A re-evaluation of arc-continent collision and along-arc variation in the Bismarck Sea region, Papua New Guinea

Article *in* Australian Journal of Earth Sciences · July 2013

DOI: 10.1080/08120099.2013.824505

Robert Holm
James Cook University

Australian Journal of Earth Sciences (2013)
60, 605–619, http://dx.doi.org/10.1080/08120099.2013.824505

A re-evaluation of arc–continent collision and along-arc variation in the Bismarck Sea region, Papua New Guinea

R. J. HOLM* AND S. W. RICHARDS

School of Earth and Environmental Sciences, James Cook University, Townsville, Queensland 4811, Australia.

The Bismarck Sea region of Papua New Guinea is marked by recent arc–continent collision giving rise to a highly dynamic tectonic environment, characterised by complex plate interactions that are yet to be fully understood. We present a new crustal and upper mantle crustal architecture model for northeastern Papua New Guinea and western New Britain that reveals complex tectonic geometries of overprinting slab subduction and partial continental subduction, resulting in a unique setting in which to investigate along-arc magmatic variation. Earthquake hypocentre databases are combined with detailed topography and seafloor structure together with geology and regional-scale gravity to unravel the sub-surface structure of northeastern Papua New Guinea. These data are used in conjunction with an updated 3-D slab map of the region to propose a new interpretation of the area whereby Australian continental crust extends as an underthrust block beneath the accreted Finisterre Terrane. The subducting continental crust combined with slab stagnation has resulted in a complex pattern of arc-related geochemical signatures from east to west along the Bismarck arc. In the east, where the Solomon Sea plate is subducting beneath New Britain, the sedimentary component is low, whereas in the west, the arc volcanics exhibit a greater sedimentary component, consistent with subduction of Australian crustal sediments. As a result, a new plate reconstruction is provided for the region together with a forward-looking reconstruction of the Papuan peninsula, the Solomon Sea plate and New Britain that illustrates that the same process will likely be repeated in some 5–10 m.y.

KEY WORDS: Papua New Guinea, Bismarck arc, arc–continent collision, gravity, seismicity, arc geochemistry.

INTRODUCTION

The boundary between the northern Australian plate and the Pacific plate, which includes the Bismarck Sea region of Papua New Guinea (Figure 1), comprises some of the youngest and most active tectonic elements of the southwest Pacific (e.g. Taylor 1979; Abbott 1995; Martinez & Taylor 1996; Weiler & Coe 2000). Northward motion of the Australian plate has led to a scenario where both continental and oceanic crust is interacting along the northern plate boundary. The complexities of present-day crustal and mantle geometries have emerged from new information and a reinterpretation of the mechanisms leading to the tectonic amalgamation of the area is required. Here we focus on just the latest 4 Ma or so in northeastern Papua New Guinea where in this short time arc–continent collision has consumed tectonic plates and uplifted mountain ranges to more than 4000 m, neighboured by contemporary island arc magmatism, culminating in highly dynamic and striking geological landscapes. Numerous workers have sought to explain these processes of, for example, arc volcanism in the western Bismarck Sea, the source of earthquakes, or the timing and nature of arc–continent collision; however, these models lack an overarching geological model with cross-disciplinary foundations that can account for all geological phenomena.

We present a compilation and reinterpretation of an extensive catalogue of previous data, including topography/bathymetry, earthquake hypocentres, regional-scale gravity, geology and geochemistry, and models depicting the complex tectonic history of Papua New Guinea and the southwest Pacific. From this we re-evaluate and address gaps in our knowledge of the present-day 3-D tectonic setting of northeast Papua New Guinea and the Bismarck Sea. Using a new and robust regional tectonic model, we assess the role of recent arc–continent collision in construction of the present-day tectonic puzzle that is Papua New Guinea.

