Continental Rifting, Low-angle Normal Faulting and Deep Biosphere: Results of Leg 180 Drilling in the Woodlark Basin

by Brian Taylor, Philippe Huchon, Adam Klaus and the Leg 180 Scientific Party

Overview

What makes the largest faults, the ones that sustain most slip, much weaker than existing theories and experiments can explain? To answer this question, Leg 180 targeted drilling of an active fault at the western apex of the Woodlark Basin, where a seafloor spreading center is propagating into rifting Papuan continental crust (Fig. 1). The crust there is being pulled apart at ~3 cm per year. The extension appears to be focused on a normal fault with shallow inclination (25-30° dip down to 9 km) that reaches the sea floor. This makes it ideal for study by vertical drilling but also particularly enigmatic: faults with low dip are locked by gravity and can only slip if unusually weak or well lubricated.

Leg 180 established a high-resolution syn-rift stratigraphy, vertical motion history, and basement petrology, of an actively rifting continental margin. The known extent of the deep-sea biosphere was deepened to 842 mbsf – partly as a result of the first use of techniques for uncontaminated sampling of moderately indurated, RCB cores. A bare rock spud-in penetrated the outcropping low-angle normal fault but characterization of the in situ fault properties at depth was thwarted by (a) the presence of trace hydrocarbons at primary Site 1108 and (b) metamorphic talus at alternate Sites 1110-13 closer to the 3 km high fault scarp. Subsequent review by PPSP has re-opened the possibility of deepening Site 1108.

Background

The processes by which continental lithosphere accommodates strain during rifting and the initiation of seafloor spreading are the subject of continuing debate. Particularly controversial is the conjecture that much of the strain may be accommodated on a really large normal detachment faults that slip at low dip angles (<30°).

In a departure from previous ocean drilling strategies, Leg 180 drilled an area of active continental break-up, as opposed to conjugate passive margins that are its fossil counterparts. Earthquake source parameters and seismic reflection data indicate that normal faulting is active at depths above 9 km in the region of incipient continental separation, and permit slip on low-angle fault planes (24-35°; Figs. 1-2; Abers, 1991; Taylor et al., 1995, 1999; Mutter et al., 1996; Abers et al., 1997). The asymmetric rift at the western apex of the Woodlark Basin is one of the most seismically active rift systems on Earth (Fig. 1). Current rifting and spreading are confirmed by kinematic measurements using GPS observations (Tregoning et al., 1998).

Structure and Stratigraphy

During Leg 180 we drilled a transect of sites just ahead of the spreading tip: Sites 1109, 1115, and 1118 on the down-flexed northern margin; Sites 1108 and 1110-1113 into the rift basin sediments above the low-angle normal fault zone; and Sites 1114, 1116, and 1117 on the footwall fault block, Moresby Seamount -Site 1114 near the crest, 1116 on the southern flank, and 1117 into the upper fault face (Figs. 1-2).

The northern margin sites (1109, 1115, and 1118), cored to 802, 803, and 927 meters below seafloor (mbsf), respectively, penetrated the syn-rift cover sequence and into pre-rift sections: dolerites at Sites 1109 and 1118, and middle Miocene forearc clastics at Site 1115. A high resolution syn-rift stratigraphy, vertical motion history, and basement petrology was established. In accord with other land and well exposures, the presence of ophiolitic conglomerates deposited on the rift-onset unconformity at all three northern margin sites indicates the widespread occurrence of ophiolite forming the basement of the orogenically thickened Papuan Peninsula and Woodlark Rise. Syn-rift sedimentation was initially paralic to inner neritic, followed by successively deeper water Plio-Pleistocene hemipelagic and turbiditic deposits, with discrete inputs of volcanic ash and volcaniclastic turbidites. The detailed record of subsidence that began 6-8 Ma at/above sea level provides primary constraints on models of the continental extension. Seismic profiles and core observations evidence only minor normal faulting of the northern margin, which indicates a long wavelength (flexural) mechanism for the more than 2 km of subsidence observed.

