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The Cape Fold Belt and Syntaxis and the rotated Falkland Islands: dextral transpressional tectonics along the southwest margin of Gondwana

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ABSTRACT—Two enigmas concerning the Cape Fold Belt (CFB), part of the Gondwanide Orogen that formerly stretched across southern Gondwana, are (1) its apparent development far-removed (≥1500 km) from the convergent margin of Gondwana; and (2) the origin of the Cape Syntaxis, a 40–80° bend in the strike of the belt that occurs near Cape Town. An additional puzzle is how the Falkland Islands, which is believed to have originally been situated off the southeastern Africa coast and may have formed the eastern continuation of the CFB, came to be rotated 180° during, or prior to, the break-up of Gondwana. In an attempt to address these enigmas, recent developments are reviewed in the study of the CFB and of the South American, Falkland Islands and Antarctic portions of the Gondwanide Orogen, provide reinterpretations of some data and suggest a new tectonic model.

Structural data (orientations relative to an east-west-trending CFB) are consistent with interpretation of the South America and Antarctic portions of the Gondwanide Orogen as northwest-trending dextral transpressional belts. The east-west-trending CFB, including the Falkland Islands, forms an inboard- or left-step within this intracontinental dextral shear zone. Dextral margin-parallel translation of the crustal block outboard of the orogen (extending from the Gondwanide belt south to the margin of Gondwana) was accommodated by strike-slip deformation in South America and Antarctica, and by convergence and the development of a foreland-verging fold and thrust belt, across the CFB. The Cape Syntaxis, and the partially obscured Port Elizabeth Antitaxis, are oroclinal bends of the CFB that developed in response to continued dextral shear along the Gondwanide belt. Clockwise rotation of the Falkland Islands occurred in two stages: (1) ~90° during oroclinal bending (the islands were incorporated in the short east limb of the Port Elizabeth Antitaxis), and (2) >60° during solid body rotation about the Euler Pole to the Falkland-Agulhas Fracture Zone, a major dextral transform fault that propagated through the hinge region of the Port Elizabeth Antitaxis during break-up of Gondwana. © 2000 Elsevier Science Limited. All rights reserved.

RÉSUMÉ—Deux énigmes se rapportent à la Chaîne du Cap (CFB), partie de l'orogène gondwanide qui s'est étendu auparavant à travers le Gondwana du sud. Elles concernent: (1) son développement apparent loin (≥1500 km) de la marge convergente du Gondwana; (2) l'origine de la Syntaxe du Cap, une courbure de la direction de la chaîne de 40 à 80° près de Cape Town. Un problème supplémentaire regarde les Îles Falkland: comment cette zone que l'on suppose située originellement en face des côtes de l'Afrique sud-orientale et formant le prolongement oriental de la CFB, a-t-elle pu tourner de 180° pendant ou avant la dislocation du Gondwana? Pour tenter d'expliquer ces énigmes, je passe en revue les développement récents des études sur la CFB et les portions

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d'Amérique du Sud, des Îles Falkland et d'Antarctique de l'orogène gondwanide, donne une réinterprétation des données et suggère un modèle tectonique nouveau.
Les données structurales (orientations mesurées par rapport à une CFB orientée est-ouest) sont cohérentes avec l'interprétation des portions d'Amérique du Sud et d'Antarctique de l'orogène gondwanide comme chaînes transpressives dextres de direction nord-ouest. La CFB orientée est-ouest, y compris les Îles Falkland, forme un échelon interne ou sénestre à l'intérieur de cette zone de cisaillement dextre intra-continentale. La translation dextre, parallèle à la marge, du bloc crustal externe de l'orogène (de la chaîne gondwanide à la marge du Gondwana au sud), a été accomodée par la déformation décrochante de l'Amérique du Sud et de l'Antarctique et par la convergence et le développement à travers la CFB d'une chaîne plissée et chevauchante à vergence vers l'avant-pays. La Syntaxe du Cap et l'Antitaxe en partie masquée de Port Elizabeth forment les courbures oroclinales de la CFB en réponse au cisaillement dextre continu le long de la chaîne gondwanide. La rotation horaire des Îles Falkland s'est déroulée en deux étapes: (1) environ 90° durant l'épisode de courbure oroclinale (les îles étaient incorporées à l'exrémité est de l'Antitaxe de Port Elizabeth); et (2) supérieure à 60° durant un épisode de rotation en bloc autour d'un pôle d'Euler situé sur la zone de fracture Falkland-Agulhas, faille transformante dextre majeure qui s'est propagée à travers la charnière de l'Antitaxe de Port Elizabeth lors de la dislocation du Gondwana.

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INTRODUCTION

The concepts of supercontinents, continental drift and plate tectonics arose in part from the study of the Permo-Triassic orogenic belts of southern Africa, the Cape Fold Belt (CFB), South America and Antarctica. The recognition that these now disparate fold and thrust belts initially formed a contiguous orogenic belt (Fig. 1) confirmed suggestions that a supercontinent, Gondwana, had existed at the end of the Palæozoic and that it had subsequently fragmented (du Toit, 1937; Wegner, 1966). In addition to its historic significance, the CFB is of interest, as there remains a number of difficult to resolve questions concerning the origin and character of the belt. These include the apparent development of the orogenic belt far-removed (≥1500 km) from the convergent southwest margin of Gondwana; the origin of the Cape Syntaxis, across which there is a significant change in structural trends and deformation style and the palæolocation of the Falkland Islands with respect to the rest of the fold belt.

Attempts to address these enigmas have, for the most part, been conducted in isolation. Explanations for the development of the CFB far removed from the active margin of Gondwana include 'flat plate subduction' (Lock, 1980), ensialic orogeny (Hälbich, 1983) and far-field stress reactivation of pre-existing (Pan-African?) structures (Daly *et al.*, 1989).

The change, in structural trend and style across the Cape Syntaxis (Figs 1 and 2), has most commonly been interpreted as a result of inheritance from a pre-existing structure. For example, Rust (1967) suggested that the geometry of the early to Mid-Palæozoic Cape Supergroup Basin controlled subsequent deformation with the syntaxis forming above a 90° bend in the underlying basin. Several researchers (de Beer, 1989; Thomas *et al.*, 1992) have suggested that syntaxis reflects the shape of the outboard margin of the Namaqua-Natal (1000 Ma) Basement. Alternative explanations include syntaxis development in response to the rotation of microplates adjacent to the syntaxis (Ransome and de Wit, 1992) or to local orthogonal compression (de Beer, 1992).

