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Invited review

Post 8 Ma reconstruction of Papua New Guinea and Solomon Islands: Microplate tectonics in a convergent plate boundary setting

Robert J. Holm [a,b,*], Gideon Rosenbaum [c], Simon W. Richards [a,b]

[a] Department of Earth and Oceans, College of Science, Technology & Engineering, James Cook University, Townsville, Queensland 4811, Australia
[b] Economic Geology Research Centre (EGRU), College of Science, Technology & Engineering, James Cook University, Townsville, Queensland 4811, Australia
[c] School of Earth Sciences, The University of Queensland, Brisbane, Queensland 4072, Australia

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A B S T R A C T

Papua New Guinea and the Solomon Islands are located in a complex tectonic setting between the converging Ontong Java Plateau on the Pacific plate and the Australian continent. Here we present a Late Neogene to Quaternary plate tectonic reconstruction for this region. The reconstruction was performed using GPlates software and is based on data derived from multiple geological datasets, including seafloor magnetic isochrons, 3D models of subducted slabs, paleomagnetic data, deformation patterns, and the spatio-temporal distribution of arc magmatism. The reconstruction shows that since ca. 6 Ma, the crustal elements that comprise Papua New Guinea and the Solomon Islands began interacting in advance of the impending collision between the Ontong Java Plateau and Australian continent, leading to the inception of regional microplate tectonics and escalation in tectonic complexity. The Bismarck Sea initially formed as a back-arc basin behind the New Britain arc, but was later modified during arc-continent collision. Following collision, the west Bismarck Sea developed into a transpressional zone associated with subduction of the Caroline plate and North Bismarck microplate at the New Guinea trench. Farther east, seafloor spreading occurred in response to the clockwise rotation of the South Bismarck microplate relative to the Australian plate. The Solomon Sea plate was subjected to anticlockwise rotation relative to Papua New Guinea, primarily due to the west-dipping subduction at the New Britain trench, which resulted in initiation of subduction at the Trobriand trough and extension in the Woodlark Basin from ca. 5 Ma. Crustal shortening in the upper plate, which now forms the Solomon Islands, resulted from the resistance of the relatively hot and buoyant Woodlark Basin lithosphere to subduction at the San Cristobal. Our reconstruction shows that tectonism at convergent plate boundaries could involve an intricate relationship between microplate rotations, seafloor spreading and subduction segmentation over timescales considerably <10 Ma. By unraveling the tectonic evolution of this complex region, we provide insights into the development of microplate tectonics at convergent margins in general, and the possible diagnostic geological records that might be preserved in ancient orogenic systems.

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* Corresponding author at: Department of Earth and Oceans, College of Science, Technology & Engineering, James Cook University, Townsville, Queensland 4811, Australia.
E-mail address: robert.holm@jcu.edu.au (R.J. Holm).

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1. Introduction

The relatively recent tectonic processes in the southwest Pacific are commonly used as an analogue for understanding the evolution of fossil orogenic systems, such as the northern Appalachians and British Caledonides (Van Staal et al., 1998), Central Asian Orogenic Belt and Arabian-Nubian shield (Kröner et al., 2007), eastern Australian Tasmanides (Collins and Richards, 2008; Glen and Meffre, 2009), and Western Alps (Malusà and Garzanti, 2012). This comparison arises from the recognition that complex tectonic interactions may occur over short geological timescales (few millions of years), involving, for example, plate sub-rotations (Cuffaro et al., 2008), multiple collisional events of discrete terranes, simultaneous development of extensional and contractional tectonics, and rapid changes in plate kinematics. Naturally, reconstructing such temporal and spatial changes in ancient orogenic belts is a challenging task due to the partial preservation of diagnostic tectono-magmatic features and the limited temporal resolution.

In this study we examine the tectonic evolution of the Papua New Guinea and Solomon Islands region since the Late Neogene (Fig. 1). This region is significant because it represents a complex plate boundary zone between the Pacific and Australian plates, and is situated between

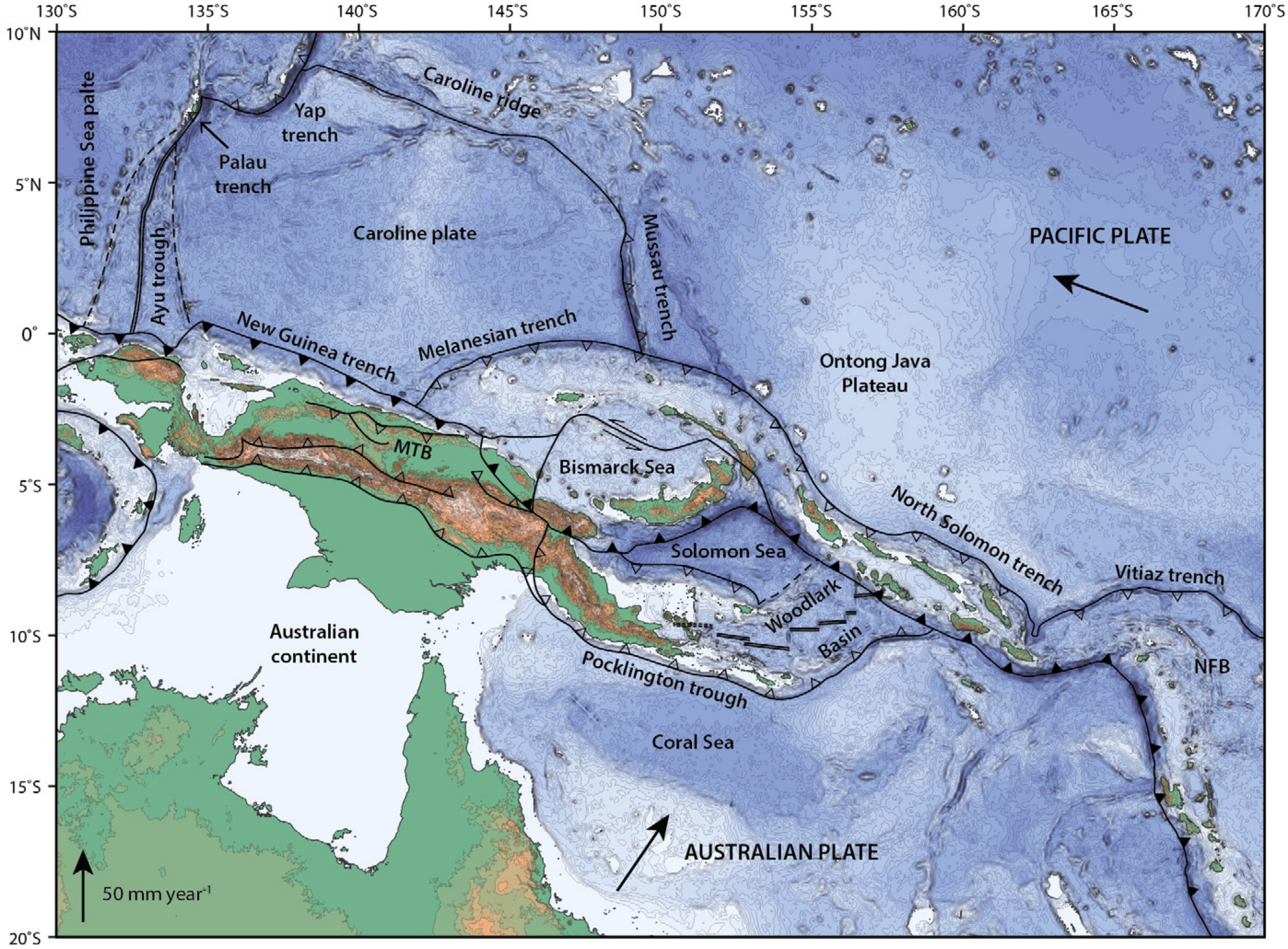

Fig. 1. Topography, bathymetry and regional tectonic setting of New Guinea and Solomon Islands. Arrows indicate rate and direction of plate motion of the Australian and Pacific plates (MORVEL, DeMets et al., 2010); Mamberamo thrust belt, Indonesia (MTB); North Fiji Basin (NFB).

the obliquely converging Ontong Java Plateau and the Australian continent. We present a plate tectonic reconstruction for this region since 8 Ma, with a particular focus on microplate tectonics in the Bismarck Sea, Solomon Sea, and Woodlark Basin.

The reconstructions integrate existing datasets of seafloor magnetic isochrons, paleomagnetic data, seismic tomography models, and additional geological and geophysical observations from numerous studies (e.g. Abbott, 1995; Petterson et al., 1999; Hall, 2002; Schellart et al., 2006; Holm and Richards, 2013; Holm et al., 2013, 2015). The reconstruction demonstrates how near and far-field changes in subduction dynamics can have a profound influence on microplate geometries and the tectono-magmatic evolution of long- and short-lived plate boundaries over time. In particular, emphasis is placed on the extremely different geometries between the initiation of microplate interaction at ca. 6 Ma and the markedly different final tectonic relationships that are recognized today.

2. Tectonic setting

Northern Papua New Guinea and Solomon Islands constitute the present-day plate boundary zone between the Australian plate and the Pacific plate (Fig. 1). The Australian plate is currently moving to the north-northeast at ca. 63 mm year^{-1}, and motion of the Pacific plate is defined by west-northwest motion at 66–67 mm year^{-1} (MORVEL, DeMets et al., 2010). The motion of these two major plates is resolved into an oblique northeast-southwest convergence across the Papua New Guinea region at 10–11 cm year^{-1}.

2.1. Subduction zones

Plate convergence is currently accommodated by subduction of the Australian and Solomon Sea plates at the San Cristobal and New Britain trenches, respectively (Fig. 2). Magmatism related to subduction at the New Britain and San Cristobal trenches occurs in the Solomon arc, the Tanga-Lihir-Tabar-Feni chain and the New Britain arc, overprinting Melanesian arc basement related to earlier subduction at the Melanesian trench (Fig 2; Woodhead et al., 1998; Petterson et al., 1999; Holm et al., 2013).

The western extension of the New Britain trench and New Britain arc are the north-dipping Ramu-Markham fault zone, which is an inactive trench, and the West Bismarck arc, respectively (Fig. 2a). Subduction of oceanic crust ceased when allochthonous Paleogene to earliest Neogene volcanic rocks of the Adelbert-Finisterre terrane were thrust over the northern margin of Papua New Guinea (Fig. 2; Jaques and Robinson, 1977; Abbott et al., 1994; Abbott, 1995; Weiler and Coe, 2000; Woodhead et al., 2010; Holm and Richards, 2013). Reverse movement marked by active seismicity, together with real-time GPS measurements of the Finisterre-Adelbert terrane and Papua New Guinea, show that the Ramu-Markham fault zone is an active plate boundary that still accommodates convergence, albeit at a reduced rate following collision (Abbott, 1995; Tregoning et al., 1998; Wallace et al., 2004).

The Palau and Yap trenches mark the northwest margin of the Caroline plate (Fig. 1). The trenches are related to west- and northwest-dipping subduction of the Caroline plate beneath the Philippine Sea. Initial subduction at the Palau trench had begun from at least 40 Ma (Kobayashi, 2004), but the arrival of the Caroline Ridge at the Yap trench is interpreted to have led to cessation of extensive arc magmatism from ca. 25 Ma (Fujiwara et al., 2000; Ohara et al., 2002). The present-day convergence rates along the Yap and Palau trenches are estimated at 0–6 mm year^{-1} (Seno et al., 1993; Lee, 2004). However, there is currently no evidence of a Benioff zone in this section of the trench (Lee, 2004). No volcanoes are currently active at the Palau and Yap trenches, and the youngest arc-related volcanic rocks (in the proximity of the Yap trench) are dated at ca. 11–7 Ma (Ohara et al., 2002).

