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Palinspastic restoration of an exhumed deep-water system: a workflow to improve paleogeographic reconstructions

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ABSTRACT

The Permian Laingsburg depocenter, Karoo Basin, South Africa is the focus of sedimentological and stratigraphic research as an exhumed analogue for offshore hydrocarbon reservoirs in deep-water basins. Thin-skinned thrust tectonics during the Permo-Triassic Cape Orogeny resulted in post-depositional deformation of the Permian basin-fill. Regional-scale cross sections reveal two structural domains: a southern domain in the Laingsburg depocenter comprising 8-11 km wavelength north-verging fault-propagation folding, driven by buried low angle ($<45^o$) reverse faults that coalesce at depth as part of a mega-detachment below the Lower Paleozoic Cape Supergroup; and a northern domain to the north of the Laingsburg depocenter of short wavelength, low amplitude, asymmetrical folding facilitated by a detachment within the Permian Ecca Group. Five detailed structural cross sections permit the palinspastic restoration, and a calculation of the amount of shortening, across a 2500 km^2 area in the Laingsburg depocenter. Average shortening across the study area is 16.9% (5.8 km), and decreases south to north. Shortening estimates from the Upper Ecca Group increase from 4.3 km near Matjiesfontein in the west to 10.4 km near Prince Albert in the east. Three dimensional restorations of stratigraphic surfaces are consistent with these figures (17%), and allow paleogeographic and isopach thickness maps to be resorted to their configuration at the time of deposition. Structural restoration can be routinely employed in outcrop

studies to improve the accuracy of dimensions (e.g. volumetrics) and reconstructions (e.g. sediment dispersal patterns) derived from ancient sedimentary systems. The workflow presented here will add value to exhumed basin analogues by presenting pre-kinematic configurations at the frontal margins of fold-thrust belts.

INTRODUCTION

The limited opportunity for direct observation of many of the world's hydrocarbon bearing reservoirs introduces inherent uncertainties to their interpretation. Any reduction in this ambiguity is desirable. A pragmatic solution is to draw parallels from exhumed basin-fills with analogous depositional and structural architectures (Alexander, 1993) and scales (Howell et al., 2014). Numerous detailed sedimentological and stratigraphic studies have been published from ancient exhumed siliciclastic deep-water systems that are used as analogues for subsurface systems. Many of these studies originate from basins with syn- and/or post-depositional compressional tectonics (e.g. Mutti, 1983; Haughton, 1994; Sinclair and Tomasso, 2002; Hodgson and Haughton, 2004; Bernhardt et al., 2011; Salles et al., 2014; Cantalejo and Pickering, 2014), although paleogeographic reconstructions rarely account for post-depositional tectonic shortening. Studies that undertake palinspastic restoration of turbidite systems, which revises the geometry and dimensions of systems to the configuration during deposition, are rare and tend to be in small depocenters (e.g. Fernandez et al., 2004; Falivene et al., 2006; Paton et al., 2007; Aas et al. 2010; Durand-Riard et al., 2011).

The exposures of deep-water strata in the Laingsburg depocenter of the Karoo Basin, South Africa (Figs. 1; 2), have been utilised as an analogue for sub-seismic scale depositional elements, and facies distributions for many hydrocarbon fields (e.g. Grecula et al., 2003, Sixsmith et al., 2004, Hodgson et al., 2011a; Flint et al., 2011; Di Celma et al., 2011; Brunt et al., 2013a, b; Morris et al., 2014). Detailed studies have culminated in the correlation of stacked deep water composite sequences across the Karoo Basin over a >2500km^2 area, allowing high resolution study of the evolution of a basin through the stages of its fill (Van der Merwe et al., 2014). The maps presented have not been restored despite the depocenter being subject to post-depositional north-south compression (e.g. Hälbich et al. 1993; Newton, 1995; Catuneanu et al., 2005; Tankard et al., 2009). This means that published paleogeographic reconstructions are too compressed in a north-south orientation (e.g. Grecula et al., 2003; Sixsmith et al., 2004; Di Celma et al., 2011; Van der Merwe et al., 2014). Palinspastic restoration will improve map view configurations such as sediment dispersal patterns, isopach maps and rates of thinning (e.g. levees and lobes), and the accuracy of volumetric calculations.

The aim of this study is to quantify the influence of post-depositional deformation on the paleogeographic reconstructions of the SW Karoo Basin deep-water system in the Laingsburg area. The methodology applied should be exportable to other exhumed ancient analogues to help refine interpretations of basin configuration at the time of deposition to improve the efficacy of analogue studies from outcrop applied to the subsurface.

REGIONAL SETTING

The Carboniferous to Jurassic Karoo Basin of South Africa (Fig. 3) overlies the Ordovician to Carboniferous Cape Basin, which itself overlies the Proterozoic basement crust in the south and the Archaean Kaapvaal Craton in the north (Tankard et al., 2009). The basins formed on the southern margin of the Gondwana paleo-continent, attributed to lithospheric flexure in the foreland of an orogen (Catuneanu et al., 2005), or subsidence of Proterozoic basement blocks (Tankard et al., 2009).

The two-armed Cape Fold Belt is broadly east-west trending in southern South Africa, but changes orientation to a north-south trend in the west (Johnston et al., 2000, Paton et al., 2006, Lindeque et al., 2012, Fagereng et al., 2014) (Fig.1). The southern arm of the belt is characterised by north verging folds that transition northwards into upright, open fold structures and grade into horizontal strata further north (Lock 1980; De Beer, 1990; de Wit and Ransome, 1992; Hälbich, 1993; Johnston et al., 2000; Paton et al., 2006; Fagereng, 2014; Fagereng and Byrnes, 2015). The fold belt is thought to be an example of both thin-skinned and thick-skinned thrusting (Paton et al., 2006); a domain of shallowly dipping thrusting under the Karoo Basin coalesces at depth with steep, basement-involved faults beneath the Swartberg Range along a common mega-detachment (Lindeque et al., 2012). Metamorphic conditions in the fold belt reached lower greenschist facies during deformation (Tinker et al., 2008; Hansma et al. 2015). By the Triassic Period, the regional compressive stress that formed the Cape Fold Belt and foreland accommodation space had propagated north, deforming the Laingsburg depocenter, forming east-west trending folds (Tankard et al., 2009) (Fig. 2). During the Mesozoic an extensional system was superimposed, by selectively reactivating faults, on the Cape Fold Belt, which itself is believed to have reactivated south dipping high angle reverse faults from an earlier extensional episode (de Wit and Ransome, 1992; Hälbich, 1993; Paton and Underhill, 2004; Paton, 2006).

The base of the stratigraphic interval of interest, the Karoo Supergroup, is the late Carboniferous Dwyka Group (Fig. 3), a ~800m thick succession of dominantly glacial diamictites (Bangert et al., 1999, Fagereng, 2014, Isbell et al., 2008). This is separated from the underlying Witteberg Group, the youngest unit of the older Cape Supergroup, by a hiatus in sedimentation of 30 Ma (Catuneanu et al., 2005; Fig. 3). The transition from the glacial Dwyka Group to the post-glacial Ecca Group deposits has been dated to approximately 290 Ma (Bangert et al., 1999).

In the study area, the Ecca Group (Fig. 3) contains an approximately 1.8 km thick succession of deep-marine deposits (Flint et al., 2011). The Lower Ecca Group comprise argillaceous units (the 120 m thick Prince Albert, 30 m thick Whitehill and 30-70 m thick Collingham Formations; Fig. 3). The Upper Ecca Group marks an overall shallowing-upward succession from distal basin-floor deposits with intercalated mass transport deposits (the 280 m-thick Vischkuil Formation, van der Merwe et al., 2009), through to sand-rich basin-floor lobe complexes (the 500 m-thick Laingsburg Formation, Sixsmith et al., 2004; Prélat and Hodgson

2013) and a channelized submarine slope (the 450 m-thick Fort Brown Formation; Grecula et al., 2003; Figueiredo et al. 2009; Hodgson et al., 2011a; Spychala et al., 2015) to wave-dominated shelf and shelf-edge deposits (the ~350 m-thick Waterford Formation, Oliveira et al., 2011, Jones et al., 2013, 2015; Fig. 3). The Ecca Group is overlain by a thick fluvial-overbank succession, the Beaufort Group (Catuneanu et al., 2005, Wilson et al., 2014; Gulliford et al. 2014). The ages of sampled ash beds from basin-floor and submarine slope deposits in the Ecca Group of the Laingsburg depocenter and the nearby Tanqua depocenter are constrained using U-Pb single grain zircon ages to maximum depositional ages of 274 Ma to 250 Ma (Fildani et al., 2007, 2009; McKay et al., 2015).