The Falkland Islands are commonly assumed to have originated off the southeast coast of Africa, rotated 180° from their current orientation (Fig. 1). This location and geometry is suggested by correlation of basement (Rex and Tanner, 1982; Thomas and Mawson, 1989; Thomas *et al.*, 1998) and overlying Mid- and Late Palæozoic strata of eastern South Africa with the stratigraphy of the islands (Adie, 1952; Visser, 1987; Cole, 1992; Marshall, 1994; Hunter, 1998). Restoration to a position adjacent to southeast Africa is also suggested by the correlation of the eastern CFB with fold and thrust trends mapped on the islands (Adie, 1952). Palæomagnetic data (Mitchell *et al.*, 1986; Taylor and Shaw, 1989) from Early Jurassic (~190 Ma) dolerite dykes in the Falkland Islands, though of poor quality, are consistent with the islands having rotated 180°. The processes and mechanisms responsible for rotation of the Falkland Islands during separation from southeastern Africa remain a matter of considerable debate (e.g. de Wit, 1992; Storey *et al.*, 1998).

Recent studies of Permo-Triassic structures in South America (Cobbold *et al.*, 1991, 1992), southern Africa (de Wit and Ransome, 1992, and references therein), the Falkland Islands (Curtis and Hyam, 1998; Hyam, 1998), and Antarctica (Dalziel and Grunow, 1992; Curtis, 1997, 1998) have demonstrated that

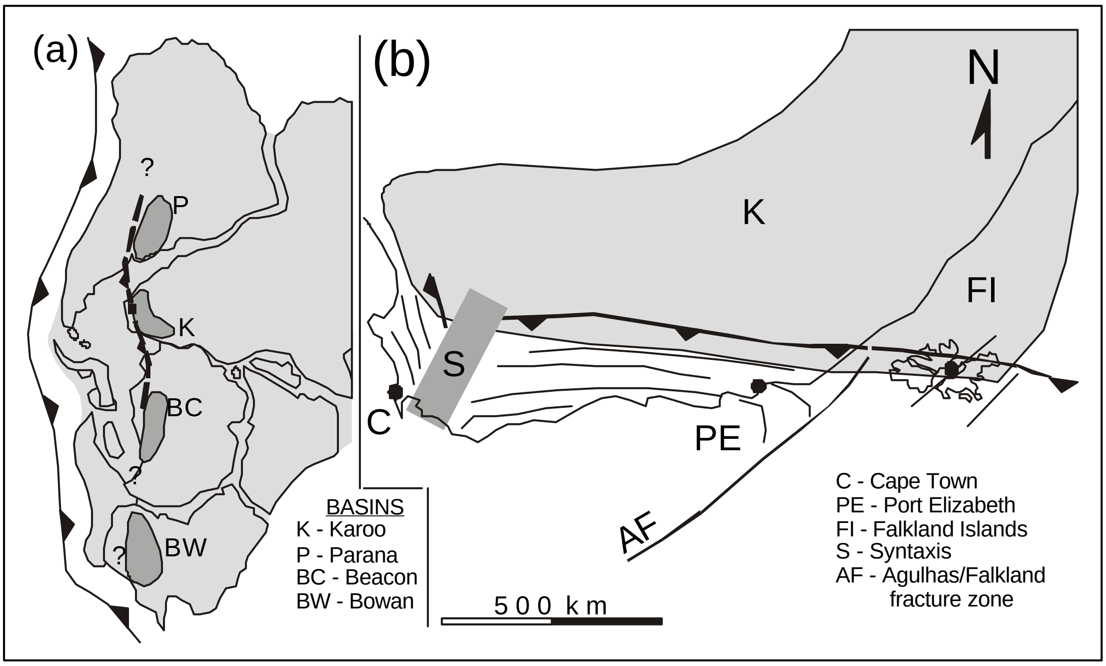

Figure 1. *(a) Gondwana, showing the Gondwanide orogen (dashed line) and related Late Palæozoic and Early Mesozoic basins (after de Wit and Ransome, 1992). (b) Detail of the Cape Fold Belt, including the restored Falkland Islands. Thrust front indicated by heavy line, with teeth pointing into the deformed region. Major fold hinges indicated by dark lines.*

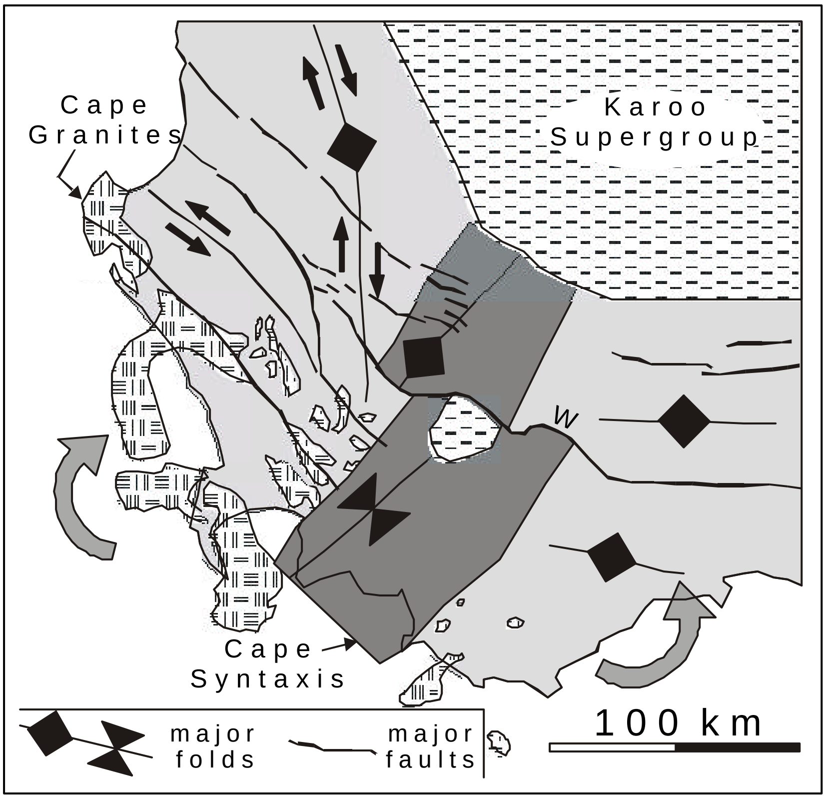

Figure 2. *Detailed map of the Cape Syntaxis and adjacent portions of the western and southern domains (after Ransome and de Wit, 1992). W: Worcester Fault, a Jura-Cretaceous south-dipping normal fault (7 km net displacement) which offsets the Cape Syntaxis and which preserves Karoo stratigraphy in its hanging wall.*

