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Calcite twin analysis in syntectonic calcite, Cape Fold Belt, South Africa: Implications for fold and cleavage formation within a shallow thrust front

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Abstract

Lithologies of two formations in the frontal ranges of the Cape Fold Belt, South Africa, host synorogenic calcite precipitated at low metamorphic grade during the end-Permian deformation of this Gondwana-wide orogen. The calcite crystals are mechanically twinned and this deformation is linked to both folding and the formation of an axial planar cleavage with associated extensional veins. Twinning strain analysis reveals a complex, rotational synfolding history in the upper, thin-layered Prince Albert Formation. Twinned calcite within the fold preserves two unique strain events. The primary shortening strain fabric is layer-parallel and transport-parallel (~north–south). The shortening strain overprint (−5.82%) is layer-normal and plunges steeply to the northeast. These results are inconsistent with a flexural-slip folding mechanism. By contrast, a homogeneous syn-cleavage stress–strain field is recorded in the underlying, massive thick-bedded Dwyka Tillite. Analyses of calcite twins in clast-hosted, syn-cleavage fibrous calcite and rare limestone clasts define a sub-horizontal N–S shortening, and sub-horizontal, E–W extension. The intermediate axis (ϵ_2) is vertical and preserves shortening (−5.3%). The extension axis (ϵ_3) is horizontal and parallel to the clast 'tension gash' (fracture) plane. These deformed syn-cleavage calcite materials provide an independent constraint to the debate about contemporaneous stress–strain fields associated with folding and formation of an axial planar cleavage.

Keywords: Folding dynamics; Cleavage; Calcite twinning; Gondwanide belt

1. Introduction

Numerous studies of folding dynamics have utilized the presence of intragranular deformation lamellae in quartz and/or calcite (in sandstones/quartzites or limestones, respectively) to understand fold kinematics and genesis, both at a regional scale (Carter and Friedman, 1965; Burger and Hamill, 1976; Friedman and Stearns, 1971; Schmid et al., 1981; Hennings, 1986; Fisher and Anastasio, 1994; Craddock and Relle, 2003) and outcrop scale (Scott et al., 1965; Spang, 1974; Chapple and Spang, 1974; Groshong, 1975; Mitra, 1978; Oertel, 1980; Spang et al., 1980, 1981; Spang and Groshong, 1981; Hudleston and Holst, 1984; Onasch, 1984; Narahara and Wiltschko, 1986; Hudleston and Tabor, 1988). The primary finding of these studies is the preservation of a pre-folding fabric that documents a layer-parallel shortening (lps) strain within the plane of thrust fault transport (plane strain) and that is mostly devoid of a strain overprint related to the folding (see, however, Spang and Groshong, 1981) or rotation across (i.e., flexural-slip) a fold axis or hinge (see, however, Craddock and Relle, 2003). Most of these folding studies are from frontal thrust belt settings where the same pre-folding lps fabric is preserved in the adjacent autochthonous foreland (e.g., Craddock and van der Pluijm, 1989; van

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der Pluijm et al., 1997; Craddock and van der Pluijm, 1999). Two studies have utilized calcite twinning strains from both limestones and syn-deformational calcite veins (Kilsdonk and Wiltschko, 1988: thin-skinned Appalachian's; Craddock and Relle, 2003: thick-skinned Laramide fold), but these yielded different results. This field setting, in the frontal Cape fold belt, presents a rare occurrence of bedding-parallel zones (1–7 cm thick) of calcite–quartz that were precipitated, and were deformed (layer-parallel foliation and striations, and mechanically twinned calcite), during folding and are close to autochthonous limestones (with twinned calcite) of the same age in the less deformed (autochthonous) foreland.

Here we describe similar strain fabrics in rocks from the frontal thrust zone of the Cape Fold Belt (CFB), where Permo-Triassic orogenesis has folded a sequence of Paleozoic clastic sediments in a para-allochthon at a low grade of metamorphism. Folded and axial-planar-cleaved black shales of the Prince Albert Formation (Permian) preserve twinning strains in layer-parallel, syn-folding calcite layers across folds that can be correlated with fabrics preserved in these same lithologies exposed in the subhorizontal, autochthonous foreland ~7 km to the north. This setting allows us to track bending strains and rotations imparted on the layer-parallel calcite during subsequent folding in the thrust belt with the lps strain fabric in the adjacent foreland. We have chosen one bedding-parallel quartz–calcite layer from one well-exposed synclinal fold section that we believe is representative of the stress–strain response (kinematics, twinning strains, etc.) of other quartz–calcite layers in this, frontal fold and thrust zone of the CFB region.

In conjunction, related deformation fabrics in the immediately underlying massive diamictites of the Permo-Carboniferous Dwyka Formation provide an additional opportunity to test the orientation of the local and regional CFB stress–strain field. In this lithology, deformation is expressed by subhorizontal extensional fractures in relatively rigid clasts of granite and quartzite randomly distributed in the fine matrix of the massive diamictite that also hosts a subvertical cleavage. Some of the fractures are filled with calcite or quartz. Twin orientations in calcite crystals precipitated in the extensional veins can be referenced, therefore, to the cleavage and to the fold axis orientation, as well as to the fractures in the clasts, if we assume that the calcite filling in these fractures records a syn-cleavage deformation. To test the latter, we also measured calcite twinning strains in limestone clasts of these Dwyka Fm. outcrops, to compare to those in the syn-cleavage calcite twinning strains of the Prince Albert Fm.

This may be a first report of calcite precipitating and immediate, contemporaneous twinning, thereby recording the evolving stress–strain field associated with the formation of an axial planar cleavage, a topic debated for nearly 150 years and confined largely to finite strain measurements of clasts, fossils or reduction spots within the cleaved host (Sorby, 1853, 1856; Maxwell, 1962; Oertel, 1970; Tullis and Wood, 1975; Wood, 1974; Beutner, 1978; Wright and Platt, 1982). Deformed syn-cleavage materials, such as described here, provide an independent constraint in this debate.

2. Regional geological setting

The Cape Fold Belt and its related Karoo Foreland Basin (KFB) of South Africa formed during the late Paleozoic-early Mesozoic convergence along the southwestern margin of Gondwana, as part of the greater Gondwanide orogenic belt. Fragments of the Gondwanides can now be found in South America, Africa, Antarctica and Australia (Fig. 1.; du Toit, 1937; de Wit and Ransome, 1992; Rapela et al., 2003). The foreland margin is characterized by classic thin-skinned thrust belts, often with a strike-slip overprint towards its outer margin, and the absence of volcanic rocks (e.g., Johnston, 2000). The outer margin contains classic arc-like sequences and high pressure metamorphic assemblages (Trouw and de Wit, 1999) with possible basement involvement and younger inversion structures (Paton et al., 2006). Many workers have related the features of the Gondwanides to subduction of the paleo-Pacific plate beneath the Gondwana plate during the Paleozoic-early Mesozoic (Lock, 1980; Cole, 1992; Smith, 1999; Johnson et al., 1997; Catuneanu et al., 1998; Milani and de Wit, 2006).