The extensive exposures of turbidite packages in the Fort Brown Formation have been mapped, from entrenched slope valleys, through channel-levee systems and intraslope lobe complexes to lobe complexes on the basin-floor, over a 2500km^2 area (van der Merwe et al., 2014). The outcrops provide a unique opportunity to study the depositional architecture of deep-water systems across multiple stratigraphic scales, from sedimentary facies- to seismic-scale, and are considered a valuable field analogue (Hodgson et al., 2011a; Flint et al., 2011; Morris et al. 2014). Several authors have published paleogeographic reconstructions at different stratigraphic intervals in the Laingsburg depocenter (e.g. Sixsmith et al., 2004, Figuereido et al., 2009; van der Merwe et al., 2009; Di Celma et al., 2011; Brunt et al., 2013a, b; Morris et al., 2014; van der Merwe et al., 2014; Jones et al., 2015; Spychala et al., 2015). Overall, sediment gravity flows entered from the south-west with net sediment dispersal direction to the north-east (Di Celma et al., 2011; Morris et al. 2014). Locally, subtle basin bathymetry influenced the flows and modified their behaviour (Grecula et al., 2003; Sixsmith et al. 2004; van der Merwe et al. 2014; Spychala et al., 2015). Outcrop data from the contemporaneous Tanqua depocenter (Wild et al. 2009) show that the basin-fill shallows to the north and that the lithostratigraphic Fort Brown Formation is absent in the most northern portions of the study area.

DATA AND METHODS

Data were extracted from 1:250000 scale geology maps, published by the South African Geological Survey (now the Council of Geosciences), of Sutherland (sheet 3220, Theron, 1983), Beaufort West (sheet 3222, Johnson and Keyser), Ladismith (sheet 3320, Theron et al. 1992) and Oudtshoorn (sheet 3322, Toerien 1979). Previous studies involving cross sections have not covered the full extent of the Laingsburg depocenter (e.g. Newton 1993, 1995, Paton et al., 2006) and include deformation to the south of the Karoo Basin, so shortening estimates are not directly applicable to paleogeographic reconstruction across the Laingsburg depocenter. Regional cross sections that extend north from the southern outcrops of the Karoo Supergroup to 32°30'S were constructed. This latitude was considered the frontal extent of contractional deformation as field observations and published geological maps indicate an absence of significant folding towards the north (sheets 3220 and 3222). Cross sections were constructed using standard methods to maintain line length and horizon interval area, using map outcrop pattern and unit dip at the surface to predict the geometry of folding at depth and infer buried fault locations (Dahlstrom, 1969, Boyer and Elliot, 1982, Elliot, 1983). Additional control on formation depths in the north of the study area is provided by three wells within the study area; KL1/65, SA 1/66, and KW 1/67 (Winter and Venter, 1970) (Fig. 1, 2). This was supplemented by detailed field mapping of the Dwyka Group to Beaufort Group geology in the Laingsburg area along five ~30km long north-south transects to produce more detailed cross sections of the Laingsburg depocenter (Fig.1, 2). The sections are sub-parallel to the north-south deformation transport direction and extend from Upper Cape Supergroup outcrops to latitude 33°S, considered to be the approximate northern-most extent of the depocenter. Field data provided further constraints on bedding orientations in the Karoo Supergroup and was used to characterise the deformation style of the folds.

To test the validity of a subsurface interpretation it is necessary to balance geometrically the pre-deformed and deformed state. Assuming plane-strain deformation, the volume of rock should be conserved such that the areal extent of a deformed section equals that of its parent undeformed section (Dahlstrom, 1969). Discrepancies between the area of those states would indicate an invalid interpretation. Given that area is a function of the bed thickness and the bed length, and if bed thickness is assumed to remain constant during deformation, it is possible to use the preservation of line lengths as an assessment of whether a section is restorable (Dahlstrom, 1969). In reality, bed thickness changes in fold cores due to mudstone (shale) thickening and out-of-plane transport (Shackleton and Cooke, 2007). For bed thickness to remain constant, deformation must be accommodated by bedding parallel slip (Tanner, 1989). The amount of shortening that a line on a plane of section has experienced (Equation 1) can be expressed as a strain (e) by dividing the difference in line length by the original line length.

$$e = (L_1 - L_0)/L_0$$ Equation 1

The form of the equation dictates that contraction results in a negative value of strain and can be expressed as either a ratio of the original length or as a percentage. The value is considered a minimum shortening estimate. The pin and loose lines, from which the beds are unfolded, should ideally be placed in undeformed beds in front of and behind the area of deformation or at the hinge of major fold structures (e.g. Dahlstrom, 1969; Elliot, 1983; Watkins et al., 2014). Beds are 'pinned' by the pin line such that they do not move during the restoration, and the loose pin is moved until a template bed is fully undeformed. The method will highlight area and line length inconsistencies. Restoration is an iterative process (Butler and Paton, 2010) and horizon geometries are adjusted until an interpretation that satisfies both field observations and geometric principles is found. Cross sections underwent a quality control to remove inconsistencies in unit thicknesses, anomalous depths, and to highlight variance in deformation styles between sections prior to restoration. Horizon depths are equivalent to published borehole data (Winter and Venter, 1970).

Field observations and previous structural analysis in the Laingsburg area (Newton, 1993, 1995; Fagereng, 2014; Fagereng and Byrnes, 2015) have indicated that the deformation transport direction is approximately south-to-north, and deformation is plane-strain accommodated by flexural slip along the beds. The complexity of the folding means that some out-of-plane thickening or thinning of beds is present, which would locally limit the effectiveness of the method. Based on the absence of observed basin-scale thrusts that crop out, and previous studies on the deformation mechanism in the Karoo (Newton, 1993, 1995; Paton et al., 2006; Fagereng, 2012, 2014), asymmetrical first order folding of the Karoo Supergroup is inferred to be controlled by shallow angle thrust faults, but is not penetrated by them. Back-limbs dip at approximately 30-45^o, therefore the dip of the underlying thrust is estimated to be equivalent, assuming a ramp during early fold development (Bower and Elliot, 1982, Mitra 1990). In the field, minor asymmetrical folding is observed to detach within the more mud-prone Lower Ecca units. Geomechanically weak mudstone horizons that facilitate detachment of overlying units are inferred in other thrust systems, for example, the Moine Thrust Zone (Watkins et al., 2014) and the offshore Orange Basin (De Vera et al., 2010; Butler and Paton, 2010; Dalton et al., in press). Lindeque et al. (2012) used subsurface data to infer that the Prince Albert and Whitehill Formations are detachment horizons (Fig. 3). Field observations, including a dominantly ductile deformation style and the presence of chevron folding (Fagereng 2012), are consistent with a concentration of strain in these units. Locally, a third order of folding, symmetrical buckle folding, is observed on the hinges of first order folding. This could also detach along the Prince Albert Formation, however the projection of constant bed thicknesses to depth in the fold creates a space problem that is solved by a localised detachment within the mudstone- and volcanic ash-rich Collingham Formation (Fig. 3, 4). This introduces the potential for a minor error in line length calculations.