At Site 1114, a south-southwest-facing normal fault offsets the basement by about 2 km near the crest of Moresby seamount (Fig. 2). A 6-m-thick tectonic breccia beneath the 286-m-thick Pliocene-Pleistocene sedimentary section occurs above a basement of metadolerite that was penetrated to 407 mbsf. Basement was not reached beneath the 159 m of coarse rift clastics at Site 1116. Sediments at these two sites document relatively proximal turbiditic and mass-flow deposition from an active arc source with additional metamorphic and ophiolitic components. There is also evidence for as much as 1 km of erosion, associated with uplift of the footwall following initial subsidence.

The most spectacular tectonic structure encountered during Leg 180 is the Moresby detachment fault, dipping at 27°±3° toward 015° (Fig. 3; Taylor et al., 1999). The apparent fault offset of the basement is 10 km horizontally and 5 km vertically (i.e., 11 km slip at 27° dip). At

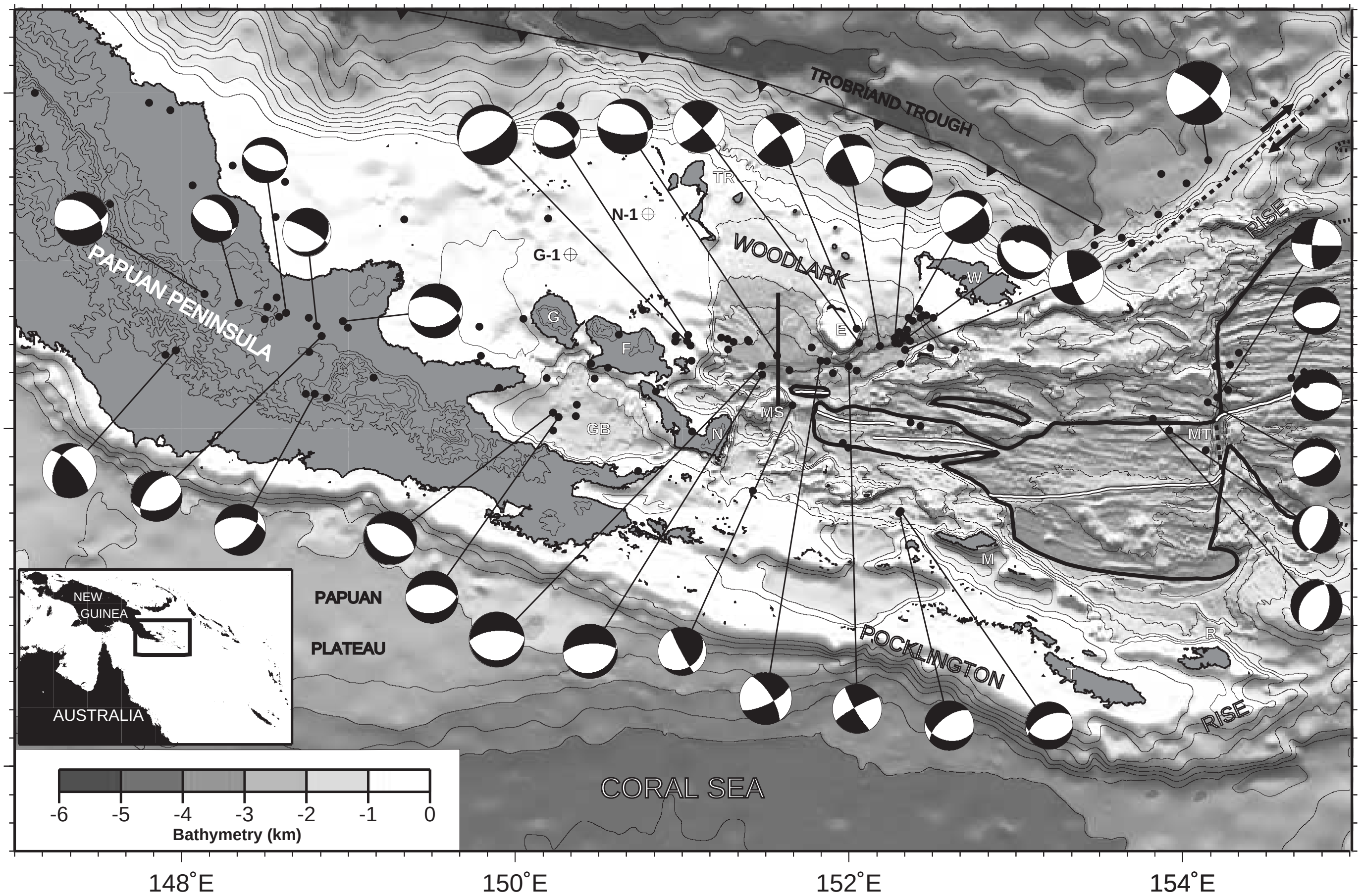

Fig 1. Topography of the Papuan Peninsula and bathymetry of the western Woodlark Basin (500 m contour intervals) showing relocated epicenters (black circles) and earthquake focal mechanisms from Abers et al. (1997). The solid line is the landward boundary of oceanic crust and the thin double lines locate the spreading axes (Taylor et al., 1995). The straight line segment at 151°34.5´E locates the Leg 180 drilling transect (see Fig. 2). Inset shows geographical location of the Woodlark Basin.

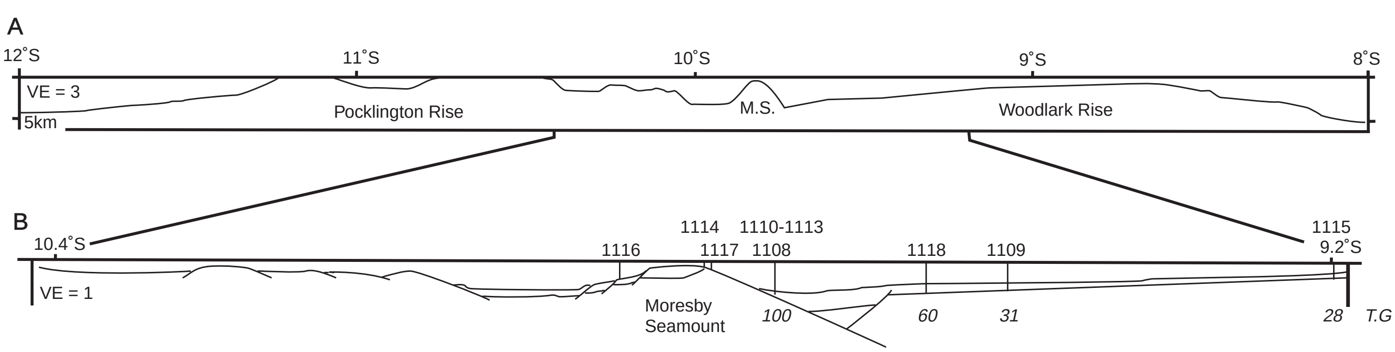

Fig 2. Nested meridional sections at 151°34.5´E showing the (A) regional bathymetry and (B) local structures across the incipient conjugate margins. Leg 180 drill sites are depicted on the B section. T.G.= thermal gradient (°C/km). VE = vertical exaggeration.

