Tectonic significance of the Lambert graben, East Antarctica: Reconstructing the Gondwanan rift

Mat Harrowfield
Guy R. Holdgate
Christopher J.L. Wilson*
Stephen McLoughlin

School of Earth Sciences, University of Melbourne, Melbourne, VIC 3010, Australia
School of Natural Resource Sciences, Queensland University of Technology, Brisbane, QLD 4001, Australia

ABSTRACT

Antarctica’s Lambert graben, Australia’s North West Shelf, and the eastern Indian Peninsula all host thick, fault-bounded Permian-Triassic successions. These terranes were adjacent to each other in Gondwana. The Lambert graben intersects the modern coastline, strikes oblique to shelf architecture, and has a geophysical signature that can be traced >1000 km inland. Vitrinite reflectance data from the graben margins record Permian-Triassic infill. Australia’s North West Shelf is the relict of an intracontinental Carboniferous-Permian rift that was infilled during the Permian-Triassic then driven to oceanic completion during Jurassic-Cretaceous Gondwana breakup. This rift was compartmentalized over length scales of ~650 km, corresponding to accommodation zones, margin-normal geophysical lineaments, and long-lived crustal weaknesses. In eastern India, similar compartmentalization is marked by extensive coal-bearing graben systems. Gondwana reconstructions indicate that the Lambert graben corresponds to the orientation and length scale of Carboniferous-Permian rift compartmentalization. The Lambert graben represents an accommodation zone of a wide intracontinental rift that extended from Australia’s North West Shelf, between India and Antarctica, to southern Africa. This rift collected Gondwana’s thick Permian-Triassic sedimentary blanket and rich alluvial coal deposits.

Keywords: Antarctica, Australian North West Shelf, Gondwana, Permian coals, rifting.

INTRODUCTION

Typical models of the Indo-Australian-Antarctic collage depict the modern coastlines of those fragments that were adjacent to each other 5yin early Mesozoic Gondwana (Fig. 1). Such studies correlate separation of India and Australia-Antarctica with Cretaceous breakup and opening of the Indian Ocean ca. 135 Ma (Veevers et al., 1996; Boger and Wilson, 2003). Local reconstructions align Antarctica’s Lambert graben with the Mahanadi Valley in eastern India, and place the tip of the Indian Peninsula adjacent to the coast of Dronning Maud Land in Antarctica (Fig. 1). In contrast, regional reconstructions depict continuity of the west Indian and Dronning Maud coastlines, in order to fit with those of Madagascar and east Africa (Fig. 1, inset). Veevers et al. (1996) argued that an extensive belt of Permian fluvial sediment, derived from a central Antarctic highland, was deposited across a then-continuous Gondwana (Fig. 1, inset). Veevers et al. (1996) considered that these deposits were buried on the Antarctic shelf, beneath synrift sediments derived from the flanks of the Cretaceous rift.

Australia and Antarctica separated during Late Cretaceous-Cenozoic time due to rifting east of the Bunger Hills (Fig. 1; Baillie et al., 1994). Prior to this, the Antarctic coastline west of the Bunger Hills was continuous with Australia’s North West Shelf (Fig. 1). The basement architecture of the North West Shelf reflects an asymmetric Permian-Carboniferous intracontinental rift with an axis ~200–300 km outboard of the modern Australian coastline (O’Brien et al., 1999; Etheridge and O’Brien, 1994). Permian-Triassic sag and infill of this rift preceded Late Jurassic-Cretaceous continental rifting (Etheridge and O’Brien, 1994). Rifting resulted in little internal modification or syn-tectonic burial of the North West Shelf (O’Brien et al., 1999; Chen et al., 2002). Similar Carboniferous-Permian rifting and Jurassic-Cretaceous rifting phases have been described from eastern India (Ghosh, 2002).

We draw comparisons of the west Australian margin, the eastern Indian Peninsula, and Antarctica’s Prydz Bay region. On the basis of new coal geochemical data and vitrinite reflectance profiles from the margins of the Lambert graben, we reassess the age, burial history, and tectonic origins of that feature and examine its likely relationship to Carboniferous-Permian rifting of Gondwana.

