellipse within the shear zone rotates from fold initiation at approximately 30° to the shear zone boundaries (perpendicular to maximum compressive stress) to smaller angles as it extends with increasing oblique strain. A prediction of this model is that the angle between fold axes and the direction of shear depends on both the angle of obliquity and increasing strain.

A contrasting paradigm is provided by the experiments of Tikoff and Peterson (1998) and the observations of Titus et al. (2007). Tikoff and Peterson (1998) performed experiments using sheets of plasticine and silicon to investigate the fold morphologies and orientations formed during transpression. They varied the angle of the shear zone with respect to the direction of maximum compression (\(\alpha = 0^\circ\) when compression is parallel to the margin; \(\alpha = 90^\circ\) when compression is normal to the margin). Their results indicate that fold axes initiate with plunges around 5 to 10° even while
compression and shear are horizontal, and that significant scatter in trend of the fold axes does not decrease with increasing strain. Most importantly, they showed that fold axes do not follow material lines within the shear zone – therefore the fold axis orientation is decoupled from both angle of obliquity and the total strain, but would be expected to steepen with increasing strain if rocks behaved passively as the system evolved. In essence, these experiments show that fold axes are not maintained as passive markers, but rather that they can continue to move relative to bedding surfaces which roll over the fold axes as the folds tighten (Smallshire, 1999).

Our fold axis observations (Figure 5C) show a similar pattern to that produced by Tikoff and Peterson (1998). Two distinct clusters of fold axes are shown. The northwest plunging folds trend 310 ± 14° and plunge 13 ± 3°. The southeast plunging folds trend 136 ± 14° and plunge 13 ± 3°. The divergent plunges and consistently variable trends of fold axes are consistent with transpressional strain.

Titus et al. (2007)'s structural and paleomagnetic study of en echelon folds formed around a slightly transpressive segment of the San Andreas Fault in central California confirmed the patterns of fold axis trend produced by Tikoff and Peterson (1998). Further, their paleomag results require vertical axis rotations of the folded strata in addition to the horizontal axis rotation imposed by tightening folds. The juxtaposition of these two rotations suggests complex rotational shearing is necessary along limbs of folds in order to accommodate the necessary stretching of limbs. Scissor faults such as those shown in Figures 5B and 5D may have formed during similar intrafolial rotations.

**Shortening recorded by the structures on Robben Island**

The pervasive northwesterly to southeasterly striking vertical pressure solution cleavage on Robben Island demonstrates strong northwesterly to southwesterly shortening. Spread in cleavage orientation (Figure 4F) reflects anastomosing (Figure 4E) and fanning (Figure 5A) of cleavage planes, suggesting the cleavage formation was early to syn- folding. The fold asymmetries suggest predominantly northeast-vergent with local southwest-vergent folds and faults (e.g. Figure 6B) representing antithetic structures. These are preferentially associated with zones of quartz-cemented breccias, suggesting they represent zones of fluid advection and hydrofracture. Although strain markers are scarce, where the cleavage is observed crosscutting sedimentary structures it is possible to comment on the bulk shortening achieved by pressure solution. In the sandstone units where cleavage crosscuts convolute bedding (e.g. Figure 3B) we estimate shortening on order 10 to 20%. In clay rich lithologies where pressure solution is more efficient, the volume loss, and therefore total shortening, is much greater. In Jan van Riebeeck Quarry, the rip-up clasts shown in Figure 4B are moderately well-aligned. The large clasts are extremely thin along an axis normal to the pressure solution cleavage (for example, the large clast in Figure 4B is 15 cm: 5 cm : 0.2 cm; sampling limitations in the World Heritage Site prevented quantitative investigations of a statistically relevant number of clasts). On this basis, we estimate that pressure-solution shortening in the clay-rich lithologies may be several times greater than the shortening in the sandstones. As demonstrated by Tikoff and Peterson (1998)'s experiments, cross-section balancing across transpressional folds is likely to overestimate the total shortening as it does not account for out-of-plane extrusion. Strain ellipses in transpression show flattened "pancake" shapes (Fossen and Tikoff, 1993), regardless of strain partitioning or the local mechanisms of strain accommodation. Analog models have predicted a transition from strike-slip dominated, sub-vertical structures toward thrust-dominated, moderately dipping structures at oblique convergence angles in the range of α = 15 to 25° (Casas et al., 2001). Given the sub-vertical orientation of faults and folds observed on Robben Island, and the wrench and rotational fault motions, we suggest that the Saldanian margin during late-Neoproterozoic to early Cambrian was oriented at α = 15 to 25° or less, relative to the direction of plate convergence. Simply stated, the direction of maximum shortening on Robben Island, as in other examples of transpressional deformation, does not correlate to the direction of maximum principle palaeostress.