To the north of New Guinea, convergence is accommodated by south-dipping subduction at the New Guinea trench (Figs. 1 and 2). The western part of the New Guinea trench accommodates subduction of the late Eocene-Oligocene Caroline plate (Gaina and Müller, 2007), whereas in the eastern part, younger crust of the western Bismarck Sea is subducting (Fig. 1). The timing and activity of subduction at the New Guinea trench, however, is not entirely understood. Geodetic constraints suggest that up to 40 mm year^{-1} of Australia-Pacific convergence is accommodated by subduction at the New Guinea trench (Puntodewo et al., 1994; McCaffrey, 1996; Stevens et al., 2002). This interpretation is supported by the pattern of active seismicity (Cooper and Taylor, 1987) and seismic tomography (Tregoning and Gorbatov, 2004). Subduction at the New Guinea trench is not associated with abundant arc magmatism; however, the Mamberamo thrust belt (Fig. 1) is characterized by active mud volcanoes associated with thrust-dominated deformation (Pubellier and Ego, 2002; Baldwin et al., 2012).

The Mussau trench in the northern part of the study area (Figs. 1 & 2) is perhaps the least understood tectonic element in the region (Seno et al., 1993; Hall, 2002). The morphology of the trench suggests that it might have been a zone of east-dipping subduction, but the timing of subduction is unconstrained (Fig. 1). A lack of any significant seismic signature or tomographic anomaly indicates that the Mussau trench does not accommodate significant present-day convergence.

The Melanesian trench (also referred to as the West Melanesian trench and Manus trench) and North Solomon trench mark the north and northeast margins of the North Bismarck microplate and Solomon Islands (Fig. 2). The Melanesian trench accommodated southwest-dipping subduction of the Pacific plate beneath the Australian plate from ca. 45 Ma (Petterson et al., 1999; Hall, 2002; Schellart et al., 2006; Holm et al., 2013). This subduction also caused magmatism at the Melanesian arc, which terminated at ca. 26–20 Ma, possibly due to the docking of the Ontong Java Plateau with the Solomon Islands (Yan and Kroenke, 1993; Petterson et al., 1999; Hall, 2002; Knesel et al., 2008; Holm et al., 2013). In the Solomon Islands, the Kia-Kaipito-Korigole fault zone (Fig. 2) has been interpreted as a relict trench interface that was the eastern extension of the Melanesian trench prior to docking of the Ontong Java Plateau (Petterson et al., 1999; Mann and Taira, 2004; Phinney et al., 2004).

The North Solomon trench has been interpreted to accommodate recent convergence between the Solomon Islands and the Ontong Java Plateau (Cowley et al., 2004; Mann and Taira, 2004; Phinney et al., 2004; Taira et al., 2004). Evidence for this convergence is associated with folding and uplift (Petterson, 2004; Phinney et al., 2004), and inversion of normal faults in the Central Solomon intra-arc basin (Cowley et al., 2004). The amount of convergence and underthrusting of the Ontong Java Plateau at the North Solomon trench since 5 Ma has been estimated at ca. 200 km (Mann and Taira, 2004; Miura et al., 2004; Phinney et al., 2004; Taira et al., 2004).

The Trobriand trough (Fig. 2) is one of the most contentious tectonic elements in the region (Hall and Spakman, 2002; Holm et al., 2015). The lack of seismicity indicative of southward subduction, combined with the absence of convincing tomographic evidence for subduction, suggest that this margin does not accommodate a major component of regional convergence (e.g. Abers et al., 2002; Hall and Spakman, 2002; Wallace et al., 2004). Furthermore, no arc magmatism has been attributed to subduction at the Trobriand trough. However, evidence for deformation has been recognized in seismic reflection data, indicating that recent convergence may have occurred at the Trobriand trough (Davies and Jaques, 1984; Lock et al., 1987).

The Pocklington trough marks the southern margin of the Woodlark Basin and Papuan Peninsula. There is no evidence for recent convergence at the Pocklington trough and it is therefore considered to represent a relict trench that accommodated north-dipping

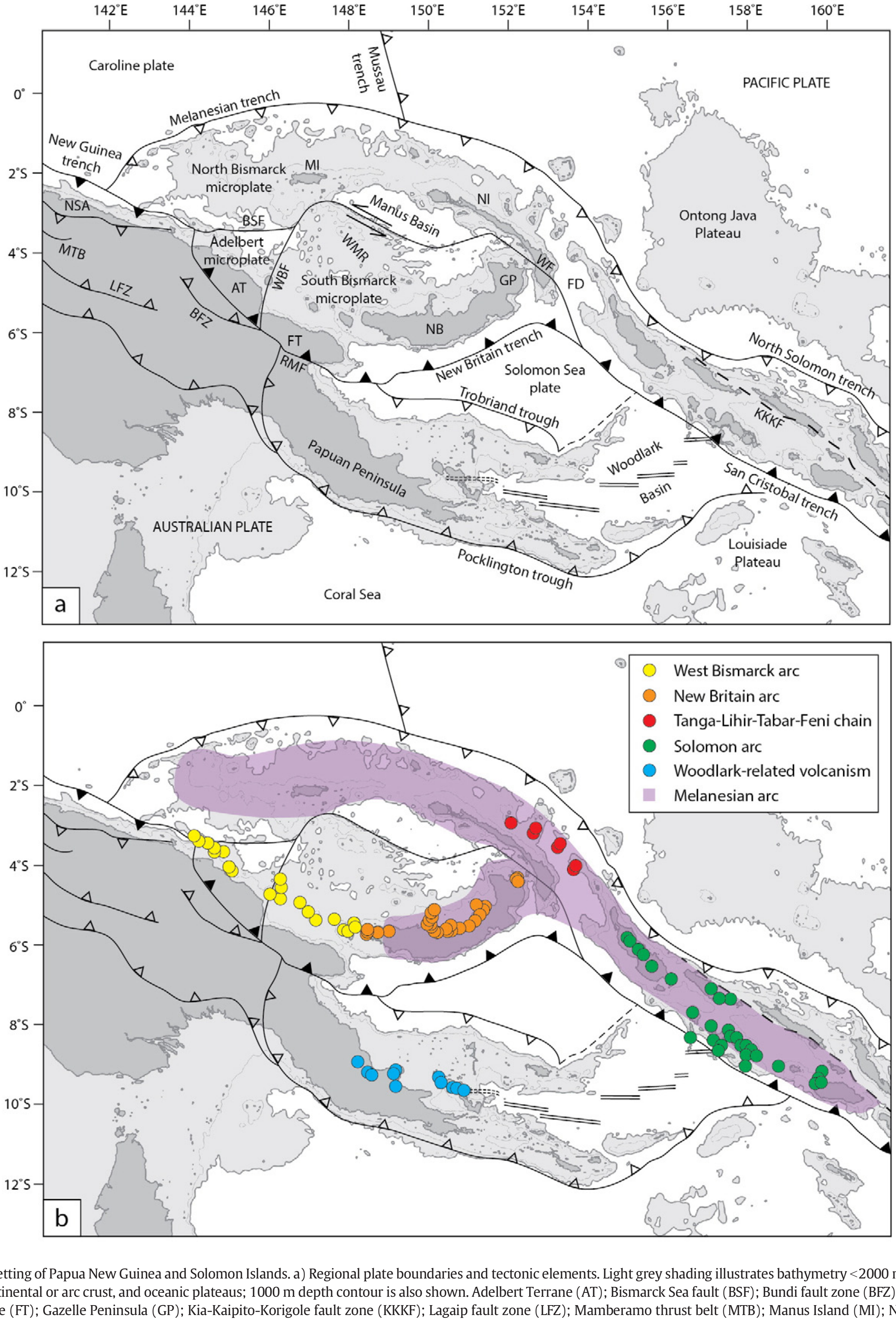

Fig. 2. Tectonic setting of Papua New Guinea and Solomon Islands. a) Regional plate boundaries and tectonic elements. Light grey shading illustrates bathymetry <2000 m below sea level indicative of continental or arc crust, and oceanic plateaus; 1000 m depth contour is also shown. Adelbert Terrane (AT); Bismarck Sea fault (BSF); Bundi fault zone (BFZ); Feni Deep (FD); Finisterre Terrane (FT); Gazelle Peninsula (GP); Kia-Kaipito-Korigole fault zone (KKKF); Lagaip fault zone (LFZ); Mamberamo thrust belt (MTB); Manus Island (MI); New Britain (NB); New Ireland (NI); North Sepik arc (NSA); Ramu-Markham fault (RMF); Weitin Fault (WF); West Bismarck fault (WBF); Willaumez-Manus Rise (WMR). b) Magmatic arcs and volcanic centers related to this study.

subduction of the Australian plate beneath New Guinea (Hill and Hall, 2003; Cloos et al., 2005; Webb et al., 2014; Holm et al., 2015). Closure of the Pocklington trough and cessation of subduction was caused by collision of the Australian continent with an outboard proto-New Guinea terrane at ca. 12 Ma (Webb et al., 2014; Holm et al., 2015).

2.2. Back-arc basins

The Bismarck Sea back-arc basin comprises two microplate (North Bismarck and South Bismarck) separated by the left-lateral strike-slip Bismarck Sea fault (Fig. 2; Denham, 1969; Taylor, 1979; Cooper and Taylor, 1987). The record of magnetic isochrons in the Bismarck Sea indicates seafloor spreading since 3.5 Ma (Taylor, 1979; Baldwin et al., 2012).The North Bismarck microplate comprises Manus Island and New Ireland, and the South Bismarck microplate comprises New Britain and the adjoining Finisterre Terrane. An additional feature in the South Bismarck microplate is the Willaumez-Manus Rise (Fig. 2) that is interpreted to have formed recently (<3.5 Ma) from either tectonic uplift or from excess magmatism related to sea floor spreading in the Bismarck Sea (Johnson et al., 1979). The Adelbert microplate forms an independent microplate adjacent to the Finisterre Terrane, separated from the South Bismarck microplate by a minor plate boundary, herein termed the West Bismarck fault (Fig. 2; Wallace et al., 2004; Holm and Richards, 2013).

At present, west-northwest motion of the North Bismarck microplate is similar to the Pacific plate, suggesting almost complete coupling between the North Bismarck microplate, Melanesian arc and Pacific plate (Tregoning et al., 1998; Wallace et al., 2004). The South Bismarck microplate is currently rotating clockwise at a rate of $8^\circ \cdot \mathrm{Ma}^{-1}$ relative to the Australian plate (Tregoning et al., 1999; Weiler and Coe, 2000). The motion of the Adelbert microplate is similar to the Papua New Guinea mainland and Australian plate (Wallace et al., 2004).

The Woodlark Basin is a back-arc basin at the southeast margin of the Papua New Guinea and Solomon Islands region (Fig. 2). Sea-floor spreading initiated at ca. 6 Ma and propagated >500 km westward at a rate of approximately 14 cm year^{-1} (Taylor et al., 1995, 1999). In the west of the Woodlark Basin, oceanic spreading gradually changes to continental rifting of the Papuan Peninsula (Benes et al., 1994; Taylor et al., 1995, 1999). The young oceanic crust and active Woodlark spreading center are currently subducting to the northeast at the San Cristobal trench (Mann et al., 1998; Chadwick et al., 2009; Schuth et al., 2009).

The Ayu trough marks the western boundary of the Caroline plate (Fig. 1). It records initial rifting at ca. 25 Ma (Fujiwara et al., 1995), but the full spreading history of the Ayu trough is uncertain due to the absence of recognizable magnetic lineations. Most authors agree that spreading has significantly decreased since 5–6 Ma but is still active (Weissel and Anderson, 1978; Fujiwara et al., 1995).