The Karoo Foreland Basin evolved as a Gondwana continental foreland basin linked to the emerging Cape Fold Belt in the late Permian and early Triassic (Halbich and Swart, 1983, Halbich, 1992; Cloetingh et al., 1992; Catuneanu et al., 1998; Trewin et al., 2002; Milani and de Wit, 2006). The CFB structures are best preserved by the quartzites of the Table Mountain Group (TMG), deposited in the Cape Basin. Derived from the north, these siliciclastics represent the lower part of an early-mid-Paleozoic, relatively stable continental shelf that bordered southwest Gondwana as a passive margin environment. In Carboniferous times, the hinterland to this shelf came to be covered by a thick Antarctic-like continental ice sheet that episodically advanced across the Cape Basin, depositing thick glacial deposits, locally known as the Dwyka tillites, and its interbedded fluvioglacial deposits (Visser, 1989). In the study area, glacial sediments of the Dwyka Group (~600–700 m thick, including several diamictite units) are abruptly overlain by the post-glacial foreland sediments of the Karoo Foreland Basin (the Ecca and Beaufort Groups) derived from the south, heralding the early onset of orogenesis in the CFB. The total thickness of the Karoo sediments ranges from 5–6 km. The lower parts of the Ecca Group, which lies directly on the Dwyka tillites, comprises predominantly black shales of the Prince Albert Formation (~150 m thick) and overlying carbonaceous and pyritic shales and cherts of the Whitehill Formation (50–70 m thick). In turn these are overlain by a thick (3000 m) sequence of turbiditic sandstones and shales of the upper Ecca and Lower Beaufort Groups. Overlying this again is a 3–4 km thick sequence of terrestrial fluvial deposits, which in their lower parts contain the Permian-Triassic boundary (approximately the time of greatest deformation in the Cape Fold Belt), but most of these are not presently exposed in the study area. Underlying the Karoo Basin deposits are the 6–10 km thick siliciclastic rocks of the early Paleozoic Cape Basin. The lowermost sections of this basin are predominantly thick-bedded mature sandstones and quartzites of the Table Mountain Group that dominate the

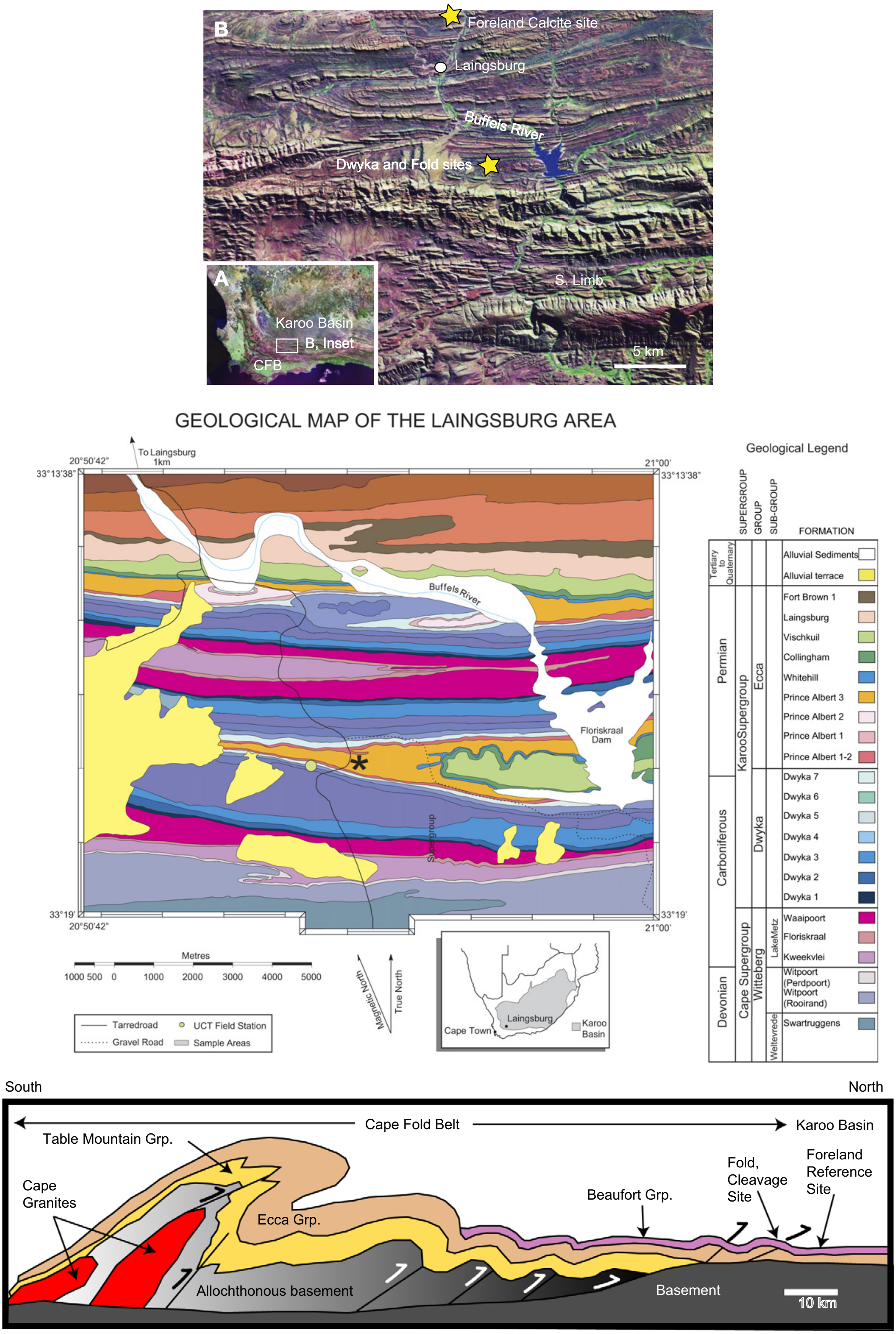

Fig. 1. Regional satellite image of the Cape Fold Belt (A) with detailed inset (B) showing the field fold and cleavage sites and the foreland site in the Karoo basin. Detailed geologic map shows the UCT field station and local geology. The simple, schematic cross section is adapted from Halbich and Swart (1983) for the Permian CFB before post-orogenic collapse along E-W, south-dipping normal faults.

main ranges of the Cape Fold Belt, but in the study area these are not exposed at the surface.

The rocks of the study area lie in the frontal ranges of the Cape Fold Belt, a relatively sharp tectonic transition zone of upright, minor folding and thrusting, between large scale northward overfolding to the south, and essentially subhorizontal and undeformed strata to the north (e.g., Newton and Boyle, 1993; Newton, 1992; Lindeque et al., 2006). All of the rocks in the tectonic transition zone have undergone significant deformation that is manifested by open-to-close folding, minor thrusting and frequently a well-developed subvertical cleavage and subhorizontal pencil (intersection) lineation, particularly in the finer clastic lithologies. Regional fluid inclusion analyses on quartz and calcite from syntectonic veins have revealed temperatures between 150–200 °C and pressures between 1 and 2 kbar during the peak of deformation in the study region (Egle, 1996; Egle et al., 1998).