Folding should be removed in an order inverse to which it occurred. The 2D restoration tested a model where second (Prince Albert Formation detachment) and third (Collingham Formation detachment) order folding are parasitic to first order folding. Third order folding is removed prior to restoring second order folds because it is geometrically up-sequence and so is further from the propagating thrust. Orders of folding are removed by unfolding the beds above the detachment horizon to a template line that is parallel to the underlying horizon and maintains an appropriate detachment unit thickness. This is acknowledged as an approximation because detachment layers have been shown to be complicated and change in thickness over multiple scales (Watkins et al., 2014). This process is repeated until deformation is removed. Errors in area and line length are iteratively corrected such that the section balances (Butler and Paton, 2010) whilst maintaining consistency with field-observed topography-horizon intersections. The cross sections have not been decompacted as the majority of the deformation occurred after burial and much of the stratigraphy consists of sandstone and siltstone rather than claystone.

The stratigraphic surfaces integrate results from balanced 2D sections and off-section predictions of horizon geometries based on interpretation of remote sensing data, to account for non-cylindrical folding and heterogeneity of structures across the Laingsburg area by projecting cross sections into adjacent 3D space such that surface-horizon intersections are honoured. Delaunay and linear triangulation are used to interpolate between known points to produce an approximation of horizons in three dimensions. Surfaces are created for the top Fort Brown Formation, due to the low ambiguity of the mappable contact between the Fort Brown and Waterford formations (Jones et al. 2015), and its stratigraphic relevance to the recent and ongoing studies of the Upper Ecca Sub-Group (Flint et al., 2011; van der Merwe et al., 2014) and top Dwyka Group, because it defines the base of the depocenter. Three dimensional restorations test two alternative hypotheses: i) Small scale deformation is parasitic to larger structures (Model A), and ii) Small scale deformation is the result of detachment along mechanically weak horizons prior to the formation of larger structures (Model B). Surfaces are unfolded using a flexural slip algorithm, parallel to azimuth 178^{o}, the principal transport direction of deformation (Fig. 5). Model A requires the removal of small scale deformation first, by restoring the top Fort Brown Formation surface to a replica of the geometry of the top Dwyka Group surface at the depth/elevation of the top Fort

Brown Formation. The top Fort Brown Formation surface can then be fully returned to its pre-deformation state by removing large scale folding from the top Dwyka Group surface. Model B involves unfolding the top Fort Brown Formation surface by removing large scale folding from the top Dwyka Group surface, followed by the removal of the small scale deformation by unfolding to a replica of the unfolded top Dwyka Group surface at the depth/elevation of the top Fort Brown Formation surface. The method follows theory similar to that of 2D restoration (e.g. Dahlstrom 1969; Elliot 1983, Butler and Paton, 2010), but accounts for deformation transport in three dimensions, and thus should account for out-of-plane transport.

Longitudinal strain estimates

Shortening values of the complete sections

Initial minimum estimates of shortening, expressed in meters, are extracted from the restored sections for each distinct horizon group (Fig. 4). In this instance, a horizon group is defined by the detachment horizon that facilitates deformation. Minor errors in line length between horizons are considered to be acceptable if their value does not exceed ~1% of the section length. Judge and Allmendinger (2011) have highlighted that such errors may be introduced to balanced cross sections due to uncertainty in stratigraphic thicknesses and sub-resolution deformation. Any error is removed from each group by calculating an arithmetic mean.

Shortening estimates in the Laingsburg depocenter

To consider the implications of restoration results for paleogeographic reconstructions it is necessary to constrain shortening estimates to the Laingsburg depocenter. These are calculated from the top Fort Brown Formation horizon between 33°0' S and 33°15'S, which have been used for published paleogeographic reconstructions (van der Merwe et al., 2014). Balanced sections are cut at those latitudes using georeferenced topographic maps, and the length of each section recorded. Discrepancies in section length due to variations in section orientation below the resolution of compass azimuth, are only 1.1% of the shortest value (306 m along 27734 m long section) and so considered insignificant. The minor discrepancies in section length are removed by calculating an arithmetic mean that was applied in the longitudinal strain calculations for each section between those latitudes.

RESULTS

Cross-sections

The fold characteristics of the northern and southern domains are distinct (Fig. 4). Folds in the southern domain have relatively high amplitudes (up to 1-2 km) and long wavelengths (up to 12 km), and contain first (up to 12 km wavelength), second (up to 1 km), and third order folding (up to 50 m) styles. Folds in the northern domain are of the second order, with relatively low amplitudes (up to 200 m) and short wavelengths. Where fold wavelengths are relatively long for the domain, the fold backlimbs are generally gently or moderately south-dipping whilst the forelimbs are steeply north dipping. First order folds are interpreted to be controlled by underlying thrust faults. The dips of these faults are estimated at $< 45^{o}$, inferred from the dips of fold back-limbs. The lack of first order folding in the northern domain implies that these thrusts do not extend beyond the southern domain. Both domains contain second order folding that has formed using a detachment horizon within the in the Prince Albert Formation (Fig. 3). Examples of asymmetrical folding must form where the fault plane becomes more structurally elevated, growing through younger strata in the Lower Ecca Sub-Group. The fold amplitudes are relatively small, so strain must have transfered farther north soon after the folds formed. Third order folds occur locally on the crest of first order anticlines in the Allemansdrift, Dwyka River, and Prince Albert sections. This implies decoupling within a detachment horizon, in this case the Collingham Formation, which occurs as a result of strain localisation at the hinge of a first order fold within the Upper Ecca stratigraphy, forcing tighter folding than below the detachment (Mitra, 2003).

Cross sections are labelled A-E, west-to-east (Fig. 1), and folds within the southern domain of each section were numbered sequentially from north-to-south (Fig. 4). For example, the most northern fold in the Matjiesfontein section is labelled A1. First order folding is considered to involve the full Karoo Supergroup sequence and folds are generally long wavelength. Second order folding is taken to involve all horizons above the top Dwyka Group horizon and these folds verge to the north or south. Third order folding is taken to involve all horizons above the top Whitehill Formation horizon, and is symmetrical. In all cases the basin is inferred to shallow to the north, with the lithostratigraphic Fort Brown Formation pinching out approximately 15-20 km south of 32°30'S. This is supported by well data (Winter and Venter, 1970)

All sections were restored using the assumptions that second order folding detached in the Prince Albert Formation and first order folding involved the complete Karoo Supergroup sequence. In Sections A and B, line lengths above and including the Prince Albert Formation can be considered horizon group 1, and the top Dwyka Group and top Cape Supergroup horizons can be considered horizon group 2. In sections C, D and E, a detachment within the Collingham Formation meant that the horizons were divided into horizon group 1, containing horizons above the Collingham Formation (including the top Collingham Formation horizon). The remainder above the Prince Albert Formation detachment (the top Whitehill and top Prince Albert formations) were considered to be horizon group 2, and the top Dwyka Group and top Cape Supergroup were considered to be horizon group 3.

Matjiesfontein section (section A)

The southern domain of the Matjiesfontein section contains three first order north verging folds, A1, A2, and A3 (Fig. 4). Folds A1 and A3 have a relatively high amplitude compared to A2 (Fig. 4). The northern domain contains low amplitude, medium wavelength second order folding.

Laingsburg section (section B)

The southern domain of the Laingsburg section contains four first order folds. Folds B2, B3, and B4 are north verging with large amplitudes (Fig. 4). Within these folds, second order folding is observed, verging to either the north or south. Fold B1 is symmetrical and of low amplitude. The northern domain of the Laingsburg section contains numerous examples of low amplitude second order folding.

Allemansdrift section (section C)

The southern domain of the Allemansdrift section contains two examples of first order folding (Fig. 4). Folds are north verging with high amplitudes. Fold C1 has a long wavelength, but the wavelength of C2 is relatively short (Fig. 4). Within those folds there are examples of second and third order folding, which are observed to verge to the north or south. The northern domain contains second order folds that verge to the north or south.

Dwyka River section (section D)

The southern domain of the Dwyka River section contains four first order folds (Fig. 4). Folds are north verging and of large amplitude. The northern domain contains north or south verging low amplitude second order folding.