the Gondwanide Orogen, including the CFB, developed in response to subduction-related compression along the convergent southwest margin of Gondwana (Trouw and de Wit, 1999). This paper re-examines the origin of the CFB within this tectonic framework. A model of oblique transpression, similar to the Mesozoic tectonic setting of the Cordilleran Orogen of North America, is suggested. Such a tectonic setting may provide an explanation of the inboard location of the CFB, the Cape Syntaxis, and the rotation of the Falkland Islands.

THE CAPE FOLD BELT

The CFB extends across the southern tip of Africa (Fig. 1), involving deformation of Precambrian (Pan African) basement, Early Palæozoic Cape Granites and Ordovician to Carboniferous continental margin sedimentary rocks of the Cape Supergroup. The fold belt deforms and defines the southern margin of the Carboniferous to Triassic Karoo Basin. Conversion of this basin from an intracontinental setting, dominated by detritus shed from a northern source (Turner, 1999) into a foreland basin increasingly filled by molasse shed from the south, occurred during end-Permian time, providing a record of emergence of the fold belt (Lock, 1980; Cole, 1992). Undeformed 'Karoo' dolerite dykes (~190 Ma) intrude deformed strata within the CFB, providing a minimum age limit to CFB tectonism. K-Ar and Ar^{40}-Ar^{39} age determinations on axial planar micas from folded strata within the CFB (Hälbich *et al.*, 1983), and Ar^{40}-Ar^{39} mineral age determinations on samples from the Precambrian basement to the CFB (Gresse *et al.*, 1992) range from 280 to 215 Ma. Except for the 215 Ma age determination, these ages have been interpreted as being the age of formation of the cleavages and, therefore, the age of deformation (Hälbich *et al.*, 1983; Gresse *et al.*, 1992). The 215 Ma age has been interpreted as a cooling age marking uplift during mantle doming or continental breakup (Hälbich *et al.*, 1983; Gresse *et al.*, 1992) and would, therefore, provide a minimum age of CFB orogenesis.

The orogen is divisible into southern and western tectonic domains (Söhnge, 1983), separated by the Cape Syntaxis, across which structural strike, and style and intensity of deformation exhibit significant change (de Beer, 1995) (Figs 1 and 2). The southern domain forms the bulk of the CFB, extending >600 km east across the continent from the east margin of the Cape Syntaxis to Port Elizabeth on the east coast. It is characterised by east-west-trending, north-verging structures including bedding parallel thrusts and north-verging folds and nappes. The total amount of shortening is estimated to be 120 km (Hälbich, 1992).

Strata in the western domain are interpreted as only being mildly deformed (de Beer, 1992). The Cape Supergroup is approximately half of its southern domain thickness (Broquet, 1992) and is generally upright with sub-horizontal to moderate dips. Folds and faults trend northwest to north (de Beer, 1990). North-trending slickensides developed on thrust planes (Ransome and de Wit, 1992) and stretching lineations (Cobbold *et al.*, 1992) indicate a component of strike-parallel displacement. The pattern of folds, faults and lineations are consistent with overall dextral strike-slip deformation (Cobbold *et al.*, 1992).

The Cape Syntaxis is a northeast-trending structural domain that separates the southern and western domains (de Beer, 1995). Based on a reconnaissance of the structure of the syntaxis and adjacent domains (de Wit, *pers. comm*.), Ransome and deWit (1992) suggested a model in which crust west of the Cape Syntaxis (the peninsular microterrane) rotated clockwise during syntaxis formation, while crust immediately to the east rotated counter-clockwise. Within the Cape Syntaxis, western and southern domain structures intersect, resulting in complex fold interference patterns (de Beer, 1995). Comparison of the geometry of the Cape Syntaxis with the results of experimental models led de Beer (1995) to conclude that the syntaxis may be in part the result of simultaneous shortening in two perpendicular (from the west and south) directions at unlike magnitudes (de Beer, 1995).

A second bend of the CFB is evident in the Port Elizabeth area (Fig. 1). The regional east-west-trending strike of folds and thrusts of the southern domain rotates >20° clockwise on approach to the coast. The off-shore geometry of the CFB structures can be inferred from the study of younger (Jurassic-Cretaceous) extensional basins, as it is believed that these developed by reactivation of thrust faults, follow the pre-existing CFB structural grain (Fouché *et al.*, 1992; Bate and Malan, 1992; Gresse *et al.*, 1992), and provide a 'proxy' for mapping of the offshore continuation of the CFB. Marine seismic-based mapping of the Jurassic-Cretaceous basins (Bate and Malan, 1992) indicate that the basin-bounding faults exhibit a significant degree of curvature, rotating clockwise about a northeast-trending hinge (vertical pole of rotation) to southerly trends near their outboard terminations, where they are truncated against the northeast-trending Agulhas-Falkland Fracture Zone (Fig. 3).

These observations imply that a second major bend in the CFB, similar in scale and orientation to the Cape Syntaxis, albeit now obscured by water and younger sedimentary rocks, exists in the Port Elizabeth area. The age and origin of this bend remain poorly constrained. The curvature of the faults may be