2.1. Local geology

Two localities in the tectonic transition zone of the CFB were sampled for detailed strain analyses. Both sample locations (a syncline with axial planar cleavage in the Prince Albert Formation, and cleaved matrix and fractured clasts in the Dwyka Formation) are exposed about 10 km south of Laingsburg near the University of Cape Town (UCT) field station (Fig. 1; Appendix 1). The rocks of the study locality are situated near the centre of a ~2 km thick open-folded para-allochtonous sheet bound by two well-mapped thrusts with ~0.5 and ~1.0 km northward displacements (the lower Geelbeck and upper Kareebome thrusts, respectively) (Newton, 1992) These folds and thrusts are ~20 km from the same lithologies in the relatively flat-lying and undeformed Karoo Basin to the north (Halbich, 1992; Lindeque et al., 2006). Much of our twinning strain interpretation is tied to the N–S and sub-horizontal shortening strain preserved in sequences of this foreland.

The Prince Albert Formation comprises calcareous shale with interbedded cherts on a decimeter scale, all of which has been deformed into E–W trending, shallowly plunging folds as part of the CFB (Fig. 1; Appendix 1). Minor folds are defined by bedding and a prevalence of layer-parallel, calcite-quartz veins that are absent to the north in the undeformed foreland shales, and have a distinctive, non-limestone geochemical signature (see paragraph below). Fold amplitudes are ~5–10 meters with wavelengths of ~10–30 meters; south-dipping thrust faults with small visible displacements are common. The rocks have a well-developed subvertical and ~E–W striking axial planar cleavage (S_1; often slightly fanning and refracted between the cherts and shales) and an intersection lineation between bedding and cleavage that results in well-developed ~E–W and sub-horizontal pencil structures in the shales. The calcite layers are interpreted to be pre- and syn-folding in age, as they are layered (foliated), locally fibrous, everywhere bedding-parallel and both cut by, and, in turn, cross-cutting the cleavage. Striations and steps in the calcite layer indicate south-to-north (top-to-the-north) motion through the synclinal fold hinge reported here. This is at odds to the systematic inversion of motion across fold hinges recorded in the area (Viola, personal communication, 2007), which is indicative of flexural slip folding and may suggest the influence of local thrust faulting mentioned above. Quartz grains display undulatory extinction and sub-grain boundary development, but no deformation lamellae were observed. Calcite is everywhere mechanically twinned, with 2–3 sets common per grain.

Regionally, the fluids were rock buffered and the veins equilibrated at depths of ~5–6 km (Egle, 1996; Egle et al., 1998). Fluid inclusions in the quartz and calcite of the veins display a well-defined peak of homogenization temperatures at 150–170 °C with fluid pressures between 1.1 and 2.0 kbar. Quartz–calcite geothermometry reveals trapping temperatures between 230–260 °C, which are in the upper range of the observed homogenization temperatures. Methane–water geothermometry yields a similar trapping temperature of 235 °C. All fluid inclusions reveal large amounts of aqueous low-salinity fluids (0.87 wt % NaCl equivalent) with varying amounts of CO_2 and sometimes methane. Hydrogen isotopes indicate a major contribution from meteoric sources; calculated oxygen isotope composition of the fluids vary between −4 and −2 ppm SMOW, suggesting a mixture of meteoric water with fluids which were generated by diagenetic devolatilization during low-grade metamorphism (Egle, 1996; Egle et al., 1998)

The Permo-Carboniferous Dwyka tillite is exposed along the Witteberg River, as well as road cuts, to the south and north of the UCT Field station (Fig. 1,) and was originally described by du Toit (1927), who noted the difficulty in finding bedding planes. The tillites contain a poorly sorted assemblage of polymictic clasts and many of these are fractured normal to S_1 (e.g., the fractures are oriented subhorizontally; Fig. 2). The clast fractures are generally sub-horizontal. Within the quartzite, granite and granitic-gneiss clasts of the polymictic Dwyka diamictites, the sub-horizontal, cleavage-normal fractures (“tension gashes”) are best developed and their vertical spacing varies from clast to clast, suggesting this to be a function of lithology and clast size (Fig. 2). Limestone clasts do not display such fractures. Most of the “tension gash” partings are filled with sparry or fibrous calcite with the fiber growth direction being vertical within the horizontal fracture plane. Analysis of this carbonate suite for twinned calcite forms the basis for describing the syn-cleavage stress–strain field.

3. Materials and methods

3.1. Calcite twinning

Calcite twins mechanically at low differential stresses (~10 MPa; see Lacombe and Laurent, 1996; Ferrill, 1998) and is largely independent of temperature and normal stress magnitudes in the uppermost crust. Twinning is possible along three glide planes and calcite strain hardens once twinned; further twinning is possible in a crystal along either of the remaining two e{0112} planes at higher stress levels, provided that stress is oriented >45° from the initial stress orientation