Prince Albert section (section E)

The southern domain of the Prince Albert section contains four first order folds (Fig. 4). Those folds are north verging, with shallow back limbs and steep to overturned fore limbs. Folds E1 and E2 contain second order folding. This folding is symmetrical in fold E1 and south verging in fold E2. Fold E1 contains tight symmetrical third order folding. The northern margin contains low amplitude second order folding. Line length restoration of the Prince Albert section shows minor line length issues, but some space issues; the Fort Brown Formation approximately doubles in thickness in the southern domain, which is attributed to lithostratigraphic variation, but may be caused by deformation at scales lower than the resolution of the section (Judge and Allmendinger, 2011).

Field data analysis

Observations

The three orders of folding identified in the cross-sections are also observed in the field. First order folding is observed with kilometers-scale wavelengths (up to 12 km). The wavelength of second order folding is up to 1 km and third order up to 50 m. Collected measurements were plotted on stereonets using the equal area projection (Cardozo and Allmendinger, 2013) and close correspondence of all data to a single great circle implies plane strain deformation with a north-south transport direction.

The transition from the Cape Supergroup (Witteberg Group quartzites, Fig. 6) to the units of the Karoo Supergroup (the glaciogenic Dwyka Group) is marked by tight folds with small interlimb angles and steeply dipping/ overturned bedding to open folds with large interlimb angles. In the Dwyka Group, the axial planar primary cleavage is dominated by a steep dip to the south. Cleavage is observed to interact with sand-rich clasts by diffracting around them. In the Lower Ecca Group, bedding orientations can be highly variable with steeply dipping limbs of short wavelength chevron folds observed (Fig. 7). Open third order folding with wavelengths of approximately one meter is also observed. The general dip of cleavage is moderately steep (approximately 60^{o}) towards the north or south and strikes consistently east-west (Fig. 5). In the Upper Ecca Group, the Vischkuil, Laingsburg, and Fort Brown formations are deformed by relatively long wavelength folds that are observed at both map-scale and outcrop-scale (Fig. 7). Folds are north-verging, with steeply dipping or overturned forelimbs and shallow to moderately dipping back limbs, with a well-developed east-west trending cleavage. Fold geometries are curvilinear at multiple scales and have shallow overall plunge to the east.

Interpretations

The geometry of asymmetrical folds can be used to infer the geometry of the underlying thrust (Bower and Elliot, 1982; Elliot 1983; Suppe 1983; Suppe and Medwedeff, 1990). There are three prominent models of fault-forced folding; the fault-bend fold (Suppe, 1983), the fault propagation fold (Mitra, 1990), and the detachment fold (Mitra, 2003). Given the lack of subsurface data, it is necessary to use surface observations in conjunction with structural models to understand the geometry of the fold and its controlling fault at depth. The geometry of first order folding observed in the Laingsburg depocenter is generally north verging and asymmetrical, with a shallowly south-dipping back limb and a steep (>60°) to overturned fore limb, is thought to best match the fault propagation model (Mitra, 1990). Slickensides on bedding planes and chevron folding suggest that strain was accommodated by intra-bed flexural slip (Tanner, 1989). Also, the geometry of second order folds share characteristics with fault-propagation folding (Pei et al., 2014).

Restorations

Two dimensional restorations

The results of the 2D restorations of the Matjiesfontein (section A), Laingsburg (section B), Allesmansdrift (section C), Dwyka River (section D), and Prince Albert (section E) sections are summarised in Table 8.

Three dimensional restorations

To quantify shortening in 3D, the loss in area due to deformation is calculated as a percentage of the original areal extent of a surface ((present day area - pre-deformational area) / pre-deformational area). This assumes area preservation during deformation. As previously described, the Laingsburg area contains examples of complicated folding, including overturned folds, detachment folds, and fault propagation folding, which implies thickening and thinning of beds around fold hinges (e.g. Mitra 1990, Erslev 1991). This could affect length in 2D restorations and, therefore, area in 3D restorations. However, the impact on paleogeographic reconstructions would be negligible at the scale of the Laingsburg depocenter. A paleogeographic reconstruction of Unit E, the Fort Brown Formation, in the Laingsburg area from van Der Merwe et al. (2014) was used. The local area change as a result of deformation can be estimated. Models A, where small-scale deformation was removed before large-scale deformation, and B, where small-scale deformation was removed after large-scale deformation result in similar estimates, -17.0% and 16.7% respectively (Table 1). Area loss increases from the west towards Laingsburg, then is locally variable with little net loss/gain until the central zone of the study area, before increasing towards the Dwyka River in the east. Three-dimensional surfaces highlight the en-echelon fold geometries that are present with examples of linked major anticlines and overlapping detachment folding (Fig. 8). Figure 9 shows the geometry of surfaces of the respective models following the initial stage of the restoration.

IMPLICATIONS FOR PALEOGEOGRAPHY

Longitudinal strain distribution across the Laingsburg depocenter

Spatial variability of minimum shortening estimates from each section (Table 1) and estimates of the distribution of strain across the depocenter indicate that strain is regionally heterogeneous (Fig. 10). Shortening is observed to increase to the south from the deformation front in the north, but within each section strain is highly variable. Shortening estimates show an approximately linear increase in strain towards the east (Table 1). All sections have at least two segments where shortening is greater than -10.0%. The easternmost sections, the Dwyka River section and the Prince Albert section, have four segments where shortening is greater than -10.0%, and three segments where shortening is greater than -15.0% (Fig. 10). Anomalous values include along the Allemansdrift section where the highest shortening is in southern-central segment, while the most northern segment of the Prince Albert section is approximately ten times higher than the northern segments in the other sections (Fig. 10). Shortening is highest in areas of concentrated folding, and the spacing between anticlinal fold axes (the fold wavelengths) changes across the depocenter (Fig. 2). In the west (Matjiesfontein and Laingsburg sections), fold wavelengths are approximately 8 km in the south and 10 km in the north. Centrally (Allemansdrift and Dwyka River sections), fold wavelengths are approximately 6 km. In the east (Prince Albert section), fold wavelengths are approximately 12 km in the south, and 9 km in the north. Folds near Laingsburg have been interpreted to have grown above shallow angle thrusts (Fagereng, 2012; 2014; Lindeque et al., 2012). This implies the location of faults could be inferred from the distribution of major anticlines in the depocentre (Fig. 4). The periclinal geometry of the anticlines would imply that faults are not laterally continuous across the study area, and the overlapping geometry of some fold hinges suggests that faults are locally en echelon. Folds B1 and B2 (Fig. 4) display a symmetrical morphology that are inconsistent with fault controlled folding. The detachment fold model (Mitra, 2003) may be more appropriate to describe deformation at this locality.

Comparison of 2D and 3D results

The 2D and 3D methodologies produce regionally comparable results in terms of shortening distribution magnitude, but the 3D restoration suggests that the resolution of the 2D restorations (Table 1) does not fully constrain the lateral shortening variation across the Laingsburg depocenter. Whilst shortening magnitude increases from west to east at the regional scale, at a local scale, shortening is heterogeneous (Fig. 10). The 2D restorations suggest shortening increases linearly to the east, however the 3D models illustrate strain magnitude variability. Areas of high shortening correlate to large scale periclines, whilst areas of low shortening appear to correlate to relay zones between major folds. Given the assumption of plane-strain deformation transport, if the value of shortening is taken as an indicator of the magnitude of strain, a relationship between local structural morphology and strain is implied. However, the relationship is likely to be more complicated; in relay zones because strain is more distributed (Long and Imber, 2012), and is not resolvable on the available data, so the apparent strain could be reduced. Shortening estimates from the Matjiesfontein, Laingsburg, Allemansdrift, and Dwyka River sections (Table 1) were used to stretch a paleogeographic map of Unit E of the Fort Brown Formation. Figure 11 shows the effect of removing deformation within the Laingsburg depocenter using 2D and 3D methodologies. The original map suggests the areal extent of deposition was 1919 km^2. In the 2D restoration, after the removal of shortening the estimate is 2211 km^2, an increase of 15.2%. The two models tested in the 3D restoration produce area estimates for the basin in its pre-deformation state of 2304 km^2 (Model A) and 2312 km^2 (Model B), area increases of 20.1% and 20.5% respectively. These values are equivalent to shortening of -13.2% for the 2D restoration, and -16.7% and -17.0% of models A and B from the 3D restoration.