*E-mail: cjlw@unimelb.edu.au.
standard Indo-Antarctic tectonic models, Stagg (1985) presumed this architecture to be Cretaceous in age. However, shallow Ocean Drilling Program wells have intersected Triassic sedimentary rocks and major unconformities, suggesting that sequential rifting probably began in Permian time (Cooper et al., 1991).

Holdgate et al. (2005) described coal-bearing Permian rocks from the margins of the Lambert graben, equivalent to rocks beneath the Amery Ice Shelf (Fig. 2B). Vitrinite reflectance (Vr) profiles show progressive thermal maturation from clastic rocks (middle to Upper Permian; Vr = ~1.0) upward into coals (Vr = ~0.5) that are below the Permian-Triassic boundary (Fig. 2C). This profile, corresponding to stratigraphic younging, is consistent with initially rapid sedimentation progressing to infill in the later Permian or Early Triassic. Apparent infill was subsequently buried beneath ~1 km of cover, much of which was potentially accounted for by Cenozoic glacialic deposition, prior to late Miocene uplift (Hambrey and McKelvey, 2000); although Jurassic-Cretaceous rocks are not recognized onshore, the data do not preclude Mesozoic burial within the graben. Low-rank Permian alluvial-valley coals preserve consistent northward paleocurrent indicators, increasing upsection geochemical maturity (Fig. 2C), and lipitute contents atypical of East Gondwana coals. Holdgate et al. (2005) concluded that these coals were deposited in a confined, trough-like Permian drainage system.

**RIFT ARCHITECTURE OF THE AUSTRALIAN NORTH WEST SHELF**

Extension of western Australia began during the Late Devonian in response to far-field Gondwana dispersal (Baillie et al., 1994). By Mississippian time, limited oblique extension had generated two small northwest-trending rifts, the Fitzroy Trough and Petrel Basin (Fig. 3), along preexisting cratonic anisotropies. By the Permian, vigorous northwest-southeast extension had formed a wide intracratonic rift along the proto-Australian margin (Etheridge and O’Brien, 1994). That rift was compartmentalized into upper- and lower-plate margins over a wavelength of ~650 km (O’Brien et al., 1999), corresponding to subdivision of all synrift and postrift basin systems to the present day (Fig. 3; Australian Geological Survey Organisation [AGSO] North West Shelf Study Group, 1994). The rift was subsequently filled by a Triassic sag succession that is locally >4 km thick (Etheridge and O’Brien, 1994).

The relict Carboniferous-Permian rift was driven to oceanic completion during Gondwana dispersal and opening of the Indian Ocean (Baillie et al., 1994); north of the Fitzroy Trough, this occurred during Jurassic separation of Argoland-Cimmeria; south of the Fitzroy Trough, during Cretaceous separation of India. The transition to rifting was effected with little internal modification or burial of the Australian margin (Etheridge and O’Brien, 1994). Despite pervasive reactivation of Paleozoic normal faults, actual strike-normal length change was <1% (Chen et al., 2002). In effect, the inherited rift failed along its central axis and the en echelon transition between opposing rift compartments (Fig. 3). Rifting of these Gondwanan fragments resulted in subtle deformation of the Carnarvon-Canning (Fitzroy Trough) and Browse-Bonaparte accommodation zones (Fig. 3; O’Brien et al., 1999).

Orthogonal spreading of the northern Indian Ocean (Fig. 3) permitted excellent preservation of Carboniferous-Permian architecture. The upper-plate basement relics that underlie the modern Bonaparte and Carnarvon Basins—comprising broad outer-margin plateaus and narrow inboard graben systems (as in Lister et al., 1991)—still correspond to rectilinear shelf protrusions (Fig. 3). Lower-plate basement relics beneath the Browse-Canning and Perth Basins preserve outboard-dipping detachments and still correspond to shelf embayments (Fig. 3; AGSO North West Shelf Study Group, 1994; O’Brien et al., 1999). Compartmentalization was inherited by the abyssal margin, resulting in coincidence of major ocean transform fractures and basement accommodation zones (Fig. 3). The >300 km width of the North West Shelf suggests >600 km of Permian separation between the Australian and greater Indian platforms.