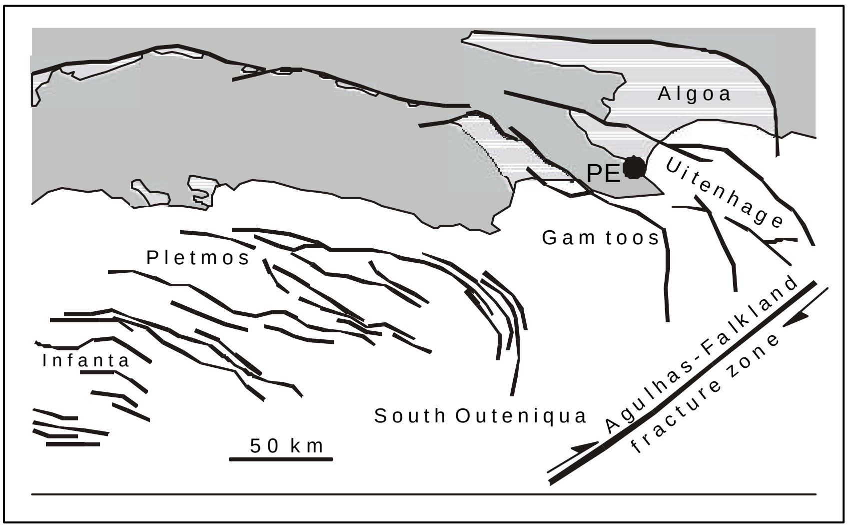

Figure 3. *Detailed map of the Port Elizabeth (PE) area, showing the distribution and geometry of Jura-Cretaceous extensional basins (names indicated) (after Bate and Malan, 1992). Clockwise bending of these structures, which developed by reactivation of older CFB structures, near their easternmost terminations defines the Port Elizabeth Antitaxis.*

attributable to drag along the dextral Agulhas-Falkland Fracture Zone (Fig. 1). This interpretation is suggested by the increased curvature of faults immediately adjacent to the Agulhas-Falkland Fracture Zone (de Beer, *written comm*.) and implies that the bend development is coeval with and in part post-dates deposition of the Jurassic-Cretaceous clastic molasse. Alternatively, the bending may predate the Jurassic extensional structures that re-activate the older CFB thrust faults. This is suggested by the lack of bend-related deformation of the Jurassic-Cretaceous strata. Here, it is assumed that this bend is a pre-Jurassic structure that is the same age as, and may have formed in a similar fashion to, the Cape Syntaxis. However, since the sense of curvature of the bend in the Port Elizabeth area is opposite that of the syntaxis, it is hereafter referred to as the Port Elizabeth Antitaxis.

REGIONAL SETTING: THE GONDWANIDE OROGEN

Regionally, the Cape Fold Belt is part of the greater Gondwanide orogenic belt which, prior to the break-up of Gondwana, extended west into South America, and east through the Falkland Islands and into Antarctica (Fig. 1). In this paper, these portions of the Gondwnaide Orogen are reviewed in order to demonstrate that the structure of the belt is consistent with it having developed, at least in part, in response to dextral transpression. Re-interpretations of some portions of the belt, in light of a model of dextral transpression, are provided.

South America

In eastern South America, Gondwanide structures can be traced through the Sierra Grande, Sierras Australes and Sierras Septentrionales south of Buenos Aires, northeast into the Pampean Ranges where they are transected by younger Andean structures. Overall, the deformed sequence forms a northwest-trending belt (Gondwana co-ordinates, assuming an east-west-trending CFB). Detailed structural studies (Cobbold *et al.*, 1986, 1991, 1992; Craddock *et al.*, 1998) indicate that deformation occurred within a dextral transpressive wrench system with minor overthrusting to the northeast (Fig. 4) (Cobbold *et al.*, 1992). Structures in the Sierras Australes define a sigmoidal belt, with fold trends rotating from west-northwest trends >60° clockwise to north-north-west, a configuration attributable to dextral trans-pression (Cobbold *et al.*, 1991). Inferred directions of maximum compressive stress are oblique to the orogenic belt, and to the convergent southern margin of Gondwana and are interpreted as resulting from oblique (dextral) subduction beneath an Andean-type margin (Cobbold *et al.*, 1992). Mechanical twin analysis of syn-orogenic calcite veins indicates sub-horizontal, orogen-parallel shortening (Craddock *et al.*, 1998) consistent with a model of dextral oblique shortening.

Falkland Islands

When restored to a position 150 km east of southeast Africa, including a 180° rotation, fold and thrust belt structures on the Falkland Islands form an eastward continuation of the CFB (all trends quoted below given

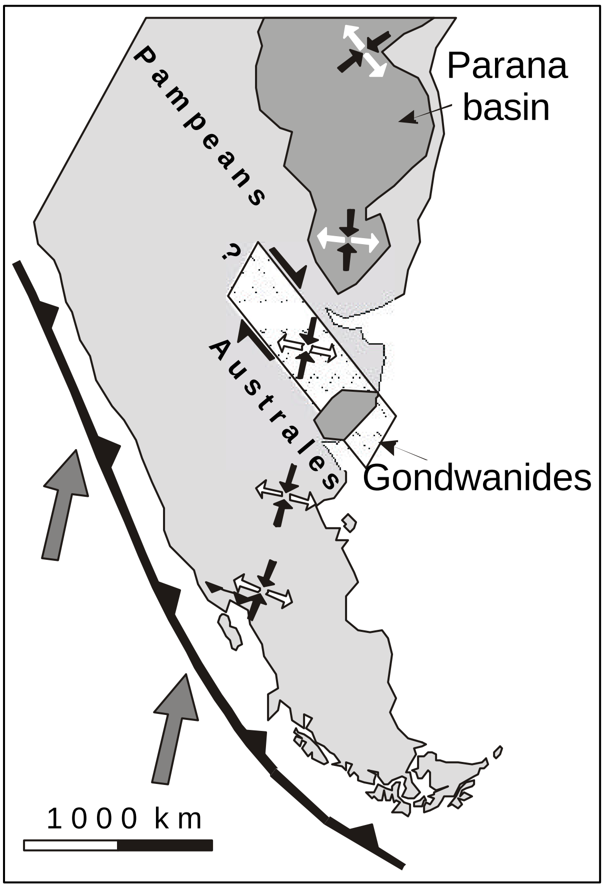

Figure 4. *South American portion of the Gondwanide Orogen (light grey stipple) (after Cobbold* et al.*, 1992). Orientation of principal compressive (black arrows) and extensional (white arrows) stress axes, based on structural studies of Cobbold* et al. *(1986, 1991, 1992) are consistent with interpretation of the orogen as a dextral transpressional belt (indicated by asymmetric arrows straddling the orogenic belt). Subduction beneath Gondwana indicated by black line with teeth pointing into the upper plate. Grey arrows indicate probable motion of obliquely subducting oceanic plate. Dark grey fill: Parana Basin.*