DISCUSSION

Deformation in the Laingsburg area

Paton et al. (2006) have indicated that deformation in the Western Cape, South Africa is controlled by a south-dipping mega detachment below the Cape Supergroup from which steep thrusts propagate north below the Cape Fold Belt and shallow thrusts propagate north below the Karoo Basin. This is in broad agreement with the results of this study, however some folds on the frontal margin of first order deformation (folds B1 and B2, Fig. 4) have a symmetrical morphology that is more indicative of detachment folding (Mitra 2003). The 3D restoration tested models for deformation initiating above propagating thrusts (Model A) and deformation initiating as small scale detachment folding (Model B), but produced similar results so does not indicate clearly a preference for either model (Fig. 9, 11). It is likely that both styles occurred during early deformation. Detachment folding has been shown to occur where competent strata overlie less competent units (Wallace and Homza, 2004), before fault-controlled deformation became dominant due to the inversion of older extensional faults (Paton et al., 2006). The depth to detachment can be estimated by calculating the area between a folded horizon and a pre-deformation datum (Groshong and Epard, 1994). This area should be equal to a rectangle with sides S and Z, where S is the amount of shortening and Z is the depth to the detachment from the horizon. The top Dwyka Group horizon is the most suitable for this calculation as it is subject to first order folding only. A previous seismic study (Lindeque et al., 2012) interpreted a line of section sub-parallel to the Prince Albert section so this section was chosen to facilitate a comparison. The depth to detachment was calculated to reside at approximately 9 km depth. This is slightly shallower than a seismic profile (Lindeque et al., 2012), which suggested that the faulting controlling the Cape Fold Belt coalesces below the Cape Supergroup, approximately 12 km below the town of Prince Albert. The deformation wedge tapers to the north and detaches along mechanically weak horizons (Laubscher, 1988). Our estimates of shortening in the Laingsburg depocenter are comparable with previous studies that were limited to smaller areas of study in Karoo Basin stratigraphy (Newton 1993, 1995) or focused further south in Cape Basin stratigraphy (Paton et al., 2006).

Reservoir analogue implications

The Laingsburg depocenter has been the focus of sedimentological and stratigraphic research as an onshore analogue for the study of basin-floor submarine slope and shelf sedimentary architectures at a sub-seismic resolution (e.g. Grecula et al. 2003; Flint et al. 2011; Hodgson et al. 2011a; Brunt et al., 2013b; van der Merwe et al., 2014; Jones et al. 2015). Post-depositional deformation around Laingsburg was previously constrained for a small area (Newton 1993, 1995), so published paleogeographic reconstructions (e.g. Grecula et al., 2003), which extrapolate those shortening estimates across the depocenter are inaccurate. In addition, recent lithostratigraphic correlation across the depocenter assumes a static geometry since deposition (van der Merwe et al., 2014). By unfolding the Fort Brown Formation in the Laingsburg area to its pre-deformation state, a more accurate areal extent of the paleogeographic maps at the time of deposition can be derived (Fig. 11), which provides a more accurate calibration of dimensional data, such as the length, width and thickness of lobes (e.g. Prélat and Hodgson, 2013; van der Merwe et al, 2014), and thus, estimate sediment volumes. Estimations could be refined by accounting for compaction, however previous studies have indicated a dominantly sandstone and siltstone rather than claystone stratigraphy (e.g. Flint et al., 2011; van der Merwe et al. 2014). As sand is less compressible than clay (Sclater and Christie, 1980; Baldwin and Butler 1985), most of the folding was post-depositional, and the paleogeographic maps are used to reduce uncertainties in subsurface, and therefore buried and compacted, analogous, the effect of compaction on results at the scale of the depocenter would be minimal. The effect of not restoring the area would be to underestimate the stratigraphic volume of the Fort Brown Formation by 150 km^3 assuming a constant thickness of 400 m (Flint et al., 2011) over an area of 2500 km^2 (van der Merwe et al. 2014) and a 15% shortening estimate. The volume of a single reservoir interval, such as Unit D, which has an average thickness of ~20 m across the study area (Brunt et al. 2013b; van der Merwe et al. 2014), would be underestimated by 7.5 km^3 without restoration under those assumptions. Both restoration methodologies produce similar results in terms of total area change across the Laingsburg depocenter, but the 3D restorations illustrate that rather than increasing linearly as suggested by the 2D restoration, longitudinal strain displays local variability (Fig. 10, 11). The resolution of the 2D restoration is not high enough to capture local variations in area change. The apparent increase in resolution of 3D restorations should not be overstated, however, as potential error is introduced during the creation of surfaces. The accuracy of surfaces are restricted by the limited number of sections used to create them, and balanced sections carry an inherent uncertainty as multiple restorable models are possible (Judge and Allmendinger, 2011). In addition, it is difficult to account for translation, vertical-axis rotation, and strain in complex fold geometries such as non-cylindrical folds, leading to underestimation of shortening (Sussman et al. 2012). In tectonic regimes similar to the Laingsburg area, where non-cylindrical folds display en-echelon relationships, restoration in three dimensions that can account for translation, rotation and strain, may be necessary to resolve shortening magnitude accurately along strike. This study demonstrates the importance of considering post-depositional deformation as an integral part of the sedimentological system, such that the architecture and sediment volumes of ancient sedimentary systems are accurately constrained in paleogeographic reconstructions and the application of dimensional data to analogues.

The role of mechanical stratigraphy

The contrasting mechanical properties of the stratigraphy of the Laingsburg depocenter is reflected in contrasting deformation styles. The pervasive anastomosing axial planar cleavage in the Dwyka Group has been interpreted to form through pressure solution creep at a developing subvertical cleavage (Fagereng, 2014). Fagereng (2014) proposes that shortening in the Cape Fold Belt is accommodated by a Dwyka Group that is relatively incompetent with respect to the underlying Cape Supergroup and overlying remainder of the Karoo Supergroup. Furthermore, the overlying Lower Ecca Group is prone to short wavelength folding and outcrop-scale faulting. This contrasts with the Upper Ecca Group where folds have a longer wavelength and show fewer examples of faulting. The Lower Ecca Group is dominantly claystones and siltstones, whilst the Upper Ecca Group is more sand-prone with intercalated mudstones (Flint et al. 2011). The differing mechanical properties could lead to variability in shortening at the microscopic scale that is not fully captured by restorations. The Lower Ecca Group is thought to be relatively incompetent, prone to the propagation of small-scale thrusts and is inferred to contain a regionally pervasive detachment horizon. The Upper Ecca Group is relatively competent and so the internal formations are prone to deforming as coherent slabs. The contrasting lithological characteristics of the Lower and Upper Ecca Groups are interpreted to reflect their different mechanical properties, which is consistent with previous studies on controls of deformation style in the Laingburg area (Fagereng, 2012, 2014; Newton 1993, 1995). The control by lithogical variation on the nature of the deformation, as well as the level of detachment and wavelength of deformation, is also observed in subaqueous fold and thrust belts (e.g. Dalton et al., in press)

CONCLUSION

Five regional-scale structural cross sections have been palinspastically restored to their pre-deformation state. Minor line length and area imbalances are attributed to sub-resolution errors and uncertainty in package thicknesses across the Karoo Basin. Post-depositional deformation in the Laingsburg depocenter is controlled by a north-propagating leading imbricate fan that coalesces onto a common south-dipping detachment at approximately 9 km depth. Analysis of longitudinal strain in the Laingsburg depocenter has indicated a pseudo-linear increase from Matjiesfontein in the west to Prince Albert in the east, suggesting that the central of the east-west trending limb of the Cape Fold Belt has experienced greater displacement than its margins. By applying shortening estimates to paleogeographic maps of the Laingsburg area (Fig. 11), this work illustrates that structural restoration should be routinely incorporated into workflows when interpreting sedimentary systems to ensure that the architecture and sediment volumes are accurately constrained and applied. For example, without restoration, the volume of sediment in Fort Brown Formation would be underestimated by up to 150 km^3. First order folds in the Laingsburg depocenter are formed above propagating fault tips that are not thought to have penetrated the Ecca Group so line length error is considered to be small, however possible thickening and thinning of beds around folds may introduce minor errors in line length and area. The variability of local shortening values has been used to infer the location of buried faults. This style of deformation is common in basins on the frontal margins of fold belts and if fold geometries are lateral variable, forms good structural traps. This is considered to add value to the Laingsburg depocenter as an analogue basin, and is of particular relevance to prospective basins on the frontal margins of fold-thrust belts.