**LAMBERT GRABEN**

The Lambert graben intersects the Antarctic coastline at Prydz Bay (Fig. 2A). Free-air gravity and magnetic data show the basement expression of the graben extending >1000 km inland beneath the Lambert Glacier, superimposed upon a Pan-African age mobile belt (Golynsky et al., 2002). Historically, the graben has been considered an isolated Permian intracontinental rift: it is filled with Permian-Triassic sediments (Holdgate et al., 2005); associated with intrusion of Carboniferous alkaline mafic dikes on the Else platform (Fig. 2B; Hand et al., 1994); and its margins yield ca. 300 Ma apatite fission-track ages (Arne, 1994). These relationships have recently been interpreted to represent excellent preservation of Carboniferous-Permian architecture. The upper-plate basement relics that underlie the modern Bonaparte and Carnarvon Basins—comprising broad outer-margin plateaus and narrow inboard graben systems (as in Lister et al., 1991)—still correspond to rectilinear shelf protrusions (Fig. 3). Lower-plate basement relics beneath the Browse-Canning and Perth Basins preserve outboard-dipping detachments and still correspond to shelf embayments (Fig. 3; AGSO North West Shelf Study Group, 1994; O’Brien et al., 1999). Compartmentalization was inherited by the abyssal margin, resulting in coincidence of major ocean transform fractures and basement accommodation zones (Fig. 3). The >300 km width of the North West Shelf suggests >600 km of Permian separation between the Australian and greater Indian platforms.

RIFT ARCHITECTURE OF EAST INDIA

East India is host to the coal-bearing rift basins of the Mahanadi, Godavari, and Damodar Valleys (Fig. 1). All three are characterized by asymmetric half-graben architectures, homoclinal basin tilts, and Permian-Triassic growth faulting, and all three exploit long-lived anisotropies between cratonic nuclei (Mishra et al., 1999; Lisker and Fachmann, 2001; Ghosh, 2002). The >600-km-long Mahanadi and Godavari Valleys form two parallel belts that trend perpendicular to the east Indian margin and are separated by ~650 km (Fig. 1).

The Mahanadi and Damodar Valleys bound two sides of the Singhbhum craton (Fig. 1). These rifts facilitated an abrupt thickening of that craton’s unformable Permian-Triassic cover and fluvial deposition of rich Late Permian coal measures (Ghosh, 2002). Apatite fission-track data indicate that rifting of the Mahanadi Valley commenced in Pennsylvania or earliest Permian time. Subsequent exhumation phases, associated with major regional angular unconformities, correspond to a Middle Triassic hiatus in clastic deposition and Cretaceous breakup (Lisker and Fachmann, 2001). The Triassic episode is of similar age and character to the “Fitzroy” movement that saw peak burial of northwestern Australia’s Fitzroy Trough (Etheridge and O’Brien, 1994).

Like northwest Australia, east India records an ~100 m.y. hiatus between rifting and rifting of Gondwana (Ghosh, 2002). Cretaceous dispersal resulted in brittle reactivation of Carboniferous-Permian basin faults: strike-slip, dip-slip, and thrust displacements are associated with hydrothermal overprints (Lisker and Fachmann, 2001). Modification and seafloor spreading at the continent-ocean boundary were synchronous with marginal magmatism and extrusion of the Rajmahal traps.

DISCUSSION: THE CARBONIFEROUS-PERMIAN GONDWANAN RIFT

The Lambert graben bears many similarities to the Carboniferous-Permian rift system of west Australia. The graben is bounded by Carboniferous-Permian extensional structures, is associated with oblique growth faulting, is terminated by the architecture of the modern continental shelf, and underwent rapid Permian burial culminating in Triassic infill. Like the Fitzroy Trough and Petrel Basin (Fig. 3), the Lambert graben coincides with margin-normal geophysical lineaments and inherited crustal anisotropies that were subject to brittle modification during Gondwana dispersal (Boger and Wilson, 2003). Significant Mesozoic burial of the graben is precluded by vitrinite reflectance profiles. We therefore reject the notion that the Lambert graben is a primarily Cretaceous feature (Veevers et al., 1996; Boger and Wilson, 2003).

