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A range of fault slip styles on progressively misoriented planes during flexural-slip folding, Cape Fold Belt, South Africa

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Abstract

Flexural slip folds are distinctive of mixed continuous-discontinuous deformation in the upper crust, as folding is accommodated by continuous bending of layers and localized, discontinuous slip along layer interfaces. The mechanism of localized, layer-parallel slip and the stress and fluid pressure conditions at which flexural slip occurs are therefore distinctive of shear localization during distributed deformation. In the Prince Albert Formation mudstone sequence of the Karoo Basin, the foreland basin to the Cape Fold Belt, chevron folds are well developed and associated with incrementally developed bedding-parallel quartz veins with slickenfibers oriented perpendicular to fold hinge lines, locally cross-cutting axial planar cleavage, and showing hanging wall motion toward the fold hinge. Bedding-parallel slickenfiber-coated veins dip at angles from 18° to 83°, implying that late increments of bedding-parallel shear occurred along unfavorably oriented planes. The local presence of tensile veins, in mutually cross-cutting relationship with bedding-parallel, slickenfiber-coated veins, indicate local fluid pressures in excess of the least compressive stress.

Slickenfiber vein microstructures include a range of quartz morphologies, dominantly blocky to elongate-blocky, but in places euhedral to subhedral; the veins are commonly laminated, with layers of quartz separated by bedding-parallel slip surfaces characterized by a quartz-phylosilicate cataclasite. Crack-seal bands imply incremental slickenfiber growth, in increments from tens of micrometers to a few millimeters, in some places, whereas other vein layers lack evidence for incremental growth and likely formed in single slip events. Single slip events, however, also involved quartz growth into open space, and are inferred to have formed by stick-slip faulting. Overall, therefore, flexural slip in this location involved bedding-parallel faulting, along progressively misoriented weak planes, with a range of slip increments.

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hydrothermal veins

1. Introduction

Subgreenschist facies folding of sedimentary sequences is commonly achieved by flexural slip, where folding is accommodated by a combination of ductile buckling of layers and localized slip along layer interfaces (e.g. Chapple and Spang, 1974; Ramsay and Huber, 1987; Tanner, 1989; Fowler, 1996). Typically, bedding-parallel slip associated with flexural slip folding is recognized through the presence of slickenfibers or striations indicating (reverse) dip slip motion on bedding planes (Tanner, 1989; Fowler, 1996; Fowler and Winsor, 1997; Horne and Culshaw, 2001). Bedding-parallel veins, that can be demonstrated to have formed during folding, have been suggested to imply that locally and transiently, fluid pressures significantly in excess of hydrostatic were achieved (Cosgrove, 1993; Horne and Culshaw, 2001). Similarly, slickenfibers in other locations have also been suggested to record fluid pressure fluctuations (Renard et al., 2005) and fault slip at low effective stress (Fagereng et al., 2010). A hypothesis to consider is therefore that flexural slip is associated with frictional shear along weak and/or overpressured planes.

Bedding-parallel veins in flexural slip folds have not exclusively been attributed to bedding-parallel shear during folding. Bedding-parallel veins may also form in sedimentary successions by syn-sedimentary increases in fluid-pressure, caused by either thermal expansion or pore fluid expulsion during burial of low-permeability sediments (e.g. Nicholson, 1978; Fitches et al., 1986; Cosgrove, 1993). If burial is associated with vertical shortening and minor applied horizontal stresses, these veins would generally be tensile, and reflect opening direction perpendicular to near-horizontal bedding. It is, however, possible that shear-related dilation occurs on syn-sedimentary veins, for example in submarine landslides or early, soft-sediment thrusting (Cosgrove, 1993). Pre-folding shear veins would, however, differ from shear veins associated with flexural slip folding, in that flexural slip folding would tend to create veins with opposite shear sense either side of a fold hinge, and development of thickened veins (saddle reefs) at fold hinges (e.g. Ramsay, 1975; Fitches et al., 1986; Tanner, 1989; Cosgrove, 1993).

Geometry and microstructure of vein systems reflect stress and fluid pressure conditions during the fracturing and sealing processes involved in vein formation (e.g. Oliver and Bons, 2001; Collettini et al., 2006; Mittempergher et al., 2009; Bons et al., 2012; Fagereng et al.,

2014). Here, we consider the geometry of flexural slip folds and the microstructure of bedding-parallel slickenfiber veins to discuss the timing of vein formation and the conditions of flexural slip. Folds in the Prince Albert Formation mudstones in the foreland basin of the Cape Fold Belt provide a natural laboratory of well-exposed structures, on which our arguments are based. The folds formed at temperatures less than 200°C (de Swart and Rowsell, 1974; Frimmel et al., 2001), and therefore record brittle-ductile deformation within the normally brittle, seismogenic crust (Sibson, 1984; Scholz, 1988). In the recently suggested continuum of fault behaviors, spanning slip velocities from aseismic creep to regular earthquakes (Peng and Gomberg, 2010), the mechanics of faulting during folding, a form of continuous-discontinuous behavior within the seismogenic zone, may be particularly useful to address the controls on localized versus distributed deformation in the upper crust.

2. Geological Setting

The Cape Fold Belt is generally thought to have formed in an Andean-type margin during subduction of the Paleo-Atlantic underneath the Gondwana supercontinent (du Toit, 1937; Lock, 1980; de Wit and Ransome, 1992), between approximately 300 and 180 Ma (Hälbich, 1992). The late Carboniferous (Pennsylvanian) to Middle Triassic Karoo basin is situated inland of the Cape Fold Belt, and interpreted as the retroarc foreland basin formed landward of the Cape Fold Belt during subduction (Fig. 1)(Catuneanu et al., 1998, 2005). Within the Karoo Basin, the Karoo Supergroup clastic sedimentary sequence unconformably overlies the Cape Supergroup. Whereas the Cape Supergroup rocks predate the formation of the Cape Fold Belt, the Karoo Supergroup was deposited syntectonically (Catuneanu et al., 1998, 2005). Here, we focus on deformation of the Prince Albert Formation, which is part of the Eccca Group of the Karoo Supergroup.

The Prince Albert Formation is the lowermost unit of the Eccca Group. The Eccca Group was deposited in the early Permian (Visser, 1990; Bangert et al., 1999), and in the southern section of the main Karoo Basin it overlies the Dwyka Group, a glacial diamictite and the oldest group of the Karoo succession (Catuneanu et al., 1998, 2005). The Whitehill Formation, a black, carbonaceous shale, overlies the Prince Albert Formation (Visser, 1992). The Prince Albert Formation is a greenish-grey, mudstone package between 40 and 300 m thick (Johnson et al., 2006), containing tuffaceous layers dated to 288 ± 3.0 Ma and 289 ± 3.8 Ma (Bangert et al., 1999). After the deposition of the Prince Albert Formation, the main Karoo Basin continued to fill concurrent with north-south shortening in the Cape Fold Belt (Hälbich, 1992;

62 Catuneanu et al., 2005), leading to burial and horizontal shortening of the Prince Albert
63 Formation. Frimmel et al. (2001) investigated the metamorphic conditions in the Cape Fold
64 Belt, and concluded that the Cape Supergroup did not experience temperatures in excess of
65 300°C. Because the Karoo sediments were deposited on top of the Cape Supergroup, it is
66 likely that the Prince Albert Formation was deformed under peak low-grade metamorphic
67 conditions between 150 and 200°C (de Swart and Rowsell, 1974).