with respect to the restored location of the islands). Detailed structural studies of the islands (Curtis and Hyam, 1998; Hyam, 1998) indicate that early foreland-verging folds and faults (F_1) were overprinted (D_2) by asymmetric map scale folds characterised by long, shallowly-dipping, east-west-trending west limbs and short, steep to overturned, north-trending southeast limbs. Curtis and Hyam (1998) interpreted these folds as having "*developed in a complex strain system of combined shortening and dextral shear*" (p. 126). Additional D_2 dextral shearing is indicated by "*dextral faulting and the reactivation of steeply dipping bedding*" along the steep southeast limbs of the map scale folds by dextral northeast-trending dextral brittle ductile shears and by "*post-cleavage dextral kink bands and faults*" that strike between north and northeast (Curtis and Hyam, 1998). Curtis and Hyam (1998) interpret these structures, in part based on recognition of two map-scale north-trending D_2 folds, as the products of east-west compressive stress. They attribute the orientation and associated dextral shearing of the bulk of the D_2 structures to reactivation of a hypothetical northeast-trending basement structure. Here, D_2 is reinterpreted as a dextral transpressive event that developed in response to oblique (northwest directed) compression (Fig. 5).

Antarctica

The Gondwanide Orogen extends east through the Ellsworth-Whitmore Mountain block and the Pensacola Mountains of Antarctica (Fig. 1). The Ellsworth-Whitmore Mountain block is interpreted to have attained its current location within West Antarctica in the Jurassic-Cretaceous in part as a result of $>90°$ of counter-clockwise rotation (Dalziel and Grunow, 1992). During Gondwanide orogenesis the block is speculated to have occupied a site intermediate between the more easterly Falkland Islands and the more westerly Pensacola Mountains (Curtis and Storey, 1996).

Like the South American portion of the Gondwanide Orogen, structures in the Ellsworth-Whitmore Mountain block trend northwest (restored co-ordinates), oblique to the east trend of the CFB. Structural analysis (Curtis, 1997, 1998) indicates contemporaneous development of gently plunging foreland-verging folds and asymmetric, steeply plunging folds indicative of dextral shear. Interspersed domains of foreland vergence and dextral shear are distinguished based on recognition of steeply pitching and sub-horizontal stretching lineations, respectively. The orientation of folds, shortening directions and strain partitioning indicate deformation within a highly oblique dextral transpressive belt (Curtis, 1997, 1998). Analysis of mechanical twins in oolitic and sparry limestone indicates a strain history involving layer-parallel shortening related to the development of foreland-verging structures, and an oblique overprint attributable to orogen-parallel shortening, probably related to dextral transpressional shear (Craddock *et al.*, 1998).

OBLIQUE DEXTRAL CONVERGENCE AND MARGIN PARALLEL DISPLACEMENTS: A MODEL

Dextral transpressional structures are evident throughout much of the Gondwanide Belt (Table 1). Therefore, the Gondwanide Orogen can be interpreted as having a dextral transpressional component in many

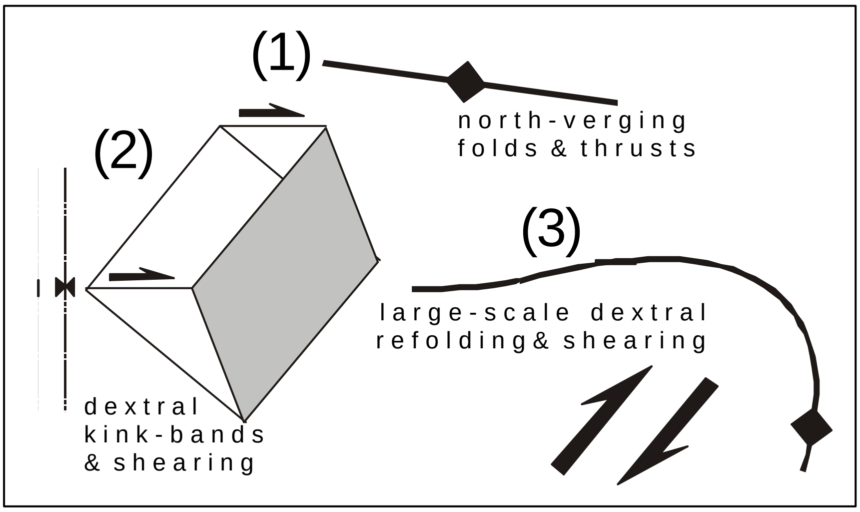

Figure 5. *A re-interpretation of the CFB-related structural evolution of the Falkland Islands, based on, and modified from, Curtis and Hyam (1998). Numbers refer to the sequential development of structures observed by Curtis and Hyam (1998).*

Table 1. Summary of Evidence for Dextral Transpression within the Gondwanide Orogenic Belt

Location	Evidence for Dextral Transpression	Reference
South America	- Sigmoidal fold belt development attributable to dextral transpression - Inferred oblique orientations of maxiumum compressive stresses consistent with dextral transpression - Mechanical twins in calcite veins indicative of sub-horizontal orogen-parallel compression attributed to dextral oblique shortening	Cobbold *et al*., 1991 Cobbold *et al*., 1992 Craddock *et al*., 1998
Cape Fold Belt – Western Domain	- North-trending sub-horizontal slickensides on thrust planes - North-trending sub-horizontal stretching lineations - Pattern of folds, faults and lineations consistent with dextral shearing	Ransome and Dewit, 1992 Cobbold *et al*., 1992 Cobbold *et al*., 1992
Cape Fold Belt – southern Domain	- No direct evidence of dextral shearing - Most significant development of foreland-verging thrusts and folds	
Falkland Islands	- Asymmetric, map-scale folds here interpreted as being indicative of dextral shearing - Northeast-trending brittle-ductile shears characterised by dextral displacement - North to northeast-striking dextral kink bands and minor faults	Curtis and Hyam, 1998 Curtis and Hyam, 1998 Curtis and Hyam, 1998
Antarctica	- Asymmetric steeply-plunging folds attributable to dextral shearing - Sub-horizontal stretching lineations (limited to discrete domains) - Pattern of folds, shortening directions and strain partitioning consistent with deformation within a highly oblique dextral transpressive regime - Mechanical twins in calcite veins and limestones indicative of sub-horizontal orogen-parallel compression attributed to dextral oblique shortening.	Curtis, 1997, 1998 Curtis, 1997, 1998 Curtis, 1997, 1998 Craddock *et al*., 1998

parts. This dextral component may provide a record of dextral displacement of the crustal block south of the orogen past the more inboard main portion of Gondwana. Margin-parallel translation was probably driven by oblique subduction (Cobbold *et al.*, 1992) beneath the convergent southern margin of Gondwana (Fig. 6).