The global importance of arc–continent collision has been addressed by several authors related to the Africa–Europe collision (e.g. Rosenbaum *et al.* 2002; Kley & Voigt 2008) or the India–Asia collision (e.g. Hendrix *et al.* 1994; Sobel & Dumitru 1997; Najman *et al.* 2010); however, the southwest Pacific offers the unique opportunity to observe the process in action. Furthermore, recognition of the subtle processes and mechanisms of collision that are not apparent at the surface, such as crustal underthrusting and associated arc magmatism, will contribute

*Corresponding author: rob.holm@my.jcu.edu.au

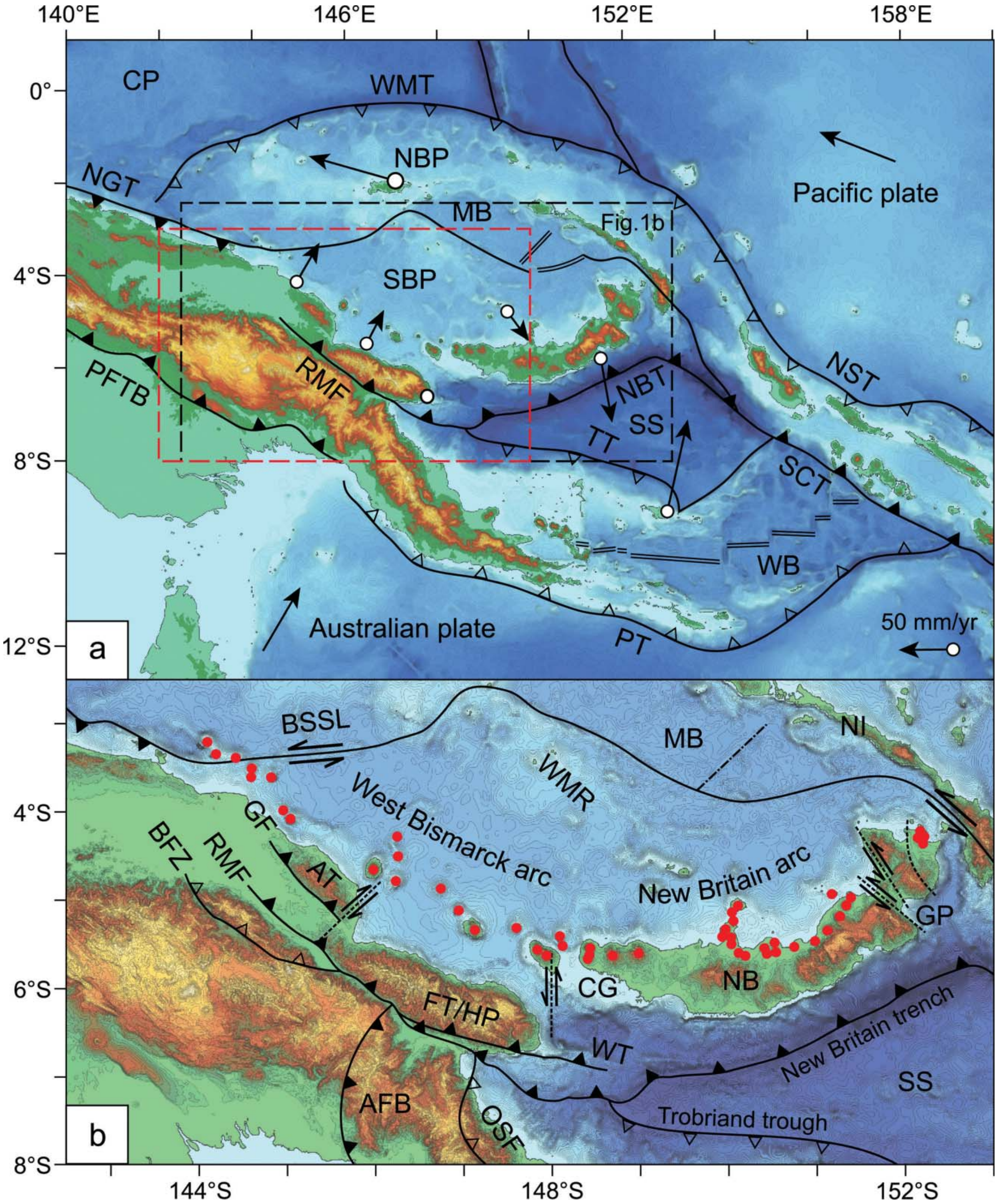

Figure 1 Topography, bathymetry and major tectonic elements of the study area. (a) Major tectonic boundaries of Papua New Guinea and the western Solomon Islands; CP, Caroline plate; MB, Manus Basin; NBP, North Bismarck plate; NBT, New Britain trench; NGT, New Guinea trench; NST, North Solomon trench; PFTB, Papuan Fold and Thrust Belt; PT, Pocklington trough; RMF, Ramu-Markham Fault; SBP, South Bismarck plate; SCT, San Cristobal trench; SS, Solomon Sea plate; TT, Trobriand trough; WB, Woodlark Basin; WMT, West Melanesian trench. Study area is indicated by rectangle labelled Figure 1b; the other inset rectangle highlights location for subsequent figures. Present day GPS motions of plates are indicated relative to the Australian plate (from Tregoning *et al.* 1998, 1999; Tregoning 2002; Wallace *et al.* 2004). (b) Detailed topography, bathymetry and structural elements significant to the South Bismarck region (terms not in common use are referenced); AFB, Aure Fold Belt (Davies 2012); AT, Adelbert Terrane (e.g. Wallace *et al.* 2004); BFZ, Bundi Fault Zone (Abbott 1995); BSSL, Bismarck Sea Seismic Lineation; CG, Cape Gloucester; FT, Finisterre Terrane; GF, Gogol Fault (Abbott 1995); GP, Gazelle Peninsula; HP, Huon Peninsula; MB, Manus Basin; NB, New Britain; NI, New Ireland; OSF, Owen Stanley Fault; RMF, Ramu-Markham Fault; SS, Solomon Sea; WMR, Willaumez-Manus Rise (Johnson *et al.* 1979); WT, Wonga Thrust (Abbott *et al.* 1994); minor strike-slip faults are shown adjacent to Huon Peninsula (Abers & McCaffrey 1994) and in east New Britain, the Gazelle Peninsula (e.g. Madsen & Lindley 1994). Circles indicate centres of Quaternary volcanism of the Bismarck arc. Filled triangles indicate active thrusting or subduction, empty triangles indicate extinct or negligible thrusting or subduction.