68 The field area of this study is located approximately 12 km south of the town of Laings-
69 burg, where the Prince Albert Formation crops out within the northern foreland of the Cape
70 Fold Belt (Fig. 1). The folds in the Prince Albert Formation mudstones in this area have
71 previously been briefly described by Fagereng (2012) who noted the presence of chevron folds
72 and abundant bedding-parallel, slickenfiber-coated flexural slip faults (Fig. 2). Craddock et al.
73 (2007) studied calcite twins within the Prince Albert Formation, and unraveled two distinct
74 deformation events; one of bedding-parallel, north-south greatest shortening, and a second
75 reflecting bedding-oblique, steeply northeast plunging greatest shortening. The first event is
76 consistent with approximate bulk pure shear and associated upright to steeply inclined folding,
77 whereas the second may reflect a subsequent episode of overthrusting (Craddock et al., 2007).

78 **3. Fold Geometry**

79 The Prince Albert Formation is characterized by chevron folding at wavelengths ranging
80 from less than a meter to about hundred meters. Folds are defined by folded bedding and
81 associated with an axial planar cleavage. Within the Prince Albert Formation, in the study
82 area, bedding thicknesses are typically ~ 30 cm, but range from thin laminations (< 1 cm) to
83 thick beds (~ 100 cm) (Fig. 2a). Beds are laterally continuous along strike for at least tens
84 of meters, where they have not been truncated by local reverse faults. Beds can further be
85 differentiated into more competent silt-rich, clay-poor units and more incompetent clay-rich,
86 silt-poor units (e.g. Fig. 2b). Tuff layers are locally present and a few centimeters thick.

87 Bedding surfaces predominantly dip to the north-northeast and south-southwest at angles
88 ranging from 20° to 80° , such that fold interlimb angles vary from open to tight (Fig. 3a).
89 Fold hinge lines are sub-horizontal and plunge gently ESE and WNW (Fig. 3a). The regional
90 fold axial plane is steeply inclined to the south-southwest, reflected by an axial planar cleavage
91 that varies from subvertical to moderately inclined (Fig. 3a). In other words, the folds are
92 upright to moderately inclined and approximately south verging. Pencil lineation, sub-parallel
93 to fold hinge lines, is abundant in clay-rich layers, and formed by the intersection of bedding

and axial planar cleavage. This lineation therefore approximates the orientation of the fold hinge line, and also plunges gently both ESE and WNW (Fig. 3a). Fold hinges are commonly angular, forming chevron folds, although more rounded fold hinge zones exist in more clay-rich horizons (Fig. 2a,b). Slickenlines and slickenfibers (Fig. 2c) plunge north-northeast and southwest at angles between 20° and 80° (Fig. 3b), and are thereby approximately orthogonal to the average ESE and WNW trending fold hinge lines (Fig. 3b). Fault planes containing the slickenfibers are generally bedding-parallel (Figs. 2a,b,3b), although in places cut upwards through bedding, particularly near fold hinges (Fig. 2a). Slickenfiber steps indicate reverse shear sense (Fig. 2c), and reversal in shear sense across fold hinges as expected in flexural slip folds.

4. Slickenfiber-Coated Veins

Bedding-parallel faults are abundant in the Prince Albert Formation and are identified from the presence of bedding-parallel slickenfiber shear veins. These veins dip at angles between 20° and 82° (Fig. 4). Some slickenfiber veins are bedding-discordant, and have dip angles in the range 18° to 83°, with a median value of 45 - 60° (Fig. 4). Single slickenfiber veins can be traced along strike for at least tens of meters. Vein thicknesses are variable both along-strike, down-dip, and between veins, but typically range from 0.5 to 20 mm.

Slickenfiber-coated veins are continuous across fold hinges of open folds with gently dipping limbs (e.g. Fig. 2b). A reverse shear sense consistent with flexural slip occurs on fold limbs on either side of fold hinges, i.e. the shear sense reverses across the hinge, and there is no sign of shear displacement at the hinge itself. Veins are commonly thickest in fold hinge zones, comparable to saddle reefs described in Horne and Culshaw (2001). Craddock et al. (2007) reported slickenfibers that do not change shear sense across the fold hinge, but we find only very rare, isolated examples of this. The examples we have found are associated with slickenfiber surfaces that cross-cut bedding, i.e. do not accommodate flexural slip folding.

The distances between consecutive shear veins along an approximately 70 m long north-south oriented outcrop transect were measured perpendicular to bedding. Figure 5a shows that there are a few distinct spikes in the cumulative distance between consecutive shear veins, which compared with field observations do not relate to thicker beds. The mean distance between shear veins is 1.2 m (s.d. = 1.3 m, n = 65), but distances range from 10 cm up to 7 m (Fig. 5b).

Slickenfibers are made up of several macroscopic quartz laminations, and are typically

126 between 5 cm and 10 cm long (Fig. 2c,d). The generally accepted macroscopic model for
 127 forming such veins is dilation along irregularities in a fault surface, where dilational sites
 128 are filled by precipitation from a fluid (Durney and Ramsay, 1973; Gratier and Gueydan,
 129 2007; Fagereng et al., 2010; Bons et al., 2012)(Fig. 6a). The shear veins comprise detached
 130 wallrock (mudstone) fragments, solid and fluid inclusions and sheet silicates cemented in vein
 131 quartz and in places calcite (Figs. 6b,7). In places, thicker than average shear veins, or layers
 132 within shear veins, contain mm-scale angular wallrock fragments in a matrix of vein quartz
 133 (Fig. 2d). We interpret these layers as hydrothermal breccias, but cannot confidently define
 134 them as either implosion or hydrofracture breccias. The brecciated fragments have variable
 135 shapes and orientations, but in general high aspect ratio fragments have long axes orientated
 136 subparallel to the vein walls.

137 5. Vein Microstructure

138 Photomicrographs were taken of thin sections cut parallel to slickenfibers and perpendicu-
 139 lar to vein margins. In the following section, we discuss vein morphology and microstructure.
 140 Crack-seal band spacing, as defined by distinct bands of fluid and solid inclusions, and angles
 141 between crack-seal bands and inferred slip surfaces were measured on scaled digital photomi-
 142 crographs using ImageJ software.