The Feni Deep (Fig. 2) is a bathymetric low that marks a break in the Melanesian arc. The origin of this feature is unknown.

3. Methods and data

Plate tectonic reconstructions were developed in GPlates software (Boyden et al., 2011; Seton et al., 2012) and constructed in 1 million year time intervals relative to the moving Indian/Atlantic hotspot reference frame (O'Neill et al., 2005; Seton et al., 2012). Tectonic plates are assumed to be rigid and non-deforming, and the creation of new oceanic crust at spreading ridges is generated with the use of dynamic topological plate polygons to maintain a closed plate circuit (Gurnis et al., 2012). Continental or thickened arc crust and the locations of plate boundaries and major structural elements are interpreted from bathymetry and topography (Amante and Eakins, 2009). Continental and arc crust is approximated from the 2000 m bathymetric contour, except for the South Bismarck microplate and Abelbert microplate where the 1000 m contour is taken as the crustal boundary due to the shallow depth of the Bismarck Sea in these regions.

3.1. Sources of data

3.1.1. Kinematic boundary conditions

The reconstruction was developed within the framework of the already well-established plate motions of the Pacific plate (Wessel and Kroenke, 2008; Seton et al., 2012), Australian plate (Royer and Chang, 1991; Seton et al., 2012 and refs therein), and Philippine Sea plate (Hall, 2002; Gaina and Müller, 2007; Seton et al., 2012 and refs therein). Mainland Papua New Guinea is assumed to behave as a rigid block attached to the Australian plate (Puntodewo et al., 1994; Wallace et al., 2004).

We initially made the assumption that the Melanesian arc was fixed to the Pacific plate and that there has been negligible convergence between the Melanesian arc and the Ontong Java Plateau since 8 Ma (see supplementary material for tectonic reconstruction under this assumption). We later revised this assumption and considered that only the motion of the North Bismarck microplate was fixed to the Pacific plate. The plate motion of the Solomon Islands segment of the Melanesian arc was instead reconstructed to accommodate an estimated 200 km convergence between the Ontong Java Plateau and Solomon Islands at the North Solomon trench, based on the findings of Taira (2004), Miura et al. (2004) and Taira et al. (2004). This revised reconstruction also provides a better fit between the Solomon Islands and the reconstructed Solomon Sea plate. Intraplate crustal shortening in the Solomon Islands is not constrained spatially and temporally, and therefore, the Solomon Islands are treated as a rigid crustal block.

The Caroline plate is bordered by five different subduction zones, and therefore its motion is difficult to constrain (Fig. 1). Only limited relative plate convergence occurred at the Palau and Yap trenches in the last ~8 Ma (Ohara et al., 2002; Lee, 2004). Together with the interpreted slow spreading rates of the Ayu trough since 5–6 Ma (Weissel and Anderson, 1978; Fujiwara et al., 1995), this suggests a lack of significant relative plate motion between the Philippine Sea plate and western Caroline plate. For the purposes of this study, we assumed that the motion of the Caroline plate was tied closely to that of the Philippine Sea plate. We used several iterations to ensure that a minimal relative motion between the Philippine Sea plate and Caroline plate is maintained, while also using the present-day plate margins for the eastern Caroline plate to ensure that the remaining plate boundaries are not in breach of the known kinematics.

3.1.2. Sea-floor magnetic isochrons

Sea floor magnetic isochrons are the most robust data used to constrain past plate motions (Fig. 3). The magnetic anomalies provide evidence for either symmetric spreading where anomalies of similar ages can be matched on both sides of a spreading ridge, or asymmetric spreading where magnetic anomalies are only apparent on one side of a spreading ridge. Fitting of the isochrons to the associated spreading ridge at the interpreted time of formation provides information on the relative motion of diverging plates, and constrains the direction and rate of basin opening. This is a crucial constraint for the reconstruction of the Bismarck Sea (Taylor, 1979); and opening of the Woodlark Basin (Taylor et al., 1999).

3.1.3. Paleomagnetic data

Paleomagnetic data can constrain the kinematics and block rotations of allochthonous terranes. Unfortunately, within the study area there are only few paleomagnetic constraints. Paleomagnetic data from the allochthonous Finisterre Terrane indicate that this terrane has undergone approximately 40° of clockwise rigid-body rotation relative to the Australian plate, at a rate of approximately $8^\circ \cdot \mathrm{Ma}^{-1}$ since 5 Ma (Weiler and Coe, 2000).

3.1.4. Subducted slabs

Modeling of subducted slabs allows us to estimate the amount of oceanic lithosphere that has been consumed at subduction zones. We

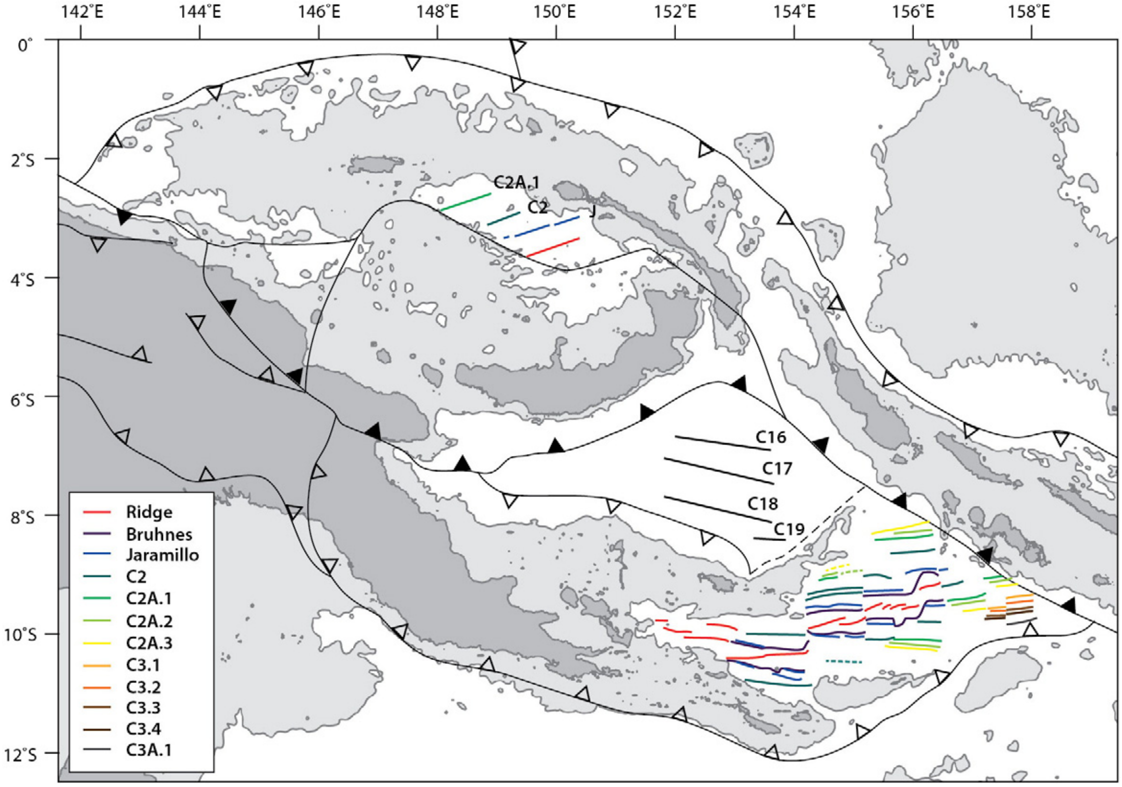

Fig. 3. Sea floor magnetic isochrons in the Papua New Guinea and Solomon Islands region. Magnetic anomalies are as labelled or indicated for the Manus Basin (Taylor, 1979), Solomon Sea (Gaina and Müller, 2007) and Woodlark Basin (Taylor et al., 1999).

used the slab models presented in Holm and Richards (2013) and Richards et al. (2011) for subduction of the Solomon Sea plate; the Woodlark Basin and Australian plate at the New Britain trench, the San Cristobal trench, and the Vanuatu trench (Fig. 4). The slab models were derived from seismic tomographic data and earthquake hypocenter datasets, with the aim of modeling the top surface of the subducted slab. The slab area was estimated by taking measured cross-sectional slab lengths from the subduction trench interface to the interpreted final depth of the slab. The measured sections of the slab model were then projected to the surface to provide an

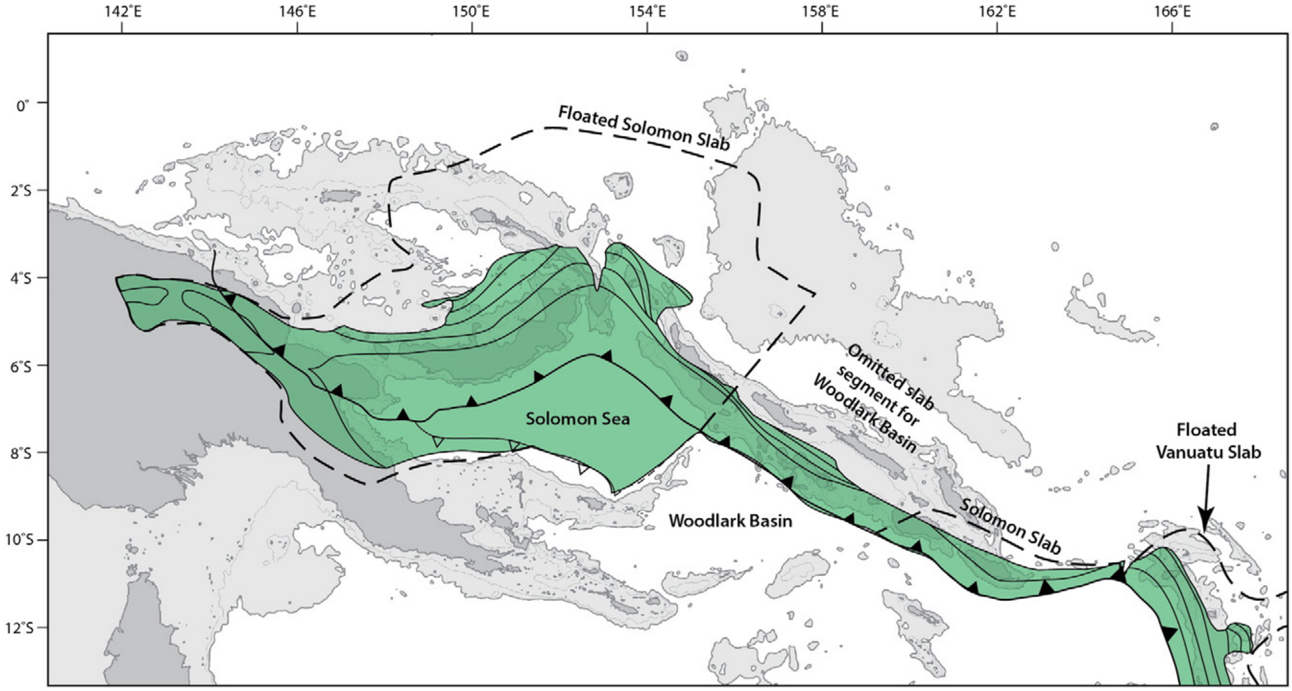

Fig. 4. Slab model and associated reconstructed slab area for the Solomon Sea plate subducted at the New Britain, San Cristobal and Trobriand trough, and slab subducted at the Vanuatu trench. Slab models for Solomon Sea slab and Vanuatu slab are after Holm and Richards (2013) and Richards et al. (2011), respectively.

approximation for the area of the Solomon Sea plate prior to subduction (Fig. 4). We assumed no change in the slab volume with subduction. We did not account for a change in lithospheric area for tearing of the Solomon Sea slab at the subduction hinge adjacent to New Ireland (Fig. 4) as the kinematics and timing of tearing is currently unconstrained. A segment of the subducted Solomon slab model adjacent to the Woodlark Basin was omitted from the interpreted floated slab area to account for spreading of the Woodlark Basin and allow for closure between the Solomon Sea and Australian plate (Fig. 4). This omitted segment was defined by the margins of the Woodlark Basin and the inferred continuation of these structures.

