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Marine and Petroleum Geology 20 (2003) 287–308

Marine and Petroleum Geology

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# Mesozoic break-up of SW Gondwana: implications for regional hydrocarbon potential of the southern South Atlantic

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Received 10 January 2002; received in revised form 5 February 2002; accepted 10 November 2002

## Abstract

This work provides new palinspastic palaeofacies reconstructions of SW Gondwana incorporating rotation of a Falkland/Malvinas microplate. We discuss the implications of this for the tectonic evolution of the southern South Atlantic and hence for the regional hydrocarbon potential.

Existing Gondwana reconstructions display good fits of major continents but poorly constrained fits of microcontinents. In most continental reconstructions, the Falkland/Malvinas Plateau was assumed to be a rigid fragment of pre-Permian South American crust. However, it has been suggested, on the basis of palaeomagnetic data, that the Falkland/Malvinas Islands were rotated by ~180° after 190 Ma. This rotation hypothesis has been successfully tested on the basis of Devonian stratigraphy and palaeontology, Permian stratigraphy and sedimentology and Late Palaeozoic and Early Mesozoic structure, making it unlikely that the plateau behaved as a rigid structure during breakup. We have explored the consequences of accepting this hypothesis for the tectonic evolution of SW Gondwana by compiling new palaeogeographic maps for the Permian–Cretaceous of the southern Atlantic area. To achieve a realistic close fit, we have devised a pre-rift proxy for the ocean–continent boundary for the South Atlantic. In order to produce the best fit, it is necessary to subdivide South America into four plates. The consequences of this are far-reaching. Our work suggests that although sedimentary basins were initiated at different times, three major tectonic phases can be recognised; in regional terms these can be thought of as pre-, syn- and post-rift.

During the pre-rift time (until the Late Triassic), the area was dominated by compressional tectonism and formed part of the Gondwana foreland. The Falkland/Malvinas Islands lay east of Africa, the Falkland/Malvinas Plateau was ~33% shorter and Patagonia was displaced east with respect to the rest of South America, in part along the line of the Gastre Fault System. Potential source facies are dominantly post-glacial black shales of Late Permian age deposited in lacustrine or hyposaline marine environments; these rocks would also be an effective regional seal. Sandstones deposited in the Late Permian would be dominantly volcaniclastic with poor reservoir qualities; Triassic sandstones tend to be more mature.

There was significant extension from about 210 Ma (end-Triassic) until the South Atlantic opened at about 130 Ma (Early Cretaceous). In the early syn-rift phase, extension was accompanied by strike-slip faulting and block rotation; later extension was accompanied by extrusion of large volumes of lava. Early opening of the South Atlantic was oblique, which created basins at high angle to the trend of the ocean on the Argentine margin, and resulted in microplate rotation in NE Brazil. Intermittent physical barriers controlled deposition of Upper Jurassic–Cretaceous anoxic sediments during breakup; some of these mudrock units are effective seals with likely regional extent. During crustal reorganisation, clastic sediments changed from a uniform volcaniclastic provenance to local derivation, with variable reservoir quality.

In the late rift and early post-rift phase, continental extension changed from oblique to normal and basins developed parallel to the continental margins of the South Atlantic. This change coincides with the main rifting in the Equatorial basins of Brazil and the early impact of the Santa Helena Plume. It resulted in widespread development of unconformities, the abandonment of

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doi:10.1016/S0264-8172(03)00045-X

the Recôncavo–Tucano–Jatoba rift and the end of NE Brazil plate rotation, which remained attached to South America. There was extensive deposition of evaporites, concentrated in (but not restricted to) the area north of the Rio Grande Rise/Walvis Ridge.

Widespread deposits can be used to define potential regional elements of hydrocarbon systems and to provide a framework for relating more local elements. Our main conclusion is that the regional hydrocarbon potential of the southern South Atlantic has been constrained by the tectonic evolution.

*Keywords:* Plate reconstruction; Reservior rock; Tectonics; Source rock; Palaeofacies map; Hydrocarbon potential

## 1. Introduction

### *1.1. Rationale*

This paper describes regional tectonic controls on the development of end-Palaeozoic–Mesozoic hydrocarbon systems in the area around the South Atlantic. A reassessment of the tectonics was necessary for two reasons.

First, although the South Atlantic was the first of the World's major oceans to be successfully palinspastically restored (Bullard, Everett, & Smith, 1965), the apparent simplicity of the fit masks a variety of problems. In particular, South America is too long by about 1–1.5° of latitude to fit to Africa, resulting in an 'underlap' zone along the line of the Agulhas–Falkland Fracture Zone. This problem was apparently solved by Rabinowitz and LaBreque (1979), when they redefined the ocean–continent boundary (OCB), outboard of the 2000 m isobath used as an OCB proxy by Bullard et al. (1965); their reconstruction is successful, in that it removes most of the over- and underlaps identified on older fits. However, it is a reconstruction at the time of breakup, by which time there had been considerable extension in the South Atlantic margins, particularly around the Falkland/Malvinas Plateau area, where the Falkland Plateau Basin is floored by ocean crust (Barker, 1999). This means that any reconstruction based on the edge of stretched continental crust will exaggerate the intercontinental spacing by 10–200% (based on $\beta = 1.1–2$).

Second, it is now clear that the Falkland/Malvinas Islands lay in a rotated position east of South Africa until Early Jurassic time (for review, see Trewin, Macdonald, & Thomas (2002)). This position can only be accommodated if southern South America has not behaved as a single rigid block during Gondwana breakup.

### *1.2. Aims*

There were two main aims to this work:

- To deduce controls on Mesozoic hydrocarbon potential by synthesising the regional geological evolution of the area around the South Atlantic (shown in Fig. 1). This geological foundation can be used to analyse and predict the quality of source, reservoir and seal rocks through time in the South Atlantic margins.
- To explore the consequences of any revised reconstruction by focused fieldwork. To date, there have been field studies in Argentina, Falkland/Malvinas Islands and southern Africa (Fig. 1).

The work was carried out as an industry-funded project between 1995–1999. This project (the South Atlantic Project: SAP) was an international research collaboration between institutes in the UK (CASP, University of Aberdeen), Argentina (CIG) and the USA (UTIG). During 1996–1999 we developed a set of new reconstructions and palaeofacies maps in 13 time slices at 15 Ma intervals from 255 to 75 Ma. Extracts from five of the 13 maps are presented here (Figs. 7, 9, 11, 13 and 15; for key to all diagrams, see Fig. 7). The work draws on six South Atlantic Project reports (Table 1). The purpose of this paper is to pull together the diverse strands in each of these works and to demonstrate the impact of accepting rotation of the Falkland Islands on thinking about basin development as far north as Brazil. This is a revised version of the poster presented at

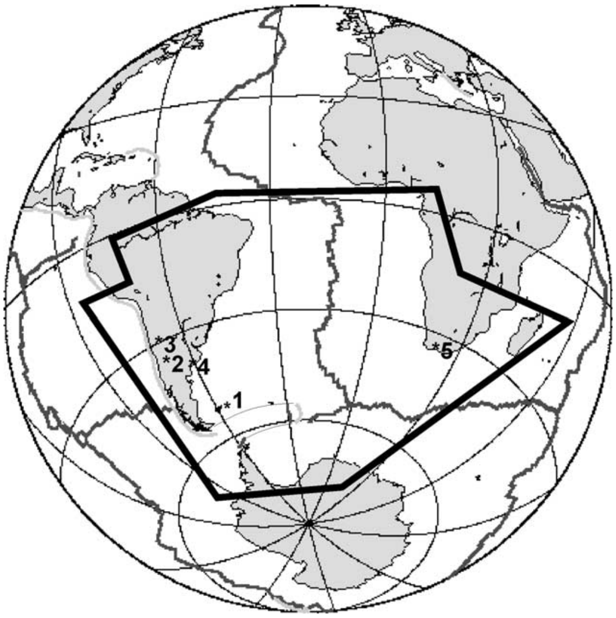

Fig. 1. Present day plate tectonic setting of the South Atlantic showing the boundary of the area covered by the Mesozoic palaeofacies maps. In addition, we have tested contentious parts of the reconstructions with fieldwork in the areas indicated by asterisks: (1) Falkland/Malvinas Islands (Permian stratigraphy and sedimentology); (2) Argentina (Gastre Fault System, structural history); (3) Argentina (syn-rift evolution of the Neuquen Basin); (4) Argentina (Sierra de la Ventana, structure and stratigraphy of the Gondwana Fold Belt); (5) South Africa (Permian stratigraphy of the Karoo Basin and structural history of the Gondwana Fold Belt).

Table 1
Unpublished reports of the joint South Atlantic Project used as a basis for this paper

| Report # | Title | Content |
|---|---|---|
| Report 1 | The geology of the Falkland Islands and its implications for the hydrocarbon potential of pre-rift strata on the Falkland Plateau | Helped to confirm the validity of the link between the Falkland/Malvinas Islands and South Africa. Now published as Trewin et al. (2002) |
| Report 3 | Mesozoic evolution of SW Gondwana: implications for the hydrocarbon potential of the Falkland/Malvinas Plateau area | First attempt to incorporate a rotated Falkland block into a numerically robust Gondwana reconstruction. Main conclusion was that South America cannot be reconstructed as a single rigid plate. The implications for South America were explored in Reports 6 and 11; reconstructions were revised in Reports 7 and 10 |
| Report 6 | New field data from Gastre, Chubut Province, Argentina: implications for the tectonic evolution of South America | Demonstrated the tectonic complexity of the Gastre Shear Zone, one of the transcontinental boundaries along which South America deformed during continental break-up |
| Report 7 | Break-up of a tight-fit, early Mesozoic Gondwana: plate reconstruction perspective | Used revised COBs for S. Atlantic to demonstrate how South America could have behaved as (at least) four blocks during Gondwana break-up |
| Report 10 | Mesozoic evolution of the South Atlantic and its influence on the Tertiary development of the region | Used the revised continental reconstructions in Report 7 to plot palaeogeographic maps across the whole of the South Atlantic region. Most of the work on hydrocarbon systems in this present work is derived from Report 10 |
| Report 11 | Syn-rift evolution of the Neuquen Basin (Argentina) in the Cerro Chachil area: preliminary results and their implications | Presented field data from the early syn-rift deposits of the southern Neuquen<br>Basin to show that the Late Triassic–Early Jurassic rift history of Neuquen (and by analogy other S. American basins) was more complex than hitherto believed |

For further details see www.casp.cam.ac.uk

the AAPG International Meeting held in 1998 in Rio de Janeiro (Macdonald et al., 1998) in the session 'Circum-Atlantic Margins: Reconstructions and Palaeogeography'. The text is intended as a commentary on the diagrams (particularly the palaeofacies reconstructions). A paper is in preparation giving the full set of palaeogeographic maps.

## 2. Regional tectonics

### 2.1. The position of the Falkland/Malvinas Islands

The starting point for the tectonic reconstruction of the South Atlantic is the fit between the Falkland/Malvinas Islands and the Eastern Cape area of South Africa. Palaeomagnetic evidence suggests that the islands have been rotated by almost 180° since 190 Ma (Mitchell, Taylor, Cox, & Shaw, 1986; Mussett & Taylor, 1994), which supported a suggestion (Adie, 1952) that the Falklands/Malvinas are the missing SE corner of the Karoo Basin (Fig. 2). This is backed by palaeontological, stratigraphic and palaeocurrent evidence from Devonian strata (Marshall, 1994a), by a remarkable stratigraphic match between the Permian successions in both areas (Trewin et al., 2002) and by close structural similarities between the respective segments of the Gondwana Foldbelt (Curtis & Hyam, 1998).

The Falkland/Malvinas block cannot be reconstructed as shown in Fig. 2 without treating South America as more than one plate (see discussion in Rapela and Pankhurst (1992)). In addition, closure of the various mid-Jurassic basins in the region (Falkland Plateau, Malvinas and North Falkland basins) helps achieve a better pre-rift fit. This closure is particularly significant in the case of the Falkland Plateau Basin, which is floored by ocean crust (Barker, 1999). We conclude that South America was deformed by oblique extension, which began in Late Triassic time, and which had brought the continent to its present shape by the time of South Atlantic opening at 130 Ma.

### 2.2. Control of Precambrian structure in Gondwana break-up

Pre-existing (mostly Precambrian) structures have played a large part in determining the line of continental break-up, as shown in Fig. 3. This figure shows that the line of continental separation and the position of the principal failed rifts in the region were controlled by both the position of boundaries between different ages of basement and the structural grain of the basement.