143 5.1. Internal Vein Geometry

144 The slickenfiber shear veins are generally composed of multiple layers of quartz and minor
 145 calcite, separated by subparallel wallrock layers or one or more cataclastic shear surfaces that
 146 are also subparallel to bedding (and thereby the vein margin) (Figs. 2d, 6a,b, 7a-d). As such,
 147 the internal geometry is consistent with type B bedding-veins as described by Koehn and
 148 Passchier (2000). The cataclasites are tens of micrometers thick surfaces, continuous for up
 149 to tens of centimeters, and characterized by fine-grained, quartz and phyllosilicate material
 150 cross-cutting vein quartz (Fig. 7c,d). Because the veins reflect bedding-parallel shear, wallrock
 151 layers parallel to the vein margin (e.g. Fig. 7a) must have been the bedding surface at some
 152 point in time, and can therefore also be interpreted as a slip surface. Consequently, the vein
 153 margin-parallel surfaces that define the internal layering of the shear veins are interpreted as
 154 localised shear surfaces, and referred to as such. These shear surfaces are comparable to the
 155 ‘micro-transforms’ defined by Fagereng et al. (2010) in slickenfiber veins from the Chrystalls
 156 Beach Complex.

157 The overall geometry of the slickenfiber veins is a laminated structure where laminae are
 158 separated by shear surfaces (Fig. 6). In the classic growth model for slickenfiber veins, this
 159 structure is achieved by slip on the shear surfaces, associated dilation in microscopic dilational
 160 jogs, and slickenfiber growth as the dilational sites fill with a precipitate, in this case mostly
 161 quartz with minor calcite (Fig. 6a). In the event that slip on the shear surfaces is episodic,
 162 crack-seal inclusion bands (Ramsay, 1980) may develop (Fig. 6a). Where crack-seal bands
 163 are clearly observed, those that lie along the same shear surface are subparallel and mimic
 164 the shape of the wallrock-slickenfiber interface at the end the shear surface. Shear surfaces
 165 are typically at an angle of 50° to 70° to crack-seal bands and extension veins (Figs. 6b,
 166 7a,b,d). Because crack-seal bands form during slickenfiber growth, this must be the original
 167 angle between shear surfaces and inclusion bands, and any subsequent rigid body rotation
 168 would not alter this angle. If the folds were unfolded, the inclusion bands would dip toward
 169 antiform hinges. This is consistent with a reverse shear sense of slickenfiber veins formed during
 170 flexural slip folding, as also inferred by Fowler (1996) in chevron folds in Bendigo-Castlemaine,
 171 Australia.

172 The microscopic structure of individual vein layers is controlled by several parameters,
 173 including stress, fluid pressure, temperature, Peclet number (diffusive vs. advective material
 174 transport), fracture opening rate, precipitation rate, among others (e.g. Durney and Ramsay,
 175 1973; Oliver and Bons, 2001; Bons et al., 2012, and references therein). We therefore describe
 176 the quartz morphology within slickenfibers in the next subsection.

177 5.2. Quartz Morphology

178 Quartz is the dominant vein mineral, and quartz crystal sizes vary from $< 10 \mu\text{m}$ to
 179 $\sim 2 \text{ mm}$. The dominant crystal shape is blocky to elongate-blocky grains of variable size (Fig.
 180 7c-e), although ‘stretched’ crystals (*sensu* Bons et al., 2012) are significant in some places
 181 (Fig. 7f). Stretched and elongate-blocky crystals typically exceed 0.5 mm in their longest
 182 dimension, commonly have serrated grain boundaries and long axes oriented at low angles
 183 ($< 45^\circ$) to slip surfaces (Fig. 7f). The slickenfibers therefore do not have a fibrous (*sensu*
 184 Bons et al., 2012) microstructure, but are rather composed of smaller aspect ratio quartz
 185 crystals. Except locally in some vein layers (Fig. 7f), quartz long axes do not have a clear
 186 preferred orientation relative to the shear surface (Fig. 7c,e). As in bedding-veins described by
 187 Koehn and Passchier (2000), quartz crystals do therefore not necessarily track vein opening,
 188 although internal layering does.

189 A range of quartz microstructures are exhibited in close proximity to each other, typically

190 separated by a shear surface or set of shear surfaces (Fig. 7c-f). In places, quartz laminae with
191 different morphology are separated by a zone containing multiple shear surfaces enveloped by
192 a thicker cataclastic damage zone (Fig. 7c). Such cataclastic zones also separate quartz- and
193 calcite-dominated laminae (Fig. 7d).

194 In places, quartz layers contain isolated wallrock fragments, which are bounded by irreg-
195 ular surfaces (Fig. 7a,b), and enveloped by blocky vein quartz. Wallrock is also incorporated
196 into veins along solid and fluid inclusion bands (Fig. 7b,c,f). In places, these wallrock frag-
197 ments contain a cleavage, implying they were incorporated after formation of the axial planar
198 cleavage. Where inclusion bands are present, they indicate a crack-seal microstructure, and
199 are commonly associated with serrated grain boundaries (Fig. 7f). However, there are numer-
200 ous examples of where inclusion bands, and thus a crack-seal structure, are not present (e.g.
201 7d,e).

202 *5.3. Inclusion Band Geometry*

203 The inclusion bands are oriented at a high angle to wallrock cleavage, and mimic the shape
204 of adjacent vein margins (Fig. 7a). Adjacent inclusion bands are subparallel, and inclined at
205 between 30° and 80° (typically 50° to 70°) to adjacent slip surfaces (Fig. 7b,c,f). Inclusion
206 bands are straight in places, but also curve or turn (Fig. 7a,f), although inclusion bands along
207 the same slip surface are typically parallel. Inclusion bands tend to be continuous across single
208 quartz layers. In places, however, inclusion bands may be discontinuous and stop at a quartz
209 grain boundary. Within the same vein, inclusion bands may be present in only parts of one
210 or more vein laminae.

211 The spacing between adjacent crack-seal inclusion bands is a measure of minimum vein
212 opening in each crack episode (Ramsay, 1980; Renard et al., 2005; Fagereng et al., 2011). To
213 quantify inclusion band spacing, spacings were measured along five transects, parallel to slip
214 surfaces, in four vein samples (Fig. 8, Table 7). The number of adjacent inclusion bands
215 varies from 17 to 165 in these transects, but it is common to find less than 17 adjacent bands
216 in slickenfiber vein samples from flexural-slip folds in the Prince Albert Formation. The
217 cumulative spacing between the inclusion bands reaches up to 17 mm, the entire length of a
218 small slickenfiber (Fig. 8).