The east-west-trending, foreland-verging CFB ends to the west and east against the northwest-trending South American and Antarctic portions of the Gondwanide Orogen, respectively. Therefore, it forms a left or inboard step within the orogen (Fig. 7). Significant shortening across the CFB may, therefore, have accommodated dextral strike-slip motion across South America and Antarctica (Fig. 7). Thus, development of the CFB 1500 km inboard from the active convergent margin of Gondwana is attributable to two factors:

i) dextral margin-parallel translation of the crustal block outboard of the Gondwanide Orogen; and

ii) the oblique (left or inboard-stepping) orientation of the CFB relative to the overall northwest-trend of the orogen.

The Canadian Cordillera: an analogue for the CFB

The development of the CFB, ~1500 km inboard of a long-lived transpressional convergent margin, may

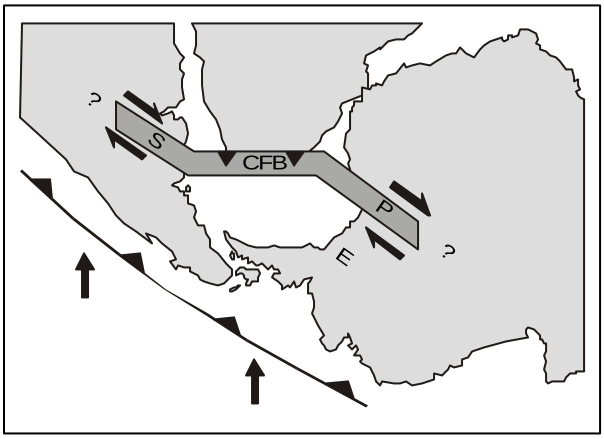

Figure 6. *Detail of the Gondwanide Orogen (modified from Martin, 1986). Regions discussed in the text are depicted in their restored (pre-break up of Gondwana) locations. The along-strike continuations of the belt into South America and Antactica remain poorly documented. Dextral transpressional northwest-trending portions of the belt in South America (S: Sierras Ventana and Sierras Australes mountains) and Antarctica (E: Ellsworth and Pensacola mountains) connect through the inboard-stepping CFB. Note that the palæolocation of the Ellsworth Mountain block remains a matter of conjecture (see Curtis and Storey, 1996, for discussion). Teeth point into the CFB and indicate a predominance of foreland-verging deformation. Oblique subduction beneath the margin of Gondwana (indicated by arrows) responsible for driving margin-parallel, dextral translation of the crustal block out-board of the orogenic belt.*

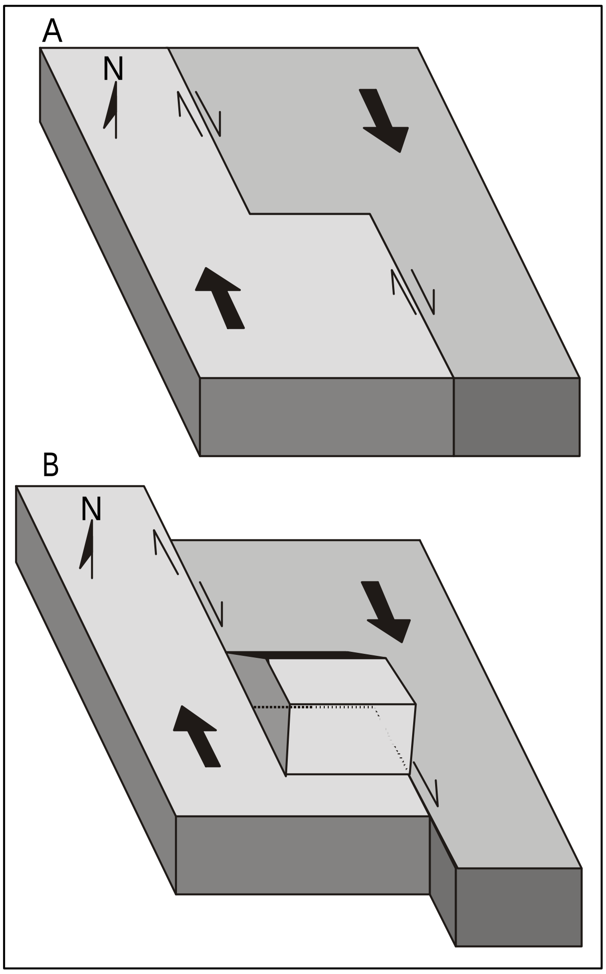

Figure 7. *(A) Initial configuration (pre-displacement) of a northwest-trending dextral strike-slip fault with an east-west-trending. The left side shows the stepping bend. (B) The same fault after an increment of motion. Strike-slip displacement along northwest-trending faults has been accommodated by thrusting of the westerly block over the easterly block, giving rise to the uplifted block. The dashed line indicates buried/hidden location of the east-west-trending left-step in fault.*

be analogous to the development of the cordilleran southern Canadian Rocky Mountain fold and thrust belt (Fig. 8). This Late Cretaceous and Tertiary thrust belt developed ~1500 km inboard of the active convergent margin (McMechan and Thompson, 1989). Oblique (dextral) subduction of oceanic plates beneath western North America, a tectonic setting which has existed from ~100 Ma to the present (Engebretson *et al.*, 1985), resulted in the development of major dextral strike-slip faults within the overriding North American crust. These included the Tintina-Northern Rocky Mountain Trench Fault, a fault that accommodated >600 km of Late Cretaceous and Tertiary dextral strike-slip movement (Gabrielse, 1985). At its southern termination, the fault ended, in part, along an inboard-stepping transfer zone across the area now occupied by the southern Canadian Rocky Mountains (Fig. 8). Dextral strike-slip displacement was taken up by convergence across the transfer zone leading to 200 km of shortening, which manifested in the development of the southern Canadian Rocky Mountain fold and thrust belt (Price and Carmichael, 1986). Thus, formation of the southern Canadian Rocky Mountains 1500 km inboard of the cordilleran margin in response to oblique subduction-driven, margin-parallel dextral translation may provide an analogue for development of the CFB.