### 2.3. Methodology of continental reconstruction

The reconstructions presented here have been carried out using the UTIG PLATES program and plate model[2]. Since this is a global model, the accuracy of a particular change to a continental fit can be checked by looking at the effect on the fits elsewhere in the world.

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[2] For details see the PLATES website: www.ig.utexas.edu/research/projects/plates/plates.htm

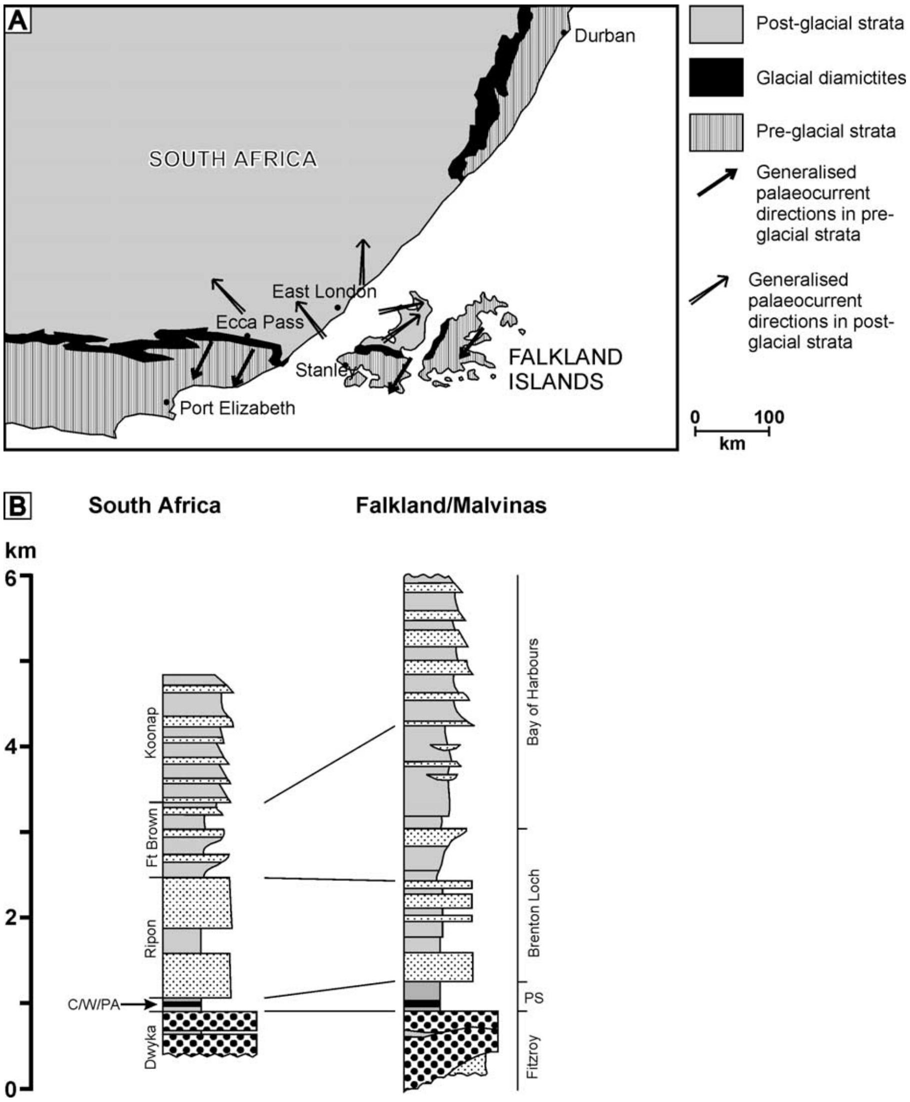


Fig. 2. (A) Pre-rotation reconstruction of the position of the Falkland/Malvinas islands in Early Jurassic time (195 Ma). This reconstruction honours palaeomagnetic, stratigraphic and structural data, but the Falkland/Malvinas block cannot be reconstructed as shown without treating South America as more than one plate. (B) Stratigraphy of the Permian (pre-rift) succession of the Falkland/Malvinas islands and the Eastern Cape of South Africa, illustrating the close correlation (C/W/PA: Prince Albert, Whitehill and Collingham formations of South Africa; PS: Port Sussex Formation of the Falkland/Malvinas islands). This is one of the tests of the rotation hypothesis illustrated in part A. (After Trewin et al., 2002).

As part of this project we decided that there was a need for tight-fit palinspastic reconstructions, so that the true pre-rift disposition of the continents could be shown (i.e. without stretched continental shelves). Hence we use a proxy for the pre-breakup OCB (PBOCB), rather than the more usual edge of stretched continental crust. Our tight-fit reconstruction of Gondwana is based on:

1. *Gravity data*. These reveal seafloor lineations that can be matched from the margin of South America across the South Atlantic to the western margin of Africa. We assume that these seafloor lineations were formed on oceanic crust produced after Gondwana break-up. We use them in our original configuration of Gondwana. The break-up plate boundary, taken to be the ocean–continental boundary (PBOCB), was assumed by Lawver, Gahagan, and Dalziel (1999) to be coincident with the major gravity anomaly as picked off the satellite gravity data set (Sandwell & Smith, 1995). The PBOCBs they picked for the margins of the South Atlantic are shown in Fig. 4. Their assumption matches very closely the ocean–continent boundary determined by Gladczenko et al. (1997) for the Namibian margin of southern Africa (Fig. 5), based on deep seismic reflection and refraction work. The tight-fit model achieved in this way leaves very few gaps and no overlaps that cannot be explained by post-break-up events.
2. *Marine magnetic anomalies*. Used to determine the timing of the continental positions.
3. Other seafloor age determinations (such as radiometric ages).

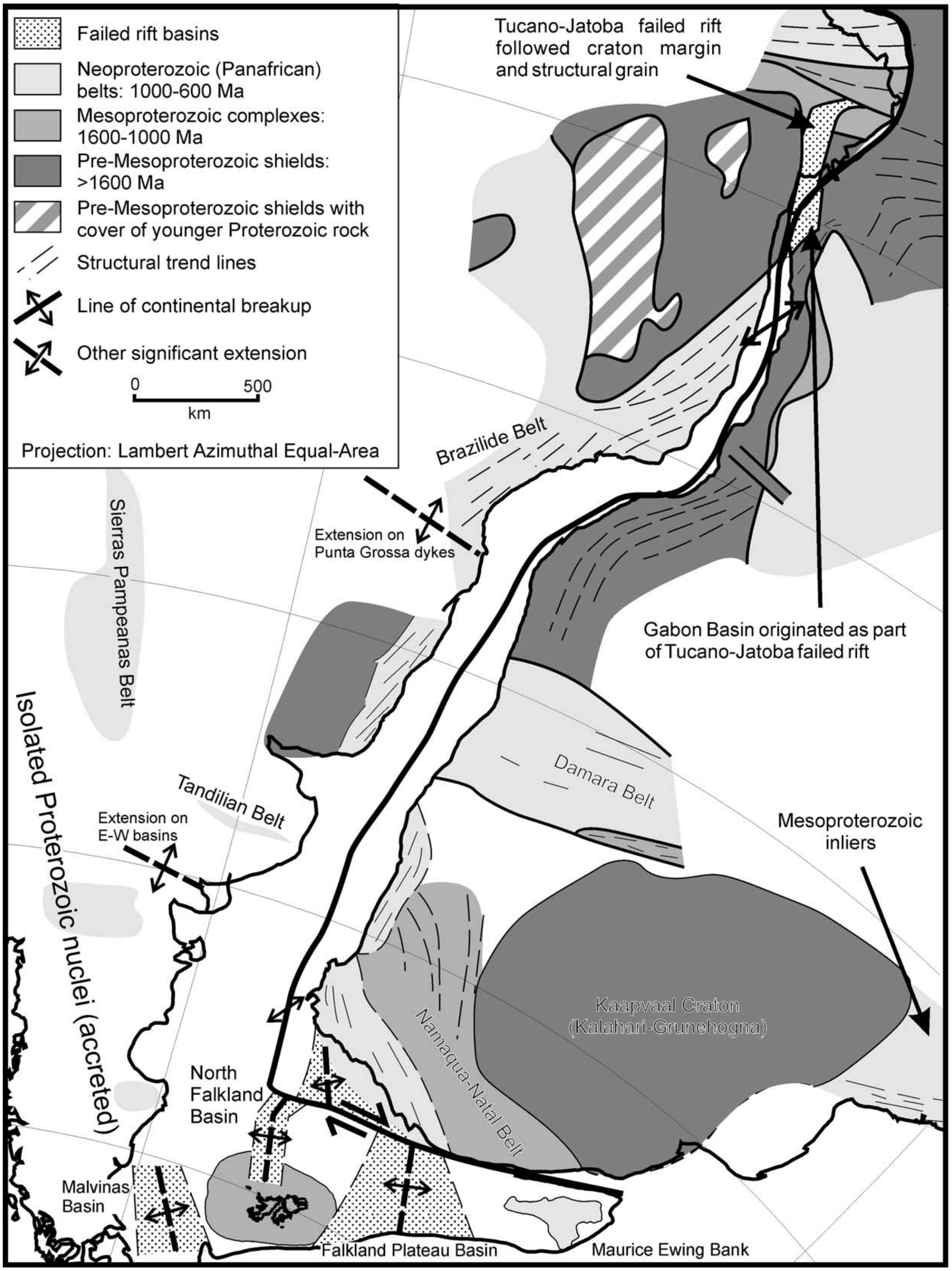


Fig. 3. Continental reconstruction at 135 Ma, immediately prior to South Atlantic opening, illustrating that the line of continental separation and the position of the principal failed rifts in the region were controlled by both the position of boundaries between different ages of basement and the structural grain of the basement. Data from the Exxon *Tectonic Map of the World* (1985), Good and de Wit (1997), Lawver et al. (1999), Unrug (1996). Most ocean–continent boundaries omitted for clarity.