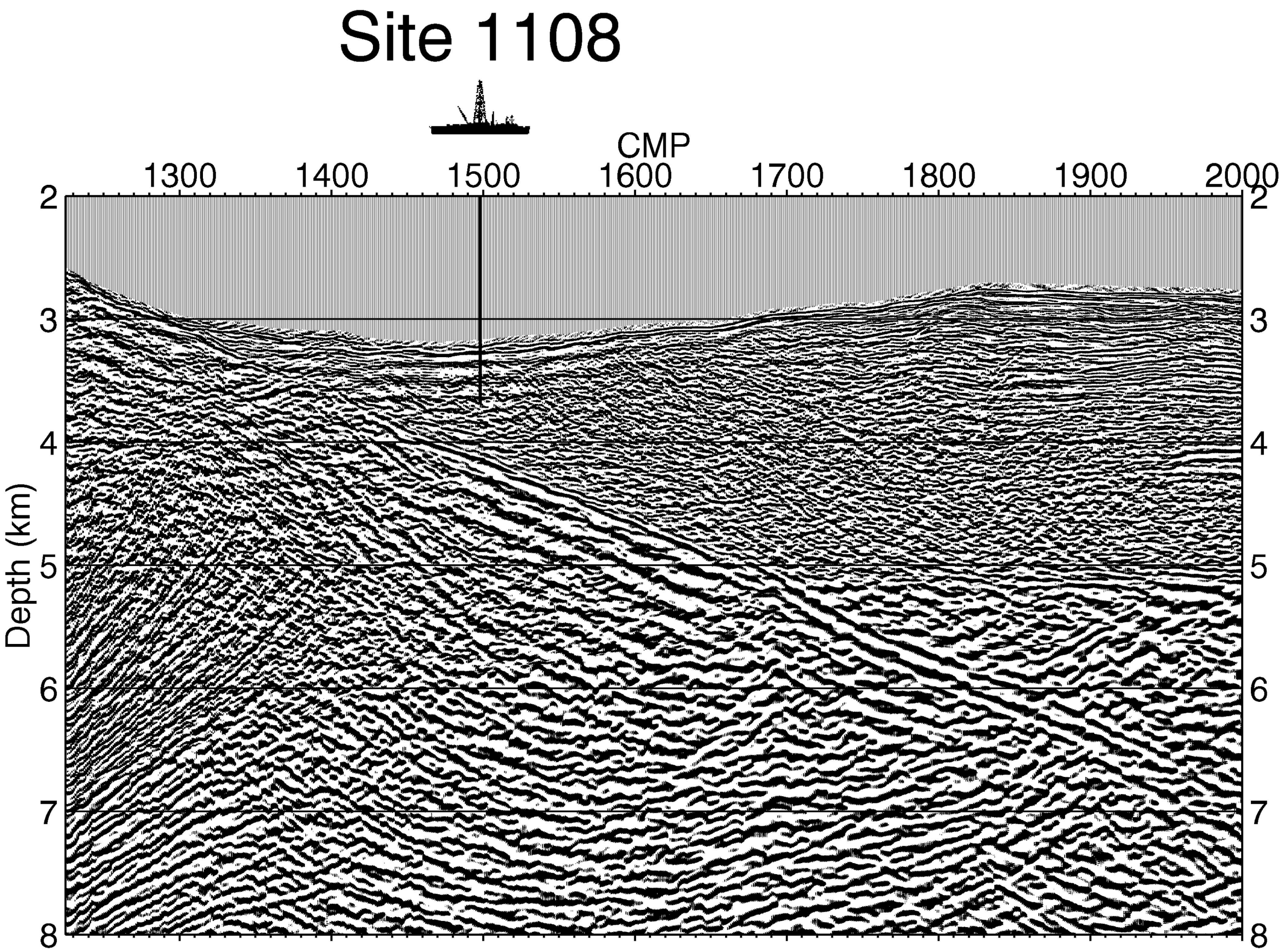

Fig 3. Stacked, migrated and depth converted multichannel seismic line through Site 1108 (modified from Taylor et al., 1999).

Site 1117, where the fault plane crops out on the northern flank of Moresby Seamount, we drilled through the ~100 m-thick succession of deformed rocks into a gabbro basement. From bottom to top, the gabbro ranges from undeformed, to brecciated, to foliated cataclasite/mylonite. Epidote and quartz dominate the secondary minerals, indicating syntectonic greenschist facies conditions. Above this, an ultracataclasite fault gouge (5 m was recovered) crops out on the seafloor and represents the most advanced stage of deformation, with evidence for fluid-assisted alteration to produce serpentinite, chlorite, talc, calcite, ankerite, and fibrous amphibole.

A triple casing reentry hole was planned to intersect the low-angle normal fault at 900 mbsf where an estimated 9 km of the 11 km of basement-basement dip-slip offset have occurred. The presence of trace hydrocarbons at Hole 1108B (drilled to 485 mbsf), and the extent of talus proximal to Moresby Seamount where the fault is shallower (Sites 1110-1113, which penetrated 25-174 mbsf), precluded use of the available technology to meet our primary objective. Although the ~100-m-thick low-angle fault zone was cored through at Site 1117, the primary objective of Leg 180 was not met. To understand how an active low-angle normal fault zone slips we need to characterize the in situ properties - stress, permeability, temperature, pressure, physical properties, and fluid pressure - at depth. A return to Site 1108 has been proposed, with the goal of penetrating to/through the fault zone so that these parameters may be measured.