to our understanding of collision events and terrane accretion at ancient convergent margins.

TECTONIC SETTING

Papua New Guinea and much of the southwest Pacific occupy a zone of oblique convergence between the Australian and Pacific plates (Figure 1). The tectonic history of the region is significantly more complex than other arcs owing to the number of recognised small plates within the region. This scenario arises from the positioning of Papua New Guinea within a regional-scale collision zone between the Australian continental crust in the south (Abbott 1995; Hall 2002; Davies 2012) and the Ontong Java Plateau in the northeast (Petterson *et al.* 1999; Hall 2002; Mann & Taira 2004). The relative direction of plate convergence has resulted in development of oblique spreading centres and the formation of numerous micro-plates and associated plate boundaries. The principal tectonic elements comprising this complex zone are shown on Figure 1, but emphasis is placed on the Australian plate, the Finisterre Terrane (described in detail below), New Britain and the North and South Bismarck plates.

Previous research has suggested that from the Upper Oligocene to the latest Neogene, northern Papua New Guinea is marked by a series of arc–continent collisions. The youngest and most significant of these collisions resulted in the accretion of the Adelbert and Finisterre Terranes, the latter of which forms a prominent topographic high known as the Finisterre Range (Figure 1; Abbott *et al.* 1994; Abbott 1995). Abbott *et al.* (1994) studied clastic sequences on the southern flanks of the Finisterre Range and concluded that the collision must have initiated at *ca* 3.7–3.0 Ma. The Adelbert and Finisterre Terranes are largely composed of Paleogene through to earliest Neogene volcanic arc rocks overlain by Miocene to Plio–Pleistocene limestone (Jaques & Robinson 1977; Weiler & Coe 2000). Collision of these terranes with Papua New Guinea is interpreted to have resulted from the closure of the Solomon Sea at the New Britain trench owing to subduction-driven convergence between the Australian and South Bismarck plates (e.g. Abbott 1995; Hill & Raza 1999; Weiler & Coe 2000). Oblique collision started in the west and propagated southeastwards, producing progressive thrusting and uplift of the north coast Adelbert and Finisterre Ranges (Johnson & Jaques 1980; Abbott 1995; Weiler & Coe 2000).