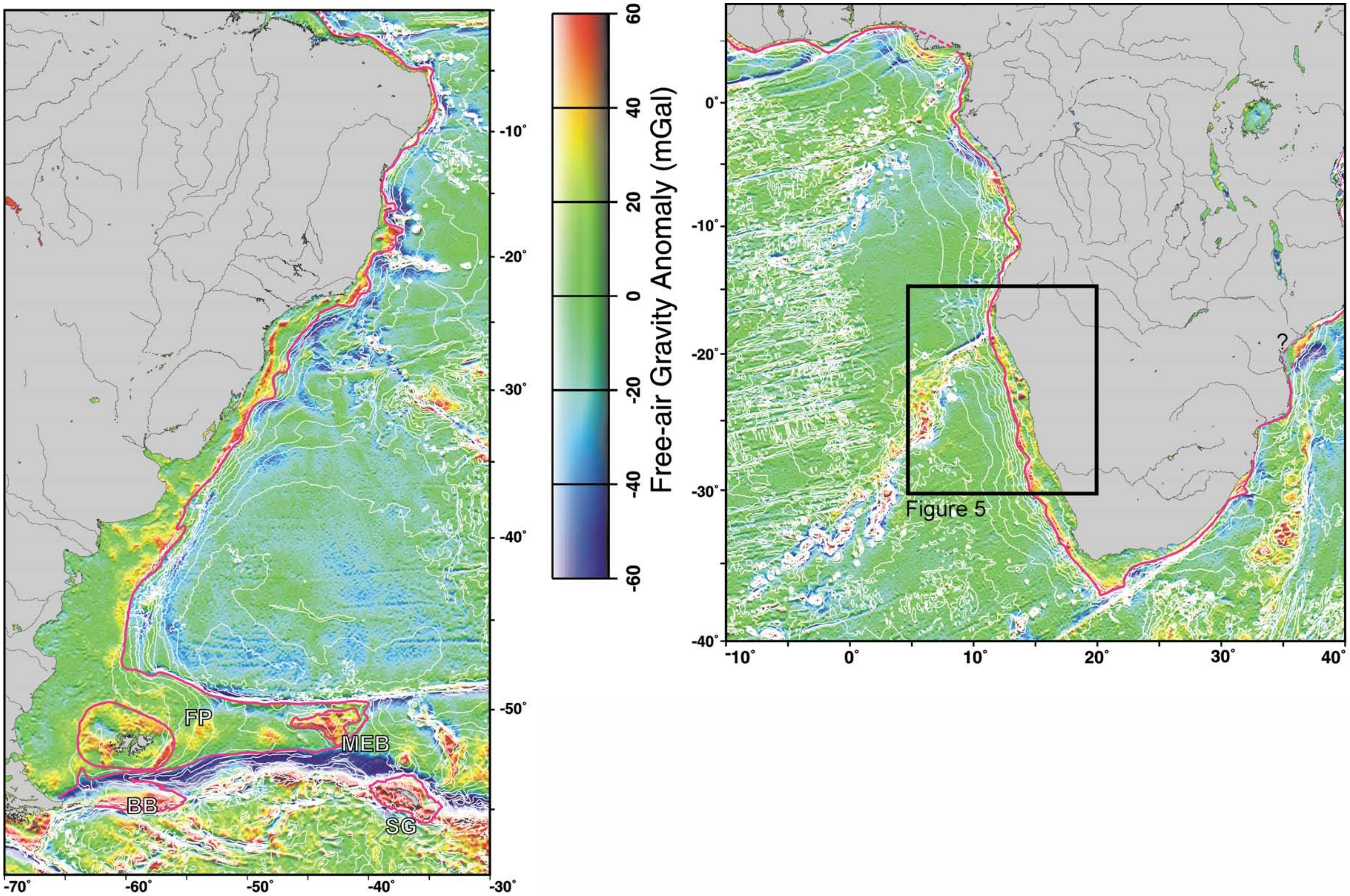


Fig. 4. Gravity anomaly map of the South Atlantic (after Sandwell and Smith (1995)), combined with bathymetric contours at 500 m intervals (light lines) from the General Bathymetric Chart of the Oceans (1997). The heavy line marks our pick for the pre-rift proxy for the ocean–continent boundary used in these reconstructions. The lines in the Falkland Plateau (FP) area mark the positions of the assumed Falkland/Malvinas microplate and the Maurice Ewing Bank (MEB) gravity high, together with the South Georgia Block (SG) and the Burdwood Bank (BB).

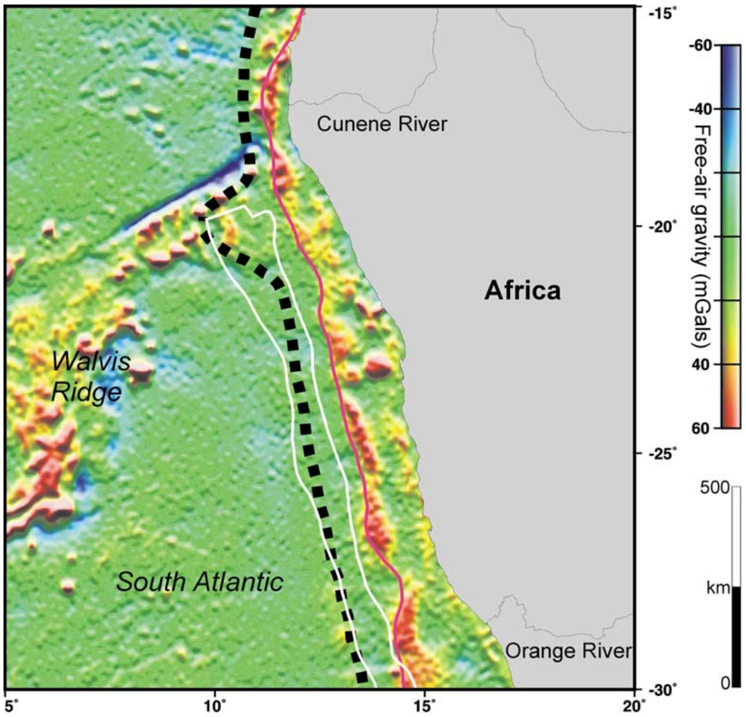


Fig. 5. Satellite gravity data (Sandwell & Smith, 1995) showing the west coast of southern Africa. The red line is our pick for the best proxy for a pre-stretching ocean–continent boundary (PBOCB) based on the dramatic change in the derived free-air gravity. The region outlined in white is the area of seaward-dipping reflectors as determined by Gladczenko et al. (1997). Our PBOCB is approximately half-way between the landward edge of the Gladczenko et al. (1997) seaward-dipping reflectors and the rift unconformity pinchout of Gladczenko et al. (1997). The Orange River delta moves our PBOCB as picked from the satellite gravity data out beyond the landward edge of the seaward-dipping reflectors of Gladczenko et al. (1997). Note that the dark dashed line is the 2000 m isobath, used in most previous reconstructions as the ocean–continent boundary.

4. Significant geological lineaments are used as piercing points, constraining the amount of lateral slip between continental fragments.

We assume uniform seafloor spreading rates over reasonable periods of time and then work forward in time, to make sure that nothing overlaps as the subsequent relative positions are determined. Reconstructions can be modified by the operator in four ways to accommodate geological data:

- Overlaps can be accepted if ages are not violated (e.g. a Precambrian shield area on one continent can be superimposed on a Tertiary delta on another).
- Poles of rotation can be modified, and continents allowed to move to the limits of the acceptable palaeomagnetic error.
- Continents can be split and treated as two or more separate plates.
- Younger blocks (e.g. of accreted material) can be left off reconstructions older than their date of creation.

Fig. 6 shows a portion of a world plate tectonic reconstruction 255 Ma, illustrating the deformation of South America necessary to achieve a close fit (Lawver et al., 1999). Note that this model is based on a four-plate South America comprising: (1) a northern (Brazilian) plate, bounded to the south by the line of the Paraná dyke swarm; (2) a north-central (Paraná) plate, bounded to the south by the Colorado–Huincul line; (3) a south-central (Río Negro) plate, bounded to the south by the Gastre Fault System; and (4) a southern (Patagonian) plate. These four plates, separated either by strike-slip fractures or by dyke swarms, are the minimum necessary to achieve a close fit; there may actually be more splits. Early Cretaceous strike-slip movements and plate rotation have also been described from NE Brazil (Pernambuco Shear Zone, Milani & Davison, 1988). Note that some of the splits are somewhat artificial, as they group dispersed extension on a single line. This is partly for clarity and partly to allow the model to deal with rigid plates.

### 2.4. Methodology of plotting palaeofacies

Original sources have been used whenever possible, rather than relying on the interpretations of others. The reference list for this report only includes references cited in the text or on the maps; full data sources will be listed in the full publication of the palaeogeographic maps (in preparation). The series of reconstructions was begun at 255 Ma: this was chosen as being just after the end of the Carboniferous–Permian glaciation. Although some hydrocarbons have been found in glacial deposits of this age in the Paraná and San Jorge basins, these are relatively

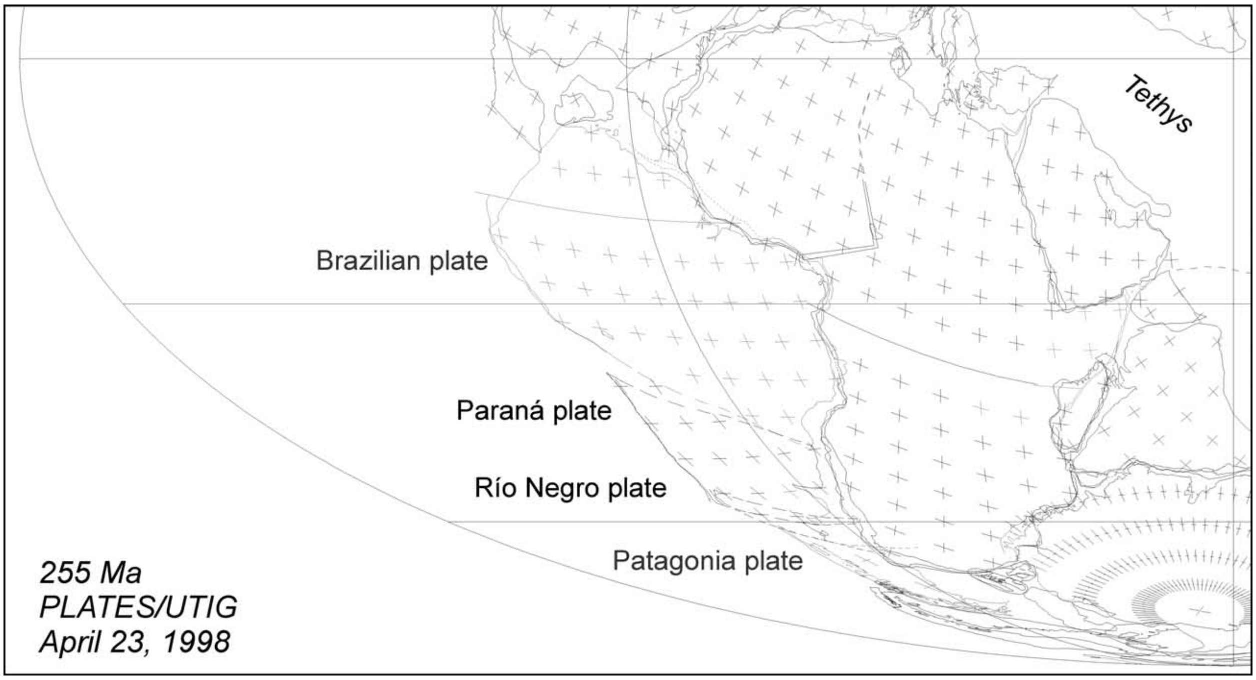


Fig. 6. Reconstruction of SW Gondwana at 255 Ma. Note that this model is based on a four-plate South America comprising: (1) a northern (Brazilian) plate, bounded to the south by the line of the Paraná dyke swarm; (2) a north-central (Paraná) plate, bounded to the south by the Colorado–Huincul line; (3) a south-central (Río Negro) plate, bounded to the south by the Gastre Fault System; and (4) a southern (Patagonian) plate. These four plates are the minimum necessary to achieve a close fit; there may actually be more splits. Note that the splits outlined above are somewhat artificial, as they group dispersed extension on a single line. This is partly for clarity and partly to allow the model to deal with rigid plates.

minor occurrences, and the top of the glacial succession is a reasonable proxy for regional economic basement. Thirteen reconstructions were done in 15 Ma steps from 255 to 75 Ma (portions of five maps are presented in this paper). Any palaeogeographic map usually purports to be a snapshot of a particular age (e.g. 150 Ma), but is actually a blurred view of a time range, reflecting the age uncertainty of geological data. For example, a 150 Ma map may show Tithonian marine muds, but if zonal data are not available, this record is a floating point in the range 152.1–145.6 Ma). As a result, compromise is required in plotting palaeogeographic maps. This problem was addressed as follows.

A standard timescale (Harland et al., 1990) was used to equate radiometric and biostratigraphic ages. This has been checked for major discrepancies against more recently published timescales, notably that of Gradstein et al. (1994); discrepancies are all less than 5%, so were considered acceptable.

The regional data compilations used data from 1/2 to 1 stage on either side of the reconstruction age. In the Late Permian–Cretaceous periods, there are 36 stages in 191 Ma (256–65 Ma), an average of 5.3 Ma per stage. Given a 15 Ma step between reconstructions, an error of ± 5 Ma was considered acceptable.