219 For each transect, cumulative inclusion band spacing and inclusion band number (num-
220 bered sequentially from one end of the transect to the other) show a near-linear relationship,
221 although there are some clear steps in places (Fig. 8). The standard deviation of the inclusion
222 band spacing is between approximately 50 and 100 % of the mean (Table 7), an effect of some

223 spacings being significantly larger than the mean, and observed as steps in the cumulative
 224 spacing plots (Fig. 8). The mean spacing ranges from 9 μm to 1 mm, a variation of over
 225 two orders of magnitude between five transects. Four out of five transects, however, have
 226 mean spacings in the range of 9 μm to 40 μm . All the transects considered have a posi-
 227 tively skewed frequency-spacing distribution (Fig. 8). These distributions also highlight some
 228 large deviations from the mean spacing, reflected in the significant standard deviations in all
 229 transects.

230 6. Discussion

231 6.1. Deformation History and Frictional Reactivation in the Prince Albert Formation

232 Hinge lines plunging gently east and west, and steeply dipping fold axial planes indicate
 233 that the studied part of the Karoo foreland basin experienced horizontal north-south short-
 234 ening. Prevalent reverse dip-slip faulting on east-west striking faults indicates a regime of
 235 subhorizontal, north-south oriented, greatest compression. Assuming Andersonian mechanics,
 236 and defining the three principal compressive stresses as $\sigma_1 \geq \sigma_2 \geq \sigma_3$, this deformation regime
 237 is associated with a subvertical σ_3 , and σ_2 parallel to fold hinge lines. The presence of pencil
 238 lineation formed by cleavage-bedding intersection in clay-rich units, implies that temperature
 239 was not sufficient to allow shortening-related, axial planar cleavage to become a more devel-
 240 oped fabric than bedding ('early deformation stage' of Ramsay and Huber, 1983). This is
 241 consistent with temperature estimates by Frimmel et al. (2001), who suggest that metamor-
 242 phism in the foreland of the Cape Fold Belt did not exceed subgreenschist conditions.

243 Slickenfiber-coated bedding-parallel veins in the Prince Albert Formation indicate that
 244 flexural slip occurred along bedding surfaces. The fact that slickenfibers trend north and south,
 245 show a reverse sense of shear, and are oriented subperpendicular to fold hinge lines implies that
 246 slickenfiber shear veins accommodated north-south shortening in the same kinematic regime
 247 as the folds. Moreover, in fold hinge zones the slickenfiber veins show a reversal in shear sense,
 248 no shear displacement at the hinge line, and significantly thickened veins, observations that
 249 put together support a syn-folding origin (cf. Fowler, 1996; Horne and Culshaw, 2001). Shear
 250 veins cross-cut wallrock cleavage (Fig. 7b), and therefore the timing of shear vein formation
 251 progressed into late stages of folding, coinciding with or post-dating the development of axial
 252 planar cleavage.

253 The optimal angle for frictional reactivation of a cohesion-less plane is $\theta_r^* = 0.5 \tan^{-1}(1/\mu_s)$
 254 (Sibson, 1985), measured from σ_1 in the $\sigma_1\sigma_3$ plane, and where μ_s is the static coefficient of

friction. The Prince Albert Formation is composed primarily of quartz and clay minerals, and μ_s is therefore likely in the range 0.3 to 0.6 (Byerlee, 1978; Morrow et al., 1992). As a result, the optimal reactivation angle is between 30° and 37° . The stress ratio σ_1/σ_3 required for reactivation is at its lowest when the angle θ_r between the plane to be reactivated and σ_1 is equal to θ_r^* (Sibson, 1985, 1990). The required σ_1/σ_3 ratio increases significantly at angles less or more than θ_r^* , so that σ_1/σ_3 required for reactivation is $\sim 50\%$ greater at angles $\pm 15^\circ$ from θ_r^* , compared to at θ_r^* (Sibson, 1990). Thus, assuming σ_1 is horizontal for reverse faulting along bedding planes in the Prince Albert Formation, flexural slip is most likely to occur along beds dipping at angles between 15° and 52° . At θ_r greater than $2\theta_r^*$, reactivation can only occur if σ'_3 is less than zero, where $\sigma'_3 = \sigma_3 - P_f$ and P_f is fluid pressure (Sibson, 1985). Therefore, unless fluid pressure is elevated to values in excess of σ_3 , bedding-parallel slip cannot occur at dip angles greater than approximately 74° .

No faults dipping at less than 15° were observed in this study (Fig. 4). Combined with the observation that slickenfiber veins in places cross-cut axial planar cleavage, this may imply that folding by flexural slip initiated only after some steepening of bedding planes had occurred by other folding mechanisms. Alternatively, continued folding after initiation of flexural slip may have led to steepening of all flexural slip faults, such that no very gentle dip angles ($< 15^\circ$) have been preserved. These options are difficult to separate; however, it is mechanically easier to explain the evolution of flexural slip folds if at least a small amount of bending occur by early, gentle folding without bedding-parallel slip.

The average dip angle of bedding-parallel slickenfiber veins accommodating flexural slip folding is $50^\circ \pm 14^\circ$ ($n = 58$), greater than expected from the predicted optimal reactivation angle of 30° to 37° in a quartz and clay dominated sequence. Some bedding-parallel faults are also present at angles greater than the inferred lock-up angle of $2\theta_r^* = 74^\circ$, reaching dip angles in excess of 80° . Because bulk horizontal shortening will lead to steepening of planes striking perpendicular the direction of greatest shortening, i.e. bedding on fold limbs in relatively upright folds, it is possible that progressive folding led to steepening of bedding-parallel faults also after they stopped being active. For example, the formation of a subvertical, axial planar cleavage would have contributed to horizontal shortening and associated steepening of bedding planes. However, the prevalence of bedding-parallel fault dip angles greater than the optimal reactivation angle, the observation that steeply dipping bedding-parallel faults cross-cut cleavage, and lack of deformation of vein material in fold hinges, implies that flexural slip folding occurred during progressive flattening and was in later stages of folding accommodated

on faults that were steeper than the optimal reactivation angle. The range of preserved dip angles in bedding-parallel slickenfiber veins may therefore preserve a range of fault orientations from well oriented to severely misprinted, developed during progressive folding where tighter folds required slip on severely misprinted planes toward the end of folding.

A likely deformation sequence involves initiation of flexural slip folding by slip on bedding surfaces after bulk shortening led to gentle folding and dip angles of $\sim 15^\circ$. Continued folding caused tightening of folds, accommodated by slip on bedding-parallel faults at progressively steeper dip. The tightness of folds is then limited by the weakness of bedding planes, which determined the steepest angle at which fault slip was possible. This appears to be $< 75^\circ$ for most faults (Fig. 4), as expected from Andersonian mechanics with clay-rich fault planes, but a few steeper exceptions exist. Craddock et al. (2007) suggested that folding was followed by transport on discrete thrust faults with a top-to-the north shear sense. This is possible, and may have occurred as folds tightened to a point where slip on larger discrete faults, not observed in the field area but possibly present at the contacts between formations (e.g. Lindeque et al., 2011), became preferable. It is also possible that the folding in the Prince Albert Formation accommodates a relatively small component of shortening, compared to displacements on gently dipping thrusts that are not exposed, but have been inferred on geophysical profiles (Stankiewicz et al., 2007; Lindeque et al., 2011).