The numerical models of Merle (1997) demonstrate that the orientation of the plane of principle flattening (represented on Robben Island by the axial planar pressure solution cleavage, Figure 4F) does not vary in orientation when the angle of oblique convergence varies. Merle (1997) points out that the unusual symmetry of the finite strain ellipse produced during transpression renders finite strain analyses relatively useless in interpreting strain paths during transpression. Similarly, the experiments of Tikoff and Peterson (1998) and the fold axis orientations observed by Titus et al. (2007) are symmetrical and do not distinguish between sinistral and dextral transpression.

As such, we are unable to measure the exact shortening represented by the structures on Robben Island, or determine the sense of transverse motion (whether sinistral or dextral). To differentiate, we would need specific measurements of the rotation in plunge direction of the long axis of the finite strain ellipse (Merle, 1997). Unfortunately, no conclusive strain markers recording this information were observed during our field studies. Citing Kisters et al. (2002)'s observations of dominantly sinistral motion for the Colenso Fault (followed by a very brief episode of dextral slip at about 540 Ma), and the southward propagation of collision indicated in the Kaoko and Gariep Belts, sinistral shear sense is considered more likely.
Regional tectonic events

Numerous orogenic belts dividing older crustal terranes formed during the construction of southwestern Gondwana in the late Neoproterozoic – early Cambrian. The closure of the Adamastor Ocean, uniting African and South American blocks, was a complex, multiphase event. Many crustal blocks were assembled (Rapela et al., 2007; da Silva et al., 2005), probably involving rotations in plate motions including changes in subduction polarity as seen in similar modern settings (Cawood et al., 2009). The southward-younging orogenic belts along the western margin of southern Africa are enigmatic because structural studies suggest highly oblique strain, with the consequence of lateral displacement of terranes, and the geometry of subduction and collision is often unclear.

The Saldania Belt, at the southern end of this trend, introduces particular questions since although there is abundant evidence of crustal shortening, there is no direct evidence of continental collision or an associated volcanic arc that would indicate subduction polarity. Therefore, the tectonic environment of deformation has not been adequately explained.

The Kaoko Belt (northern Namibian coast) records oblique accretion of an exotic terrane (the Coastal Terrane, during east-dipping subduction; Goscombe and Gray, 2007), or west-dipping subduction at 650 to 600 Ma, with the Granite Zone of the Dom Feliciano Belt as the associated arc complex; (Oyhantçabal et al. (2009)) and compression beginning at 660 Ma, with peak metamorphism at 585 to 560 Ma and shear zones active until 530 Ma (Goscombe and Gray, 2008).

In the Gariep Belt (southern Namibia-South Africa), basin filling and shortening is dated at 576 to 573 Ma and deformation peaked between 545 to 530 Ma (Frimmel and Frank, 1998; Frimmel et al., 1996; Frimmel and Basei, 2006). In this case, the basin is interpreted as a retro-arc extensional setting during west-dipping subduction, again citing the Dom Feliciano granites as the associated arc (Frimmel and Basei, 2006; Basei et al., 2005). Meanwhile, de Ameida et al. (2002) interpret the Camaquã Basin (and equivalents) in southern Brazil to either voluminous deposition or significant normal faulting at this time has been reported.

In the Saldania Belt, oblique shortening was complete by the intrusion of the undeformed units in the Cape Granite Suite (e.g. Peninsula Batholith at 540 ± 4 Ma; Armstrong et al. (1998)), simultaneous with the late-stage reversal in transpression direction at about 540 Ma (Kisters et al., 2002). In contrast to the Kaoko and Gariep Belts, no collisional phase or metamorphic event followed. As pointed out by Frimmel and Frank (1998), this southward-younging tectonism is consistent with a zipper-like, south-progressing closure of the Adamastor Ocean, although other models are possible (e.g. southward extrusion of the arc complex, as discussed by Miller et al. (2009)).

The youngest detrital zircons reported in the Tygerberg Formation are ~560 Ma, (uncertainty not reported; Armstrong et al., 1998), roughly the same age as the oldest Cape Granites (552 ± 6 Ma; Scheepers and Armstrong, 2002). The Cape Granites are the only known source for zircons of this age. Folds and cleavage in the Tygerberg Formation are cut by the late-tectonic Sea Point granites (540 ± 4 Ma; Armstrong et al., 1998; Von Veh, 1982), which solidified at 3 to 4 kbar (Villaros et al., 2006) (approximately 11 to 15 km depth assuming a typical psammitic crustal density of 2650 kg/m³). Volcanics erupted at the same structural level as the granites (following their exhumation) by 515 Ma (Scheepers and Poujol, 2002). These constraints allow a minimum estimate of the regional uplift rate during the early Cambrian, between the intrusion of the Sea Point granite and the eruption of the Postberg Ignimbrite: 11 to 15 km / ~25 Ma gives an uplift rate of ~0.4 to 0.6 mm/yr. This minimum estimate of uplift rate is less than or similar to uplift rates in currently active areas of transpression (e.g. Southern Alps at 6 to 9 mm/yr; Little et al., 2005, 0.13 - 0.35 mm/yr San Andreas fault in the Santa Cruz Mountains; Valensise and Ward 1991).