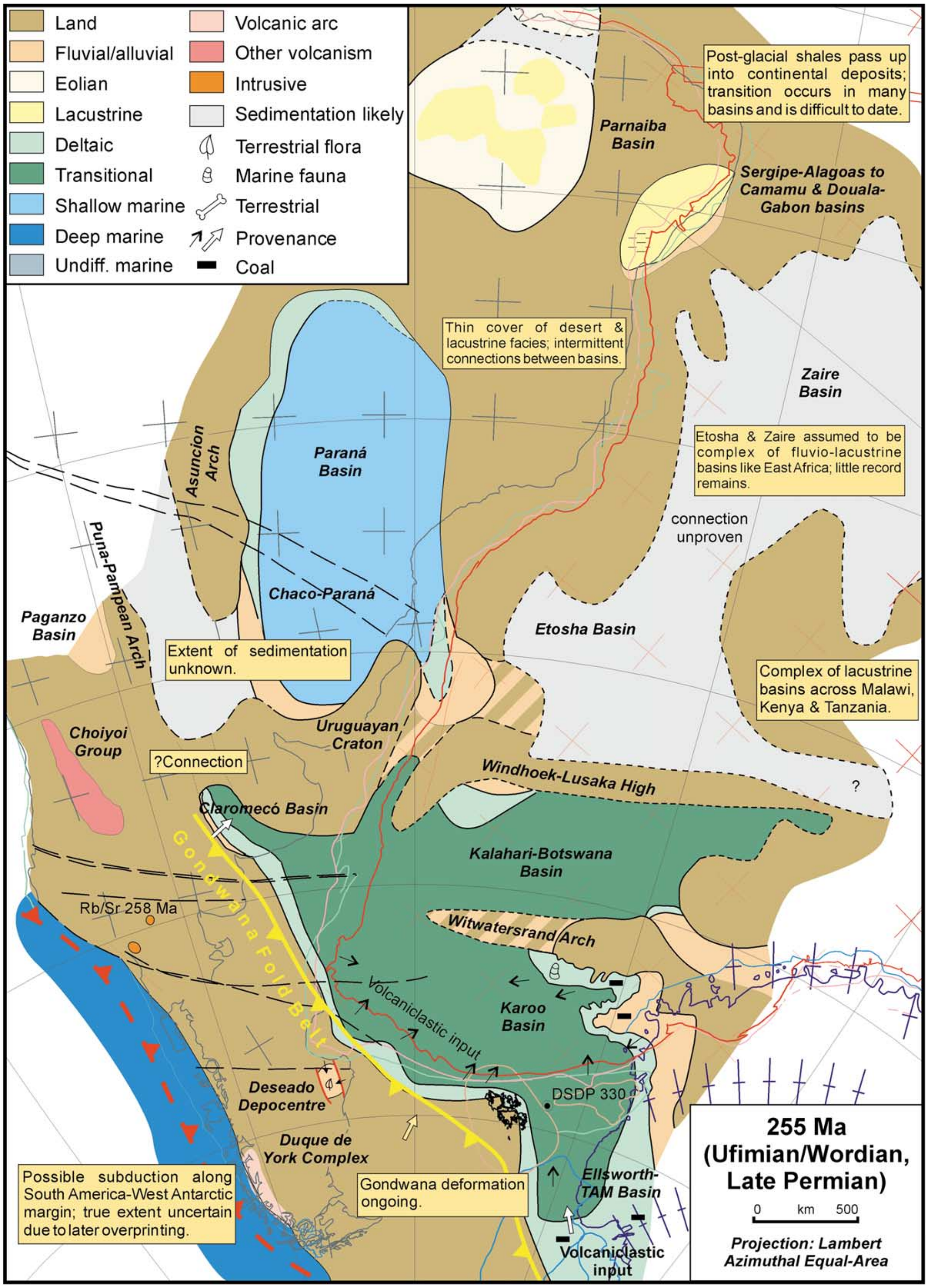
The error is trivial if there is uniformity of facies through the interval. Greater problems occur when there is more than one event or environment recognised in a particular interval. For instance, if a particular succession has an unconformity between marine facies below and fluvial above, at about a reconstruction age, it may be acceptable to put this point on the maps as marine, as an area of non-deposition, or as fluvial. The decision is a matter of judgement, bringing in factors such as local variation and knowledge of the accuracy of stratigraphic dating.

## 3. Pre-rift phase (Late Permian–Late Triassic; Figs. 7 and 8)

### 3.1. General situation

Most of Gondwana was covered by low-relief basins and swells. Much of the continent had a blanket of glacial diamictite deposited in Late Carboniferous–Early Permian time. This was being covered by dark, organic-rich shales deposited in a major fresh or brackish transgression at the end of the glaciation. The main stratigraphic motif is of progradation of deltas into lacustrine or hyposaline marine basins; deltaic areas were sites of formation of extensive coal deposits. Basins subsequently dried out to more arid continental environments in the Triassic.

The northern and eastern margin of the Gondwana Foreland basins (Claromeco–Karoo–Ellsworth–Transantarctic Mountains basins) is a low relief onlap onto cratonic areas (Fig. 7); as such, the position of the depositional margin in highly dependent on base-level changes. Farther inboard (west) of this edge, the extent of sedimentation across Precambrian craton areas is unknown. It is likely that



Post-glacial shales pass up into continental deposits; transition occurs in many basins and is difficult to date.

Thin cover of desert & lacustrine facies; intermittent connections between basins.

Etosha & Zaire assumed to be complex of fluvio-lacustrine basins like East Africa; little record remains.

Extent of sedimentation unknown.

Complex of lacustrine basins across Malawi, Kenya & Tanzania.

Possible subduction along South America-West Antarctic margin; true extent uncertain due to later overprinting.

Gondwana deformation ongoing.

Fig. 7. Reconstruction of the South Atlantic region at 255 Ma, when Gondwana was covered by low-relief basins and swells; dark, organic-rich post glacial shales were being deposited on glacial diamictite (of Carboniferous–Early Permian age). The main stratigraphic motif was of progradation of deltas into lacustrine or hyposaline marine basins; deltaic areas host extensive coal deposits. Basins subsequently dried out to an arid continental environment. The extent of Permian sedimentation in East Antarctica is unknown; it is likely that the craton was covered by veneer of sediment, with scattered fluvio-lacustrine basins, as in Africa.

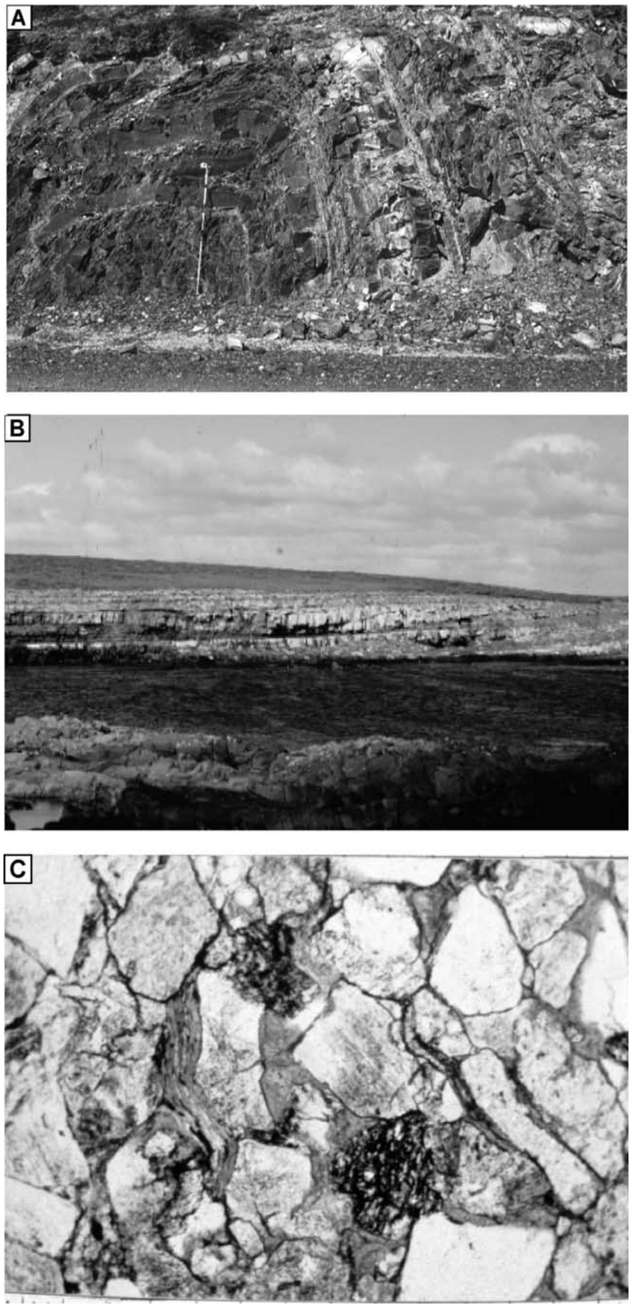


Fig. 8. Elements of the Gondwana potential pre-rift hydrocarbon system. (A) Potential source rocks: post-glacial black shales of the Black Rock Member, Port Sussex Formation, Antioja Quarry, East Falkland (Isla Soledad); note the contrast between dark, high-TOC paper shale facies (TOC up to 40%) and the paler, blocky weathering, siliceous mudstone (TOC 0.5–1%). These rocks have been severely deformed in the Late Permian–Triassic Gondwanian Orogeny; they correlate with the Irati Formation shales of the Paraná Basin and the Whitehill Formation, South Africa. (B) Potential reservoir rocks: sandstone-filled deltaic channel, Egg Harbour Member, Bay of Harbours Formation, Speedwell Island, Falklands/-Malvinas Islands. These sandstones are very well-sorted, but have poor reservoir quality (porosity $<5\%$; permeability $<1$ mD); this is due to the very high content of volcanic clasts. (C) Photomicrograph of medium grained sandstone from the channel facies in Fig. 8b, showing the clouded lithic clasts and the pervasive diagenetic clay matrix.

there was thin fluvial or aeolian cover over much of the land area, which was probably low-relief. Small relicts may be preserved under later Mesozoic basins.

It is likely that our representation of the Andean (western) margin of Gondwana is inaccurate as there has been considerable Late Mesozoic–Tertiary crustal growth.

### *3.2. Hydrocarbon potential*

*Source*. Organic-rich postglacial shales are widespread; TOC reaches 40% (Marshall, 1994b; unpublished CASP data) in places though now mostly overmature. Geochemical evidence suggests that these shales are mostly oil-prone.

*Reservoir*. Broad regional predictions can be made. Western areas (west and south of the Asunción–Witwatersrand Arch) received volcaniclastic sands with very poor reservoir quality ($<5\%$, $<5$ mD; unpublished CASP data from Permian sandstones in the Falkland/Malvinas Islands). Interior areas received cratonic-derived material, possibly with slightly better properties. Triassic sandstones tend to be more quartz-rich, albeit with a significant proportion of lithic clasts (Johnson, 1991).

*Seal*. The postglacial shales would make an effective seal with a broad regional extent.

*Maturation and trap formation*. The area was tectonically quiescent with low subsidence rates except in the area of the Gondwana Fold Belt and its foreland (Veevers, Cole, & Cowan, 1994). Thermal gradients were probably low.

## 4. Early syn-rift phase (Late Triassic–Early Jurassic; Figs. 9 and 10)

### *4.1. General situation*

Continental extension began in isolated centres in South America during the Late Triassic. Almost all of south and west Gondwana was affected by magmatism: volcanic arcs on the active (western) margin and the beginning of a huge outpouring of silicic extensional volcanism between the margin and the line of the old Gondwana foldbelt. East of the foldbelt was an immense basic magmatic province overlying the Karoo–Ferrar mantle plume; this covered most of South Africa and a large part of East Antarctica, with associated basic dykes in the Falkland/Malvinas Islands. These dykes are problematical, as they are dated at around 190 Ma (Mussett & Taylor, 1994) 10-12 Ma earlier than the dates of 178–180 Ma found elsewhere in the Karoo–Ferrar province. Much of Africa was elevated (probably as a result of thermal doming), leading to a widespread hiatus in sedimentation.

