Falkland Plateau evolution and a mobile southernmost South America

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Abstract: Assessment of southwest Gondwana break-up and its implications for regional hydrocarbon prospectivity must now take into account the origin of the southeast margin of the Falkland Islands as a volcanic rifted continental margin, and of the floor of the major part of the Falkland Plateau Basin as elevated oceanic crust. A reconstruction of the Falkland Plateau against southern Africa shows a southward extensional widening of the Outeniqua Basin across the line of the Falkland–Agulhas Fracture Zone, changing from stretched continental to oceanic crustal structure. Such a model for Outeniqua Basin opening, and the independent westward and clockwise rotation of the Falkland Islands block, suggests that southernmost South America was also a collection of microplates moving independently within a generally extensional environment in the Late Triassic–Early Jurassic. This is incompatible with assumptions of a rigid southernmost South America over this time, and a dominant role for a continuous dextral strike-slip Gastre Fault.

For almost 30 years, models of the evolution of southwest Gondwanaland have had to deal with the unacceptable overlap of the Falkland Plateau and West Antarctica, pointed out by Smith & Hallam (1970). They have done so by regarding West Antarctica as a mosaic of mobile microplates at the margin of a stable East Antarctic craton during the early part of post-break-up evolution (e.g., Barker & Griffiths 1977; Storey *et al.* 1988). The stability of the Falkland Plateau itself had been questioned implicitly by Adie (1952) on the basis of comparisons of Falkland Islands and southern African geology. However, this option was only raised again when palaeomagnetic data from onshore dykes of Karoo age (and chemistry) suggested that the Falkland Islands had undergone independent post-emplacement rotation (Taylor & Shaw 1989; Mussett & Taylor 1994). Although many workers now accept such rotation for its insights into onshore geology (e.g. Cole 1992; Curtis & Hyam 1998) a minority reject it (e.g. Richards *et al.* 1996), citing uncertainties in the palaeomagnetic data. Other aspects of this problem, relevant to regional hydrocarbon prospectivity, were not pursued: the nature and origin of much of the Falkland Plateau remained enigmatic (Lorenzo & Mutter 1988), and consequences for the evolution of southernmost South America (e.g. Rapela & Pankhurst 1992) were not fully examined. However, a recent analysis of magnetic, gravity and seismic data from the western Falkland Plateau allows these aspects to be considered further.

The geophysical data have been interpreted by Barker (1999) to show that the southeastern margin of the Falkland Islands block is a volcanic rifted continental margin, and that the central basin province of the Falkland Plateau is largely oceanic, produced by 'subaerial' seafloor spreading shortly after 190 Ma. The linear gravity and magnetic anomalies at the Falkland Islands margin, the crustal structure of the basin constrained by gravity and seismic reflection data, the existing seismic refraction data set from the basin (when corrected for the effects of thermal subsidence and sediment load) and the character of deep seismic reflectors, all support this interpretation. Further, the existence of dolerite dykes onshore, with chemistry, age and magnetic remanence implying formation within the Karoo–Bouvet hotspot province, and linked offshore dykes detected by their magnetic signature, make such a structure and origin entirely plausible.

Strictly, identification of a volcanic rifted margin southeast of the Falkland Islands, and designation of an oceanic origin for most of the Falkland Plateau Basin, do not demonstrate independent rotation of the Falkland Islands block. However, if the Falkland Islands block has rotated away from southern Africa, as the balance of geological evidence now overwhelmingly suggests, then rotation most probably began with creation of the volcanic rifted southeastern block margin, and continued with formation of the largely oceanic basin province. These associations bear on several aspects of the evolution of southwest Gondwana: in particular, on the other margins of the Falkland Islands block and the environment in which it may have moved, on the relationship of the Falkland Plateau Basin to the Outeniqua Basin of South Africa, and on the role of the Gastre Fault of South America.