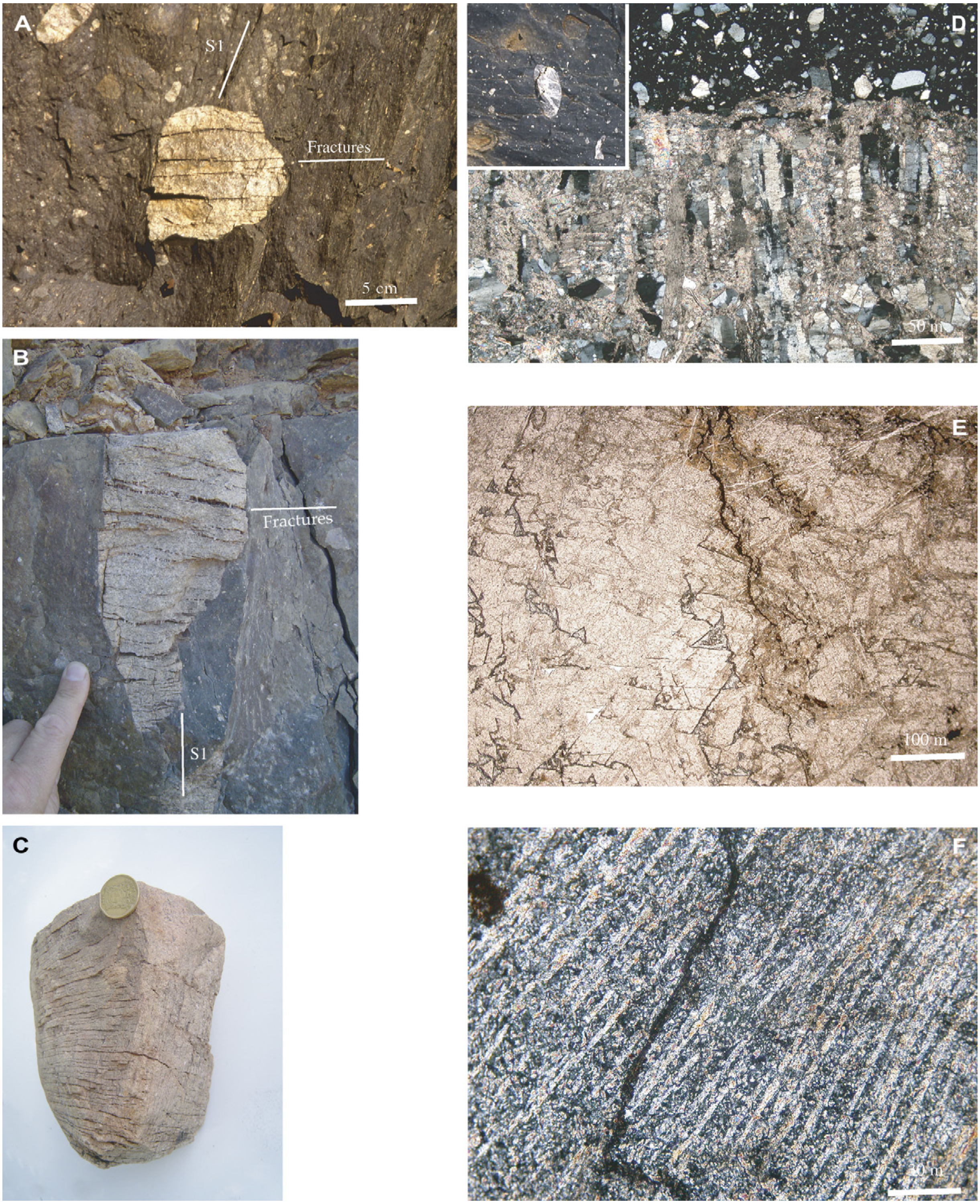

Fig. 2. Photo mosaic of Dwyka tillite structures with the preserved field orientations. (A–D): Tillite matrix surrounding clasts with horizontal fractures and vertical cleavage (S1). (C): Fractured clast removed from the Dwyka matrix. (D): Inset of tillite clast (upper left) with inclusive, cleavage-normal fibrous, twinned calcite veins (vertical fibers in a horizontal plane) shown in thin section (polarized light). (E and F): Foreland limestone in plane and polarized light (mechanical twins are oriented from lower left to upper right).

(Teufel, 1980). The application of twinned calcite to structural and tectonic problems has been primarily restricted to studies of limestones (e.g., Groshong, 1975; Engelder, 1979; Spang and Groshong, 1981; Wiltschko et al., 1985; Craddock et al., 1993), calcite veins (e.g., Kilsdonk and Wiltschko, 1988), or, more rarely, marbles (e.g., Craddock et al., 1991). Amygdule and vein calcite in basalts also yield interpretable results (DSDP Hole 433C (Craddock and Pearson, 1994); Keweenaw rift (Craddock et al., 1997); Iceland (Craddock et al., 2004)). Rowe and Rutter (1990) and Burkhard (1993) have recently reviewed the variety of methods applied to utilizing twinned calcite in a host of geologic environments.

Paleostress (paleopiezometry of Engelder, 1993) responsible for twinning can be calculated in terms of its compressional (or tensile) orientation (Turner, 1953) and magnitude (Jamison and Spang, 1976; Rowe and Rutter, 1990). Strain ellipsoid axis orientations are computed using the calcite strain gauge (Groshong, 1972, 1974) and are quite accurate for strains ranging from 1–17% (Groshong et al., 1984). Strain magnitudes vary greatly, however, depending on factors such as lithology, grain size, and porosity, and are a function of twin thickness. Three orthogonal sections were used for each of the fold samples and 1–2 sections for the cleavages samples. Thin twins (~0.5 microns) are dominant in our sample suite, and are characteristic of calcite deformed below 200°C (Ferrill, 1991, 1998; Ferrill et al., 2004). The calcite strain gauge technique also computes positive and negative expected values (PEV and NEV, respectively) for all the twins in a given thin section. A NEV for a twinned grain indicates that this grain was unfavorably oriented relative to the stress field that caused the twinning in the majority of the grains in a given thin section. A high percentage of negative expected values (>40%) indicates that a second, non-coaxial twinning event occurred (Teufel, 1980). Two twinning strains (PEV and NEV groups, respectively) can be analyzed separately.

4. Analyses and results

4.1. Syncline in the Prince Albert Formation

This syncline is part of a series of outcrop-scale folds exposed along a road section near the thrust belt-foreland margin (e.g., Newton, 1992). The folds are open, upright anticline-syncline pairs, proximal along a strike to a minor south-dipping thrust fault (the Floriskraal thrust with a small albeit unquantified displacement) (Newton, 1992). An axial planar cleavage is