Around this time, Antarctica started to move eastward and southern South America moved westward from a fixed Africa. Movement of Patagonia was accommodated by dextral movement on the Gastre Fault System. South of this line there was major re-organisation of crustal blocks in

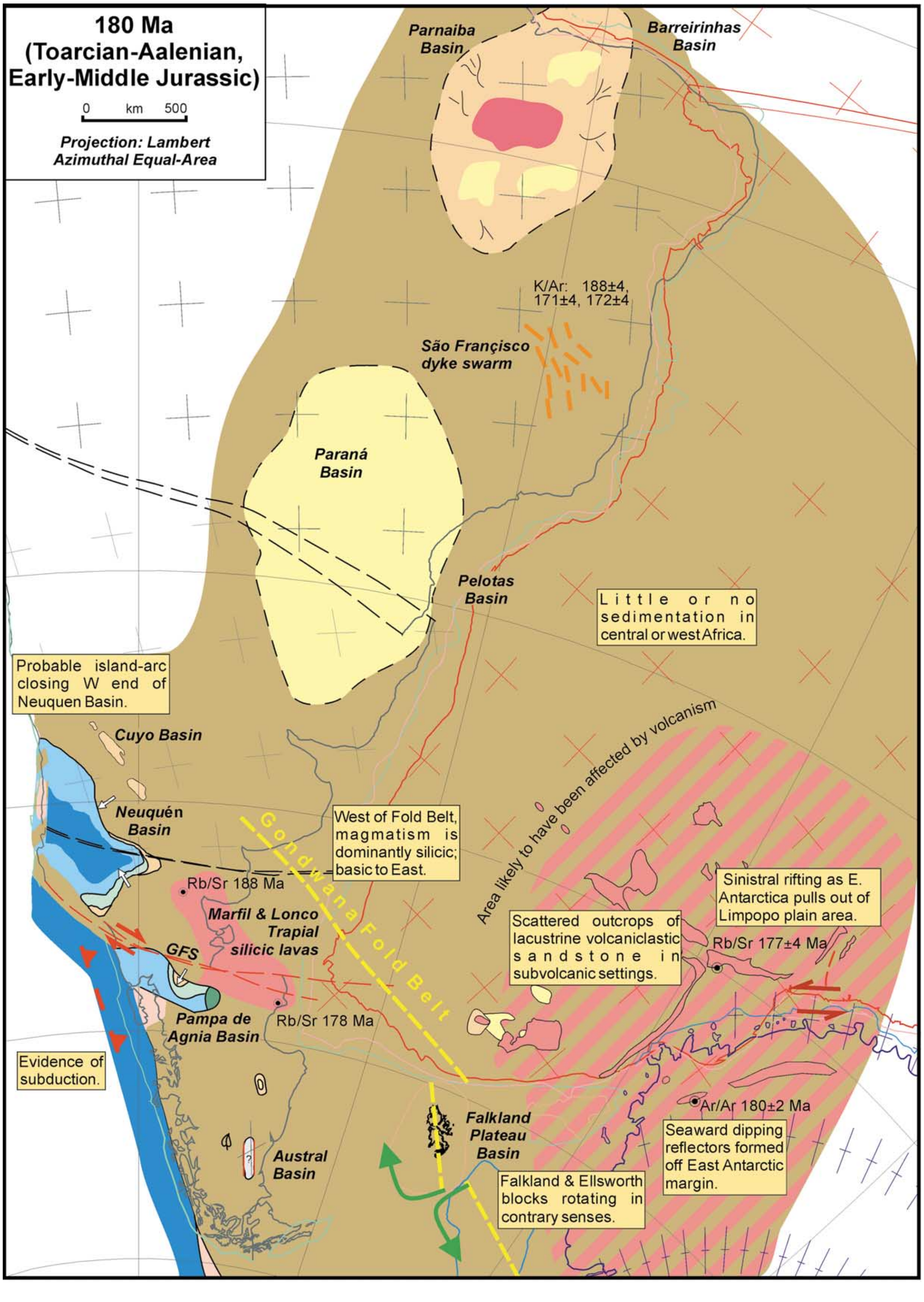


Fig. 9. Reconstruction at 180 Ma, showing widespread magmatism: marginal volcanic arcs and the start of silicic extensional volcanism between the arcs and old Gondwana foldbelt. East of the foldbelt was a huge basic magmatic province overlying a mantle plume. South of the Gastre Fault System (GFS), there was major re-organisation of crustal blocks. In particular the Falkland/Malvinas block rotated in an overall extensional regime, with movement driven by extension in the Falkland Plateau Basin. Much of Africa was elevated, probably as a result of thermal doming, leading to a widespread hiatus in sedimentation.

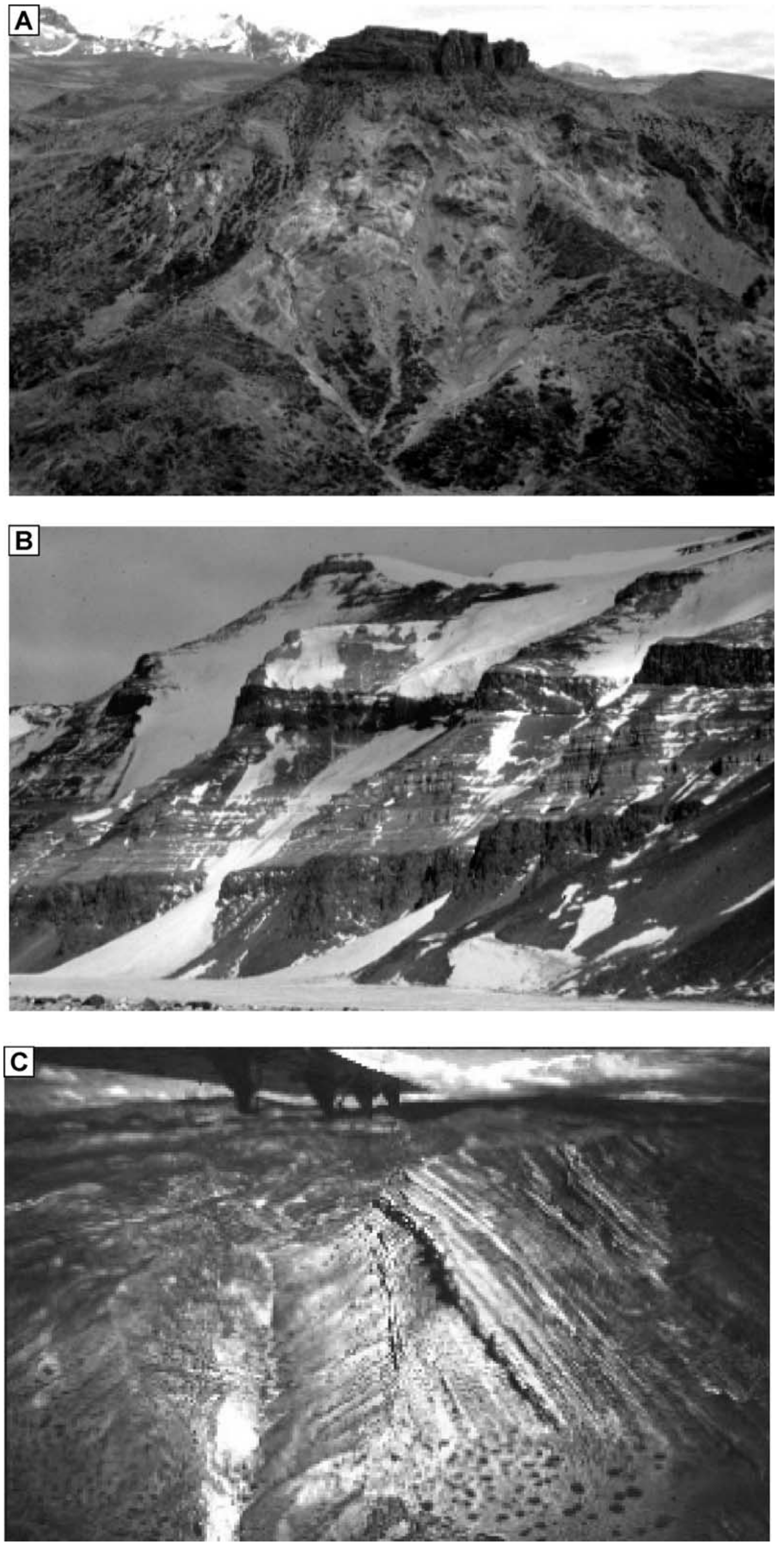


Fig. 10. Elements of the potential early synrift hydrocarbon system in the Late Triassic–Early Jurassic basins of SW Gondwana. (A) Typical early syn-rift volcanic, pyroclastic and sedimentary rocks of the Choiyoi, Lapa, and Chachil formations (Late Triassic–Early Jurassic); Piedra del Aguila, southern Neuquen Basin, Argentina; about 200 m of strata can be seen on the front face of the rock. (B) Breakup magmatism: basic sills of the Ferrar Supergroup (178 Ma) intruding pre-rift sediments of the Buckley Fm. (Permian) and fluvial clastics of the Fremouw Fm. (Triassic); Beardmore Glacier, Transantarctic Mountains, Antarctica; total thickness more than 1500 m. (C) Potential synrift source and reservoir facies: Pliensbachian-Toarcian basinal black shales and turbidite sandstones (Los Molles Fm), overlain by tidal sandstones (Lajas Fm), Neuquen Basin, Argentina.

Patagonia, the Falkland/Malvinas Plateau and West Antarctica; this included clockwise rotation of the Falklands/Malvinas block in an overall extensional regime, which was complete by 165 Ma. The Ellsworth Mountains Block simultaneously undertook anticlockwise rotation, as Antarctica moved eastward.

### 4.2. Hydrocarbon potential

*Source*. There is some marine source potential in NW Patagonia and some lacustrine sources: e.g. Triassic source rocks in the Cuyo Basin and Late Triassic–Early Jurassic syn-rift lacustrine source rocks in the Neuquen Basin (Uliana, Legarreta, Laffitte, & Villar, 1999).

*Reservoir*. Widespread volcanism and pyroclastic deposition suggest that reservoir quality is likely to be poor, although there are local fluvial reservoirs in the Cuyo Basin.

*Seal*. Although some of the lacustrine source rocks would make effective seals locally, no regional seal facies were deposited at this time.

*Maturation and trap formation*. There was very high heat flow and steep thermal gradients associated with extensive magmatism. Many pre-rift source rocks were matured rapidly by hypabyssal intrusions and foreland deformation (see, for example, Marshall (1994b)). Rifting was becoming more widespread than in previous times, leading to the possible creation of fault-block traps.

## 5. Late syn-rift phase (Middle–Late Jurassic; Figs. 11 and 12)

### 5.1. General situation

Ocean crust had started to form in the Weddell Sea as East Gondwana (Antarctica, India and Australia) rotated away from the rest of the supercontinent (see papers in Storey, King, & Livermore (1996)). Extensive volcanism continued, particularly in the silicic province of Patagonia (Tobífera Series), which represents a southward migration of igneous activity in South America. Block rotation was complete and extension began in the Falkland Plateau, Outeniqua and Malvinas basins (with marine incursion into Malvinas). There was probably extension in the San Julian and North Falkland basins.

### 5.2. Hydrocarbon potential

*Source*. There are extensive Late Jurassic anoxic marine mudrocks in basins surrounding the ancestral Weddell Sea, including the Falkland plateau area and the Malvinas Basin, where black shales are observed interbedded with late stages of the Tobífera volcanism. The significance of this anoxic event has been debated, with suggestions of mid-water anoxia (Farquharson, 1982) and a barred basin (Jaquin & de Graciansky, 1988; Macdonald & Butterworth, 1990). Fig. 12 shows considerable variation in the timing of anoxia across the region; even allowing for the errors in dating (see the three DSDP sites on the Murice Ewing Bank, for instance), it is more likely that the anoxia is a function of local tectonism than of a purely oceanographic driver.

*Reservoir*. Although basic volcanism is now more restricted, poor reservoir quality will be likely in many areas. There is, however, good reservoir potential in more mature basins, such as Neuquen.

*Seal*. The Late Jurassic marine anoxic facies would provide an effective regional seal.

*Maturation and trap formation*. Heat flow was still high and active rifting occurred across a very wide area.

## 6. Latest syn-rift phase (Early Cretaceous,Neocomian–Aptian; Figs. 13 and 14)

### 6.1. General situation

In the period leading up to continental separation at 130 Ma, the region was affected by widespread rifting and the impact of a second mantle plume (Paraná–Etendeka) centred on Brazil and Namibia. Volcanism was widespread in Brazil (Thompson et al., 1998), with flood basalts in the Paraná and Parnaíba basins. There was also significant eruption of flood basalts in Namibia, where they overwhelmed a desert depositional system (Jerram, Mountney, & Stollhofen, 1999). Volcanic rocks have been found in many of the Brazilian basins along the margins of the proto-Atlantic; it is not clear whether these are relicts of the plume-related flood basalts or independent rift-related volcanics.

Oblique extension started in the South Atlantic. One effect of this is the number of basins on the Argentine shelf at high angle to the eventual continental margin; these basins were filled by alluvial, fluvial and lacustrine clastic sediments. In the northern area of the South Atlantic, oblique extension resulted in rotation of the NE Brazil microplate, and strike-slip movements along the Pernambuco Shear Zone; transtensional depocentres were created in the Sergipe–Alagoas and Gabon basins, with maximum rift subsidence occurring in the Recôncavo Basin (Milani & Davison, 1988). These depocentres were infilled by continental fluvial and lacustrine deposits. Rifting of the Brazilian Equatorial basins and the Benue Trough from the Late Aptian, related to the early impact of the Santa Helena Plume, resulted in connection of the central and South Atlantic by the latest Aptian (Bengtson & Koutsoukos, 1992).