3.1.5. Subduction, arc magmatism and terrane collision

The age for initiation of subduction zones is commonly interpreted from the timing of initiation of arc magmatism, although the latter provide the latest possible age for subduction initiation, up to several million years after subduction begins. Unfortunately the age of arc magmatism related to subduction at the New Britain and San Cristobal trenches is not well constrained. Previous authors assumed that subduction had begun between 10 Ma and 6 Ma (Coleman and Kroenke, 1981; Tregoning et al., 1998; Petterson et al., 1999; Mann and Taira, 2004). Rather than inferring a precise timing for subduction initiation, we instead leave the relative plate motion at the New Britain and San Cristobal subduction interface unconstrained over the time span of the reconstruction. We treat subduction at the New Guinea trench and the Trobriand trough in a similar fashion where the relative motions of the plates are unconstrained and the assumption that all convergence was accommodated by subduction.

Closure of subduction zones due to impinging and colliding terranes provides key information for the reconstructions. Abbott et al. (1994) and Abbott (1995) investigated sedimentary sequences and provenance shifts on the Finisterre Terrane that indicate that this terrane collided with northern Papua New Guinea at 3.0–3.7 Ma. The extent of the continental margin of northern Papua New Guinea prior to the arc-continent collision event has been interpreted by Holm and Richards (2013) on the basis of seismicity, regional gravity studies and geochemistry of the adjacent West Bismarck arc (Woodhead et al., 2001, 2010). Both the timing of arc-continent collision, and the extent of the (now underthrust) leading continental margin of Papua New Guinea, are incorporated into the reconstructions.

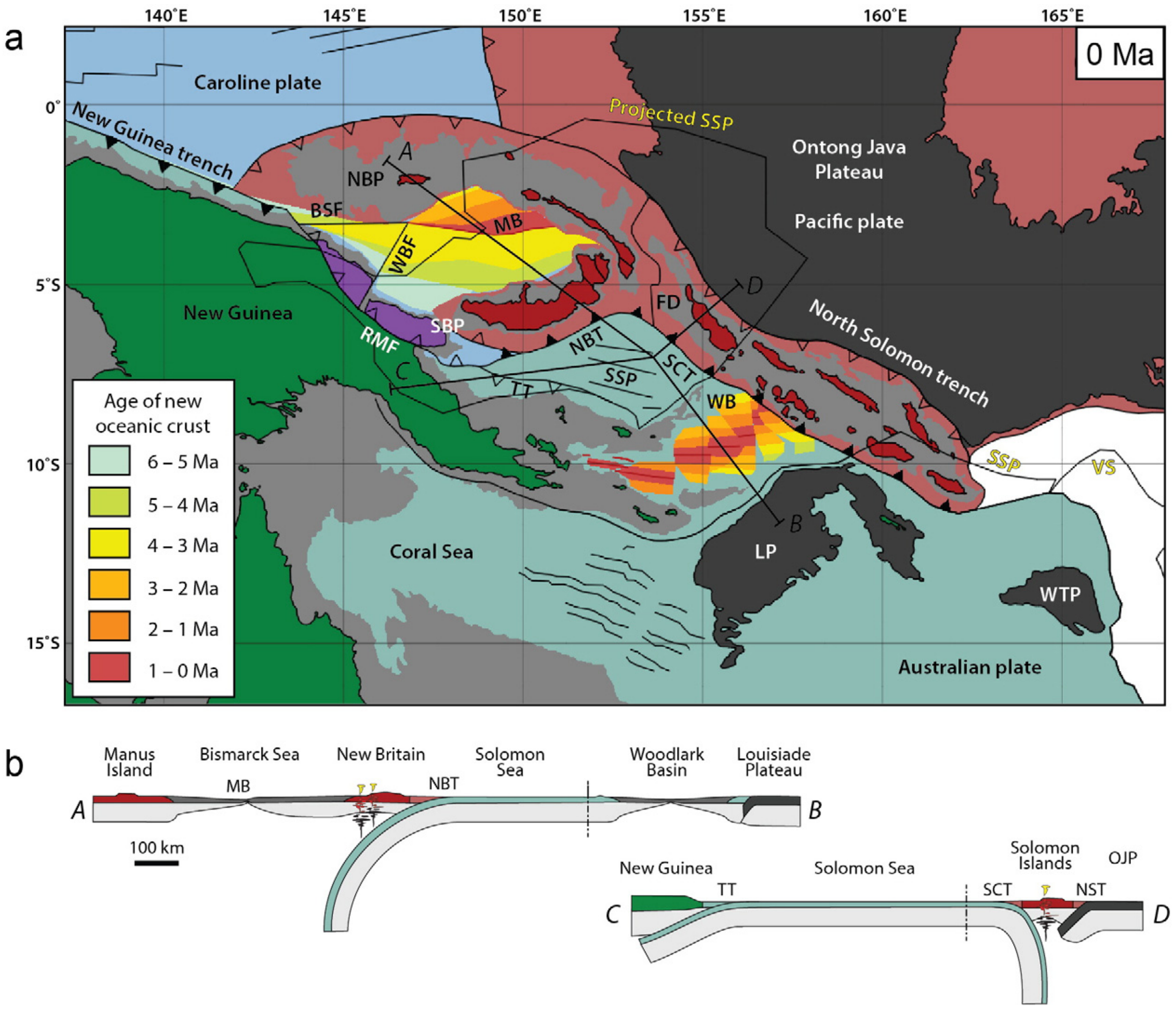

Fig. 5. a) Present day tectonic features of the Papua New Guinea and Solomon Islands region as shown in plate reconstructions. Sea floor magnetic anomalies are shown for the Caroline plate (Gaina and Müller, 2007), Solomon Sea plate (Gaina and Müller, 2007) and Coral Sea (Weissel and Watts, 1979). Outline of the reconstructed Solomon Sea slab (SSP) and Vanuatu slab (VS) models are as indicated. b) Cross-sections related to the present day tectonic setting. Section locations are as indicated. Bismarck Sea fault (BSF); Feni Deep (FD); Louisiade Plateau (LP); Manus Basin (MB); New Britain trench (NBT); North Bismarck microplate (NBP); North Solomon trench (NST); Ontong Java Plateau (OJP); Ramu-Markham fault (RMF); San Cristobal trench (SCT); Solomon Sea plate (SSP); South Bismarck microplate (SBP); Trobriand trough (TT); projected Vanuatu slab (VS); West Bismarck fault (WBF); West Torres Plateau (WTP); Woodlark Basin (WB).

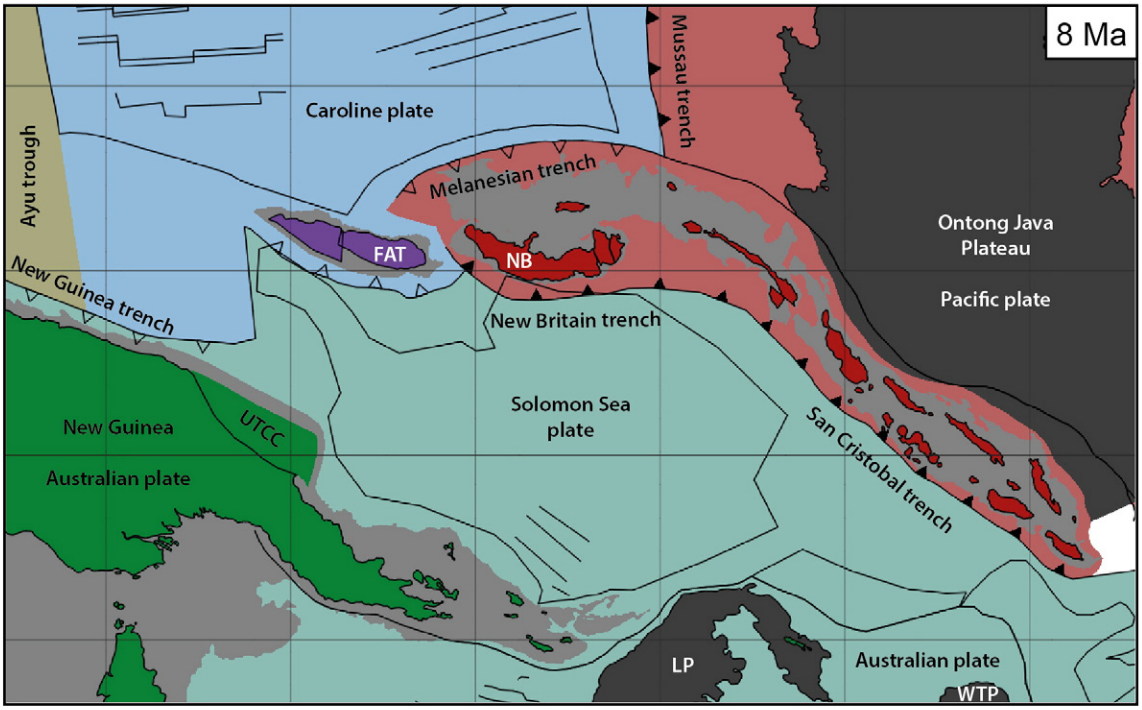

Fig. 6. Reconstruction at 8 Ma. On all reconstructions (Figs. 5–12) the projected slab model of the Solomon Sea plate is shown as an outline as indicated, and reconstructed as a rigid object that is represented at the surface of the Earth. Outlines for the present day extent of the Caroline plate and Australian plate are shown for reference. Age of new oceanic crust is according to the legend in Fig. 5. Continental or thickened arc crust is colored grey and oceanic plateaus are denoted by darkened shaded areas on the corresponding plate. Subduction zones are indicated by bold black lines and annotated with filled triangles to illustrate active subduction, or empty triangles illustrating absent or slow subduction at the trench. Active spreading centers are shown as red lines. From 8 Ma convergence is accommodated by subduction at the Mussau trench, New Britain trench and San Cristobal trench. Finisterre-Adelbert Terrane (FAT); New Britain (NB); Louisiade Plateau (LP); present day underthrust continental crust (UTCC); West Torres Plateau (WTP).

4. Reconstruction

A reconstruction relative to the moving Indian/Atlantic hotspot reference frame is presented in the time intervals 8–6 Ma, 6–4 Ma, 4–2 Ma, and 2–0 Ma (Figs. 5–12). Alternatives reconstructions relative to fixed Australia or Pacific reference frames, and associated animations, can be downloaded from the supplementary material.

4.1. Tortonian-Messinian (8–6 Ma)

At 8 Ma, the tectonic setting of Papua New Guinea and Solomon Islands was largely dominated by north-dipping subduction of the Solomon Sea plate and Australian plate at the New Britain and San Cristobal trenches (Fig. 6). This subduction regime was established following collision of the Australian continent with New Guinea and cessation of subduction at the Pocklington trough from ca. 12 Ma (Cloos et al., 2005; Webb et al., 2014; Holm et al., 2015).