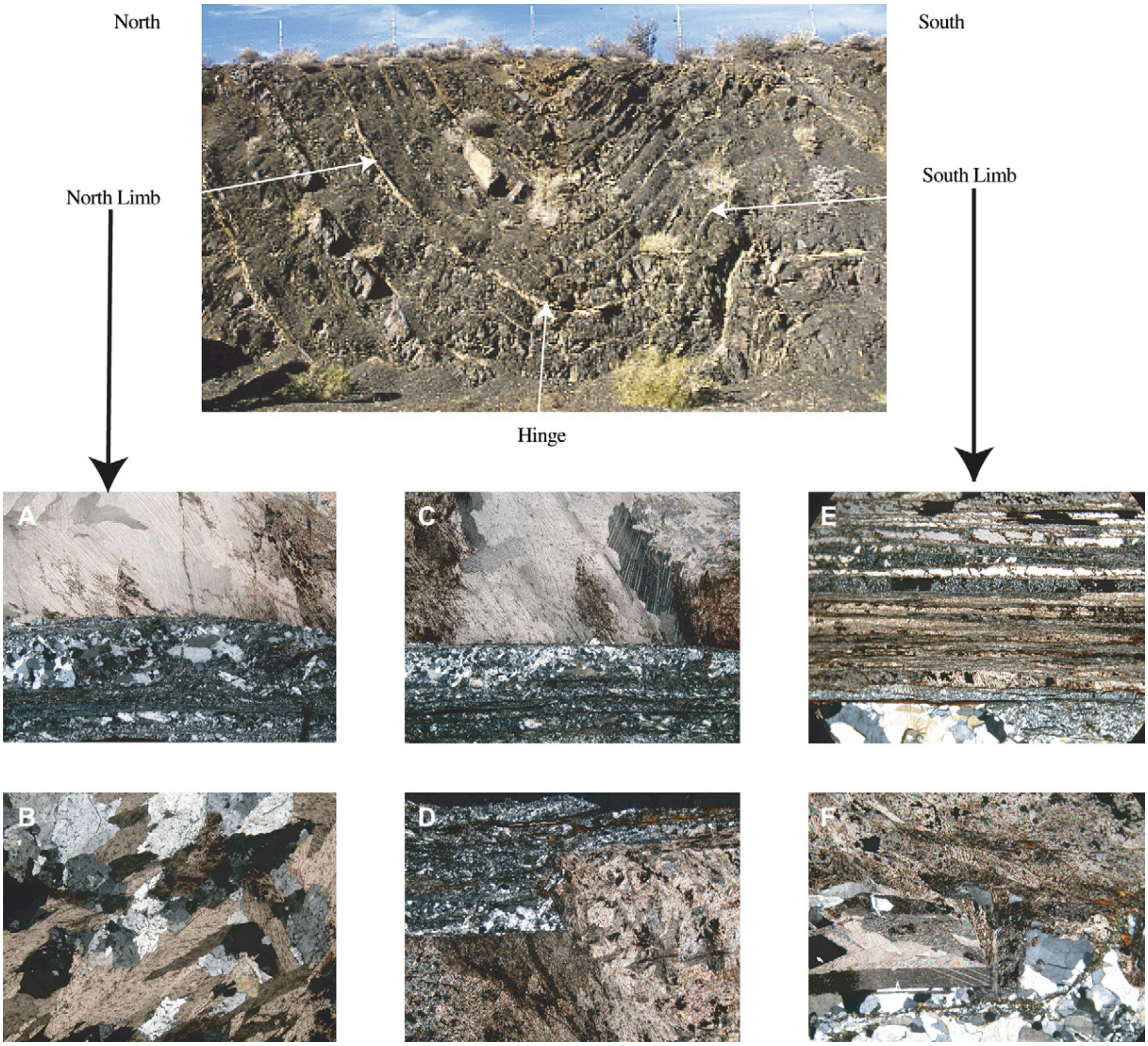

Fig. 3. Prince Albert Fm. syncline (view East, photo width is 10 m) with polarized light mosaic of north limb (A,B), hinge (C,D) and south limb (E,F) samples from the identical syn-folding calcite-quartz layer. (A): Layered calcite (upper)-quartz. (B): Mixed quartz-calcite. (C): Layered calcite (upper)-quartz. (D): Layered quartz (upper)-calcite with a top-to-the-left (north) fault striation step. (E): Layered calcite-quartz. (F): Layered calcite (upper)-quartz (lower) with a top-to-the-left (north) fault striation step. Polarized light in A–E, photo widths are ~250 microns.

Table 1
Calcite twinning strain results: Prince Albert syncline and Dwyka Fm. cleavage

Sample	Rock unit	Orientation	Grains (*n*)	e1	e2	e3	e1 (%)	e2 (%)	e3 (%)	NEV (%)	Δσ (MPa)	Fabric interp.	Location
Foreland													
1	PAF	Horizontal	34	1°, 5°	87°, 5°	181°, 87°	−4.5	−2.3	6.7	5	−34	LPS	Karoo Foreland
Fold													
2-PEV	PAF-vein	E–W, 35° S	48	211°,22°	87°, 17°	350° 7°	−6.15	2.56	3.6	0	−71	LPS	North limb
2-NEV	PAF-vein	E–W, 35° S	19	67°, 65°	168°, 5°	212°, 21°	−7.99	1.45	6.53	100	−71	LNS	North limb
3-PEV	PAF-vein	Horizontal	43	175°, 14°	261°, 47°	45°, 31°	−3.65	0.46	3.64	0	−72	LPS	Hinge
3-NEV	PAF-vein	Horizontal	23	251°, 71	55°, 71°	322°, 12°	−3.76	0.58	3.18	100	−72	LNS	Hinge
4	PAF-vein	E–W, 35° N Qtz., no twins											South limb
5	PAF-vein	E–W, 35° N	65	357°, 28°	91°, 12°	177°, 64°	−6.4	−5.6	12.1	2	−32	LPS	South limb
6	PAF-vein	E–W, 35° N	24	28°, 31°	104°, 7°	201°, 76°	−5.8	−5.5	11.4	0	−37	LPS	South limb
							−5.625				Avg = −59		
Cleavage													
7	LS clast	N/A	25	0°, 15°	178°, 55°	88°, 35°	−4.6	−2.1	6.7	0	−34	CNS	Dwyka
8	Vein	E–W, 90°	24	192°, 2°	300°, 62°	121°, 19°	−5.1	−1.8	6.9	0	−56	CNS	Dwyka
9	Fibrous vein	Horizontal	25	182°, 4°	11°, 81°	282°, 1°	−4.8	−1.3	6.1	0	−48	CNS	Dwyka
Composite	Composite	Combined	74	181°, 2°	350°, 88°	91°, 3°	−5	−1.5	6.5	8	−46	CNS	Dwyka
							Avg = − 4.8				Avg = − 46		

PAF, Prince Albert formation; LPS, layer-parallel shortening; LNS, layer-normal shortening; CNS, cleavage-normal shortening. Differential stress calculated using Rutter and Rowe (1990).

well developed (~E–W, 90°, but fans locally). Discontinuous bedding-parallel quartz–calcite layers (1–7 cm thick) are common and often are regularly spaced stratigraphically (Fig. 3). Because cleavage selvages are found within the quartz–calcite layers separated by layer-parallel slip zones (Fig. 3), the formation of the cleavage and bedding-plane quartz–calcite layers are assumed to be contemporaneous structures. Additionally, the quartz–calcite layers are not found in the Prince Albert Fm. in the nearby foreland and the quartz–calcite layers precipitated along bedding planes after the quartz and calcite were mobilized within the deforming Prince Albert shales. Optic axis plots of calcite preserve a random pattern. The quartz–calcite layer contains striations that trend N–S and are within the plane of bedding; and stepping directions indicate top-to-the-north motion within this layer around the syncline, a field observation confirmed in thin sections (Fig. 3; striation steps, S-C structures), consistent with the northward displacement along the three nearby thrusts (Newton, 1992). One could argue that each quartz–calcite layer is itself, *locally*, a multi-layer separated by a layer-parallel slip (foliation) plane (Fig. 3e), but there is great variability in foliation spacing and grain size within a layer.

Three oriented samples were collected around the syncline (Fig. 3) and the mechanical twins in calcite were analyzed (Table 1; Fig. 4) and compared to calcite in a sample from the undeformed Prince Albert Formation in the Karoo Foreland Basin to the north (Figs. 1, 4). Quartz is present and we observed undulatory extinction and serrated grain boundaries but no deformation lamellae in the syncline. Two hundred twenty-two twins were measured from 14 thin sections from the north limb, hinge and south limb samples. Two distinctive strains are preserved in these samples, a positive expected value (PEV) shortening strain that is layer-parallel and a negative expected value (NEV) shortening strain overprint that is layer-normal, but not present in the south limb sample. The orientations of the two strain ellipsoids document a northeasterly 43° rotation from the hinge to the north limb along a great circle that strikes N 33° E. The stable foreland sample records a sub-horizontal, N–S shortening strain.

4.2. Discussion

Flat-lying limestone lenses in Permian shales are exposed in the undeformed foreland, adjacent to those same strata in the proximal thrust belt (Figs. 1, 2e,f, 4). Both the allochthonous quartz–calcite folded layers and autochthonous foreland limestones preserve identical layer-parallel, thrust transport-parallel twinning strains. Parallelism of a pre-thrusting lps fabric between the foreland and thrust belt indicates instead that thrust sheet motions did not involve rotation out of the plane of thrust transport (Appalachian's, Kilsdonk and Wiltschko, 1988; Mazatzal orogen, Craddock and McKiernan, in press). A lack of lps fabric parallelism, between a thrust belt and foreland, indicates that thrust motions were accommodated by thrust and/or fold rotation in the thrust belt (Idaho-Wyoming belt, Craddock, 1992). A comparison of our foreland twinning strain results (N–S horizontal