Margins of the Falkland Islands block

If the association of linear gravity high and strongly lineated magnetic anomalies, together with a dyke swarm offshore, serve to define the

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southeastern (ocean–continent) boundary of an independent Falkland Islands block, and if, as seems most likely, this block migrated westward and rotated about a near pole to the north (i.e. clockwise) during the earliest stages of Gondwana break-up, then what were its other boundaries? Near-pole rotation is not unknown, but the larger the block, the more difficult is a large, near-pole rotation to envisage.

A free-air gravity high and associated shallow-origin magnetic anomalies are seen elsewhere close to the Falkland Islands: a gravity high extends west-northwestward from the southern end of West Falkland, and a high with a similar orientation lies to the north of both islands. Platt & Philip (1995) report magnetic anomalies approximately coincident with the gravity high west of the Falkland Islands, and attribute them to igneous rocks, citing the mid-Jurassic basaltic dykes found onshore (Taylor & Shaw 1989; Mussett & Taylor 1994) and the essentially acidic late Jurassic Serie Tobifera volcanics found at depth beneath the Magallanes Basin to the west, and elsewhere in Patagonia (e.g. Winslow 1982). Neither gravity high is so well formed as that at the southeast margin, but they are similar in length and peak gravity value. The west-northwest trending dykes exposed onshore on West Falkland (Greenway 1972), dated at 189 Ma by Mussett & Taylor (1994), would run into one of these gravity highs if extended westward offshore. The gravity highs may mark block margins created at the same time as the southeast margin, and in the same way. They probably define the smallest block that is plausible, and are used in what follows: for a larger block, the consequences of block rotation become greater and more difficult to explain.

Reconstruction to 130 Ma

The position of the Falkland Plateau before South Atlantic opening, and relations to South African geology, have been considered in great detail by Dingle *et al.* (1983) and by many others. Figure 1a is a reconstruction to *c.* 130 Ma of a rigid Falkland Plateau against southern Africa that shows the Outeniqua Basin, the outline of Maurice Ewing Bank and the proposed Falkland Islands block, and the extent of the Falkland Plateau Basin. A shallow water, presumed mainly continental, area of the Falkland Plateau lies north of the Falkland Islands block (the northwest Falkland Plateau). Basement in the northwest Falkland Plateau is generally shallow, but it contains the narrow, north–south North Falkland Basin. It appears to be a southward extension of the Columbine–Agulhas Arch of southern Africa. The Falkland Plateau Basin may be seen as a southward extension of the Outeniqua Basin, and Maurice Ewing Bank as a southward extension of the Port Alfred Arch (east of the Outeniqua Basin) and the region to the northeast. Lorenzo & Mutter (1988) map a small area of thinner sediment cover and block-faulted basement close to the northern margin of the Falkland Plateau that lies adjacent to the Outeniqua Basin in the reconstruction, and is probably a southward extension of its thinned continental crust.

Outeniqua Basin, South Africa

The Outeniqua Basin (Dingle *et al.* 1983) is a collection of smaller basins, exposed onshore, that expand and merge southeastward on the east coast of South Africa between the Columbine–Agulhas Arch in the west and the Port Alfred Arch in the east. The basins are asymmetric: each has a bounding normal fault on its northern side, downthrown to the south. The faults are west–east, curving around to northwest–southeast at their eastern end, and to north–south offshore. Basement, where seen, is downfaulted continental and the style is of continental extension, increasing in extent to the southeast. The only constraint on basin age is a whole-rock K–Ar date of 162±7 Ma on lavas within a basal conglomerate (McLachlan & McMillan 1976; Dingle *et al.* 1983). The Falkland Plateau Basin may be seen as a southward extension of the Outeniqua Basin, that was therefore wider still, opening sufficiently to create ocean floor. The transition between continental stretching in the north and seafloor spreading in the south is taken here to be the southern boundary of the thinned continental crust province in Fig. 1a, on the basis of seismic character. A modern analogue is the zone of stretched continental crust in North Island, New Zealand, in the south, leading to oceanic crust in the Lau-Havre Basin to the north (Karig 1970; Lewis & Pantin 1984; Gamble & Wright 1995).