REFERENCES

Aas, T. E., J. A. Howell, M. Janocko, and I. Midtkandal, 2010, Re-created Early Oligocene seabed bathymetry and process-based simulations of the Peïra Cava turbidite system: *Journal of the Geological Society*, **167**, 857-875.

Alexander, J., 1993, A discussion on the use of analogues for reservoir geology, in M. Ashton, ed., 1993, Advances in Reservoir Geology: Geological Society, London, Special Publications, 69, 175–194.

Baldwin, B., and C. O. Butler, 1985, Compaction curves: *AAPG Bulletin*, **69**, 622-626.

Bangert, B., H. Stollhofen, V. Lorenz, and R. Armstrong, 1999, The geochronology and significance of ash-fall tuffs in the glaciogenic Carboniferous-Permian Dwyka Group of Namibia and South Africa: *Journal of African Earth Sciences*, **29**, 33–49.

Bernhardt, A., Z. R. Jobe, and D. R. Lowe, 2011, Stratigraphic evolution of a submarine channel–lobe complex system in a narrow fairway within the Magallanes foreland basin, Cerro Toro Formation, southern Chile: *Marine and Petroleum Geology*, **28**, 785-806.

Boyer, S., and D. Elliott, 1982, Thrust systems: *AAPG Bulletin*, **66**, 1196–1230.

Brunt, R. L., D. M. Hodgson, S. S. Flint, J. K. Pringle, C. Di Celma, A. Prélat, and M. Grecula, 2013a, Confined to unconfined: Anatomy of a base of slope succession, Karoo Basin, South Africa: *Marine and Petroleum Geology*, **41**, 206–221.

Brunt, R. L., C. N. Di Celma, D. M. Hodgson, S. S. Flint, J. P. Kavanagh, and W. C. van der Merwe, 2013b, Driving a channel through a levee when the levee is high: an outcrop example of submarine down-dip entrenchment: *Marine and Petroleum Geology*, **41**, 134-145.

Butler, R. W. H., and D. A. Paton, 2010, Evaluating lateral compaction in deepwater fold and thrust belts: How much are we missing from “nature’s sandbox”? *GSA Today*, **20**, 4–10.

Cantalejo, B. and K. T. Pickering, 2014, Climate forcing of fine-grained deep-marine systems in an active tectonic setting: Middle Eocene, Ainsa Basin, Spanish Pyrenees: Palaeogeography, Palaeoclimatology, Palaeoecology,**410**, 351-371.

Cardozo, N., and R. W. Allmendinger, 2013, Spherical projections with OSXStereonet: *Computers & Geosciences*, **51**, 193–205.

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

Dahlstrom, C. D. A., 1969, Balanced cross sections: *Canadian Journal of Earth Sciences*, **6**, 743–757.

Dalton, T. J. S., D. A. Paton, and, D. T. Needham, In Press, Temporal and Spatial Evolution of Deep Water Fold Thrust Belts; Implications for Quantifying Strain Imbalance: Journal of Interpretation, this volume.

De Beer, C. H., 1990, Simultaneous folding in the western and southern branches of the Cape Fold Belt: *South African Journal of Geology*, **93**, 583-591.

De Vera, J., P. Granado, and K. McClay, 2010, Structural evolution of the Orange Basin gravity-driven system, offshore Namibia: *Marine and Petroleum Geology*, **27**, 223–237.

de Wit, M.J., I. G. D. Ransome, 1992, The Cape Fold Belt; a challenge for an integrated approach to inversion tectonics, in M. J. de Wit, and I. G. D. Ransome, eds., Inversion Tectonics of the Cape Fold Belt, Karoo and Cretaceous Basins of Southern Africa: Balkema, Rotterdam, pp. 3–14.

Di Celma, C. N., R. L. Brunt, D. M. Hodgson, S. S. Flint, and J. P. Kavanagh, 2011, Spatial and Temporal Evolution of a Permian Submarine Slope Channel-Levee System, Karoo Basin, South Africa: *Journal of Sedimentary Research*, **81**, 579–599.

Durand-Riard, P., L. Salles, M. Ford, G. Caumon, and J. Pellerin, 2011, Understanding the evolution of syn-depositional folds: Coupling decompaction and 3D sequential restoration: *Marine and Petroleum Geology*, **28**, 1530-1539.

Elliott, D., 1983, The construction of balanced cross-sections: *Journal of Structural Geology*, **5**, 8141.

Erslev, E., 1991, Trishear fault-propagation folding: *Geology*, **19**, 617-620

Fagereng, A., 2012, A note on folding mechanisms in the Cape Fold Belt, South Africa: *South African Journal of Geology*, **115**, 137–144.

Fagereng, A., 2014, Significant shortening by pressure solution creep in the Dwyka diamictite, Cape Fold Belt, South Africa: *Journal of African Earth Sciences*, **97**, 9–18.

Fagereng, A., and G. Byrnes, 2015, A range of fault slip styles on progressively misoriented planes during flexural-slip folding, Cape Fold Belt, South Africa: *Journal of Structural Geology*, **70**, 156–169.

Falivene, O., P. Arbués, J. A. Howell, J. A. Muñoz, O. Fernández, and M. Marzo, 2006, Hierarchical geocellular facies modelling of a turbidite reservoir analogue from the Eocene of the Ainsa basin, NE Spain: *Marine and Petroleum Geology*, **23**, 679-701.

Fernández, O., J. A. Muñoz, P. Arbués, O. Falivene, and M. Marzo, 2004, Three-dimensional reconstruction of geological surfaces: An example of growth strata and turbidite systems from the Ainsa basin (Pyrenees, Spain): *AAPG Bulletin,* **88**, 1049-1068.

Fildani, A., N. J. Drinkwater, A. Weislogel, T. McHargue, D. M. Hodgson, and S. S. Flint,2007, Age Controls on the Tanqua and Laingsburg Deep-Water Systems: New Insights on the Evolution and Sedimentary Fill of the Karoo Basin, South Africa: *Journal of Sedimentary Research,* **77**, 901–908.

Fildani, A., A. Weislogel, N. J. Drinkwater, T. McHargue, A. Tankard, J. Wooden, J., Hodgson, D.M., and S. S. Flint, 2009, U-Pb zircon ages from the southwestern Karoo Basin, South Africa—Implications for the Permian-Triassic boundary: Geology, **37**, 719-722.

Flint, S. S., D. M. Hodgson, A. R. Sprague, R. L. Brunt, W. C. Van der Merwe, J. Figueiredo, A. Prélat, D. Box, C. Di Celma, J. P. Kavanagh, 2011, Depositional architecture and sequence stratigraphy of the Karoo basin floor to shelf edge succession, Laingsburg depocenter, South Africa: *Marine and Petroleum Geology*, **28**, 658–674.

Grecula, M., S. S. Flint, and G. Potts, 2003, Partial ponding of turbidite systems in a basin with subtle growth-fold topography: Laingsburg-Karoo, South Africa: *Journal of Sedimentary Research*, **73**, 603–620.

Groshong, R. H., and J. L. Epard, 1994, The role of strain in area-constant detachment folding: Journal of Structural Geology, **16**, 613-618.

Gulliford, A. R., S. S. Flint, and D. M. Hodgson, 2014, Testing Applicability of Models Of Distributive Fluvial Systems Or Trunk Rivers In Ephemeral Systems: Reconstructing 3-D Fluvial Architecture In the Beaufort Group, South Africa: *Journal of Sedimentary Research*, **84**, 1147-1169.