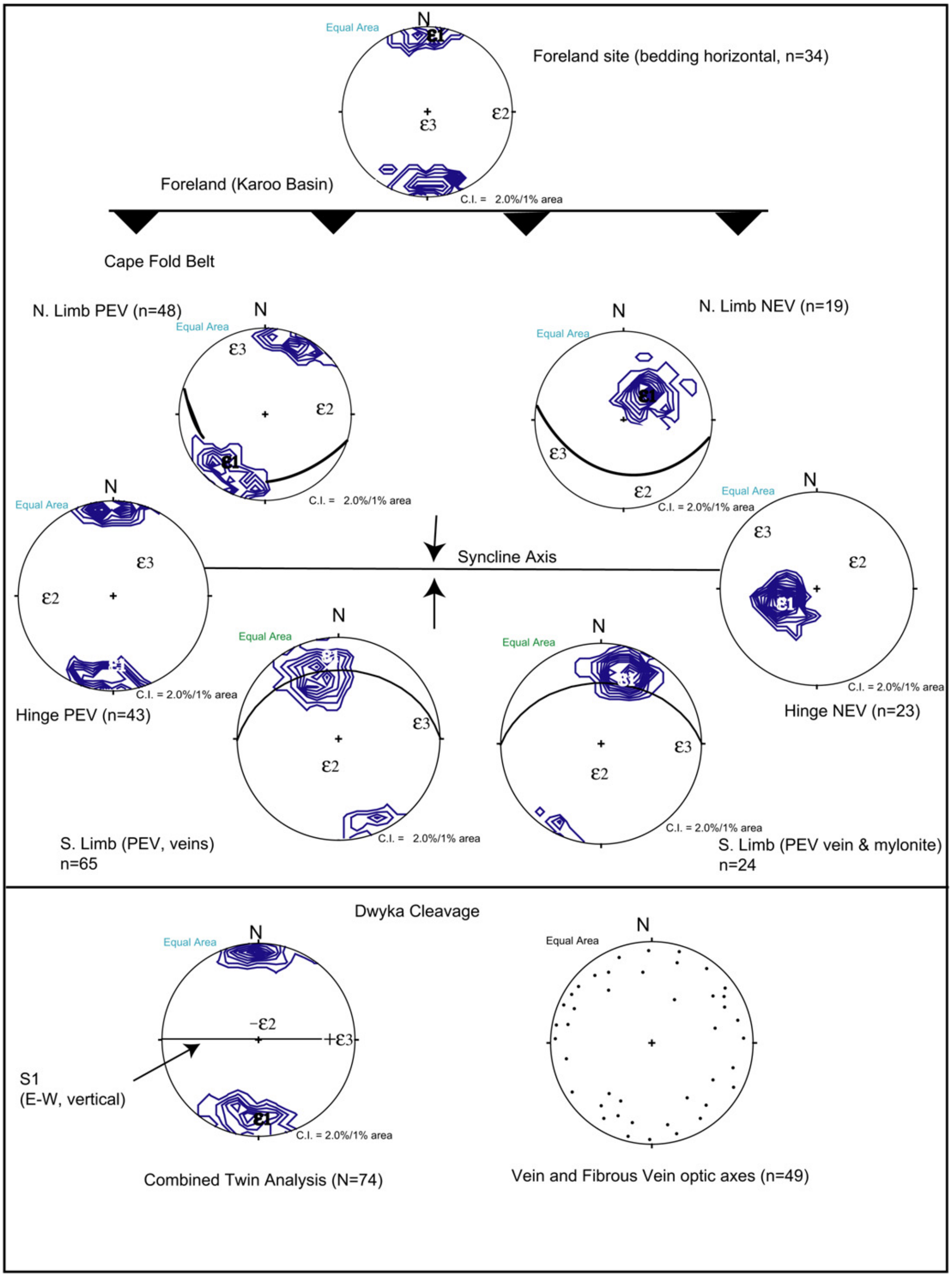

Fig. 4. Lower hemisphere plots of calcite strain gage data for the foreland limestone, Prince Albert Fm. syncline and Dwyka syn-cleavage calcite. Great circles are bedding orientations, contoured areas are Turner (1953) compression axes. Axes of the strain ellipsoid are ϵ_1 (maximum shortening [negative]), ϵ_2 (intermediate axis), and ϵ_3 (extension axis (positive)). See Table 1.

shortening) with those in the syn-folding twinning strains, documented in the Prince Albert Formation syncline quartz–calcite layers, indicates that more than 40° of rotation in plan view has occurred during folding. We do not know if this rotation resulted from motion along underlying thrusts, migration of the synclinal fold axis, rotation of the calcite–quartz layers through the fold (i.e., flexural-slip), or some combination of all three.

Fabric studies in folds, usually from thrust belts, commonly preserve a lps fabric that is interpreted as a pre-folding strain (see reference in Section 1, and Spang and Groshong, 1981). Our results, from a syn-folding calcite–quartz layer, provide a strain record where the early layer-parallel shortening (PEV) strain is overprinted by a secondary (NEV) layer-normal shortening strain. The orientations of the NEV shortening axis for the hinge and north limb samples show the same north-easterly rotation within the fold, in comparison to the autochthonous foreland sample. Folding seems the likely explanation for both these twinning strains, as the Prince Albert Formation was deformed shortly after deposition and the region has been nearly atectonic since the early Triassic.

Outcrop and petrographic observations suggest that layer-parallel slip was important during folding and all the motion in this layer was N–S, with top-to-the north kinematics (Fig. 3). The CFB tectonic transport direction was also to the north, often generated S-dipping thrusts and hanging wall folds that are overturned toward the north (Sohnge and Halbich, 1983; Newton and Boyle, 1993; Newton, 1992; Shone and Booth, 2005). The folds in the Prince Albert Formation possibly formed as hanging wall folds underlain by a S-dipping thrust fault (e.g., the Geelback thrust, Newton, 1992) and all the thrust transport was directed to the north. How then do we explain the layer-normal strain overprint and consistent north-easterly rotation (i.e., non-plane strain) of the PEV and NEV shortening strain through the fold?

We have analyzed the deformation in one quartz–calcite layer in a multi-layered sequence of shale and quartz–calcite layers in one syncline representative of minor folds on the north limb of a regional CFB syncline (kilometer-scale wavelength). The open nature of the syncline precludes the layer-normal shortening strain being related to progressive steepening of the limb dips, and a number of unconstrained deformation path choices can be proposed to interpret the twinning results (Fig. 5): (1) local, layer-normal shortening by a curvilinear stress–strain field after folding (see Dietrich and Carter, 1969), perhaps by thrust sheet burial; (2) migration of the precipitating calcite–quartz layer through the hinge of the fold from south to northeast where the layer-normal shortening is imposed as a bending strain (fault-bend fold; Wiltschko, 1981); (3) migration of the entire syncline (and other, adjacent folds) northward as part of the CFB allochthon (fault-propagation fold; Suppe and Medwedeff, 1990); or (4) a combination of (2) and (3; see also Suppe, 1983) above. It seems unlikely that a local, curvilinear stress field could impose a secondary twinning strain only on the north limb and hinge, and not the south limb, as suggested by interpretation (1). Interpretation (2) requires a local, layer-normal differential stress that exceeds −46 MPa (see Teufel, 1980) to impose the LNS strain overprint as the layer passes through the fold hinge. A comprehensive calcite twinning study of all quartz–calcite layers throughout a single fold (Fig. 3) and in a number of folds in the region would provide a better data set to address questions of folding mechanics. Such an approach might identify a strain-neutral surface between the outer arc extension (layer-normal shortening) and inner arc shortening (layer-parallel shortening), as proposed for tangential longitudinal shortening or strain gradients around a fold separated by layer-parallel slip zones suggested by flexural slip (flow) models (Ramsay, 1967; Hudleston and Lan, 1993).