Biosphere

The longest profiles to date of the deep sub-seafloor biosphere were made at Sites 1115 and 1118 (Fig. 4). Bacteria were present in all samples analyzed at the three northern sites drilled to >800 mbsf. Both dividing and divided cells were present to 842 mbsf, although there is an indication that numbers are decreasing more rapidly than the model of Parkes et al. (1994) predicts, resulting in a sigmoidal depth distribution.

Because bacteria play a dominant role in the degradation of organic matter, and consequently drive chemical changes and diagenesis in sediments, their deep subsurface activity is evident in geochemical data from these sites (Fig. 4). Pore-water sulfate concentrations are depleted in the uppermost sediments, below which methane concentrations increase rapidly as methanogenic bacteria gain a competitive advantage over sulfate-reducing bacteria for common organic substrates. Biological decomposition of organic matter is also evident from the accumulation of ammo-

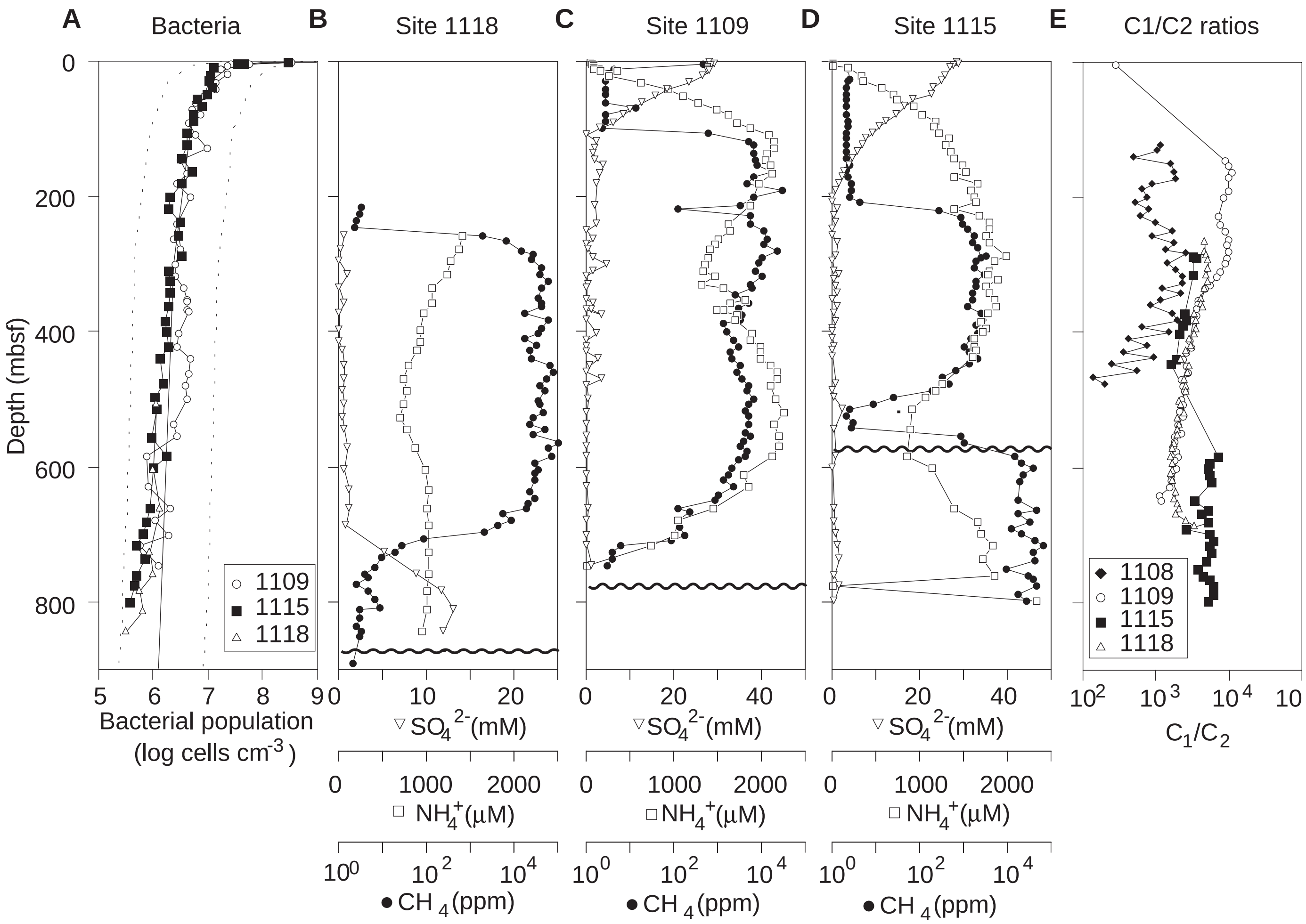

Fig 4. Biogeochemical profiles at Leg 180 sites: A. Total bacterial populations. The solid curve represents a general regression line of bacterial numbers vs. depth in deep-sea sediments (Parkes et al., 1994), with 95% upper and lower prediction limits shown by dashed curves. B-D. Sulfate, ammonia, and methane depth profiles. Wavy line depicts unconformity. E. Methane/ethane ratios.

nia in the pore waters.

The persistence of microbial life into indurated sedimentary rock adds to a steadily growing body of evidence for a more extensive biosphere than previously imagined. That life is not merely a surface phenomenon has profound implications for the biodiversity of our planet, fossil fuel formation, the origins of life on Earth, and the potential for life on other planets. For a more complete summary of Leg 180 drilling results, see http://www-odp.tamu.edu/publications/prelim/180_prel/180toc.html.