Hälbich, I. W., S. D. Coetzee, and J. H. De Beer, 1993, The Cape Fold Belt–Agulhas Bank transect across Gondwana Suture, Southern Africa. Global Geoscience Transect 9, American Geophysical Union, Publication No 202 of International Lithosphere Program, Washington, 18pp.

Hansma, J., E., Tohver, C. Schrank, F. Jourdan, and D. Adams, 2015, The timing of the Cape Orogeny: New 40 Ar/39 Ar age constraints on deformation and cooling of the Cape Fold Belt, South Africa: online at *Gondwana Research*.

Haughton, P. D. W., 1994, Deposits of deflected and ponded turbidity currents, Sorbas Basin, Southeast Spain: *Journal of Sedimentary Research*, **64**, 233-246.

Hodgson, D. M., C. N. Di Celma, R. L. Brunt, and S. S. Flint, 2011a, Submarine slope degradation and aggradation and the stratigraphic evolution of channel–levee systems: *Journal of the Geological Society*, **168**, 625-628.

Hodgson, D. M. and P. D. W. Haughton, 2004, Impact of syn-depositional faulting on gravity current behaviour and deep-water stratigraphy, in S. Lomas and P. Joseph, eds., Confined turbidite systems: Geological Society Special Publications, 222, 135-158

Hodgson, D. M., W. C. van der Merwe, and S. S. Flint, 2011b,. Distribution of submarine mass movement deposits: an exhumed basin perspective, in Y. Yamada, K. Kawamura, K. Ikehara, Y. Ogawa, R. Urgeles, D. Mosher, J. Chaytor, M. Strasser, eds, Advances in Natural and Technological Hazards Research - Submarine Mass Movements and Their Consequences, 4th Edition, Springer

Howell, J. A., A. W. Martinius, and T. R. Good, 2014, The application of outcrop analogues in geological modelling: a review, present status and future outlook, in A. W. Martinius, J. A. Howell and T. R. Good, Sediment-Body Geometry and Heterogeneity: Analogue Studies for Modelling the Subsurface: Geological Society, London, Special Publications, 387, 1-12.

Isbell, J., D. Cole, and O. Catuneanu, 2008, Carboniferous-Permian glaciation in the main Karoo Basin, South Africa: Stratigraphy, depositional controls, and glacial dynamics, in C. E.

Fielding, T.D. Frank, J. L. Isbell, eds., Resolving the Late Paleozoic Ice Age in Time and Space: Geological Society of America Special Paper, 441, 71–82.

Johnston, S. T., 2000, The Cape Fold Belt and Syntaxis and the rotated Falkland Islands: dextral transpressional tectonics along the southwest margin of Gondwana: *Journal of African Earth Sciences*, **31**, 51–63.

Johnson, M. R., and A. W. Keyser, 1979, The geology of the Beaufort West area, Explanation to Sheet 3222 Scale 1: 250 000. Government Printer, South Africa.

Jones, G. E. D., D. M. Hodgson, and S. S. Flint, 2013, Contrast in the process response of stacked clinothems to the shelf-slope rollover: *Geosphere*, **9**, 299-316.

Jones, G. E. D., D. M. Hodgson, and S. S. Flint, 2015, Lateral variability in clinoform trajectory, process regime, and sediment dispersal patterns beyond the shelf-edge rollover in exhumed basin margin-scale clinothems: online at *Basin Research,* DOI: 10.1111/bre.12092.

Judge, P. A., and R. W. Allmendinger, 2011, Assessing uncertainties in balanced cross sections: *Journal of Structural Geology*, **33**, 458–467.

Laubscher, H. P., 1988, Décollement in the Alpine system : an overview: *Geologische Rundschau*, **77**, 1–9.

Lindeque, A., M. J. De Wit, T. Ryberg, M. Weber, and L. Chevallier, 2012, Deep Crustal Profile Across the Southern Karoo Basin and Beattie Magnetic Anomaly, South Africa: an Integrated Interpretation With Tectonic Implications: *South African Journal of Geology*, **114**, 265–292.

Lock, B. E., 1980, Flat-plate subduction and the Cape Fold belt of South Africa: *Geology*, **8**, 35-39.

Long, J. J., and J. Imber, 2012, Strain compatibility and fault linkage in relay zones on normal faults: *Journal of Structural Geology*, **36**, 16–26.

McKay, M. P., A. L. Weislogel, A. Fildani, R. L. Brunt, D. M. Hodgson, and S. S. Flint, 2015, U-PB zircon tuff geochronology from the Karoo Basin, South Africa: implications of zircon recycling on stratigraphic age controls: *International Geology Review*, **57**, 393-410.

Mitra, S., 2003, A unified kinematic model for the evolution of detachment folds: *Journal of Structural Geology*, **25**, 1659–1673.

Mitra, S., 1990, Fault-Propagation Folds: Geometry, Kinematic Evolution, and Hydrocarbon Traps: *AAPG Bulletin*, **74**, 921–945.

Morris, E. A., D. M. Hodgson, S. S. Flint, R. L. Brunt, P. J. Butterworth, and J. Verhaeghe, 2014, Sedimentology, Stratigraphic Architecture, and Depositional Context of Submarine Frontal-Lobe Complexes: *Journal of Sedimentary Research*, **84**, 763-780.

Mutti, E., 1983, The Hecho Eocene submarine fan system, south-central Pyrenees, Spain: *Geo-marine letters*, **3**, 199-202.

NASA Land Processes Distributed Active Archive Center (LP DAAC) (2014) ASTER Global DEM, LP DAAC 2014

Newton, A., 1993, Thrusting on the northern margin of the Cape Fold Belt, near Laingsburg: *South African Journal of Geology*, **96**, 22–30.

Newton, A., 1995, Thrusting northwest of Laingsburg, Cape Province: *South African Journal of Geology*, **98**, 217–223.

Oliveira, C. M. M., D. M. Hodgson, and S. S. Flint, 2011, Distribution of soft-sediment deformation structures in clinoform successions of the Permian Ecca Group, Karoo Basin, South Africa: *Sedimentary Geology*, **235**, 314–330.

Paton, D.A. and J. R. Underhill, 2004, Role of crustal anisotropy in modifying the structural and sedimentological evolution of extensional basins: the Gamtoos Basin, South Africa: *Basin Research*, **16**, 339-359.

Paton, D. A., 2006, Influence of crustal heterogeneity on normal fault dimensions and evolution: southern South Africa extensional system: *Journal of Structural Geology*, **28**, 868-886.

Paton, D. A., D. I. M. Macdonald, and J. R. Underhill, 2006, Applicability of thin or thick skinned structural models in a region of multiple inversion episodes; southern South Africa: *Journal of Structural Geology*, **28**, 1933–1947.

Paton, D. A., M. Carr, B. Trudgill, H. Ortner, D. A. Medwedeff, 2007, Alpine-scale 3D geospatial modeling: Applying new techniques to old problems: *Geosphere*, **3**, 527-549.

Pei, Y., D. A. Paton, and R. J. Knipe, 2014, Defining a 3-dimensional trishear parameter space to understand the temporal evolution of fault propagation folds: *Journal of Structural Geology*, **66**, 284–297.

Prélat, A., and D. M. Hodgson, 2013, The full range of turbidite bed thickness patterns in submarine lobes: controls and implications: *Journal of the Geological Society of London*, **170**, 209–214.

Salles, L., M. Ford, and P. Joseph, 2014, Characteristics of axially-sourced turbidite sedimentation on an active wedge-top basin (Annot Sandstone, SE France: *Marine and Petroleum Geology*, **56**, 305-323.

Sclater, J. G., and P. Christie, 1980, Continental stretching: An explanation of the post-mid-Cretaceous subsidence of the central North Sea basin: *Journal of Geophysical Research: Solid Earth*, **85 (B7)**, 3711-3739.