To address some of these uncertainties further, we now turn to the results from the second, nearby sampling locality in the underlying Dwyka Fm.

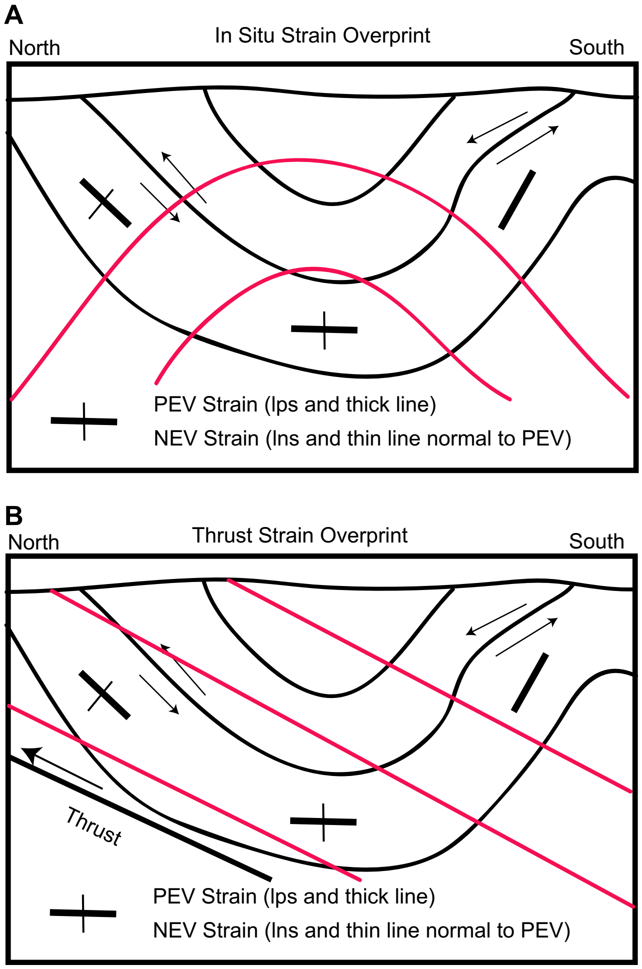

Fig. 5. Schematic interpretation of the syncline calcite twinning data where the early LPS strain is overprinted by a younger LNS strain. A: Static, in situ, layer-normal shortening after folding (see Dietrich and Carter, 1969) and, B: Layer-normal shortening parallel to the dip of local thrusts where the NEV strain is imposed on the calcite-quartz layer as it migrates through the fold from south to north. Red lines (in web version) represent lines of equipotential compressive stress (or shortening strain) magnitude.

4.3. Cleavage and fractures in the Dwyka Formation and clasts

Where the Dwyka tillite is exposed near the University of Cape Town field station (Fig. 1; Appendix 1) we sampled calcite fillings in horizontal, cleavage-normal fractures in rigid clasts, as well as rare carbonate clasts. Mechanical twins were analyzed in five thin sections from four samples (two veins, one limestone clast) that yield a consistent result (Figs. 2, 4). The shortening axis (ϵ_1) is oriented ∼N–S and horizontal, a result consistent with the regional shortening direction (Fig. 4). The intermediate strain axis (ϵ_2) records a small, vertical shortening strain and the extension axis (ϵ_3) is E–W and horizontal. The twining strains are without NEVs, indicating the absence of a strain overprint. The average shortening strain (ϵ_1) is −4.8% in response to a differential stress of −46 MPa (Table 1). Calcite optic axis orientations are random in the sample suite.

4.4. Discussion

The Dwyka deformational chronology was: (1) Gondwanide orogenic stresses (horizontal, N–S compression) commenced with twinning of the foreland Prince Albert Fm. limestone and limestone clasts in the Dwyka Fm. and the formation of the axial planar cleavage, including (2) propagation of horizontal fracture planes in rigid clasts, many of which filled with vertical, syn-cleavage quartz or calcite fibers (vertical dilation) that (3) crystallized immediately, then twinned mechanically (calcite, quartz remained undeformed), preserving the orientation of the stress–strain field associated with cleavage formation in the Dwyka Tillite. Three different calcite types in the Dwyka diamictite clasts preserve a consistent twinning strain fabric where shortening is parallel to the regional thrust tectonic pattern (N–S, horizontal), the intermediate axis (ϵ_2) preserves vertical shortening, and the extension axis is E–W and horizontal with no strain overprint. Our syn-cleavage twinning strain results are similar to finite strain studies of pre-cleavage elements (fossils, reduction spots, etc.) and preserve a consistent strain fabric (i.e., no rotation) that is consistent with the regional shortening strain orientation, which was sub-horizontal and cleavage-normal. The twinning strain extension direction is normal to the growth direction of the fibrous calcite (up-down (vertical) growth) in the horizontal veins, suggesting that caution should be used with terms like "tension gash" in association with vein fillings (see Ramsay and Graham, 1970; Hancock, 1972; Beach, 1975; Pollard et al., 1982; Craddock and van der Pluijm, 1988) where no temporal or genetic stress–strain information is available. We can also argue that although the fracture dilation direction was vertical and along horizontal planes, once the fractures filled with quartz–calcite solutions and crystallized, they closed slightly, as recorded by the small vertical shortening strains (ϵ_2; -1.5%). The twinning strain ellipsoid is consistent throughout the sample suite (Table 1) and consistent with regard to orientation, magnitude and precision of the strain ellipsoid technique (see Groshong et al., 1984). The clast parting direction (horizontal plane, up-down (vertical) parting) and the presumed parting propagation direction in each clast population (W–E or E–W) is also normal to the regional horizontal shortening direction, which is a common deformational observation in Gondwana tillites (e.g., Sauce Grande Fm., Argentina; Whiteout Conglomerate, Ellsworth Mtns., Antarctica; Craddock, personal observations).

5. Conclusions

The shales of the Permian Prince Albert Fm. responded to thin-skinned Gondwanide tectonism by deforming into north-verging, hanging wall anticlines as part of the CFB at a depth of ~6 km, differential stresses of −50 MPa and in the presence of metamorphic fluids with temperatures of ~230 °C. The well-developed layering in the shales accommodated formation of minor folds and, in conjunction with lowermost greenschist-grade metamorphic conditions, mobilized calcite and quartz-rich fluids which migrated and precipitated along bedding planes as these minor folds evolved with an axial planar cleavage. The deformation recorded in this syn-folding bedding plane quartz–calcite layer indicates top-to-the-north bedding-parallel slip from the south to north limb. Our twinning strain results record a layer-parallel shortening strain that is overprinted by a layer-normal shortening with migration through (and/or migration of) the fold hinge. The CFB field kinematics indicate N–S motion, parallel to the regional thrust shortening, whereas the twinning strains record N–E migration through the fold hinge, which could be interpreted as a local, curvilinear (non-plane strain) stress–strain field overprint or part of a regional thrust sheet rotation as a distal response to dextral motion along the Gondwanide orogen margin (see Cobbold et al., 1991; Buggisch, 1987; Curtis, 1997; Craddock et al., 1998; Johnston, 2000) with displacement of the fold or flexural-slip motion of the layers through the fold hinge. Conversely, in the underlying massive Dwyka tillites, bedding planes are hard to identify (i.e., the "boulder bed" of du Toit) and there are no weak zones of anisotropy to accommodate dip-slip motions. The response of the Dwyka Formation was to undergo significant layer parallel shortening within large-scale hanging wall folds (~90° fold trends, shallow E–W plunges), and develop an axial-planar cleavage (strike 90°, 90° dip) in response to N–S sub-horizontal Gondwanide shortening. The rigid clasts in the Dwyka responded by forming sub-horizontal fractures with sub-vertical fibrous quartz– calcite growth fillings, and its syn-cleavage calcite records N–S sub-horizontal shortening and E–W sub-horizontal extension. There is no rotation in the strain ellipsoid when comparing the Dwyka and autochthonous foreland limestone, and there is no strain overprint in the syn-cleavage calcite. Both the cleavage and fold twinning results preserve subhorizontal, E–W extension.