Syntaxis and antitaxis development: products of dextral shearing?

Development of the Cape Syntaxis and the Port Elizabeth Antitaxis, and a significant proportion of the rotation of the Falkland Islands may be additional manifestations of the dextral transpressive character of the Gondwanide Orogen. The Cape Syntaxis and Port Elizabeth Antitaxis form northeast-trending hinge zones oriented sub-perpendicular to the northwest trend of the South American and Antarctic portions of the Gondwanide Belt. They are, therefore, oriented at a high angle to the presumed main margin-parallel transport direction of the crustal block south of the Gondwanide Orogen.

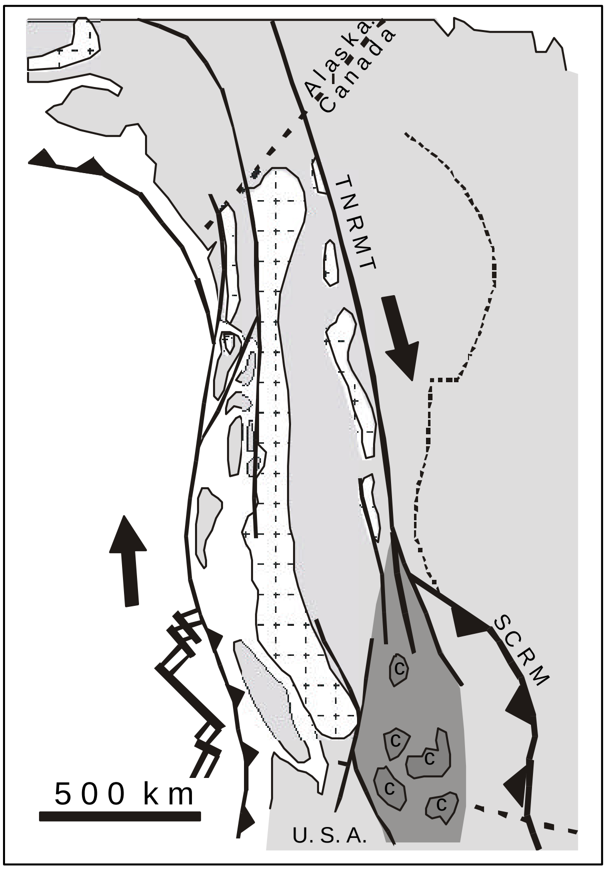

***Figure 8.** Cordilleran orogen of western North America (after Price and Carmichael, 1986). Oblique translation of oceanic plates past and beneath the west margin of North America (bold arrows) resulted in shearing of the continental margin and the development of major dextral transcurrent faults (black lines) including the Tintina-North Rocky Mountain Trench (TNRMT) Fault. Along the TNRMT, 600 km of strike-slip were accommodated at its southern termination by compression across the inboard-stepping, southern Canadian Rocky Mountains (SCRM) (teeth point into the fold and thrust belt). Extension (dark grey) and core complex formation (C) occurred across an outboard-stepping transfer zone (Price and Carmichael, 1986).*

A model of refolding of an east-west-trending, foreland-verging fold and thrust belt in response to this margin-parallel transport is proposed for formation of the Cape Syntaxis and the Port Elizabeth Antitaxis (Fig. 9). In this model, the syn- and antitaxial structures are interpreted as asymmetric oroclines attributable to dextral shear acting across the CFB. The western domain is interpreted as the short (~300 km), north-trending limb of an asymmetric syntaxial orocline. The east-west-trending southern domain forms a long (~600 km) limb that ends at the hinge of the Port Elizabeth Antitaxis. The short north-trending east limb of the Port Elizabeth Antitaxis has subsequently been truncated by propagation of the Falkland-Agulhas Fracture Zone through the hinge region of the antitaxial orocline. A model of orocline development during dextral shearing is consistent with the suggestion that crustal blocks adjacent to Cape Syntaxis rotated during CFB development (Ransome and de Wit, 1992) by the development of fold-interference patterns within the syntaxis (de Beer, 1995) and by dextral shear within the western domain of the CFB (Cobbold *et al.*, 1992; Ransome and de Wit, 1992) (for a review of oroclines see Marshak, 1988).

Late dextral folds in the Falkland Islands provide small-scale analogues for syn- and antitaxis formation (Fig. 5). These sigmoidal, asymmetric dextral folds post-dated early developed foreland-verging folds and thrust and are characterised by axial surfaces parallel to the axial surfaces of the Cape Syntaxis and Port Elizabeth Antitaxis and by long east-west-trending limbs and short north-trending limbs (restored co-ordinates). Folding resulted in >90° of clockwise rotation of the short north to north-northeast-trending limbs of these structures from their initial east-west trends (Curtis and Hyam, 1998).

Orocline formation may explain rotation of the Falkland Islands (Fig. 9). The islands (restored location) fall within that portion of the CFB that formed the short east limb of the Port Elizabeth Antitaxis. Approximately 90° of clockwise rotation of the islands is, therefore, probably attributable to orocline formation.