Shackleton, J. R., and M. L. Cooke, 2007, Is plane strain a valid assumption in non-cylindrical fault-cored folds? *Journal of Structural Geology*, **29**, 1229–1240.

Sinclair, H. D., and M. Tomasso, 2002, Depositional evolution of confined turbidite basins: *Journal of Sedimentary Research*, **72**, 451-456.

Sixsmith, P., S. S. Flint, H. DeV Wickens, and S. D. Johnson, 2004, Anatomy and stratigraphic development of a basin floor turbidite system in the Laingsburg Formation, main Karoo Basin, South Africa. *Journal of Sedimentary Research*, **74**, 239–254.

Spychala, Y. T., D. M. Hodgson, S. S. Flint, and N. P. Mountney, 2015, Constraining the sedimentology and stratigraphy of submarine intraslope lobe deposits using exhumed examples from the Karoo Basin, South Africa: Sedimentary Geology, **322**, 67-81.

Suppe, J., 1983, Geometry and kinematics of fault-bend folding: *American Journal of Science*, **283**, 684–721.

Suppe, J., and D. A. Medwedeff, 1990, Geometry and kinematics of fault-propagation folding: *Eclogae Geologicae Helvetiae*, **454**, 409–454.

Sussman, A. J., E. L. Pueyo, C. G. Chase, G. Mitra, and A. B. Weil, 2012, The impact of vertical-axis rotations on shortening estimates: *Lithosphere* , **4**, 383–394.

Tankard, A., H. Welsink, P. Aukes, R. Newton, and E. Stettler, 2009, Tectonic evolution of the Cape and Karoo basins of South Africa: *Marine and Petroleum Geology*, **26**, 1379–1412.

Tanner, P. G., 1989, The flexural-slip mechanism: *Journal of Structural Geology*, **11**, 635–655.

Theron, J. N., 1983, The Geology of the Sutherland Are, Explanation to Sheet 3220, Scale 1: 250 000. Government Printer, South Africa.

Theron, J. N., H. deV., Wickens, and P.G. Gresse, 1992, Geological map of Ladismith, Sheet 3320; 1:250,000. Geological Survey South Africa, Pretoria.

Tinker, J., M. de Wit, and R. Brown, 2008, Mesozoic exhumation of the southern Cape, South Africa, quantified using apatite fission track thermochronology: *Tectonophysics*, **455**, 77–93.

Toerien, D. K., 1979, The Geology of the Oudtshoorn Area, Explanation to Sheet 3322, Scale 1: 250 000. Government Printer, South Africa.

Van Der Merwe, W. C., D. M. Hodgson, and S. S. Flint, 2011, Origin and terminal architecture of a submarine slide: a case study from the Permian Vischkuil Formation, Karoo Basin, South Africa: *Sedimentology*, **58**, 2012–2038.

Van der Merwe, W. C., D. M. Hodgson, R. L. Brunt, and S. S. Flint, 2014, Depositional architecture of sand-attached and sand-detached channel-lobe transition zones on an exhumed stepped slope mapped over a 2500 km^2 area: *Geosphere*, **10**, 1076-1093.

Wallace, W. K., and T. X. Homza, 2004, Detachment Folds versus fault-propagation folds, and their truncation by thrust faults, in McClay, K. R., Thrust tectonics and hydrocarbon systems: AAPG Memoir, 82, 324-355.

Watkins, H., C. E. Bond, and R. W. H. Butler, 2014, Identifying multiple detachment horizons and an evolving thrust history through cross-section restoration and appraisal in the Moine Thrust Belt, NW Scotland: *Journal of Structural Geology*, **66**, 1–10.

Wickens, H. DeV., 1994, Basin Floor Fan Building Turbidites of the Southwestern Karoo Basin, Permian Ecca Group, South Africa *[unpublished Ph.D. Thesis]: University of Port Elizabeth, Port Elizabeth*, 233.

Wilson, A., S. S. Flint, T. Payenberg, E. Tohver, and L. Lanci, 2014, Architectural Styles and Sedimentology of the Fluvial Lower Beaufort Group, Karoo Basin, South Africa: Journal of Sedimentary Research, **84**, 326-348.

Winter, H. de la R., and J. J. Venter, 1970, Lithostratigraphic correlation of recent deep boreholes in the Karroo-Cape sequence, in S. H. Haughton, ed., 2nd IUGS Symposium on Gondwana Stratigraphy and Paleontology, 395–408

LIST OF FIGURES

Figure 1: Location map of the study area in the Laingsburg depocenter, with cross section positions indicated: (A) Matjiesfontein section; (B) Laingsburg section; (C) Allemansdrift section; (D) Dwyka River section; (E) Prince Albert section. The location of research boreholes KW 1/67, SA 1/66, and KL 1/65 are marked on the map.

Figure 2: Simplified geological map of Laingsburg study area, showing lithostratigraphy and major (first order) syncline and anticline fold axes.

Figure 3: A) Lithostratigraphy of the Western Cape area of South Africa, redrawn after Wickens (1994). Note the position of the first order detachment (d'ment) in the Cape Supergroup, and the

position of B) and C). Lithostratigraphy of the Tanqua (B) and Laingsburg (C) depocenters of the Karoo Basin, South Africa, adapted from Hodgson et al. (2011b). Note the location of second (Prince Albert Formation) and third (Collingham Formation) order detachments in the study area.

Figure 4: Balanced cross sections from 2D restoration of sections A-D (see Fig. 1 for locations). Two domains of deformation are observed in the post-deformation sections: a southern domain of high amplitude, long wavelength folding controlled by buried thrusts, and a northern domain of low amplitude short wavelength folding facilitated by detachment within the Lower Ecca Group.

Figure 5: Stereonet plots of bedding measurements (left plot) and cleavage measurements (right plot) from the study area. The plots indicate a deformation transport direction towards the north, parallel to azimuth 178^{o}. Bedding measurements show little scatter and contouring of poles indicate that whilst folds appear north-verging at outcrop scale, at the regional scale folds are open and symmetrical.

Figure 6: Deformation styles in the Witteberg Group: (A) North verging anticline on the Matjiesfontein section. (B) Sinistral tension gashes within siliciclastic stratum near Laingsburg. (C) Box fold near Dwyka River. Detachment within Witteberg Group showing characteristic double fold axes. (D) Incoherent bedding due to shearing in argillaceous strata within the Witteberg Group near Laingsburg.

Figure 7: Folding styles in the Ecca Group: (A) Ductile short wavelength folding in the Collingham Fm. Change of bedding orientation occurs within meters. (B) Ductile folding in Prince Albert Fm. with parasitic folding on limbs of main anticline. (C) Tight north-verging syncline in Waterford Fm. (D) Angular north-verging second order anticline in the Laingsburg Fm. A flexural slip towards the hinge results in a larger cross-sectional area.

Figure 8: Images from the 3D restoration highlighting the geometry of structures in the Laingsburg area.

Figure 9: Images from the 3D restoration after the removal of the last stage of deformation in both models. Model A shows linked periclinal folding across the depocenter. Model B shows en echelon detachment folding. Red arrow indicates direction of north.

Figure 10: Strain distribution across the Laingsburg depocenter and its relationship to folding. Strain ellipses are compressed along their axis parallel to maximum stress, 178^{o}.

Figure 11: Panels illustrating the restoration result from the 2D restoration and the two models of the 3D restoration using the Fort Brown Formation as example. The models produce similar results; both the 2D and 3D restorations indicate an increase in shortening to the east, though the 3D restorations indicate that deformation intensity is locally heterogenous, rather than linearly increasing from west to east.

Table 1: Data results from 2D and 3D restorations. Shortening estimates calculated for 2D restorations in terms of the full section lengths for horizon groups 1, 2, and 3, and partial section lengths (33^{o} S and 33^{o} 15’ S) reflecting the Fort Brown Fm. study area in the Laingsburg depocenter. Three dimensional restoration estimates are calculated for the Fort Brown Fm. and are restricted to the Laingsburg depocenter (33^{o} S and 33^{o} 15’ S). Estimates are expressed as percentages.