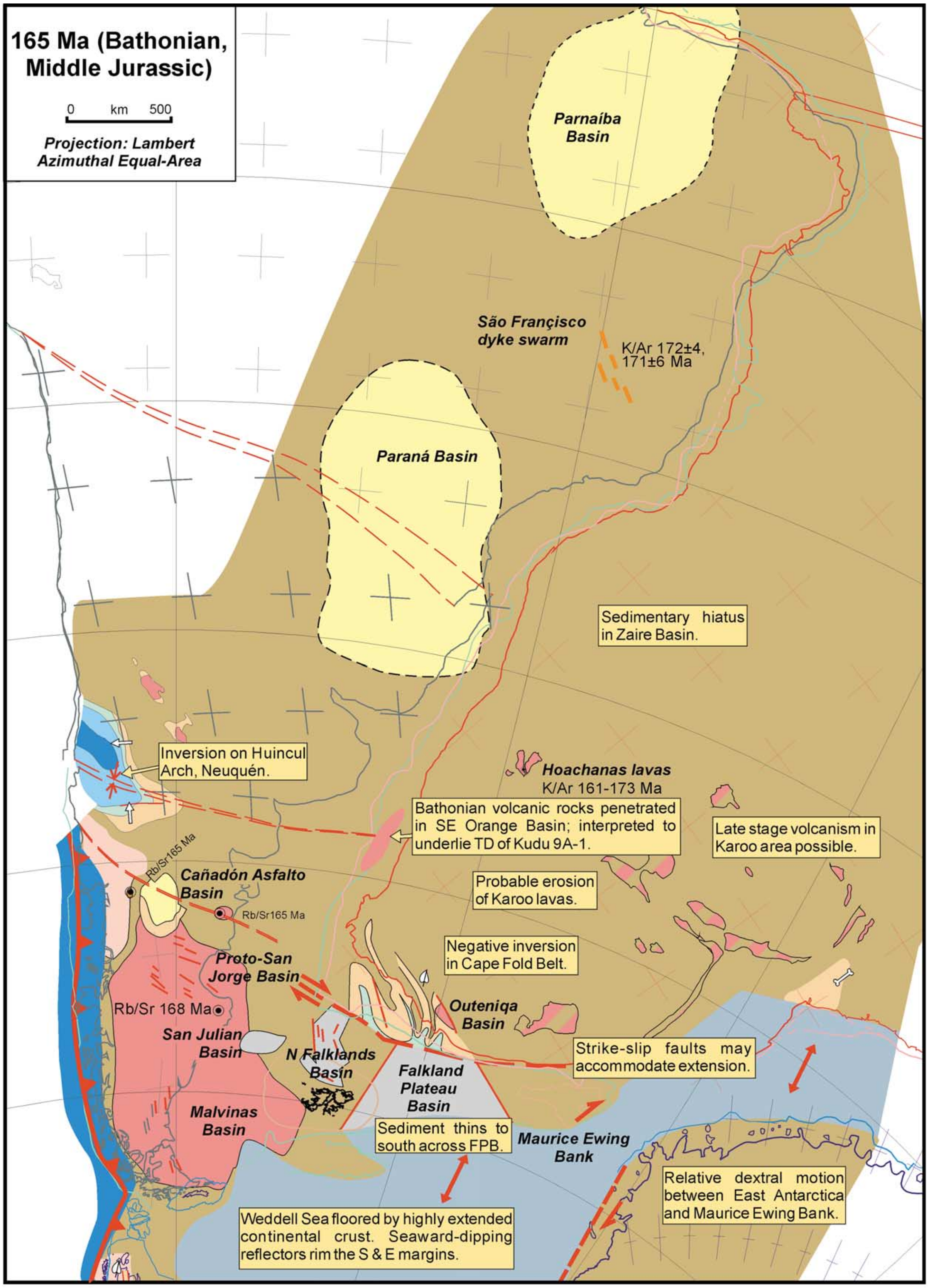


Fig. 11. Reconstruction of the South Atlantic region at 165 Ma, when volcanism was still extensive, particularly in southern South America (the silicic Tobífera Series of Patagonia), which represents a southward migration of igneous activity. Block rotation was complete and extension had begun in the Falkland Plateau, Outeniqua and Malvinas basins (with marine incursion into Malvinas). There was probably extension in the San Julian and North Falkland basins.

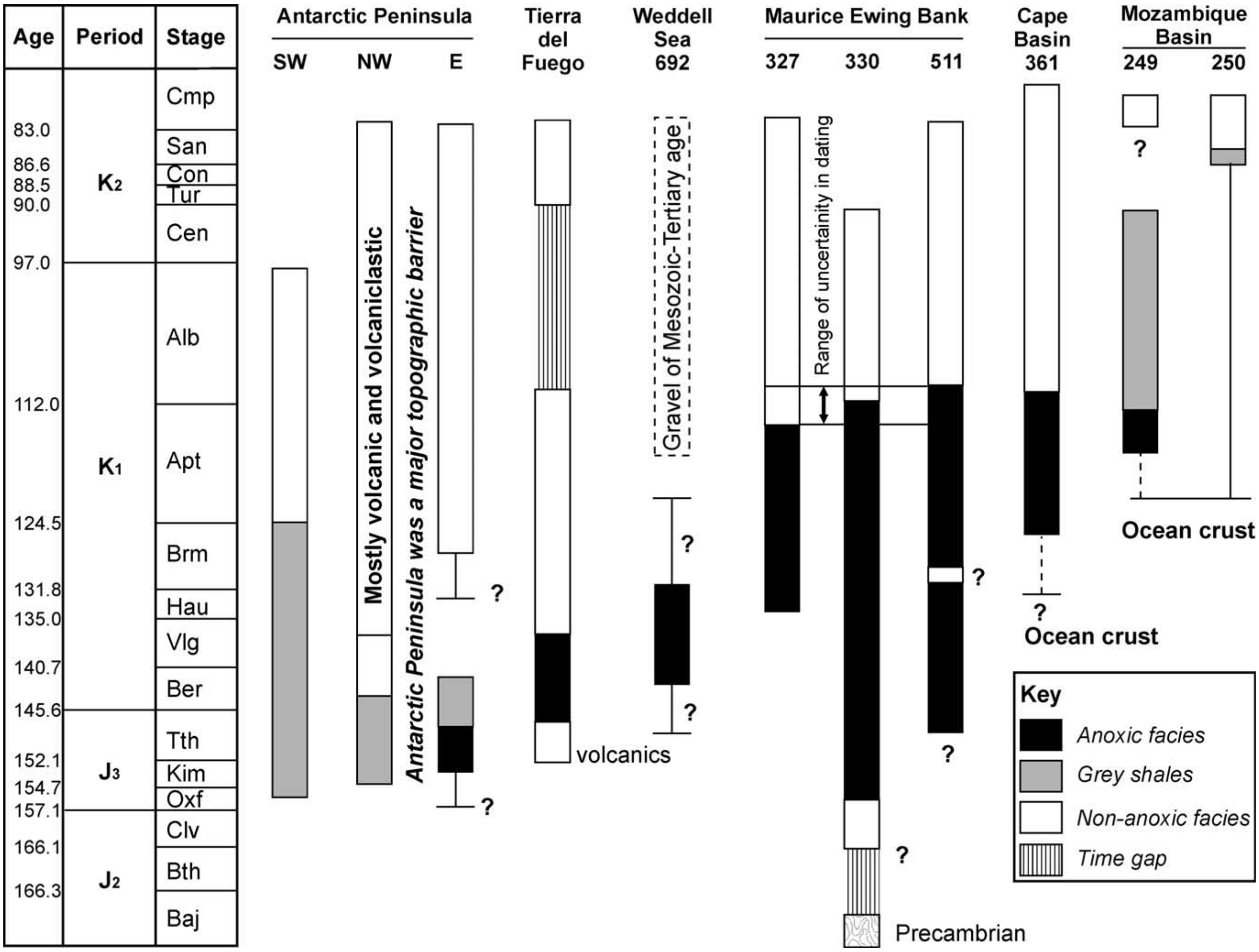


Fig. 12. Diagram illustrating the variation in timing of early anoxia across the project area. Timescale from Harland et al. (1990); numbers at the heads of some columns refer to DSDP/ODP sites.

### 6.2. Hydrocarbon potential

*Source*. Organic rich lacustrine black shales were deposited in the Brazilian basins, where they form some of the main source rocks. Lacustrine source rocks have a Neocomian age in the northern area of the South Atlantic and are as young as end-Barremian in the Campos Basin. Aptian transitional source rocks were deposited in the Sergipe–Alagoas, Gabon and Rio Muni Basins associated with evaporites. TOC can be as high as 14% (see Table 1 of Davison (1999)). Marine anoxia continued in the Weddell Sea, with black shales being deposited until the end of the Berriasian (Macdonald & Butterworth, 1990).

*Reservoir*. In southern South America, Neocomian transgression onto the top of the Tobífera volcanic rocks produced the thin, high quality reservoir sands of the Springhill Formation (Galeazzi, 1996). Lacustrine turbidite sandstones and fluvio-deltaic conglomerates are producing reservoir facies in some Brazilian basins. Build-up of marine deltas and submarine fans started in the southern African basins.

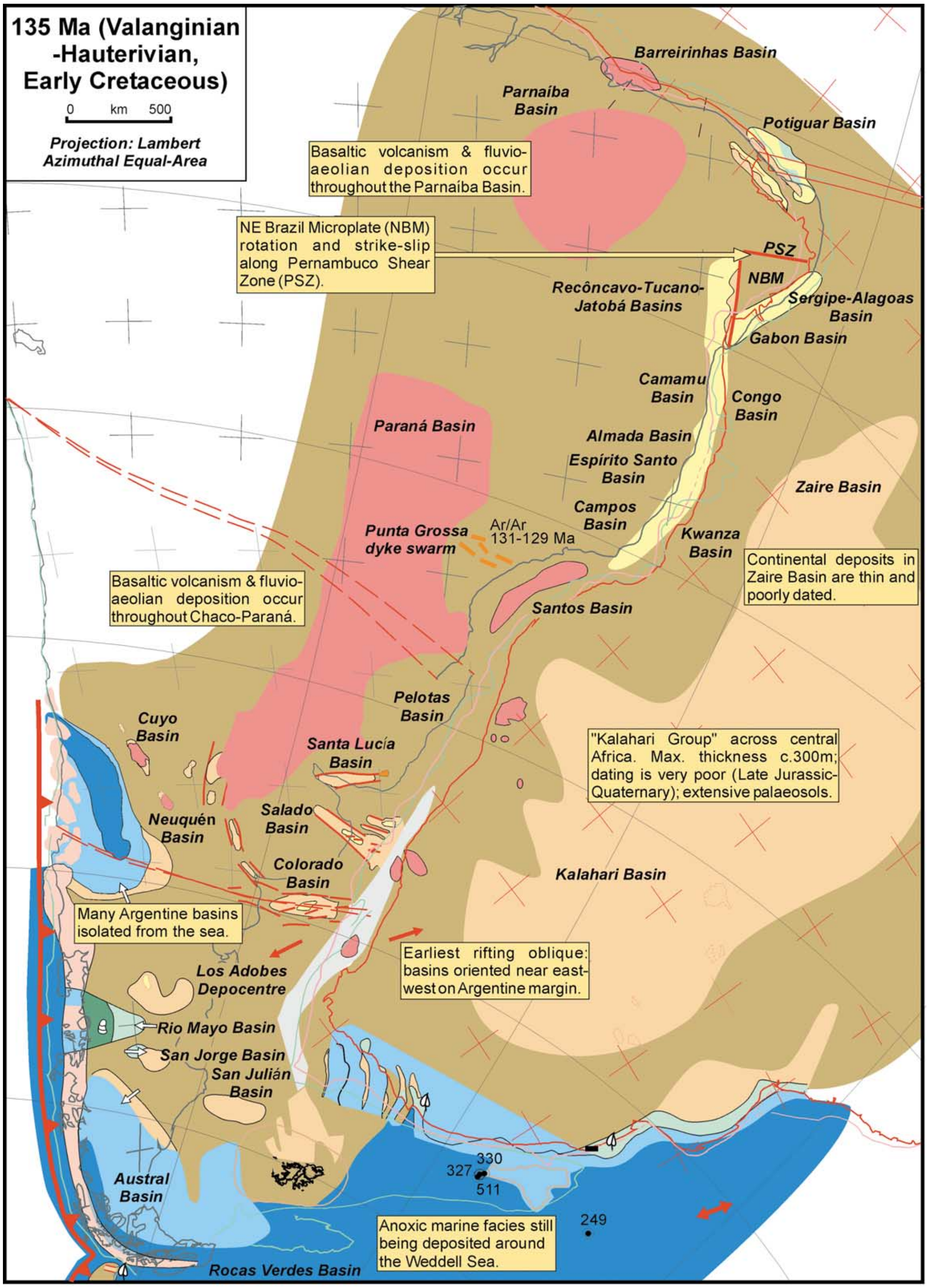
*Seal*. The most significant seal facies in the South Atlantic is found in the Brazilian and West African salt basins. These extensive evaporites were deposited around the time of continental separation from late Barremian–early Albian time, with most being deposited in the late Aptian. Evaporite deposition is commonly ascribed to the physical barrier to marine recharge caused by the Walvis Ridge–Rio Grande Rise system. However, since evaporites occur in the Pelotas Basin, south of this barrier, there must be other contributory factors.