Reconstruction to 190 Ma

Figure 1b shows a reconstruction to 190 Ma, before any independent rotation of the Falkland Islands block. The reconstruction is incomplete but illustrates the consequences of what is now known and the associated uncertainties. The stretched continental crust of the Outeniqua Basin is closed (nominally, its southern end is

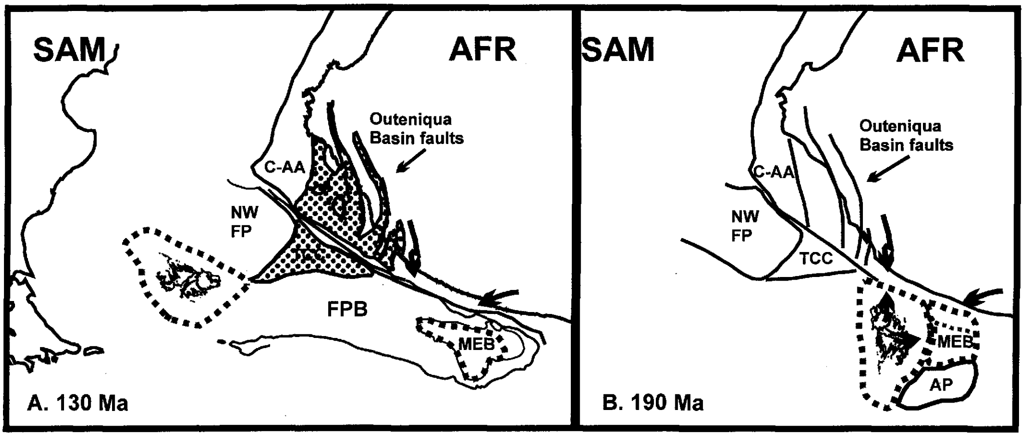

Fig. 1. Schematic reconstruction of Falkland Islands block and Maurice Ewing Bank against southern (**a**) *c.* 130 Ma before South Atlantic opening and (**b**) *c.* 190 Ma before Falkland Islands block rotation. Shaded areas in (a) are the Outeniqua Basin and corresponding thinned continental crust (TCC) of Falkland Plateau. Arrows mark strike projections of Lafonia and Dwyka tillites. Dotted line around Falkland Islands marks positions of block boundaries based on magnetic and gravity anomalies. MEB, Maurice Ewing Bank; FPB, Falkland Plateau basin province; AP, Agulhas Plateau; NWFP, northwest Falkland Plateau, either [as drawn in (b)] unmodified continent attached to Columbine–Agulhas Arch (C–AA), or part of a more mobile, microcontinent province of southernmost South America.

shortened by 80 km, representing an original extension of *c.* 150%). The northernmost basin (TCC) province is shortened also, but the northwest Falkland Plateau is unchanged. Maurice Ewing Bank is against the Africa margin (closing the St Johns Basin: Dingle *et al.* 1983), and made more compact [it was stretched by block faulting (Lorenzo & Mutter 1988), presumably during break-up]. The Falkland Islands block is restored to the position favoured on geological grounds (Adie 1952; Visser 1987; Curtis & Hyam 1998) and supported by palaeomagnetic measurement (Taylor & Shaw 1989; Mussett & Taylor 1994). The arrows on the Falkland Islands block and the African margin mark the line of outcrop of the correlated Lafonian and Dwyka tillites, which is insensitive to exposure level as the tillites have a regional dip into the Karoo Basin. The conjugate margin to the volcanic southeast margin of the Falkland Islands block is a section of the African margin off East London. The line of opening runs from the western end of the (closed) Outeniqua Basin faults, north of the Falkland Islands block, then south between there and Maurice Ewing Bank. The Agulhas Plateau, partly continental (Tucholke *et al.* 1981) and separating from the Falkland Plateau during South Atlantic break-up, is located next to Maurice Ewing Bank. The region to the south is not considered here, but the Cape Fold Belt may continue towards Antarctica with the present northwest trending chain of islands off West Falkland, with associated gravity low, forming a useful marker for West Antarctic reconstruction (e.g. Curtis & Storey 1996).