The premise of this study was to use calcite precipitated during the Permian Gondwanide orogen as a recorder of Gondwanide deformation in the frontal CFB. This region has been atectonic for ~240 Ma thus preserving the calcite twinning strains without the complication of a younger orogenic event. Conversely, none of the calcite is radiometrically dated, so our deformation chronology relies on the continuity of consistent field observations, cross-cutting relations and the strain data: (1) the foreland limestone and Dwyka limestone clasts preserve identical pre-thrusting, in-transport N–S layer-parallel shortening, (2) the same strain field present during northward thrust sheet motion and metamorphic fluid migration and cleavage formation (90°, 90°) and (3) during development of regional ramp-anticlines and minor folds. Fold development was accommodated by bedding anisotropy contrasts in the Prince Albert Fm., fluid migration along bedding planes, and layer-parallel slip along crystallized quartz–calcite layers. Calcite in this setting records a layer-parallel shortening strain and layer-normal shortening overprint as part of a complex process of fold formation. Detailed studies of local structures can bear on regional and tectonic processes.

On a regional scale, our work has defined in detail the specific strain facies preserved in the frontal ranges of the Cape Fold Belt. This, and other frontal zones of the Gondwanide orogen have specific characteristics that can be, and have been, used in regional correlations of sectors of the Gondwanide belt that were once conterminous. The details of these correlations however are based on limited information about the structural history of the orogenic fronts, and there is still considerable controversy about these correlations on which detailed reconstruction models of this Gondwanide orogen are based (e.g., Curtis and Hyam, 1989; Trouw and de Wit, 1999; Milani and de Wit, 2006). The results of this study may help to further refine these models.

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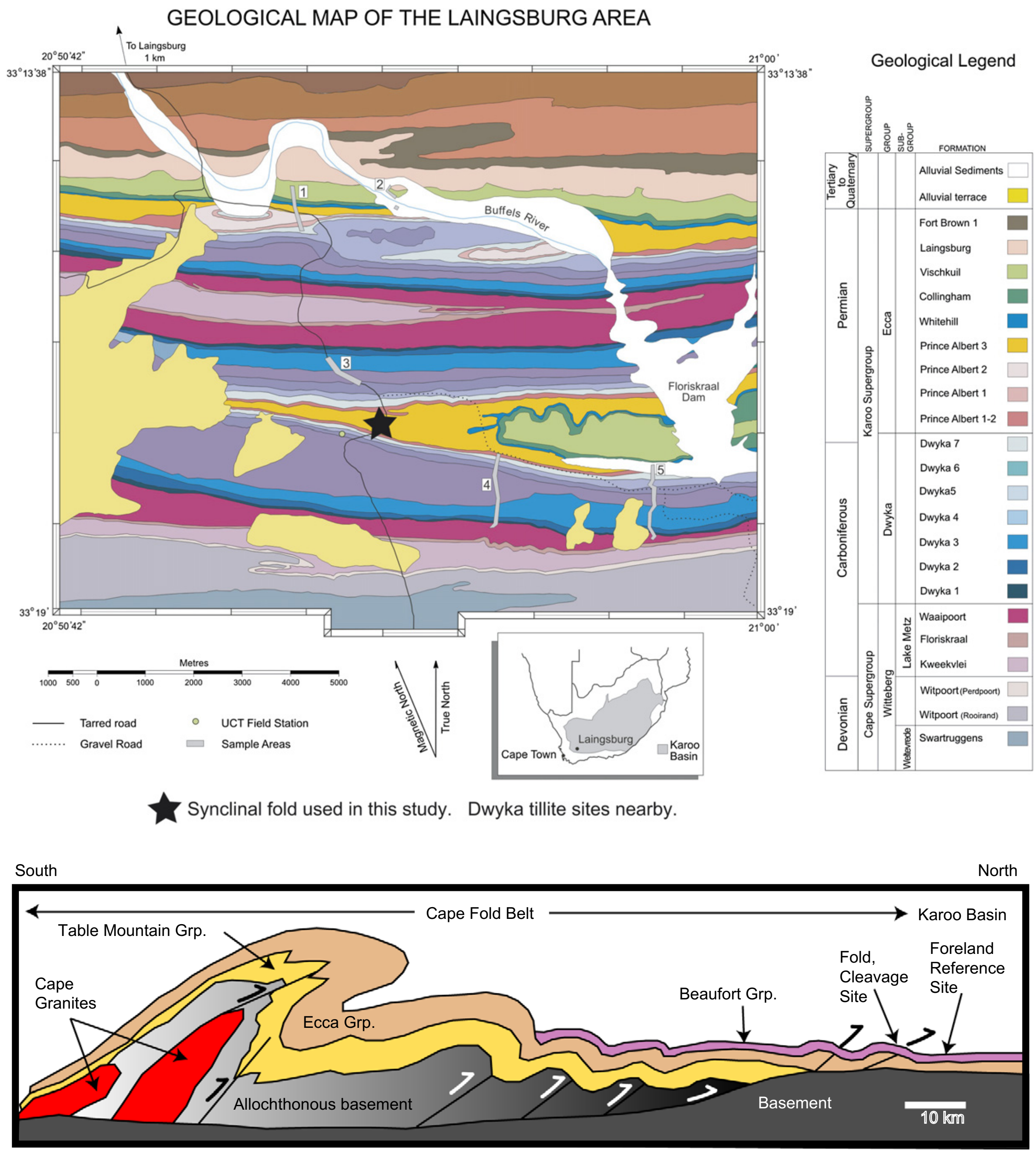

Fig. A1.

a sabbatical in Erlangen, Germany, which allowed for manuscript preparation, preceded by a Wallace Grant support in 1998 to get to Cape Town. CFB studies of de Wit are funded through the South African National Research Foundation. The manuscript benefited from careful reviews by Stephen T. Johnston, Giulio Viola, and Rick Groshong.

Appendix 1: Geologic map of UCT field station area

Fig. A.1 shows the geologic map of the field area in the frontal CFB near the UCT field station. Simple, schematic cross section is adapted from Halbich and Swart (1983) and Paton et al. (2006) and represents the CFB in the Permian before post-orogenic collapse along Jurassic E–W, south-dipping normal faults. Beaufort Grp. includes the Prince Albert Fm; Ecca Grp. includes the Dwyka Tillite.

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