In the west, motion of the Caroline plate is interpreted to have been similar to west-northwest motion of the Pacific plate, but at a lesser rate. The differential rate of plate motion between the Caroline and Pacific plates resulted in convergence that was accommodated at the east-dipping Mussau trench, and slow transpressional convergence at the south-dipping Melanesian trench (Fig. 6). Relative motion between the coupled Finisterre-Adelbert Terrane and Caroline plate, and western New Britain resulted in slow convergence between the two plates, likely along a pre-existing extension of the north-dipping New Britain trench. The location of the Finisterre-Adelbert Terrane at this time was constrained between the surrounding Caroline plate, Melanesian arc and reconstructed Solomon Sea slab (Fig. 6). Relative plate motion between the Caroline plate and New Guinea was accommodated by north-dipping subduction adjacent to the Finisterre-Adelbert Terrane in the east (Abbott, 1995), south-dipping subduction at the New Guinea trench in the west with a left-lateral subduction component (Hall, 2002; Tregoning and Gorbatov, 2004).

4.2. Messinian-Zanclean (6–4 Ma)

From approximately 6 Ma, convergence between the Finisterre-Adelbert Terrane and western New Britain resulted in suturing of the two terranes to form the precursor of the South Bismarck microplate (Figs. 7 & 8). Capture of the Finisterre-Adelbert Terrane by the Melanesian arc terranes and subsequent adoption of Pacific plate motion led to increased convergence rates with the Solomon Sea plate. This convergence was accommodated at the New Britain trench and its westward continuation (Figs. 7 & 8). We interpret that the new western addition to the New Britain trench provided a slab edge that stimulated subduction hinge retreat (e.g. Govers and Wortel, 2005; Stegman et al., 2006; Doglioni et al., 2007) and resulted in back-arc extension and rifting of the newly amalgamated South Bismarck microplate from the Caroline plate. It is possible that rifting began in the west in response to the formation of a slab edge. The eastward propagation of rifting acted to tear New Britain from the remainder of the Melanesian arc, and led to the initiation of sea floor spreading in the Bismarck Sea at ca. 6 Ma (Figs. 7 & 8). From the initial basin opening to ca. 3 Ma the rate of spreading in the Bismarck Sea was ca. 13–14 cm year^{-1} (Fig. 6); this is comparable to modern spreading rates of up to 16 cm year^{-1} in the Lau Basin (Bevis et al., 1995).

Subduction hinge retreat and anticlockwise rotation of the New Britain trench relative to Australia introduced a westward subduction component that was quite distinct from the earlier subduction regime. We interpret that this change in regional kinematics resulted in an anti-clockwise torque applied to the Solomon Sea plate, similar to the findings of Wallace et al. (2014) and Ott and Mann (2015). The applied torque resulted in decoupling of the Solomon Sea plate from the Australian plate, which was expressed by convergence and

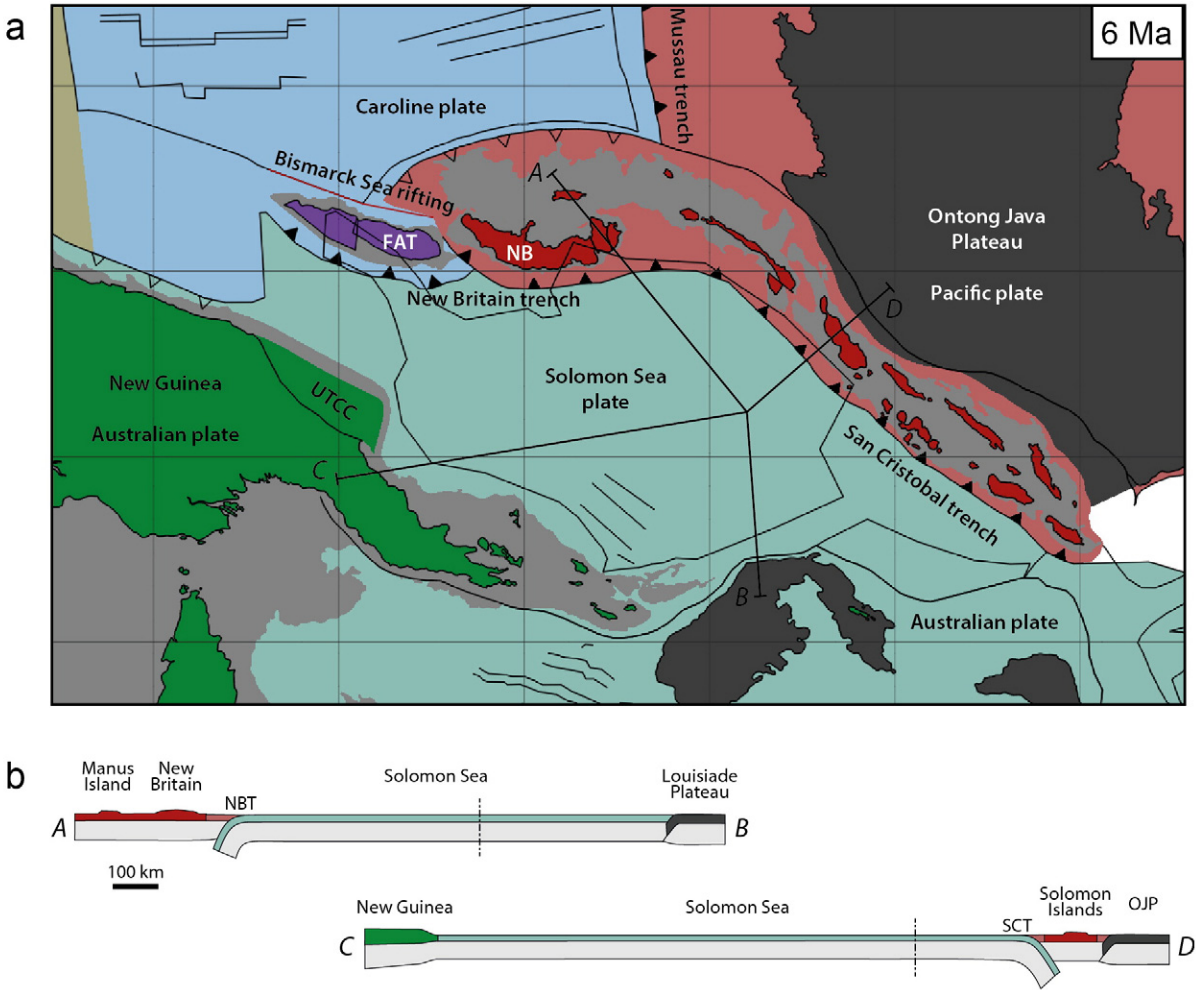

Fig. 7. a) Reconstruction at 6 Ma, and b) related cross-sections. Collision and suturing of the Finisterre-Adelbert Terrane to New Britain leads to westward extension of the New Britain trench and initial rifting of the Finisterre-Adelbert Terrane from the Caroline plate. Finisterre-Adelbert Terrane (FAT); Ontong Java Plateau (OJP); New Britain (NB); New Britain trench (NBT); San Cristobal trench (SCT); present day underthrust continental crust (UTCC).

underthrusting of the southwest Solomon Sea plate beneath Papua New Guinea forming the Trobriand trough from ca. 5 Ma (Fig. 8). In the east, rotational extension initiated rifting and sea floor spreading in the Woodlark Basin, in line with findings from Taylor et al. (1999) and Wallace et al. (2014).

The involvement of the Woodlark spreading center in the lower plate of the San Cristobal subduction resulted in a profound tectonic response for the Solomon Islands in the upper plate. The timing of ridge subduction overlaps with shortening across the Solomon Islands and convergence at the North Solomon trench adjacent to the Ontong Java Plateau from ca. 5 Ma (Fig. 8; Petterson et al., 1997, 1999; Cowley et al., 2004; Mann and Taira, 2004; Phinney et al., 2004; Taira et al., 2004; Holm et al., 2013). The contemporaneous timing for development of the Woodlark Basin and onset of crustal shortening in the Solomon Islands led Chadwick et al. (2009) and Holm et al. (2013) to interpret that crustal shortening may have resulted from the resistance to subduction provided by the young, buoyant oceanic lithosphere of the Woodlark Basin.

Convergence between the Solomon Islands and the Ontong Java Plateau resulted in differential plate motions between the Solomon Islands and the North Bismarck microplate. Although minor, the relative differences in plate motions must have been accommodated within the Melanesian arc crust. We interpret that the resultant kinematics was expressed by extension and formation of the Feni Deep between the islands of New Ireland and Bougainville (Fig. 8). An extensional origin for the Feni Deep is supported by geochemical studies of the Tabar-Lihir-Tanga-Feni island arc chain (Fig. 2) that suggested that the unusual volcanoes were produced by adiabatic decompression melting of subduction-modified upper mantle (Patterson et al., 1997; Stracke and Hegner, 1998).

From approximately 5 Ma, motion of the Caroline plate became closely aligned with that of the Pacific plate. The reason for this behavior is not clear as there are no obvious hindrances to subduction of the Caroline plate at the New Guinea trench, the Mussau trench or Melanesian trench. Hall (2002) suggested that far-field stresses in Southeast Asia, such as initiation of subduction at the Philippine trench from ca. 5 Ma, may have led to the change in Caroline plate motion. Nonetheless, the change in plate motion resulted in increased convergence rate at the New Guinea trench (Hall, 2002).

4.3. Pliocene (4–2 Ma)

From approximately 4 Ma, convergence between New Guinea and the South Bismarck microplate led to arc-continent collision at the northeast margin of Papua New Guinea (Figs. 9 & 10). This collision event is well documented in Papua New Guinea (e.g. Abbott et al., 1994; Abbott, 1995; Woodhead et al., 2010; Holm and Richards, 2013). Thrusting of the Finisterre-Adelbert Terrane over the continental margin of Papua New Guinea occurred along the western New Britain trench to form the Ramu-Markham fault zone (Figs. 9 & 10; Abbott et al., 1994; Abbott, 1995). Moreover, arc-continent collision and semi-coupling of the Finisterre-Adelbert Terrane to Papua New Guinea