Pre-Cretaceous southernmost South America

Figure 1b illustrates the general problem of Falkland Islands block rotation. If the block rotated clockwise away from South Africa and Maurice Ewing Bank, as many lines of evidence now suggest, then one of two main conditions must have been fulfilled. Either the block converged upon a stable southernmost South America to the west, to produce underthrusting and ultimately a suture, or the motion took place within an essentially mobile and extensional southern South American environment, involving other, equally mobile, small blocks to the west of it and behind a west-migrating subducting Pacific margin. For example, in Fig. 1b, either the Falkland Island block converged upon a static northwest Falkland Plateau block as it rotated, or the plateau and its surroundings were themselves also in process of migration and possible deformation, so that their positions 190 Ma ago were not as drawn here, but farther east, and their shapes were probably different too. Figure 1b poses the question but does not solve it.

Rapela & Pankhurst (1992) did not appreciate this dilemma. They hypothesized a northwest–southeast trending dextral Gastre Fault Zone in Patagonia, based on two features: at Gastre, some 600–700 km along-strike from the Pacific margin, a 30 km wide mylonite zone cuts plutonic rocks that yield a 208 Ma Rb–Sr age for dextral strike-slip displacement. At the Atlantic coast, pervasive normal faulting with the same strike affected acidic volcanics, Rb–Sr dated at 178 Ma. The curved line joining these two occurrences separates regions of different Mesozoic geology, characterized as a stable platform to the north, with a narrow Pacific margin component, and a more mobile environment to the south with a more widely distributed subduction signature. Rapela & Pankhurst (1992) pointed out that this line is virtually homopolar with the Falkland–Agulhas Fracture Zone, which formed the northern boundary of a by-then, rigid Falkland Plateau during South Atlantic opening (130 Ma onward). They hypothesized a precursor to the Falkland–Agulhas Fracture Zone, continuous with the Gastre Fault Zone and active during a 208–178 Ma strike-slip episode, as the means whereby the Falkland Islands block moved westward. Under this hypothesis, a rigid, more easterly southern Patagonia and Falkland Plateau lay south of the Gastre Fault Zone–Falkland-Agulhas Fracture Zone line before 208 Ma, and the Pacific margin of Gondwanaland had a pronounced corner at present-day 38°S. In view of the key role envisaged for the Gastre Fault Zone–Falkland-Agulhas Fracture Zone and the assumed rigidity of South America to the south, this may be called the 'single slice' model of Triassic–Jurassic evolution of southernmost South America.

Falkland Islands block rotation and Falkland Plateau Basin opening at the southern end of the Outeniqua Basin (a 'splay' model) are incompatible with this role for the Gastre Fault. The apparent continuity of older structures across the line of the Cretaceous strike-slip motion along it, and the rotation involved in opening the Outeniqua Basin, would have degraded an earlier coincidence of Euler poles. Both alternatives for the environment of Falkland Islands rotation, convergence with suturing or pervasive extension, are incompatible with the extent of Gastre Fault strike-slip envisaged by Rapela & Pankhurst (1992).

This is not to deny the reality of dextral strike-slip in Patagonia, or the associated ages. These observations can easily be reconciled with Falkland Plateau development: widespread westward extension at the southwest Gondwana margin, from before 200 Ma until ultimate major break-up, could have been taken up partly by dextral shear at the margins of several small rigid blocks, as at the Gastre Fault and others within southern South America farther south, as well as by the kind of oroclinal bending and near-pole extension represented by the 'splay' model for Outeniqua Basin opening. The Gastre Fault may have marked the northern boundary of a more mobile Triassic–Jurassic southernmost South America, but was not necessarily long-lived, or more extensive eastward, or the sole site of dextral strike-slip.