Folding clearly dominates the deformation within the Prince Albert Formation, but appears largely accommodated by localized bedding-parallel slip, with subsidiary bedding-discordant faults. Bedding-discordant faults have a similar frequency-distribution of dip angles as bedding-parallel faults, with prevalence of dip angles in the range 30° to 60° , but with some faults dipping at more than 80° . Some of the very steep faults are in fold hinges (e.g. Fig. 2a), and appear to have initiated as bedding-parallel, and cross-cut bedding where the dip angle is gentle near the fold hinge. Other steep faults are at relatively low (30° or less) angles to bedding, and may represent faults that occurred before folding, and were then rotated into their current orientation during folding. This interpretation, and the observation that there is little soft sediment deformation in the Prince Albert Formation, is important because it seems likely that the Prince Albert Formation was lithified and comprising rigid beds separated by weak bedding planes before north-south shortening occurred. This supports the suggestion of Tankard et al. (2009) that deformation in the Cape Fold Belt initiated in the Triassic (rather than the Permian or Carboniferous), after burial and diagenesis of Permian sediments.

320 6.2. Fault Spacing

321 Distances between adjacent bedding-parallel shear veins are variable (0.1 - 7 m) and het-
322 erogeneous (Fig. 5). Typically, shear surfaces in flexural slip folds are closer together in
323 steeper dipping fold limbs to accommodate greater flexural slip, whereas in gently dipping
324 fold limbs the relative amount of flexural slip is less and therefore shear surfaces are spaced
325 further apart (Horne and Culshaw, 2001; Hayes and Hanks, 2008). However, the studied folds
326 are relatively upright and do not vary greatly in interlimb angle, so that variation in limb dip
327 is unlikely to be a major factor explaining the variation in slickenfiber vein spacing.

328 Although the shear veins accommodating flexural slip are along bedding planes, they are
329 spaced further apart than the typical bedding thickness of ~ 0.3 m in the Prince Albert
330 Formation. Fowler and Winsor (1997) argue that the formation of bedding-parallel shear
331 veins occurs at interfaces between relatively competent and incompetent sedimentary layers
332 during progressive folding, driven by a gradient in shear strain rate at such interfaces. This
333 effect may have played a role in developing shear veins at the interface between massive (clay-
334 poor) and cleaved (clay-rich) layers in the Prince Albert Formation; however, there are closely
335 spaced shear veins also between clay-rich layers (e.g. Fig. 2a), where this explanation is not
336 sufficient.

337 Opening vein-filled fractures, particularly fractures filled by subhedral to euhedral quartz
338 that indicates growth into a fluid filled crack (such as in Fig. 7c), requires elevated fluid
339 pressure (Oliver and Bons, 2001; Bons et al., 2012). High fluid pressure assisting vein opening
340 and growth may have been accentuated by the presence of relatively impermeable bedding
341 layers within the Prince Albert Formation that could behave as seals (e.g. Sibson, 1990; Cox
342 et al., 2001). This could result in localized areas of high fluid pressure and associated formation
343 of bedding-parallel veins. Fold hinge zones are generally zones toward which material migrate
344 during fluid-assisted deformation by pressure solution (Ramsay, 1977), and it is clear in Fig.
345 2a that the density of slickenfiber-coated bedding-parallel veins, at least locally, increases in
346 the fold hinge region. This may relate to decreased slip and increased bedding-perpendicular
347 dilation in the hinge region, such that bedding-parallel veins become dominantly tensile. More
348 tensile opening would require thicker veins or a greater density of veins. This is consistent
349 with slickenfiber-coated bedding-parallel veins forming during flexural slip, because bedding-
350 parallel displacement along fold limbs would need to be accompanied by bedding-normal
351 displacement at the fold hinge, as testified by thickened veins and reversal in shear sense
352 across hinge regions.

Although bedding-layer competency contrast is also likely to have an effect, fluid pressure variations may have been the primary control on the spacing of bedding-parallel veins in the Prince Albert Formation. This interpretation may be biased by the relatively easy preservation of bedding-parallel slickenfiber veins compared to any bedding-parallel slip surfaces along which no vein developed. It could be that the observed spacing of bedding-parallel slickenfiber veins differs from the actual spacing of shear surfaces during folding. An alternative to a fluid pressure controlled fault spacing is therefore that the fault spacing was controlled by competency contrasts (Fowler and Winsor, 1997), but as veins formed preferentially along high fluid pressure faults, slip surfaces from high fluid pressure zones have been preferentially preserved.

6.3. *Stress and Fluid Pressure Conditions During Flexural Slip*

Where developed, tensile fractures in the Cape Fold Belt, and in the Prince Albert Formation, are commonly subhorizontal (Craddock et al., 2007), as expected for an Andersonian stress regime favoring reverse faulting. An exception, however, is bedding-normal veins developed in some fold hinges, where these veins accommodate local tensile stresses caused by bending of relatively rigid beds. In addition, inclusion bands developed within flexural slip shear veins are generally at 50° to 70° to vein margins dipping at 50° to 70° , i.e. also roughly horizontal. These inclusion bands are developed by consecutive cracking and sealing (Ramsay, 1980; Cox and Etheridge, 1983; Renard et al., 2005; Fagereng et al., 2010), and likely reflect the orientation of tensile fractures in a micro-dilational jog (Fig. 6a). Subvertical, pressure solution cleavage also supports a regime where σ_1 is horizontal, and σ_3 is vertical. For the following discussion, the assumption is therefore made that during flexural slip folding, σ_1 was horizontal, and perpendicular to cleavage, i.e. north trending, and σ_3 was vertical. We apply traditional Mohr-Coulomb mechanics and consider conditions of slip nucleation on existing weak surfaces within otherwise intact rock.