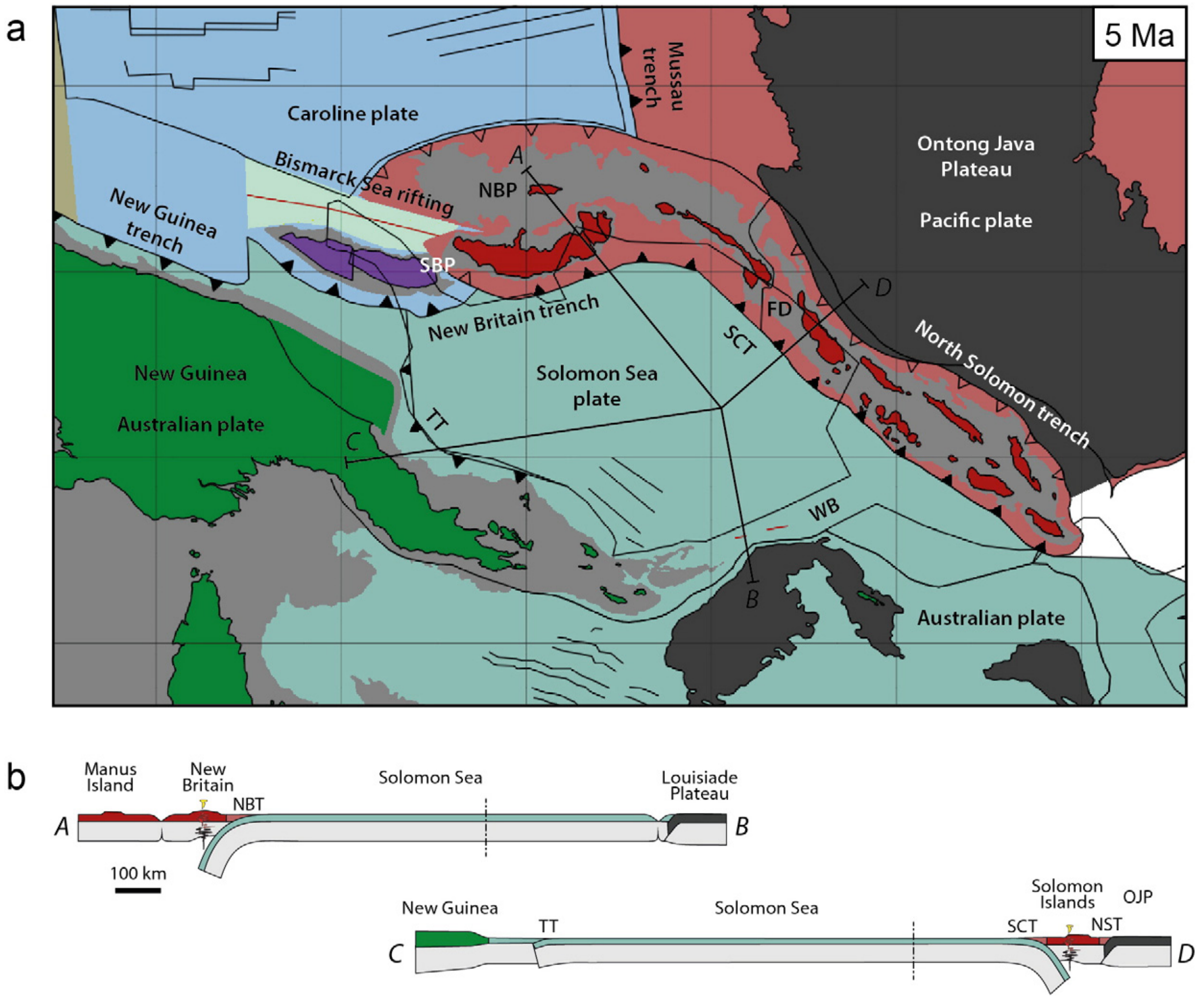

Fig. 8. a) Reconstruction at 5 Ma, and b) related cross-sections. Subduction hinge retreat at the New Britain trench induced extension in the Bismarck Sea and anticlockwise rotation of the Solomon Sea plate relative to Australia. Rotation of the Solomon Sea plate was accommodated by formation of the Trobriand trough and initiation of rifting in the Woodlark Basin. Convergence between the Solomon Islands and the Ontong Java Plateau at the North Solomon trench resulted in differential plate motion between the Solomon Islands and the North Bismarck microplate, and initial opening of the Feni Deep. Feni Deep (FD); New Britain trench (NBT); North Bismarck microplate (NBP); North Solomon trench (NST); Ontong Java Plateau (OJP); South Bismarck microplate (SBP); San Cristobal trench (SCT); Trobriand trough (TT); Woodlark Basin (WB).

caused the anticlockwise rotation of the New Britain trench to stall adjacent to the Finisterre-Adelbert Terrane. With continued subduction hinge retreat of the New Britain trench to the east, the South Bismarck microplate adopted the clockwise rotation relative to Papua New Guinea as indicated by paleomagnetic data (Weiler and Coe, 2000).

Arc-continent collision and clockwise rotation of the South Bismarck microplate marked a major turning point in the plate kinematics of the region. Firstly, semi-coupling of the South Bismarck microplate to Papua New Guinea resulted in complete decoupling of the South Bismarck microplate from the North Bismarck microplate and Melanesian arc along the left-lateral Bismarck Sea fault from ca. 3.5 Ma (Figs. 9 & 10; Taylor, 1979; Martinez and Taylor, 1996). The North Bismarck microplate retained the west-northwest motion of the Pacific plate. Additionally, collision and impinging of the leading Papua New Guinea continental shelf beneath the Finisterre-Adelbert Terrane began to break-up the South Bismarck microplate along the north-south orientated West Bismarck fault, creating a separate Adelbert microplate (Figs. 9 & 10; Wallace et al., 2004; Holm and Richards, 2013). Although relative motion on this structure was slow, the cumulative movement has resulted in noteworthy displacement between the Adelbert and Finisterre Terranes at the present day (Fig. 2; Jaques and Robinson, 1977; Abbott et al., 1994; Holm and Richards, 2013).

Decoupling of the South Bismarck and North Bismarck microplates allowed sea floor spreading to continue in the eastern Bismarck Sea. However, the earlier north-south directed spreading prior to arc-continent collision was replaced by asymmetric southeast directed spreading to form the Manus Basin (Fig. 10; Taylor, 1979; Martinez and Taylor, 1996). In contrast, from 3.5 Ma convergence in the western Bismarck Sea caused the existing Bismarck lithosphere to approach and became subducted at the south-dipping New Guinea trench (Figs. 9 & 10). This subduction of young oceanic lithosphere is in stark contrast to the older Eocene lithosphere of the Caroline plate along strike to the west.

In the east, anti-clockwise rotation of the Solomon Sea plate continued unabated with subduction of the western Solomon Sea at both the New Britain trench and Trobriand trough (Figs. 9 & 10). Continued subduction hinge retreat of the New Britain trench in response to clockwise rotation of the South Bismarck microplate, in combination with westward motion of the Solomon Islands, led to constriction in the curvature of the New Britain trench adjacent to eastern New Britain and New Ireland. Maximum curvature of the New Britain trench was reached at approximately 3 Ma (Fig. 10). By this time, sea floor spreading in the Woodlark Basin was propagating into the continental margin that extended eastward from the Papuan Peninsula (Fig. 10; Taylor et al., 1999; Little et al., 2007). Meanwhile, the established Woodlark spreading center was subducting at the San Cristobal trench adjacent to the central Solomon Islands, and caused extensive arc magmatism (Mann et al., 1998; Chadwick et al., 2009; Schuth et al., 2009). This

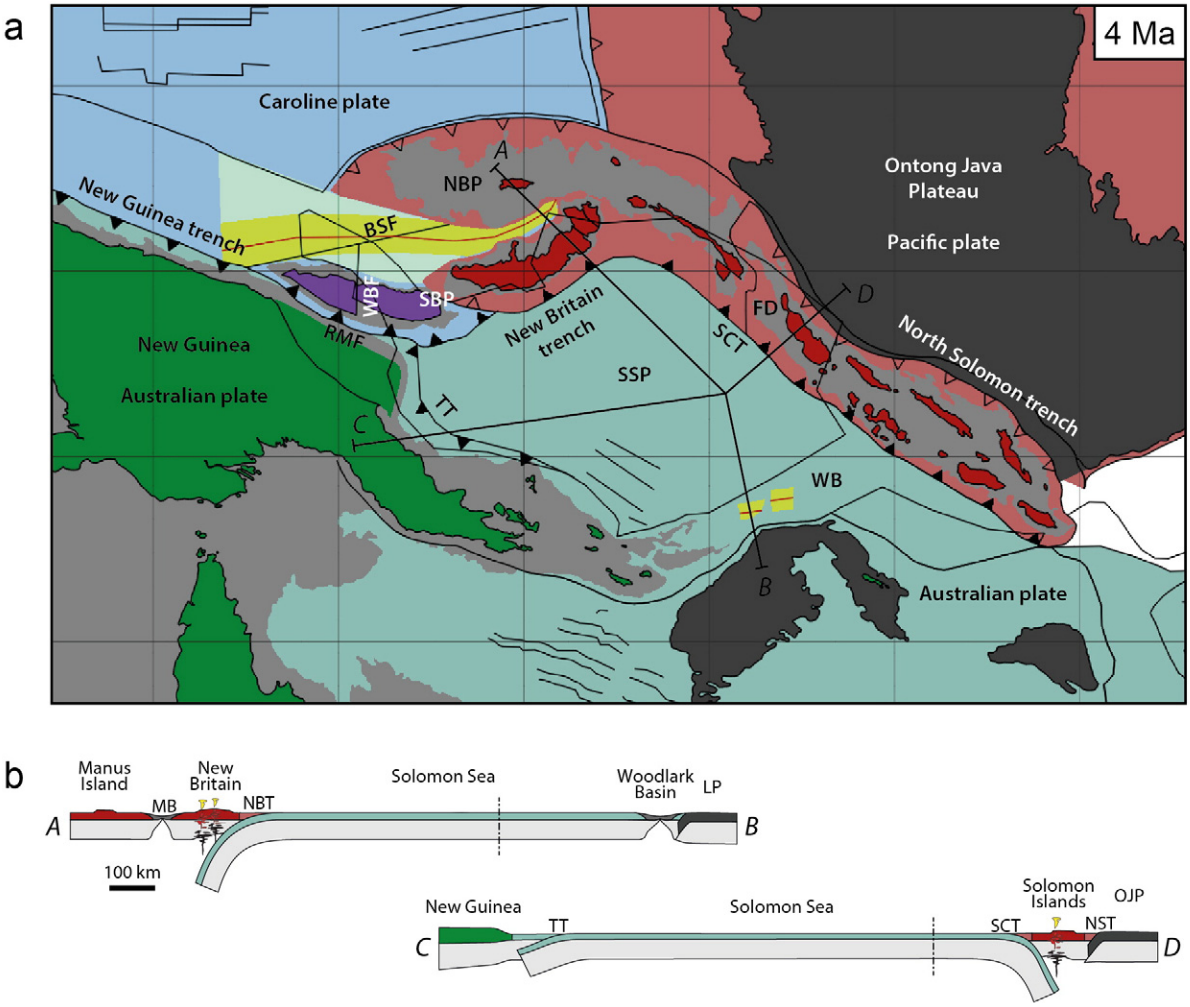

Fig. 9. a) Reconstruction at 4 Ma, and b) related cross-sections. Arc-continent collision thrust the Finisterre-Adelbert Terrane over the continental margin of New Guinea, forming the Ramu-Markham fault. This collision resulted in break-up of the South Bismarck microplate along the Bismarck Sea fault and the West Bismarck fault. The Caroline plate and western Bismarck Sea were subducted at the New Guinea trench. Rotation of the Solomon Sea plate continued with subduction at the Trobriand trough, New Britain trench, and San Cristobal trench; extension continued in the Woodlark Basin and Feni Deep. Bismarck Sea fault (BSF); Feni Deep (FD); Manus Basin (MB); North Bismarck microplate (NBP); New Britain trench (NBT); North Solomon trench (NST); Ontong Java Plateau (OJP); Ramu-Markham fault (RMF); South Bismarck microplate (SBP); San Cristobal trench (SCT); Solomon Sea plate (SSP); Trobriand trough (TT); West Bismarck fault (WBF); Woodlark Basin (WB).

was exemplified by formation of the New Georgia group islands from ca. 3.5 Ma that coincide with the location of spreading ridge subduction (Petterson et al., 1999; Chadwick et al., 2009; Schuth et al., 2009).

4.4. Quaternary (2–0 Ma)

Recent tectonic activity in the Papua New Guinea and Solomon Islands region is presented in Figs. 5, 11 and 12. In the western Bismarck Sea, subduction of the North Bismarck microplate and the Caroline plate continued at the New Guinea trench (Cooper and Taylor, 1987; Tregoning and Gorbatov, 2004). The boundary between the Caroline plate and younger North Bismarck microplate was not fixed relative to the New Guinea trench (and New Guinea) but progressively moved to the west.