It is reasonable to expect that the Carboniferous-Permian rift architecture of the west Australian margin penetrated prebreakup Gondwana (Fig. 4). Based on standard reconstructions, the position and orientation of the Permian Lambert graben correspond closely to the ~650 km length scale of basement compartmentalization observed on both the adjacent Australian and the opposing Indian margins. This correspondence suggests that the Antarctic margin incorporated three
rift segments between the Lambert graben and Perth Abyssal Plain (Fig. 4). Whereas evidence of the two intervening accommodation zones is concealed by the Antarctic Ice Sheet, corresponding features are discernible on the facing Indian margin (Fig. 1).

We propose that the Lambert graben was an accommodation zone of the same Carboniferous-Permian intracontinental rift that defined >4000 km of the west Australian and east Indian margins (Fig. 4). This accommodation zone exploited an inherited weakness at wavelengths appropriate to the scale and eventual width of the developing rift. Late-synrift dilation of this weakness permitted deposition of Permian coal measures in a narrow graben. Coeval coal-bearing sequences accumulated in similar structures on the Indian Peninsula and in southwestern Australia (Fig. 4). We therefore consider the >300-km-wide Antarctic shelf to be primarily a Permian feature that, like the Australian shelf (Chen et al., 2002), was modified little by Mesozoic breakup.

The Lambert graben has previously been correlated with India’s Mahanadi Valley (Fig. 1; Stagg, 1985; Mishra et al., 1999). That correlation, however, seems inconsistent with the petrologies and ranks of coals from the two drainage systems (Holdgate et al., 2005), with regional Gondwana reconstructions (Fig. 1, inset), and with the width of the relict Antarctic shelf (Fig. 4). Instead, we envisage Permian separation of the Indian and Antarctic platforms and across-rift alignment of the Lambert graben and Godavari Valley (Fig. 4). This model suggests that the Mahanadi Valley and a parallel belt of coal-bearing basins in the Rajmahal Hills, ~650 km northeast, correspond to the two “missing” accommodation zones of East Antarctica (Fig. 4). An inflection of the continent-ocean boundary, coinciding with a major crustal discontinuity ~650 km southwest of Prydz Bay (Stagg et al., 2005), is inferred to mark a further accommodation zone (Fig. 4).

The proposed intra-Gondwanan rift corresponds closely to the Permian superbasin of Veevers et al. (1996) (Fig. 1, inset). We reinterpret that depocenter to reflect the erosion of uplifted Permian rift flanks, as in the provenance of the Australian North West Shelf (Etheridge and O’Brien, 1994). Infill of marginal grabens and maximum sag-induced burial of the North West Shelf (Etheridge and O’Brien, 1994) are consistent with continuity of paleocurrents (Fig. 1, inset) across the mature rift. Southward narrowing of relict continental shelves and southward progression from marine (Etheridge and O’Brien, 1994) to fluvial Permian sedimentation are consistent with the shallowing and narrowing of the rift toward the Indo-Antarctic-African junction. Transtensional dilation of southern accommodation zones might also indicate closer proximity to the rift’s pole of rotation. We therefore speculate that the >6000-km-long Gondwana rift founded in the extensive nonmarine Permian-Triassic basin of southern Africa (Fig. 4). Inheritance of compartmentalized rift architecture might thus characterize other Mesozoic Gondwana passive margins in East Africa, Madagascar, and South America.

ACKNOWLEDGMENTS
This research was supported by the Australian Research Council (grants DP0209157 to Mike Sandiford and DP0343406 to Wilson), and Australian National Antarctic Research Expeditions. We thank Steve Boger, Howard Stagg, Geoscience Australia for contributing information, and Chris Morley and Michael Hambrey for invaluable reviews.

REFERENCES CITED
Manuscript received 16 November 2004
Printed in USA

GEOLOGY, March 2005