Others have considered the regional tectonic environment in which Falkland Island block motion might have taken place (e.g. Ben-Avraham *et al.* 1993; Curtis & Storey 1996). The initial tectonic regime could have involved a combination of Karoo hotspot-induced divergence and regional back-arc extension close to the subducting Gondwana margin. Extension was initiated after convergent deformation of the Cape Fold Belt in the Triassic and (in South America) may have lasted until the late Early Cretaceous (Albian) start of closure of the Rocas Verdes back-arc basin in southern Chile (Barker *et al.* 1991; Dalziel 1992). Within this environment, convergence may be rare, but should be detectable since it would most probably create local uplift, and thus subaerial, sutured outcrop. To date, this has not been described. Detailed examination of Late Triassic–Early Jurassic outcrop and drilled subcrop in Patagonia seems essential, but large areas will remain inaccessible.

Outeniqua Basin opening

There is significant difference between the 162 Ma whole-rock K–Ar age for a lava in basal conglomerates in an Outeniqua sub-basin onshore (McLachlan & McMillan 1976; Dingle *et al.* 1983), and the 190 Ma age of doleritic dykes on the Falkland Islands. Cox (1992) notes a difference between the North Atlantic Volcanic Province where volcanism and spreading are near-synchronous, and the Karoo province where long delays are apparent in places. In partial resolution, he postulates an early (*c.* 190 Ma) North Atlantic Volcanic Province-like opening phase more directly related to early volcanism. This involved the Lebombo Monocline and possibly the Explora Wedge off Dronning Maud Land, and presumably the Falkland Islands block. The onset of Falkland Island block rotation may have preceded Outeniqua Basin opening, which could eliminate the geometric offset apparent in Fig. 1b; however, better age control would be useful here, since a chemical affinity is noted of the dated Outeniqua Basin lavas and Lebombo Monocline volcanics (Dingle *et al.* 1983).

Otherwise, constraints on Falkland Plateau Basin opening are loose: after 190 Ma and before 130 Ma. Seismic evidence based on DSDP Site 330 on Maurice Ewing Bank (Barker 1976) suggests that the basin existed by Oxfordian times, and initial opening some 7–15 Ma after dyke injection (see White 1977) seems most likely. Falkland Plateau Basin within 15 Ma would have involved half-spreading rates < 20 mm a^{-1}, so that opening could have been complete by 165–160 Ma.

Regional hydrocarbon prospectivity

It is beyond the scope of this brief note to discuss fully the implications for regional prospectivity of a rotated Falkland Islands block and an oceanic Falkland Plateau Basin. The main implications concern possible ages of early basin development, early thermal history and provenance of basin fill, and may extend beyond the Falkland Plateau itself, over large parts of southernmost South America. In general terms, widespread Late Triassic or Early Jurassic extension would lead to an earlier and broader distribution of terrigenous reservoir sands than has been assumed. So far as is known, circulation within the intra-Gondwana basins was restricted into the Aptian, so there is no shortage of source rocks. The age and origin of a small, isolated basin, such as the North Falkland Basin, remain enigmatic: a Jurassic opening, post-rotation and perhaps effectively black-arc, is not ruled out.

Conclusions

The identification of the southeast margin of an independent Falkland Islands block and of an oceanic origin for the central basin province of the Falkland Plateau raises questions about southwest Gondwana evolution that are relevant to regional hydrocarbon prospectivity. The basin province of the Falkland Plateau may be seen as a southward extension of the Outeniqua Basin of South Africa, which opened further, creating ocean floor, after 190 Ma. This is incompatible with a view of the Gastre Fault of southern South America as a singular, long-lived strike-slip fault that accommodated all of the westward movement of the Falkland Islands block, and of a rigid southernmost South America ahead of it. Rather, Falkland Islands block rotation implies either convergence upon other parts of southernmost South America (with consequences that are not seen in outcrop) or a more widespread extensional environment within southernmost South America in the Late Triassic–Early Jurassic, involving the independent westward movement of other small blocks behind a west migrating subducting Pacific margin. The Gastre Fault could mark the boundary between this mobile southern zone and a more rigid northern South America but would have been only one of several zones of relative motion between blocks.

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