The Ramu-Markham fault zone accommodated convergence and overthrusting of the Finisterre and Adelbert Terranes above the leading New Guinea continental margin (Figs. 11 & 12). Associated underthrusting of the continental margin to approximately 100 km depth in the mantle resulted in crustal-derived arc magmatism in the West Bismarck arc (Fig. 2; Woodhead et al., 2010; Holm and Richards, 2013). In the eastern Bismarck Sea, the clockwise rotation of the South Bismarck microplate resulted in continued extension in the Manus Basin. Displacement between New Britain and New Ireland related to plate rotation induced faulting of the Gazelle Peninsula of east New Britain, and similar displacement at the Wietin fault in southeast New Ireland (Fig. 2; Madsen and Lindley, 1994; Lindley, 2006).

In the east, sea floor spreading was sustained in the Woodlark Basin. The spreading center continued to propagate westward into the continental crust of the Papuan Peninsula (Figs. 5, 11 & 12; Taylor et al., 1999; Little et al., 2007). In the northeast, subduction of the young Woodlark Basin and active spreading center continued at the San Cristobal trench (Mann et al., 1998; Chadwick et al., 2009; Schuth et al., 2009). From the reconstructions, it seems that the location for subduction of the Woodlark spreading center has likely remained somewhat constant relative to the Solomon Islands and adjacent to the New Georgia Group islands (Figs. 5; 10–12).

Subduction of the Solomon Sea plate continued, predominantly at the New Britain trench and San Cristobal trench. The rotational component of the Solomon Sea plate motion appeared to slow significantly from ca. 2 Ma, and similarly, the rate of subduction at the Trobriand trough appears to slow from ca. 2 Ma. We interpret that this change in the kinematics of the Solomon Sea plate resulted from the propagation of the Woodlark spreading center to the west of the previous rotational pole, which was located in the southern tip of the Solomon Sea (Fig. 11).

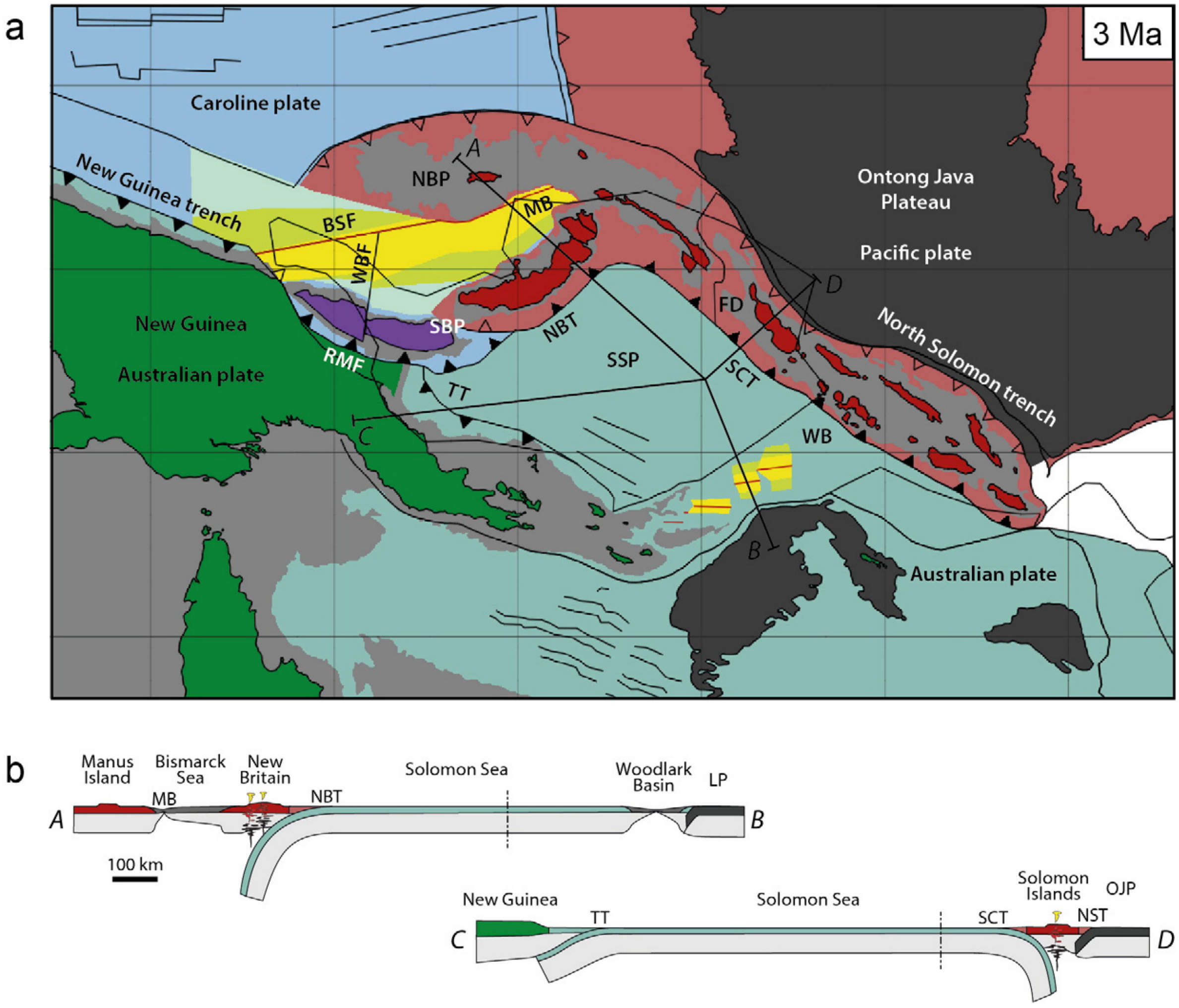

Fig. 10. a) Reconstruction at 3 Ma, and b) related cross-sections. Arc-continent collision of the Finisterre-Adelbert Terrane continued at the Ramu-Markham fault. Clockwise rotation of the South Bismarck plate led to extension in the eastern Bismarck Sea with formation of the Manus Basin. Subduction continued at the New Guinea trench and marginal to the Solomon Sea plate, together with continued extension of the Woodlark Basin. Bismarck Sea fault (BSF); Feni Deep (FD); Louisiade Plateau (LP); Manus Basin (MB); North Bismarck microplate (NBP); New Britain trench (NBT); North Solomon trench (NST); Ontong Java Plateau (OJP); Ramu-Markham fault (RMF); South Bismarck microplate (SBP); San Cristobal trench (SCT); Solomon Sea plate (SSP); Trobriand trough (TT); West Bismarck fault (WBF); Woodlark Basin.

5. Discussion

5.1. Subduction of the Caroline Plate and western Bismarck Sea

The reconstruction provides an updated account of convergence between the coupled Caroline plate and North Bismarck microplate with New Guinea, and subduction of both the Eocene Caroline plate lithosphere and young Bismarck Sea lithosphere at the New Guinea trench (Figs. 9–12; Cooper and Taylor, 1987; Tregoning and Gorbatov, 2004). Evidence for this crustal interface has now been largely removed from the surface by subduction at the New Guinea trench (Fig. 5). Contrasting ages and morphology of subducting slabs arriving at subduction zones have previously been attributed to changes in the angle of the subducting slab, which may impact significantly on the dynamics and kinematics of the adjacent upper plate (Lallemand et al., 1992; Cloos, 1993; Rosenbaum et al., 2005; Billen and Hirth, 2007; Schellart, 2008; Rosenbaum and Mo, 2011; Richards and Holm, 2013). A shallow dip angle has commonly been linked to crustal shortening in the upper plate (Cloos, 1993; Schellart, 2008; Rosenbaum and Mo, 2011). Previous studies have highlighted the difficulty in correlating slab age with subduction angle (e.g. Cruciani et al., 2005; Di Giuseppe et al., 2009). However, Billen and Hirth (2007) demonstrated that in young oceanic lithosphere (<90 Ma) that is limited to upper mantle depths (i.e. slab depths <670 km) there is a correlation between younger slab ages and a decrease in slab dip over the length of the slab.

In the New Guinea trench, it is clear that the change in lithosphere age at the Caroline-Bismarck interface coincides with significant upper plate tectonic phenomena. These include a change in the morphology of the New Guinea trench adjacent to the plate interface, and the coincident development of the overriding Mamberamo thrust belt (Figs. 1, 5 & 11). Crustal shortening in the Mamberamo thrust belt occurred in the Pleistocene (Dow and Sukamto, 1984) and was generated by northeast-southwest compression (Pubellier and Ego, 2002). These upper crustal shortening features are consistent with subduction hinge advance related to a shallow slab dip at the New Guinea trench.

There are several similarities between subduction of the young Bismarck lithosphere at the New Guinea trench and subduction of the Woodlark Basin at the San Cristobal trench. Firstly, subduction of young, buoyant Woodlark Basin lithosphere beneath the Solomon Islands resulted in crustal shortening in the upper plate (Chadwick et al., 2009; Rosenbaum and Mo, 2011; Holm et al., 2013), and secondly, subduction of both the Woodlark Basin at the San Cristobal trench and the Bismarck lithosphere at the New Guinea trench are associated with an absence of extensive seismicity that would normally characterize such convergent plate boundary settings (Curtis, 1973; Weissel et al., 1982; Hall and Spakman, 2002). This may reflect a lack of coherence and