Maturation and trap formation: Rifting continued, volcanism was widespread, and heat flow was likely to still be high regionally.

## 7. Early post-rift phase (Albian–Cenomanian, mid-Cretaceous; Figs. 15 and 16)

### 7.1. General situation

Tectonic reorganisation in the South Atlantic resulted in change from oblique to margin-normal extension.



Basaltic volcanism & fluvio-aeolian deposition occur throughout the Parnaíba Basin.

NE Brazil Microplate (NBM) rotation and strike-slip along Pernambuco Shear Zone (PSZ).

Continental deposits in Zaire Basin are thin and poorly dated.

Basaltic volcanism & fluvio-aeolian deposition occur throughout Chaco-Paraná.

"Kalahari Group" across central Africa. Max. thickness c.300m; dating is very poor (Late Jurassic-Quaternary); extensive palaeosols.

Many Argentine basins isolated from the sea.

Earliest rifting oblique: basins oriented near east-west on Argentine margin.

Anoxic marine facies still being deposited around the Weddell Sea.

Fig. 13. Reconstruction of the South Atlantic region at 135 Ma, just before impact of the Paraná-Etendeka plume at 133 Ma. Oblique extension had started in the southernmost South Atlantic. To the north, there was rifting along the line of the future South Atlantic from Late Jurassic-end Neocomian time. The resultant broad depression was infilled by continental sediments. Subduction continued along the western Gondwana margin. Volcanism associated with the Parana–Etendeka mantle plume was widespread in Brazil and Namibia, while probable rift-related volcanic rocks were extruded in the Brazilian basins along the margins of the proto-Atlantic.

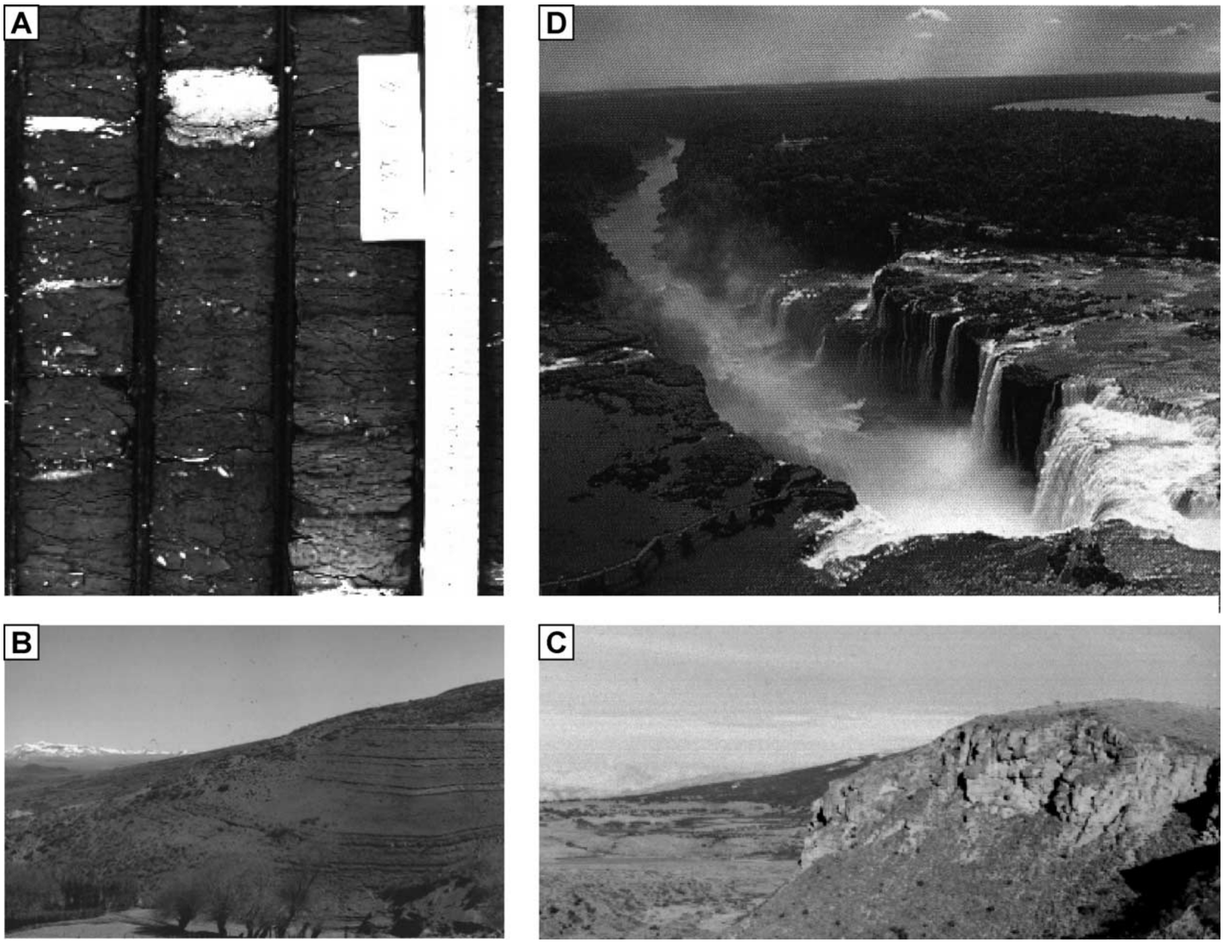


Fig. 14. Elements of the Gondwana potential hydrocarbon system in the late syn-rift period until the time of South Atlantic opening. (A) Potential source rocks: Kimmeridgian sapropelic claystone, DSDP Site 330, core 6, section 4 (depth 315 m), Maurice Ewing Bank. (B) Source and reservoir rocks: continental clastics and marine black shales and sandstones of the Tordillo and Vaca Muerta formations, Neuquen Basin, Argentina; the Vaca Muerta Fm. is the main source rock in the Neuquen Basin; the Andes can be seen in the background. (C) Late synrift ignimbrites of the Chon Aike Formation (Serie Tobífera), Bajo de San Julian, Argentina (by permission of the late Mario Mazzoni, Centro de Investigaciones Geologicas, La Plata, Argentina). (D) Breakup magmatism: Paraná Flood Basalts (Cretaceous), Iguazu Falls, Argentina–Brazil.

The Recôncavo–Tucano–Jatoba rift was abandoned and extension progressed along the Sergipe–Alagoas and Gabon basins. The rotation of the NE Brazil microplate stopped and it remained attached to South America. By this time, there was a full marine connection of the central and South Atlantic and marine incursion from both the north and the south; these remained at least partly restricted until the end of the Cretaceous. The Walvis Ridge was overtopped in the Albian and the northern part of the South Atlantic was now dominated by carbonate platforms. Most of the basins on the ocean margins were now in a thermal sag phase and had been transgressed. However, interior basins had no marine influence at all.

From this point on, there are significant differences in the petroleum geology between the African and South American margins of the South Atlantic.

### 7.2. Hydrocarbon potential

*Source*. The main regional anoxic phase had ended. There were still some areas of partially restricted circulation receiving organic rich shales but less homogeneously than hitherto. It is important to note that post-rift source rocks are more common on the African margin (where they are known in the latest Aptian, Albian, Cenomanian and Turonian, e.g. sourcing the hydrocarbons in the Angolan deep-water play) than in the South American margin, reflecting the different, asymmetrical patterns of oceanic circulation established after South Atlantic opening (see Fig. 6 of Davison (1999)). These differences prevent correlation of post-rift petroleum systems across the South Atlantic.

*Reservoir*. Andean deformation and uplift (at about 100 Ma) led to a considerable increase in clastic supply to many South American basins. In post-Albian times there

105 Ma (Albian, Early Cretaceous)

Projection: Lambert Azimuthal Equal-Area

Transgression in Benue Trough.

Periodic marine incursions, route unknown.

Brazil margin characterised by near-continuous carbonate platform.

Area of sedimentation in Brazilian interior basins greatly reduced.

Late evaporites drowned by transgression.

Thin veneer of terrestrial sediment in Zaire-Kalahari.

Most Argentine basins isolated from the sea.

Widespread inversion & erosion at c. 100 Ma.

Present day South African coastline largely established.

Significant uplift and erosion on Maurice Ewing Bank which is elevated to near sea level.

Deformation of the Rocas Verdes basin at 100 Ma; Austral Basin changed from backarc to foreland with NE migration of foldbelt through Late Cretaceous-Tertiary.

Fig. 15. Reconstruction of the region at 105 Ma. Most of the margins are now in the thermal sag phase and have been transgressed. However interior basins have no marine influence at all. In the north, rifting in the Maranhao and Barreirinhas basins led to the establishment of a continuous marine connection between North and South Atlantic. Walvis Ridge has been overtopped and the northern part of the South Atlantic is now dominated by carbonate platforms. Maurice Ewing Bank has cleared the tip of Africa, ending anoxia south of Walvis Ridge. The geometry of the Patagonia/Antarctica cusp is problematical; there was probably an intermittent land bridge across this continuing barrier to deep marine circulation.