This uplift was associated with a brief period of local extension by the formation of elongate grabens parallel to regional structure, (the intra-orogen pull-apart basins suggested by Rozendaal et al. (1999)) followed by long term regional subsidence (Tankard et al., 2009). This fault-paralleled, graben-bounded geometry is well preserved today (Figure 1) and the conglomerates are unconformably overlain by the regionally extensive Paleozoic Table Mountain Group (Hartnady et al., 1974; Theron et al., 1992; Tankard et al., 2009). Although some previous authors have suggested that the rifting was regionally significant and the extent of the conglomerates was originally much greater than is seen today (e.g. Theron et al., 1992), no direct evidence for either voluminous deposition or significant normal faulting at this time has been reported.

Two tectonic settings are suggested, which could explain the deposition and deformation of the Tygerberg Formation in a supra-subduction setting, link the regional uplift to the switch in shear sense on the Colenso Fault at 540 Ma, and provide context for the deformation of the graben-bounded conglomerates.
Triple-junction migration (or ridge-trench interaction) is associated with transient localized extension caused by the passage of a thermal high with or without associated slab window volcanism (Unruh et al., 2007; Farris and Paterson, 2009; Ayuso et al., 2009; Cole and Steward, 2009), which we suggest may correlate to the Cape Granite Suite. Alternatively, migration of releasing bends along a transform boundary can produce chains of grabens along strike-slip faults without regional extension (Seeber et al., 2010; Wakabayashi et al., 2004). These two models can be compared and tested by further studies distinguishing: the age and distribution of the lower Cambrian conglomerates, and the age progression and tectonic setting of melting which produced the Cape Granite Suite, in particular, the relationships in age and petrogenesis between the S-type and I-type granites.

Although numerous authors have suggested a subduction setting for the Saldania Belt and associated granites (Belcher, 2003; Da Silva et al., 2000; Dunleavy, 1992; Scheepers, 1995; Stevens et al., 2007 and others), no associated arc complex has been uniquely identified. Our data presented here do not allow us to suggest a direction of subduction vergence, only that the sedimentological and tectonic setting is consistent with a supra-subduction zone basin, as would be expected around the edges of the disappearing Adamastor Ocean basin. If the closure of the Adamastor Ocean was a complex, multi-stage event involving multiple terranes as implied by Germs and Gresse (1991) and Stanistreet et al. (1991), a forearc basin may display complex provenance and source directions (e.g. the Wrangel Mountains Basin, which laps onto the accreted Wrangellia Terrane of southern Alaska, Trop et al. (1999)).

In similar transpressional subduction environments, significant strike-slip in the forearc region has been shown to laterally separate arc complexes from associated forearc basins (e.g. Alaska’s Kodiak Complex, Sample and Reid, 2003). In addition, periods of magmatic hiatus are reported in numerous Mesozoic subduction complexes around the Pacific Rim (e.g. Cretaceous Mexican Trench, (Solari et al., 2007) or Miocene Cascadia (Dostal et al., 2008)) during which significant transverse motion may have occurred. Therefore, the highly oblique transpression in the Tygerberg Formation implies the potential for substantial forearc displacement. We note that due to the oblique setting, matching of ~750 Ma belts likely does not apply to correlations of ~550 Ma belts, especially when attempted on a Mesozoic (pre-Gondwana rift) tectonic map, as demonstrated by the spatial mismatch of metamorphic and magmatic ages (Gray et al., 2008, Figure 12).

As obliquity is characteristic of all the Neoproterozoic belts on the western margin of southern Africa, it is unlikely that the current attempts to reconstruct the Cambrian geometry of southwest Gondwana can be accurate when using a plate fit model based on the mid-Mesozoic configuration. A large number of the attempts at reconstruction use these Jurassic plate configurations (e.g. Bossi and Goucher (2004); Da Silva et al. (2005); Frimmel et al. (1996); Frimmel and Frank (1998); Gaucher et al. (2004); Gresse (1995); Gresse and Scheepers (1993) and Rozendaal et al. (1999) which all refer to Porada (1979; 1989), which reuse the models of Smith and Hallam (1970) and Norton and Sclater, (1979)). Therefore, future reconstructions of Cambrian (late Pan-African) plate geometries must consider this additional complication.

Conclusion

The Tygerberg Formation was deposited in a high-energy, high deposition-rate, tectonically deepening basin during the late Neoproterozoic to very early Cambrian. These characteristics as well as the unconformable relationship to highly sheared, slightly higher metamorphic grade underlying sedimentary units are consistent with deposition in a forearc basin. Syn-to immediately post-depositional deformation occurred in an overall regime of highly oblique transpression and rapid regional exhumation ended the life of the basin. Although direct correlations with South American equivalents are not yet possible and most attempts at regional reconstruction end at the Gariep Belt, we hope this study might contribute an additional constraint toward filling the gaps in Pan-African southern Gondwana.

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