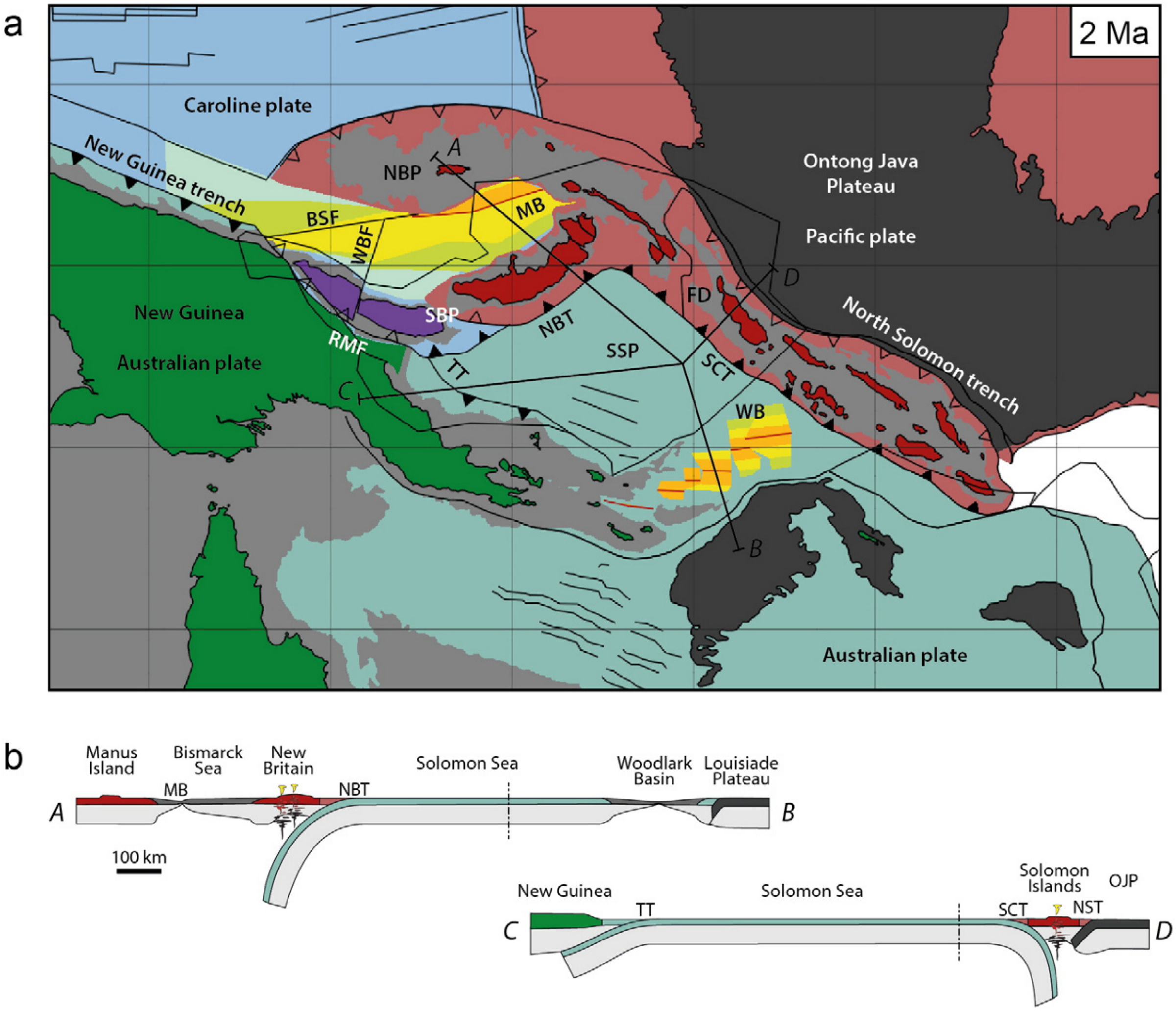

Fig. 11. a) Reconstruction at 2 Ma, and b) related cross-sections. Convergence across the region is accommodated at the New Guinea trench, Ramu-Markham fault, New Britain trench and the San Cristobal trench. Extension continued in the Manus Basin and Woodlark Basin. Bismarck Sea fault (BSF); Feni Deep (FD); Manus Basin (MB); North Bismarck microplate (NBP); New Britain trench (NBT); North Solomon trench (NST); Ontong Java Plateau (OJP); Ramu-Markham fault (RMF); South Bismarck microplate (SBP); San Cristobal trench (SCT); Solomon Sea plate (SSP); Trobriand trough (TT); West Bismarck fault (WBF); Woodlark Basin (WB).

strength in very young lithosphere where the crust may yield and deform rather than fracture.

5.2. Subduction at the Trobriand trough

The Trobriand trough is interpreted in our reconstruction as a zone of active convergence and subduction since ca. 5 Ma. Its formation was likely related to the onset of Solomon Sea microplate tectonics, triggered by the collision of New Britain and the Finisterre-Adelbert Terrane, and the anticlockwise rotation of the New Britain trench relative to Australia (Figs. 5; 7–12). The interpreted timing for subduction and convergence at the Trobriand trough also coincides with shortening of the Aure-Moresby fold-thrust belt of the Papuan Peninsula from the late Miocene (Ott and Mann, 2015).

At present the Trobriand trough does not appear to accommodate significant convergence and thus is not an active plate boundary (Abers et al., 2002; Hall and Spakman, 2002; Wallace et al., 2004). Our proposed plate kinematic reconstructions explains the absence of widespread subduction-related seismicity and tomographic anomalies adjacent to the trench (Abers et al., 2002; Hall and Spakman, 2002) in that only limited subduction occurred in the south and east of the Trobriand trough compared to the north (Holm and Richards, 2013).

5.3. The Solomon Arc, North Solomon Trench, and Feni Deep

Like the Trobriand Trough, the Feni Deep represents seafloor structure that has hitherto not been explained. Our reconstruction helps to resolve the origin of this bathymetric low in a complex triple point plate boundary setting. As shown in the reconstruction, anticlockwise rotation of the Solomon Sea plate resulted in extension and the formation of the Woodlark Basin from at least ca. 5 Ma (Figs. 5; 8–12; Taylor et al., 1995, 1999; Wallace et al., 2014). Much of the evidence for this early extension has been obliterated from the geological record by subduction at the San Cristobal trench (Taylor et al., 1999). However, the timing for the interpreted onset of Woodlark Basin spreading coincides with evidence for crustal shortening across the Solomon Islands and at the North Solomon trench from ca. 5 Ma (Fig. 8). The continued subduction at the San Cristobal trench induced shortening across the Solomon Islands arc crust that resulted in convergence between the Solomon Islands and the Ontong Java Plateau at the North Solomon trench (e.g. Cowley et al., 2004; Mann and Taira, 2004; Phinney et al., 2004; Taira et al., 2004).

The suggestions for crustal shortening in the Solomon Islands and activation of the North Solomon trench are not new ideas, but the implications of this interpretation within the Melanesian arc have not yet been fully considered. Given the absence of any evidence for

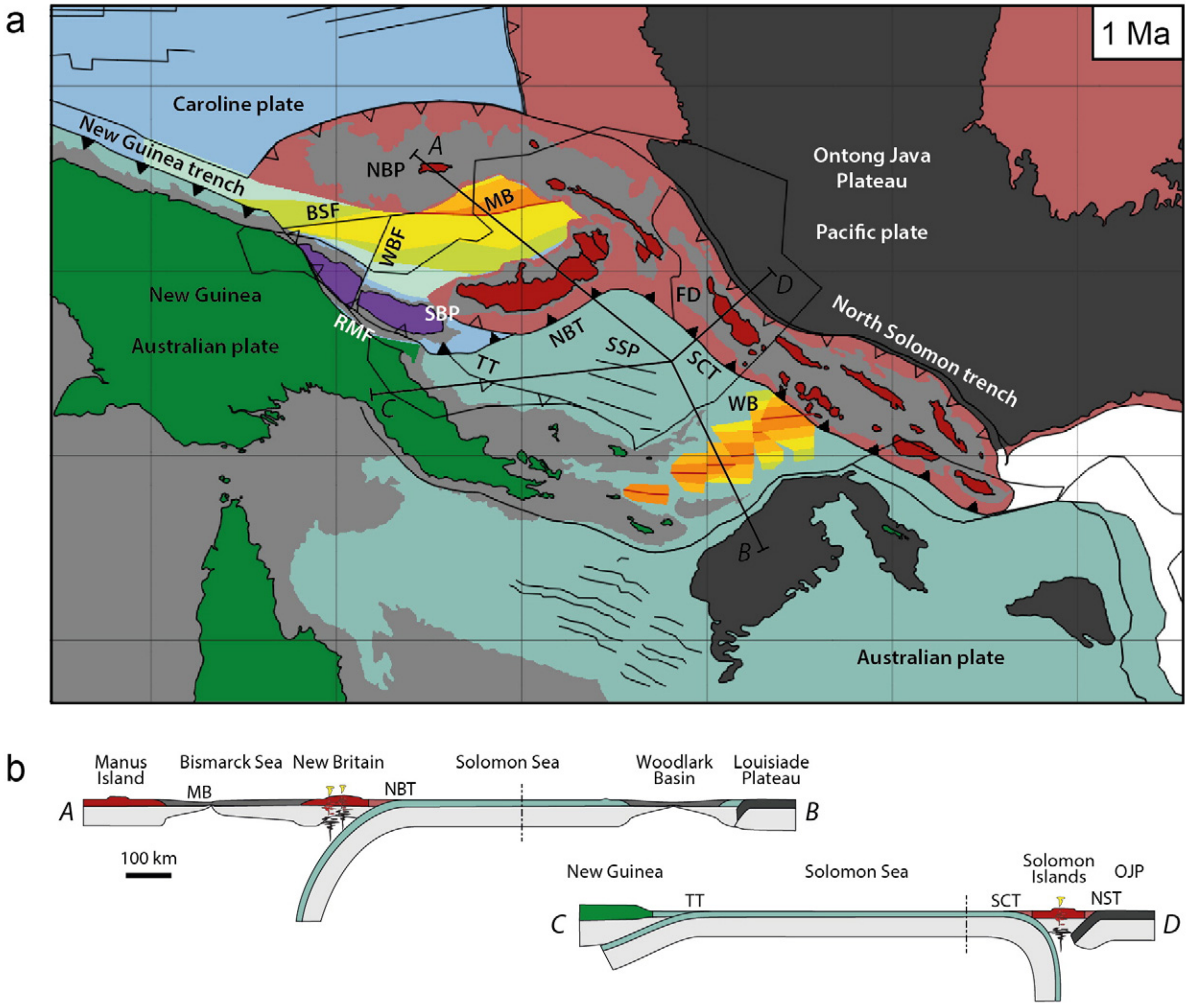

Fig. 12. a) Reconstruction at 1 Ma, and b) related cross-sections. The region began to closely resemble the present day tectonic setting with subduction at the New Guinea trench, the New Britain trench, and the San Cristobal trench; with extension and seafloor spreading in the Manus Basin and Woodlark Basin. Bismarck Sea fault (BSF); Feni Deep (FD); Manus Basin (MB); North Bismarck microplate (NBP); New Britain trench (NBT); North Solomon trench (NST); Ontong Java Plateau (OJP); Ramu-Markham fault (RMF); South Bismarck microplate (SBP); San Cristobal trench (SCT); Solomon Sea plate (SSP); Trobriand trough (TT); West Bismarck fault (WBF); Woodlark Basin (WB).

convergence between the North Bismarck microplate and Pacific plate at the Melanesian trench, convergence at the North Solomon trench requires differential plate kinematics between North Bismarck microplate and Solomon Islands segments of the Melanesian arc (Figs. 5; 8–12). Furthermore, the reconstruction illustrates that slowing of the plate motion of the Solomon Islands with continued motion of the North Bismarck microplate introduced a component of extension within the Melanesian arc. We interpret that this intra-arc extension was expressed by oblique rifting and formation of the Feni Deep from ca. 5 Ma (Fig. 8). This proposed mechanism for the origin of the Feni Deep is supported by previous geochemical interpretations of an extension related origin for the Tabar-Lihir-Tanga-Feni island arc (Patterson et al., 1997; Stracke and Hegner, 1998).

6. Conclusions

A new plate tectonic reconstruction for the Papua New Guinea and Solomon Islands region shows that from 8 Ma, the region was dominated by subduction of the Solomon Sea plate and Australian plate at the New Britain and San Cristobal trenches. At ca. 6 Ma, crustal elements began to interact across the wider Pacific-Australia plate boundary, with suturing of the Finisterre-Adelbert Terrane and New Britain forming the South Bismarck microplate. Subduction hinge retreat at the New Britain trench coincided with rifting of the South Bismarck microplate, which formed the Bismarck Sea from ca. 6 Ma. Anti-clockwise rotation of the Solomon Sea plate relative to Australian resulted in convergence and underthrusting of the Solomon Sea plate beneath Papua New Guinea, which formed the Trobriand trough from ca. 5 Ma, and coincided with rifting and sea floor spreading in the Woodlark Basin. Subduction of the Woodlark Basin at the San Cristobal trench, from ca. 5 Ma, resulted in crustal shortening across the Solomon Islands and convergence with the Ontong Java Plateau at the North Solomon trench, and the associated formation of the Feni Deep. From ca. 4 Ma, arc-continent collision between the Finisterre-Adelbert Terrane and Papua New Guinea formed the Ramu-Markham fault zone. This collision was marked by (1) decoupling of the South and North Bismarck microplates along the left-lateral Bismarck Sea fault from ca. 3.5 Ma; (2) break-up of the South Bismarck microplate along the West Bismarck fault, creating a separate Adelbert microplate; and (3) initiation of seafloor spreading in the Manus Basin. The reconstruction provides an insight into the plate kinematic history of the region and highlights specific tectonic events and processes that have not previously been documented. Such tectonic interactions illustrate the role of microplate tectonics in complex convergent margins and provide an analogue for plate kinematics that may be preserved in ancient orogenic systems.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.earscirev.2016.03.005.

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