Leg 180 Shipboard Scientific Party

Philippe Huchon and Brian Taylor, co-chief scientists; Adam Klaus, staff scientist; Sherif Awadallah, Charles Brooks, Bernard Celerier, Eric DeCarlo, Jacqueline Floyd, Gina Frost, Veronique Gardien, Stefania Gerbaudo, Andrew Goodliffe, Jimmy Haumu, Naoto Ishikawa, Garry Karner, Paul Kia, Achim Kopf, Klas Lackschewitz, Robert Laronga, Bernard Le Gall, Ian Mather, Brian Monteleone, Russell Perembo, Johanna Resig, Alastair Robertson, Elizabeth Screaton, Timothy Sharp, William Siesser, Shannon Stover, Kyoma Takahashi, and Peter Wellsbury.

References

Abers, G.A., 1991. Possible seismogenic shallow-dipping normal faults in the Woodlark-D'Entrecasteaux extensional province, Papua New Guinea. Geology, 19: 1205-1208.

Abers, G.A., Mutter, C.Z., and Fang, J., 1997. Shallow dips of normal faults during rapid extension: Earthquakes in the Woodlark-D'Entrecasteaux rift system, Papua New Guinea. J. Geophys. Res., 102: 15301-15317.

Mutter, J.C., Mutter, C.Z., and Fang, J., 1996. Analogies to oceanic behaviour in the continental breakup of the Western Woodlark Basin. Nature, 380: 333-336.

Parkes, R.J., Cragg, B.A., Bale, S.J., Getliff, J.M., Goodman, K., Rochelle, P.A., Fry, J.C., Weightman, A.J., and Harvey, S.M., 1994. A deep bacterial biosphere in Pacific Ocean sediments. Nature, 371: 10-413.

Taylor, B., Goodliffe, A., Martinez, F., and Hey, R., 1995. Continental rifting and initial seafloor spreading in the Woodlark Basin. Nature, 374: 534-537.

Taylor, B., Goodliffe, A.M., and Martinez, F., 1999. How continents break-up: Insights from Papua New Guinea. J. Geophys. Res., 104: 7497-7512.

Tregoning, P., Lambeck, K., Stolz, A., Morgan, P., McClusky, S.C., van der Beek, P., McQueen, H., Jackson, R., Little, R., Laing, A., and Murphy, B., J. Geophys. Res., 103: 12181-12203, 1998.