As discussed above, slickenfiber veins represent incremental slip on surfaces ranging from well to poorly oriented, implying that reshear occurred on progressively more unfavourably oriented surfaces as folding progressed. Ideally oriented faults would be dipping at 30° to 37° in these quartz-clay rocks, and lack of optimally oriented discordant faults (Fig. 4) implies that frictional failure of surrounding rock, initiating new faults, was not a preferred brittle deformation mode during folding. However, tensile failure of rock immediately surrounding slip surfaces must have occurred to create macroscopic, layered, slickenfbers containing wall rock fragments. One mechanism to grow such fibers was suggested by Fagereng et al. (2010)

and termed ‘dilational hydroshear’. In this mechanism, shear failure along weak planes occurs coincidentally with tensile failure of surrounding rock, such that conditions must prevail where a shear failure criterion is reached along a pre-existing surface at the same time as the hydrofracture criterion is achieved in the host rock of this shear surface. This implies the fluid pressure, P_f , must equal σ_3 plus the tensile strength of the host rock, T_0 , and that differential stress is less than $4T_0$ (Secor, 1965; Etheridge, 1983). For frictional reactivation to occur at the same time as tensile failure, the following criterion must be met (Sibson, 2009; Fagereng et al., 2010):

$$(\sigma_1 - \sigma_3) = \frac{\tan \theta_r + \cot \theta_r}{1 - \mu_s \tan \theta_r} \times (c - \mu_s T_0) \quad (1)$$

where c is the cohesion of the slip surface. For shear surfaces with low cohesion (0.1 MPa) and assuming a tensile strength of 1 to 10 MPa for surrounding mudstone (Lockner, 1995), conditions for ‘dilational hydroshear’ as a function of reactivation angle θ_r are estimated in Fig. 9. This mechanism of concurrent slip and tensile fracture appears to only occur on unfavorable to severely misoriented faults, as a positive $(\sigma_1 - \sigma_3)$ value is only obtained for θ_r in excess of about 60° for μ_s of 0.6, and over 75° for μ_s of 0.3. It may therefore be that flexural slip occurred along bedding planes from an early stage of folding, but only produced slickenfiber-coated fault surfaces involving coincident shear and dilation as progressive folding led to steepening of fold limbs and slip occurred on weak, unfavorably oriented planes. If this interpretation is correct, then at least some slickenfibers reflect slip allowed by high fluid pressure at unfavorable conditions for reactivation. In this case, that would mean than flexural slip folding in the Prince Albert Formation mudstones continued, at least locally, after faults steepened to unfavorable angles, and that this was allowed by fluid pressures in excess of lithostatic along weak bedding planes. Slickenfibre laminae with quartz morphology not involving crack-seal bands at high angles to slip surfaces, may have formed by frictional reactivation of more preferably oriented planes, but it is then intriguing that crack-seal bands were not preserved. This lack of crack-seal band preservation may indicate a difference in fault slip style between well and poorly oriented planes, potentially governed by the maximum contained overpressure.

An alternative mechanism for slickenfiber growth involves slip assisted by dissolution-precipitation creep, a viable mechanism in fine grained rocks with a pressure solution cleavage (Bos et al., 2000; Bos and Spiers, 2001; Niemeijer and Spiers, 2006; Gratier and Gueydan, 2007; den Hartog and Spiers, 2014). In this model, pressure solution allows for dissolution of

417 asperities (irregularities) along the slip surface, and precipitation occurs in low-stress dilatant
418 sites, without necessarily requiring brittle fracture (Gratier and Gueydan, 2007). This is
419 a possible mechanism in the temperature window of 150 - 200°C that is proposed for the
420 Cape Fold Belt, as fine grain sizes and mobility of silica in solution at these conditions are
421 favorable for pressure solution (Fagereng, 2014). However, the highly localized slip required
422 for flexural slip rather than flexural flow, velocity-weakening behavior observed in quartz in
423 this temperature range (Blanpied et al., 1995), and the presence of cataclasites along slip
424 surfaces, indicate that at least a component of frictional sliding is likely for the flexural slip
425 folds in the Prince Albert Formation.

426 6.4. *Fault Slip Style*

427 Vein quartz in shear veins from the Prince Albert Formation is largely unaffected by post-
428 precipitation deformation and recrystallization, an effect of the low temperature of precipita-
429 tion (well below the onset of quartz plasticity at $\sim 350^\circ\text{C}$, Hirth et al., 2001). We therefore
430 use the microstructure of these veins to discuss the kinematics and mechanics of flexural slip
431 that accommodated deformation during the folding in the Prince Albert Formation.

432 In places, the shear veins preserve a crack-seal microstructure. The crack-seal bands have
433 a relatively consistent spacing (within an order of magnitude) along single shear surfaces,
434 but spacing varies by orders of magnitude between transects from different veins (Fig. 8).
435 The spacing between inclusion bands reflects the sealed crack from each individual crack-
436 seal episode (Ramsay, 1980; Cox and Etheridge, 1983; Cox, 1987). This spacing is therefore
437 a minimum estimate for the crack aperture, as the crack may not have been completely
438 sealed. It is possible for a crack-seal structure to form by continuous fault slip, if continuous
439 vein opening is coupled to a precipitation rate that increases with time until the crack is
440 filled, and then a new crack forms adjacent to the sealed crack (Lee and Wiltschko, 2000).
441 This mechanism would, however, require that vein growth rate can increase during sealing
442 of each growth increment. In the veins studied here, crystals are usually continuous across
443 inclusion bands, implying that the size and orientation of crystal faces stay approximately
444 constant, and unless other parameters change significantly growth rate should not increase
445 during sealing. Alternatively, the presence of inclusion bands implies incremental slickenfiber
446 growth (e.g. Renard et al., 2005; Fagereng et al., 2011). In this case, vein opening is faster
447 than precipitation, and sealing occurs at a constant or decreasing rate (e.g. Lee and Wiltschko,
448 2000). The blocky and elongate-blocky quartz morphology that is predominant in the Prince
449 Albert Formation veins is generally inferred to be associated with growth into open cracks

(Cox, 1987; Oliver and Bons, 2001; Bons et al., 2012), rather than slow subcritical grain growth which is more commonly associated with fibrous growth (Urai et al., 1991; Fisher and Brantley, 1992). Therefore, we infer that the crack-seal bands developed along faults accommodating flexural slip in the Prince Albert Formation reflect incremental slip where each slip episode created a dilatant crack which was subsequently filled by quartz precipitation.

A number of interpretations can be made based on the inference that crack-seal bands reflect episodic fault slip. Another inference we have made, is that the slickenfiber veins containing crack-seal bands, reflecting tensile cracks, formed on faults active at fluid pressures locally in excess of σ_3 . Each crack event is then associated with a point in time where fluid pressure was locally lithostatic, because σ_3 is inferred as vertical, and sealing reflects precipitation of quartz driven by the fluid pressure drop induced by crack dilation. In this case, slip along bedding planes occurs as fluid pressure reaches a critical value, and is relatively independent of fluctuations in shear stress. Consequently, the relatively consistent inclusion band spacing along any transect implies cycling of fluid pressure levels and failure at a relatively constant maximum contained fluid pressure. These two interpretations, that slip on slickenfiber-coated bedding surfaces was controlled by fluid pressure fluctuations, and led to creation of open space in characteristic increments, lead to a third inference; flexural slip involved stick-slip motion along unfavourably oriented bedding planes, at least in late stages of folding.