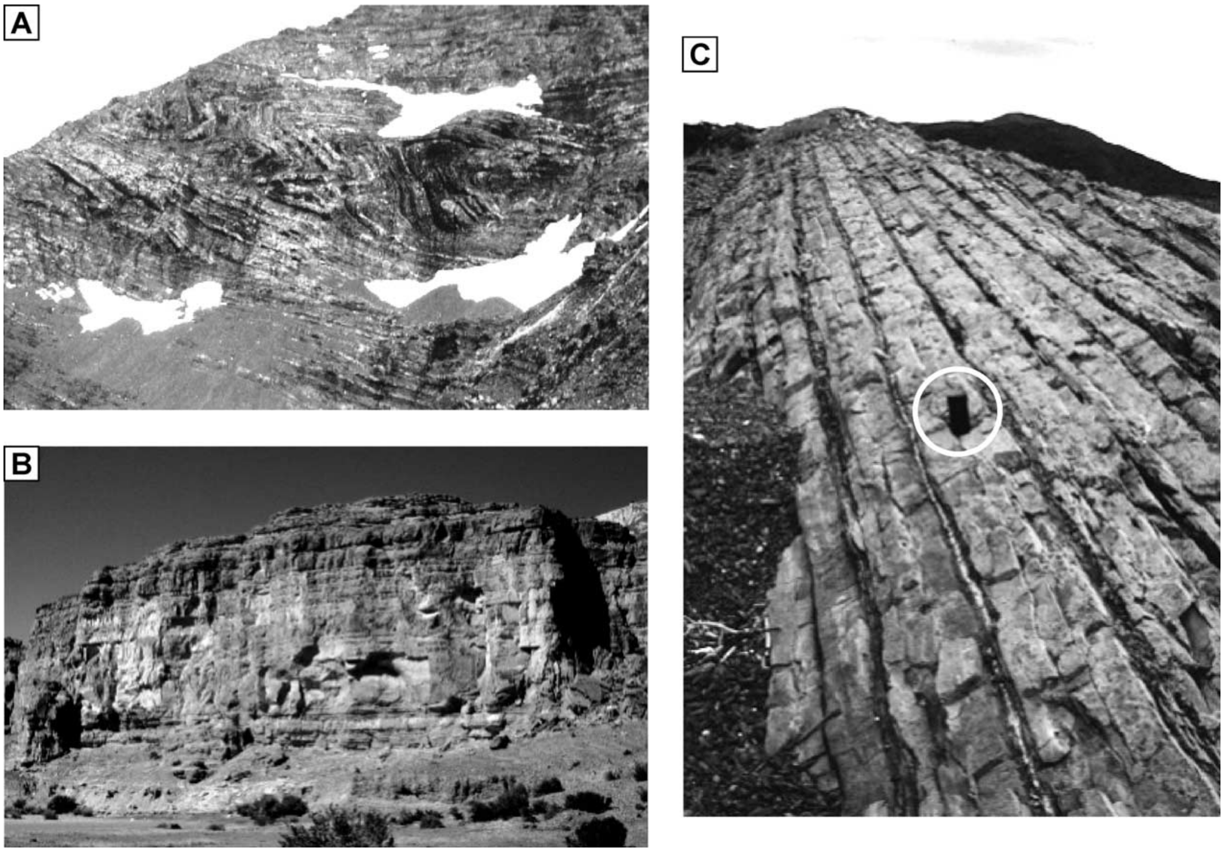


Fig. 16. Elements of the potential hydrocarbon system in the early post-rift period around the South Atlantic. (A) Andean deformation: Aptian–Albian turbidites deformed by late Albian Andean tectonism; Cumberland Bay Formation, Rocas Verdes back-arc Basin, South Georgia (equivalent to the Yahgan Formation, Tierra del Fuego); height of cliff about 120 m. (B) Potential reservoir rocks: well sorted Upper Cretaceous continental sandstones; Paso del Sapo Formation, Pampo de Agnia Basin, Argentina; about 35 m of strata shown. (C) The deep-water play: Campanian–Maastrichtian storm-deposited, outer shelf sandstone beds, Rocallosa Formation, Punta Santa Ana, near Punta Arenas, Chile (Magellanes or Austral Basin); these rocks are laterally equivalent to deep marine deposits and prefigure the deep water clastic systems which dominate the latest Mesozoic and Tertiary hydrocarbon systems around the South Atlantic; lens case (circled) is 18 cm long.

was an increase in compositional maturity as volcanic source areas became eroded.

*Seal*. Salt deposition ended in the latest Aptian in most areas, with evaporites still being deposited locally in the Kwanza Basin (personal communication from Dr N.R. Cameron (2002))

Maturation and trap formation: Regional heat flow along the rift was now much less and most margins were in thermal subsidence. However, the role of hot-spot magmatism on the thermal evolution of the Brazilian margin has yet to be fully assessed (Cobbold, Meisling, & Mount, 2001). There was significant inversion caused by Andean deformation in southern South America.

## 8. Later post-rift phase (Cenomanian–Maastrichtian, Late Cretaceous)

### 8.1. General situation

The Atlantic Ocean was fully open, in a drift stage, and its margins were submerged. Siliciclastic deposition dominated on marine platforms and within deep marine fans, although platform carbonates are locally present. Salt tectonism occurred in the basins of the northern South Atlantic. There was continuing subduction along the western margin of South America and Antarctica driving a foreland basin phase in the Austral Basin and providing large amounts of sediments to the Argentine basins. Continental deposition occurred discontinuously in interior areas of Africa and South America. Plate reorganisation associated with changes in poles of plate rotation in the Campanian led to development of a major regional unconformity (Guiraud & Bosworth, 1997).

### 8.2. Hydrocarbon potential

*Source*. There was cyclic anoxia associated with a mid-water oxygen minimum in Santonian–Campanian time (Jaquin & de Graciansky, 1988). On many of the margins, these deposits are immature. Source rock deposition continued in some west African basins into the Tertiary.

*Reservoir*. Reservoir quality sands were being deposited in both African and South American basins, though in basins in the southern part of South America there are problems with high volcaniclastic content. Turbidite sandstones were deposited in deep marine fans formed along the Brazilian and West African margins.

*Seal*. Many of the marine mudstones deposited during this time can form effective seals, at least locally.

*Maturation and trap formation*. Sedimentation rates along the continental margins became highly variable, depending on the location of major river systems, which led to development of discrete kitchen areas. Salt tectonics controlled the distribution of deep marine turbidite reservoir facies and began to create traps.

## 9. Summary and conclusions

Our conclusions are summarised in Fig. 17, where we detail the main regional elements of the South Atlantic hydrocarbon system. It is relatively easy to draw specific conclusions about the distribution of source and seal facies, however, the paucity of published data on reservoir properties in the region has forced us to make more general inferences on reservoir quality, principally focused on the likely volcaniclastic content.

Palinspastic reconstruction of the South Atlantic is not a straightforward process. To accommodate rotated blocks in the Falkland/Malvinas–West Antarctic area and to create an adequate picture of continental disposition prior to regional extension, it is necessary to use a four-plate model for South America. For a very detailed reconstruction, more plates (such as the NE Brazil Microplate) may be required. It is clear that South Atlantic opening and location of failed rifts were controlled by the structure and age of the Precambrian basement. However, despite the complexity of the tectonic evolution, three broad regional tectonic phases can be recognised in the development of the South Atlantic.

The ‘Pre-rift’ phase in SW Gondwana (Permian–Late Triassic) was characterised by foreland processes.

The ‘Syn-rift’ phase (Late Triassic–Early Cretaceous) was characterised by rifting and crustal reorganisation leading up to South Atlantic opening at 130 Ma. This phase can be divided into a series of stages (Fig. 17):

> *Stage 1 (210–ca. 180 Ma)*. Strike slip faulting, oblique extension and block rotation across a wide area south and west of the Kaapvaal Craton.

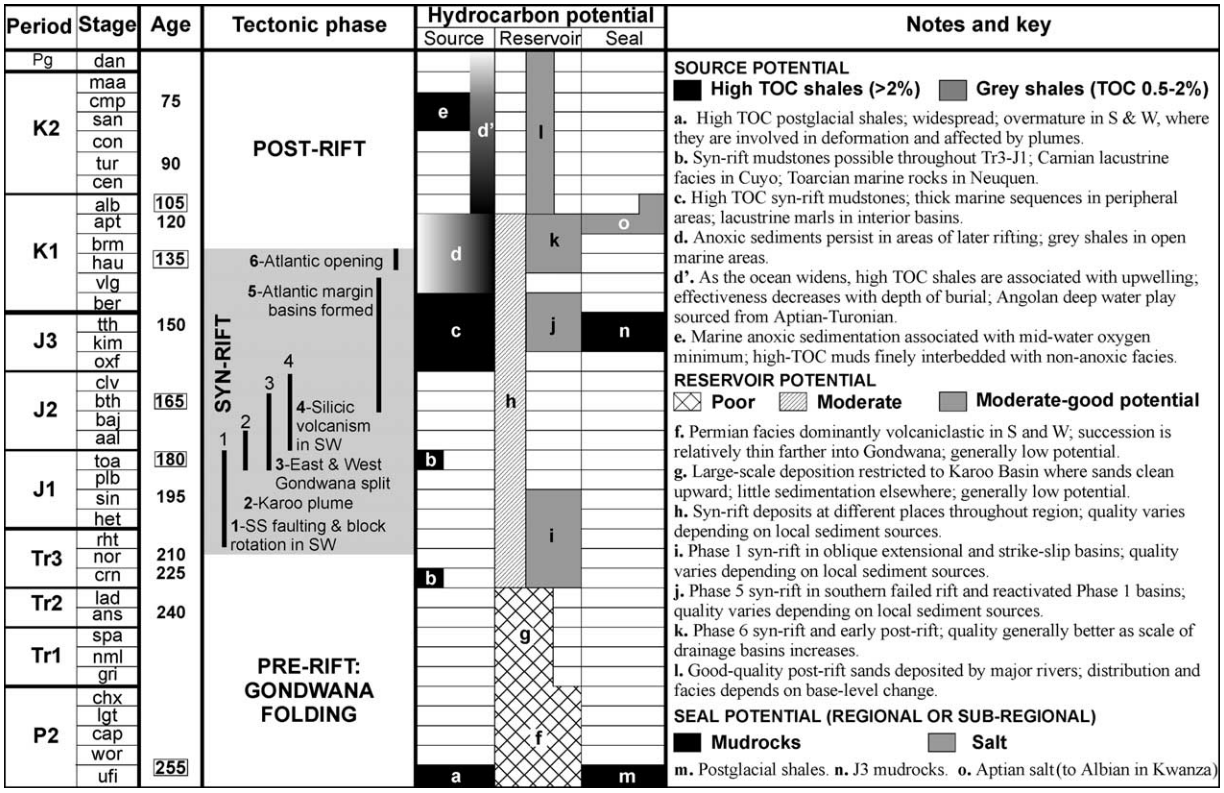


Fig. 17. Diagram summarising the elements of the latest Palaeozoic–Mesozoic regional hydrocarbon system within the area of the South Atlantic outlined on Fig. 1. In the ‘Age’ column, the ages shown are those of the 13 reconstructions forming part of our study; those in boxes have been presented in this paper. In the ‘Tectonic phase’ column, ss: strike-slip. In each of the three sub-columns of ‘Hydrocarbon potential’, symbols crossing the entire width imply a regionally widespread deposit; for symbols of lesser width, left is used for deposits in the east of the area, while right is for deposits in the west.

*Stage 2 (180 Ma).* Main impact of Karoo plume just to south of Kaapvaal craton. Earliest influence may be as old as 190 Ma in the Falkland/Malvinas Islands; there is little basaltic volcanism younger than 175 Ma.

*Stage 3 (180–?165 Ma).* Split between East and West Gondwana propagated between Madagascar/India/East Antarctica and Africa/Falkland Plateau/West Antarctica.

*Stage 4 (178–ca. 165 Ma).* Extensive silicic volcanism across much of southern South America and the Malvinas Basin, accompanying early stages of Jurassic–Cretaceous rifting.

*Stage 5 (165–135 Ma).* A series of basins formed along the proto-Atlantic margins. Notable failed rifts include the Falkland Plateau, Outeniqua and North Falkland basins. As initial extension was oblique (NE–SW), basins on the Argentine shelf and the (later) Paraná dyke swarm are at high angle to the eventual rift. The position of Argentine basins was controlled by earlier structural lineaments, including strike-slip faults formed in Stage 1.

*Stage 6 (135–120 Ma).* Change from oblique to normal, strike-slip movements and block rotation ended. The South Atlantic Ocean (N–S branch) opens synchronously along its whole length, strongly influenced by the impact of the Paraná–Etendeka plume at ca. 133 Ma. The oldest dated seafloor anomalies are Chron M9 (ca. 130 Ma; Austin & Uchupi, 1982).

The 'Post-rift' phase (Late Cretaceous) was characterised by thermal subsidence of the margins, the beginning of salt tectonics and the initiation of open ocean circulation. As this circulation developed, oceanographic factors began to outweigh tectonic factors and different hydrocarbon system elements were developed on conjugate margins of the South Atlantic.

Looking at the tectonic evolution across a broad area and through a long time-period allows us to distinguish major events. Microplate reorganisation and intraplate deformation from 210 to 130 Ma can be viewed as precursors to South Atlantic opening. In particular, basins south of the Gastre fault system and the Golfo de San Jorge have a different history to those in the north. The northern group of basins on the South American side (from San Jorge to Santos) have significant north-south extension (parallel to the continental margin) which is a direct consequence of early oblique opening of the South Atlantic and of pre-existing structures. It remains to be seen whether margin-parallel extension has had a significant effect on prospect-scale structures in these basins.

During the 'Pre-rift' phase, elements of a potential hydrocarbon systems were deposited across a wide area with good source potential and very poor reservoir potential. We conclude that the later Mesozoic tectonic evolution controlled source, reservoir and seal rock distribution, with a general change from these widespread regional elements to more variable, locally controlled elements as the Atlantic opened.

## Acknowledgements

Nick Cameron and Jonathan Redfern are thanked for their thorough reviews of this paper, and Jan Golonka was a constant reminder of our commitments! We are grateful to the following subscribers for funding the South Atlantic Project: Amerada Hess, British Gas, Exxon, Lasmo, Sands Petroleum, Texaco, Total and YPF. Additional funding was provided by the British Council (Argentina). We are grateful to Amerada Hess for a generous donation towards the cost of production of the colour diagrams. This paper is a contribution to IGCP Project 436.

## Note added in proof

The full set of reconstructions will be available to download from 1 October 2003 at www.casp.cam.ac.uk, www.abdn.ac.uk/ geology, or www.ig.utexas.edu/research/projects/plates.htm

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