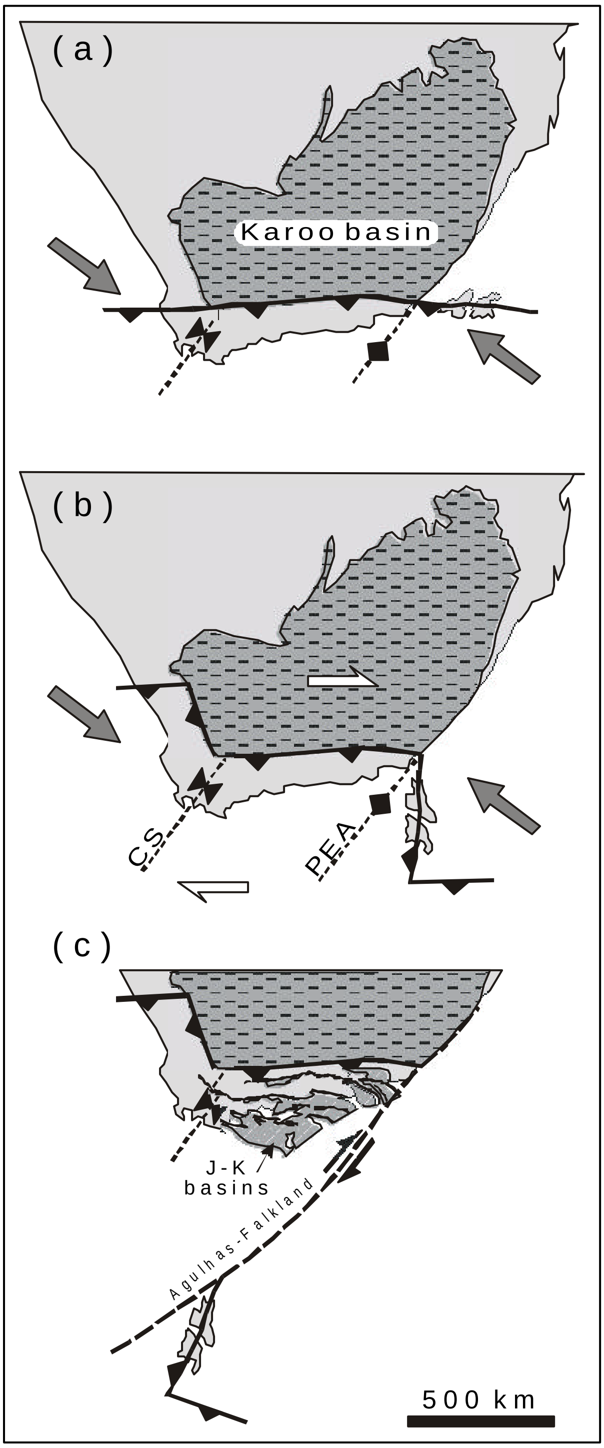

Figure 9. *(a) Pre-oroclinal configuration of the CFB. Grey arrows: regional principal compressive stress related to dextral translation of crustal block outboard of the orogen. Dashed lines: axial surfaces of incipient oroclinal bends. Dark grey stipple: Karoo Basin. (b) Orocinal development of the Cape Syntaxis (CS) and Port Elizabeth Antaxis (PEA), and related rotation of the Falkland Islands. Asymmetric white arrows: accommodation of overall dextral shear by orocline development. (c) Separation of the Falkland Islands from southeast Africa along the Agulhas-Falkland Fracture Zone with related extensional reactivation of CFB structures and development of Jurassic-Cretaceous basins (grey tone). Note solid-body rotation of the islands in response to translation along the fracture zone.*

Subsequent to orocline development, the hinge region of the Port Elizabeth Antitaxis may have acted as a zone of weakness along which the Agulhas Falkland Fracture Zone propagated during separation of South America from Africa (Fig. 9). A further 60–70° of solid body rotation about the Euler Pole of the fracture zone, during the movement of South America away from Africa, accounts for ~160° of rotation of the Falklands (~90° during orocline formation plus 70° about the Euler pole of the fracture zone). The remaining 20° of the estimated 180° of rotation of the islands may be attributable to minor vertical axis rotation of the islands during shear along the Agulhas-Falkland Fracture Zone.

This model predicts that the Cape Syntaxis and Port Elizabeth Antitaxis are genetically related oroclines, that they developed roughly synchronously during CFB orogenesis in response to dextral transpressional shearing and that orocline formation was responsible for ~90° rotation of the Falkland Islands. This model is in direct conflict with previous models of rotation of the Falkland Islands that have assumed that rotation post-dated CFB tectonism. This assumption is based on the observation that the palæomagnetic pole for dykes that intrude the Falkland Islands is roughly coincident with the apparent magnetic pole for coeval dykes in southeastern Africa, thereby restricting rotation to being post 190 Ma (the age of the dykes) (Mitchell *et al.*, 1986; Taylor and Shaw, 1989). Resolution of this conflict constitutes a critical test of the orocline model.

CONCLUSIONS

The Gondwanide Orogen is a transpressional orogenic belt developed in response to the margin-parallel dextral translation of a crustal block past the more internal part of Gondwana. The South American and Antarctic portions of the belt trend northwest, sub-parallel to the direction of transport, and are largely characterised by dextral transpression with relatively minor development of foreland-verging structures. These transpressive portions of the orogenic belt are connected through the oblique, left- or inboard-stepping CFB; dextral transpression in South America and Antarctica was accommodated by compression across the CFB, consistent with the development of a large, foreland-verging fold and thrust belt. Thus, development of the CFB 1500 km inboard of the convergent margin of Gondwana is attributable to a left-step along a major intracontinental dextral shear zone. Dextral translation was probably driven by oblique subduction beneath the outboard margin of Gondwana.

Oroclinal bending, a late-tectonic manifestation of dextral transpression across the CFB, gave rise to the Cape Syntaxis and Port Elizabeth Antitaxis. These asymmetric ‘folds’ of the CFB are characterised by short (300 km long) north-trending limbs joined by a long (600 km) east-west-trending limb. The Falkland Islands, which originally lay 150 km due east of Port Elizabeth, were incorporated in the short east limb of the Port Elizabeth Antitaxis, resulting in ~90° clockwise rotation during orocline development. During separation of South America from Africa, the hinge region of the Port Elizabeth Antitaxis formed a zone of weakness along which the dextral Falkland-Agulhas Fracture Zone, the fault along which the Falkland Islands separated from southeastern Africa, propagated. Solid body rotation of the Falkland Islands about the Euler pole to the fracture zone accounts for 60–70° of additional clockwise rotation of the islands. The remaining 20° of rotation may be attributable to local block rotation about a nearby vertical axis due to shear along the Agulhas-Falkland Fracture Zone.

Critical tests of the dextral transpressional-orocline model are available. For the model to remain viable, resolution of the conflict between the assumed post 190 Ma age of rotation of the Falkland Islands (based on palæomagnetic constraints) and the presumed syn-CFB (pre 215 Ma) rotation implied by the model, is necessary. Recognition of dextral transpressional structures within the hinterland of the southern domain of the CFB would be strong evidence in favour of the model. Finally, recognition of dextral transpression along the New Zealand-Australian portion of the Gondwana Margin would further bolster the case for transpression being driven by oblique subduction beneath Gondwana. This makes recent suggestions, based on provenance studies of the Permian Sandstones outcropping in New Zealand (Barley *et al.*, 1998; Adams *et al.*, 1998), of Permian-Triassic dextral transport of terranes along the Gondwanide Margin of Australia of distances of ~2500 km, particularly intriguing.

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