Stick-slip motion is generally associated with earthquake slip, and incrementally grown slickenfibers with crack-seal bands at a high angle to vein walls may therefore reflect episodic earthquake slip on unfavorably oriented faults under low effective stress conditions. Slip increments on the order of $10\ \mu\text{m}$ to $1000\ \mu\text{m}$ on faults that are continuous for tens to hundreds of meters, imply a ratio of average slip, $\bar{u}$, to potential rupture length, L , of $10^{-6} < \bar{u}/L < 10^{-5}$. Because fault length likely increases as a fault grows by incremental slip, this is likely an underestimate of $\bar{u}/L$, as each slip event likely had a smaller L than the entire available fault length. Stress drop, $\Delta\tau$, is related to $\bar{u}/L$ with the relation $\Delta\tau = CG\bar{u}/L$ (Kanamori and Anderson, 1975), where C is a geometrical factor, and G is the shear modulus and typically 30 GPa in the brittle crust (Turcotte and Schubert, 2002). For a circular rupture where $C = 7\pi/16$, the stress drop for slip increments in this study can then be estimated as roughly between 40 and 400 kPa, although locally higher and lower stress drops could have occurred. Although significant uncertainties are involved in these numbers, episodic slip events recorded in crack-seal slickenfiber veins here appear to have stress drops of no more than a few hundred

483 kPa, on the low end of the range of stress drops calculated for geophysically observed events
484 (Scholz, 2002). The magnitudes of such events would be small; an average slip of $30\ \mu\text{m}$ on a
485 $10\ \text{m}$ radius (r) fault would give a moment, defined as $M_0 = G\pi r^2 \bar{u}$ for a circular rupture (Aki,
486 1967), of approximately $3 \times 10^8\ \text{Nm}$. Larger slip of $1\ \text{mm}$ over a $100\ \text{m}$ radius fault would give
487 a moment of about $9 \times 10^{11}\ \text{Nm}$. Taking moment magnitude, M_w , as equal to $2/3(\log M_0 - 9.1)$
488 (Purcaru and Berckenhmer, 1978; Hanks and Kanamori, 1979), this moment range translates
489 to a moment magnitude range of -0.5 to $+1.9$. Repeating low stress drop events in this small
490 magnitude range is comparable to observations of low frequency earthquakes in subduction
491 zones (Ito and Obara, 2006; Peng and Gomberg, 2010) and repeating microseismicity on the
492 San Andreas fault (Nadeau et al., 1995; Nadeau and McEvilly, 2004). A mechanism analogous
493 to repeating small, possibly low stress drop, earthquakes, was also suggested for the formation
494 of slickenfiber veins in an exhumed accretionary mélangé by Fagereng et al. (2011).

495 As opposed to slickenfiber veins studied by Fagereng et al. (2011), the slickenfibers involved
496 in flexural slip folding in this study do not have a uniform crack-seal structure, but also include
497 significant segments and layers defined by a blocky microstructure. Blocky quartz, as well as
498 subhedral and elongate-blocky crystals present in places, imply growth into an open space
499 that opened in one event. Also, for these microstructures to be preserved, rather than fibrous
500 quartz, vein opening rate likely exceeded growth rate (Lee and Wiltschko, 2000; Bons et al.,
501 2012). Accordingly, the slickenfiber veins do not exclusively record episodic crack-seal growth
502 representing tens to hundreds of events (as depicted in Fig. 8), but also single slip events
503 of greater magnitude. There is also a possibility that some of these events occurred by a
504 ‘crack-seal, slip’ mechanism as proposed by Petit et al. (1999). This would imply that slip
505 along shear surfaces, preserved as cataclasites, led to dilatant opening of zones between slip
506 surfaces (as in Fig. 6a), and these areas were then sealed over time, until a new slip event may
507 have occurred. There is no constraint on reactivation angle relative to σ_3 in slickenfiber veins
508 that lack crack-seal bands reflecting tensile opening in cracks at a high angle to slip surfaces.
509 It is possible, therefore, that slickenfibers formed by this ‘crack-seal. slip’ mechanism reflect
510 shear under lower contained fluid pressure, at optimal or less unfavourable orientation than
511 the slip by the dilational shear mechanism outlined above.

512 Overall, the slickenfiber veins reflect a variety of slip increment magnitudes, associated
513 with dilatancy allowing for quartz precipitation. In places, incremental stick-slip is evident
514 from blocky quartz microstructures and crack-seal inclusion bands, reflecting tens to hun-
515 dreds of slip increments of characteristic order of magnitude, and possibly reflecting repeating

516 micro-earthquakes. We infer these microstructures to have formed under high fluid pressures
 517 to explain the high angle between coincident shear and tensile fracture. In other places, larger
 518 zones of blocky, elongate-blocky, and euhedral to subhedral quartz, adjacent to cataclastic
 519 slip surfaces, indicate larger and possibly single event slip increments. This latter slip style
 520 may reflect shear under lower fluid pressure conditions along well-oriented to slightly misori-
 521 ented planes. This variety in slickenfiber microstructures may indicate that multiple fault slip
 522 styles occurred on a single fault segment, potentially as a function of increasingly unfavorable
 523 orientation as faults steepened with progressive folding.

524 7. Conclusions

525 In conclusion, we have made a number of observations and inferences regarding slickenfiber
 526 veins associated with flexural slip folding in the Prince Albert Formation of the Karoo foreland
 527 basin of the Cape Fold Belt. We suggest that these veins formed by localised frictional sliding
 528 within a zone of distributed deformation. The veins therefore reflect fault slip styles recorded
 529 from a zone of mixed continuous-discontinuous deformation.

- 530 1. Bedding-parallel slickenfiber veins thicken in fold hinges and show a reversal in shear-
 531 sense such that the hanging wall moves toward the hinge line on both sides of the
 532 hinge. As a result, there is no shear displacement at the hinge, but rather a com-
 533 ponent of bedding-perpendicular extension. The veins commonly also cross-cut axial
 534 planar cleavage. Bedding-parallel slickenfiber veins are therefore inferred to have formed
 535 progressively during flexural slip folding.
- 536 2. Bedding planes that accommodated flexural slip during folding are characterized by
 537 slickenfiber-coated surfaces, and typically dip at angles greater than the optimal reactiva-
 538 tion angle of 30° to 37° . The range in dip angles indicates faults ranging in orientation
 539 from well to poorly oriented, as expected if folds tighten progressively until lock-up an-
 540 gles are reached.
- 541 3. Slickenfiber veins formed by a mixture of slip styles, but generally involving stick-slip
 542 behavior along one or more shear surfaces. Some veins record tens to hundreds of slip
 543 increments on the order of tens of micrometers to a few millimeters, whereas other veins
 544 reflect quartz precipitation into open spaces that imply slip increments of as much as a
 545 few centimeters.
- 546 4. Shear veins locally contain subhorizontal crack-seal bands and are in places associated
 547 with subhorizontal tensile fractures. Formation of these tensile fractures imply fluid

pressures in excess of the least compressive stress, which was subvertical and therefore approximately lithostatic. Flexural slip folding in this location therefore, locally and likely in late stages of folding, involved slip on low cohesion, weak planes, assisted by local and transient lithostatic fluid pressure conditions.

5. Stick-slip deformation along bedding-planes, occurring under low effective stress conditions, may reflect low stress drop seismic events as recorded in some subduction zones and along the San Andreas fault. The mixture of slip increments and vein quartz microstructures within any one slickenfiber vein highlights the possibility that a single fault can be capable of several fault slip styles, including slow, fast, and intermediate slip rates. The type of fault slip may be governed by the local maximum contained overpressure, which is again governed by the degree of misorientation of planes available for reactivation. Increasing misorientation as folds progressively tighten, may therefore lead to slip at decreasing effective stress in late phases of folding as faults begin to lock up. Active flexural slip folding may therefore be associated with a complex deformation pattern involving continuous deformation of folded layers accompanied by variable magnitude frictional stick-slip along discrete, mostly bedding-parallel, fault surfaces, at least until slip on new, through-going fault surfaces becomes preferable.

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Figure 1: Location of the study area. a) Overview of southern Africa, with the extent of the Main Karoo Basin and the Cape Fold Belt (after Johnson et al., 1996), the rectangle showing the study area related to the map in panel (c). b) Schematic cross-section of the Cape Fold Belt and the Karoo Basin, based on a composite cross-section east of the study area, compiled by Tankard et al. (2009). c) Local geology in the area around Laingsburg, same legend as in (b), after the 1:1,000,000 geological map of South Africa. The dashed rectangle shows the area from which samples and measurements were collected.

Figure 2: Field photographs. a) Small antiform within the Prince Albert Formation, bedding-parallel slickenfiber-coated veins are highlighted in dashed red lines, discordant slickenfiber-coated faults are in yellow. b) Fold hinge zone with massive, fractured, clay-poor bed and cleaved, clay-rich beds, separated by slickenfiber-coated shear veins. Note thickening of bedding-parallel vein in the fold hinge, where the shear displacement is zero as the vein opening vector is bedding-normal rather than bedding-oblique in this location. c) Close-up of slickenfiber coated bedding plane.

Figure 3: Lower hemisphere, equal area, stereoplots showing orientations of (a) poles to bedding bedding (open circles, $n = 103$), fold hinge lines (black triangles, $n = 29$), pencil lineation (red open diamonds, $n = 35$), and cleavage (dashed great circles, $n = 45$); and (b) bedding-parallel faults (black solid great circles, $n = 57$), discordant faults (red dashed great circles, $n = 20$), and slickenfibers (black, filled circles, $n = 79$).

Figure 4: Histogram showing the frequency distribution of fault dip angles for bedding-parallel ($n = 57$) and discordant ($n = 20$) faults, identified by slickenfiber-coated surfaces.

Figure 5: Spacing of bedding-parallel, slickenfiber-coated veins along a north-south transect, where spacing was measured perpendicular to bedding. a) Cumulative spacing against vein number, where veins are numbered sequentially as they intersect the transect line. Note a few large steps in spacing, within an otherwise near-linear relationship. b) Histogram showing the frequency distribution of vein spacing ($n = 65$), note a positively skewed distribution with most spacings less than 1 m, but a few instances of several meters spacing between adjacent fault veins.

Figure 6: Geometry of slickenfiber veins. a) Typical model for the development of slickenfiber vein geometry by incremental dilation on an uneven fault surface (after Fagereng et al., 2010; Bons et al., 2012). At time $= 0$ the fault initiates, and at each increment of slip, dilatant zones open by an amount dependent on the slip magnitude. After n increments of slip (at time $= n$), a macroscopic slickenfiber with n crack-seal bands has opened. Note that whether crack-seal bands are preserved depends on the relative rates of vein opening and mineral precipitation (Lee and Wiltschko, 2000). In the final vein, fibers may be laminated, with laminae separated by slip surfaces, and containing crack-seal bands (dashed lines in sketch). b) Scanned thin section cut parallel to slickenfibers and perpendicular to the slickenfiber-coated bedding plane. Like the model in (a), this vein comprises multiple quartz laminae separated by slip surfaces (dashed red lines). Note relatively high angle ($60 - 70^\circ$) between inclusion bands, extension veins (that are parallel to inclusion bands and shown in blue dashed lines), and slip surfaces.

Figure 7: Photomicrographs illustrating the internal geometry and morphology of slickenfiber-coated, bedding-parallel veins from flexural slip folds in the Prince Albert Formation. (a) and (b) are in plane-polarized light, the rest in cross-polarized light. a) Numerous subparallel slip surfaces, defined by wallrock fragments and/or thin cataclasites, lie at approximately 60° to inclusion bands, and separate multiple layers of vein quartz. b) Closer-up view of slip surface and inclusion bands, in a vein that cross-cuts wall rock foliation, which is near-perpendicular to inclusion bands. c) Elongate-blocky quartz within a slickenfiber vein, surrounding a zone of multiple cataclasite slip surfaces. d) Layers of block quartz and calcite separated by slip surfaces that are defined by multiple cataclasites separated by thin damage zones. e) Layers of blocky and euhedral to subhedral quartz separated by a thin slip surface. f) Quartz layer characterised by stretched quartz crystals, with serrated grain boundaries and inclusion bands indicating a crack-seal microstructure.

Figure 8: Locations and data from transects along slip surfaces to measure the spacing between inclusion bands. Left column: sample numbers and thin section scans showing the location of the transects in red lines (circled to be more visible). Middle column: Cumulative spacing of inclusion bands against inclusion band number, where the bands were numbered sequentially as they intersect the transect line. Right column: Histograms illustrating the frequency distribution of inclusion band spacings along each transect.

Figure 9: Conditions for simultaneous frictional reactivation of bedding surfaces with cohesive strength 0.1 MPa , frictional coefficient of μ_s and dip θ_r , and tensile opening of surrounding rock with tensile strength T_0 . Calculations using Eq. 1 from Sibson (2009), as adapted by Fagereng et al. (2010). These conditions allow for a mechanism of slickenfiber growth by shear along weak surfaces and concomitant opening of dilational zones between these slip surfaces (as in Fig. 6a), and is only possible for the parameters that yield $(\sigma_1 - \sigma_3) > 1$. For other conditions, shear failure will occur at fluid pressures that are insufficient for concomitant hydrofracturing.

Table 1: Statistics of measured spacing between adjacent inclusion bands along transects shown in Figure 8.

a)

b)

Table 1: Statistics of measured spacing between adjacent inclusion bands along transects shown in Figure 8.

Sample	LB10	LB11-1	LB11-2	LB13	LB17
Number of inclusion bands	24	65	63	165	17
Cumulative spacing (mm)	0.89	2.6	0.54	3.6	17
Mean spacing (μm)	37	40	9	22	1000
Standard deviation (μm)	19	47	5	16	555
Minimum spacing (μm)	10	4	3	3	180
Maximum spacing (μm)	67	220	25	82	2600