At present, the ongoing convergence between the Finisterre Terrane and the Australian plate is accommodated by activity along the Ramu-Markham Thrust Fault (e.g. Cooper & Taylor 1987; Abbott *et al.* 1994; Pegler *et al.* 1995). All previous studies regarding this episode of arc–continent collision have focused on the Finisterre Terrane, the uplifted and exposed upper plate. The outstanding topography of the Finisterre Range, however, only arises as the Finisterre Terrane is thrust over the former northern coastward margin of Papua New Guinea. This concept, and the nature or expanse of the now underthrust Papua New Guinea margin has only been suggested in passing by previous studies, but should be regarded as an important, although missing piece of Papua New Guinea. This statement is particularly significant given the prominence of major suture zones and structures converging with the Ramu-Markham Fault and underthrust beneath the Finisterre Terrane, for example the Owen Stanley Fault and the Aure Fold Belt (Figure 1).

The recent collision of the Adelbert and Finisterre Terranes is reflected in the regional tectonics of the Bismarck Sea. The inferred timing of plate coupling at 3.7 Ma (Abbott *et al.* 1994) is coincident with the earliest breakup and opening of the New Britain back-arc, which in turn created two new micro-plates, the North and South Bismarck plates (Taylor 1979). The South Bismarck plate is currently rotating clockwise at a rate of 8°/Ma relative to Australia (Tregoning *et al.* 1999; Weiler & Coe 2000; Wallace *et al.* 2004) while the west-northwest motion of the North Bismarck plate is similar to the Pacific plate (Tregoning *et al.* 1998; Wallace *et al.* 2004) suggesting almost complete coupling between the North Bismarck and Pacific plates (Figure 1). In the eastern Bismarck Sea, the East Manus spreading centre separates the North and South Bismarck Sea plates (Martinez & Taylor 1996). However, in the western Bismarck Sea, the boundary becomes the Bismarck Sea seismic lineation, defined primarily by earthquake epicentre locations and characterised by left-lateral transform faults and associated step-over rifts (Denham 1969; Taylor 1979). Thus, the Manus Basin accommodates the majority of extension and rotation in the eastern part of the Bismarck Sea while in the west, the Bismarck Sea seismic lineation becomes a discrete, east–west oriented strike-slip plate boundary (Figure 1; Cooper & Taylor 1987; Llanes *et al.* 2009).

North-dipping subduction of the Solomon Sea plate beneath New Britain, in addition to the convergence responsible for terrane accretion, has resulted in the formation of the active Bismarck volcanic arc. The arc occupies the northern part of the island of New Britain and extends to the west where it is present as a series of volcanic islands off the northwest coast of New Britain and northeast coast of the Papua New Guinea mainland where it forms the West Bismarck Arc (Figure 1). The composition of the volcanics centred on and around the island of New Britain range from basalt to rhyolite with typical low-K, island arc tholeiite signatures (Jakes & Gill 1970). The compositions differ markedly in the West Bismarck arc with predominantly a medium-K character (Woodhead *et al.* 2010). Along-arc variation, recently been investigated by Woodhead *et al.* (2010), is discussed below.

DATA AND DATA-ANALYSIS TECHNIQUES

Earthquakes

The interpretations and reconstructions presented below have been resolved using a variety of datasets combined into a single 3-D tectonic map of the region using the software GOCAD. Seismic data provide a useful indicator for active tectonic structures such as faults and subducting slabs (Figure 2). We utilise a combination of earthquake records including the EHB hypocentre catalogue (Engdahl *et al.* 1998; Engdahl 2006) and

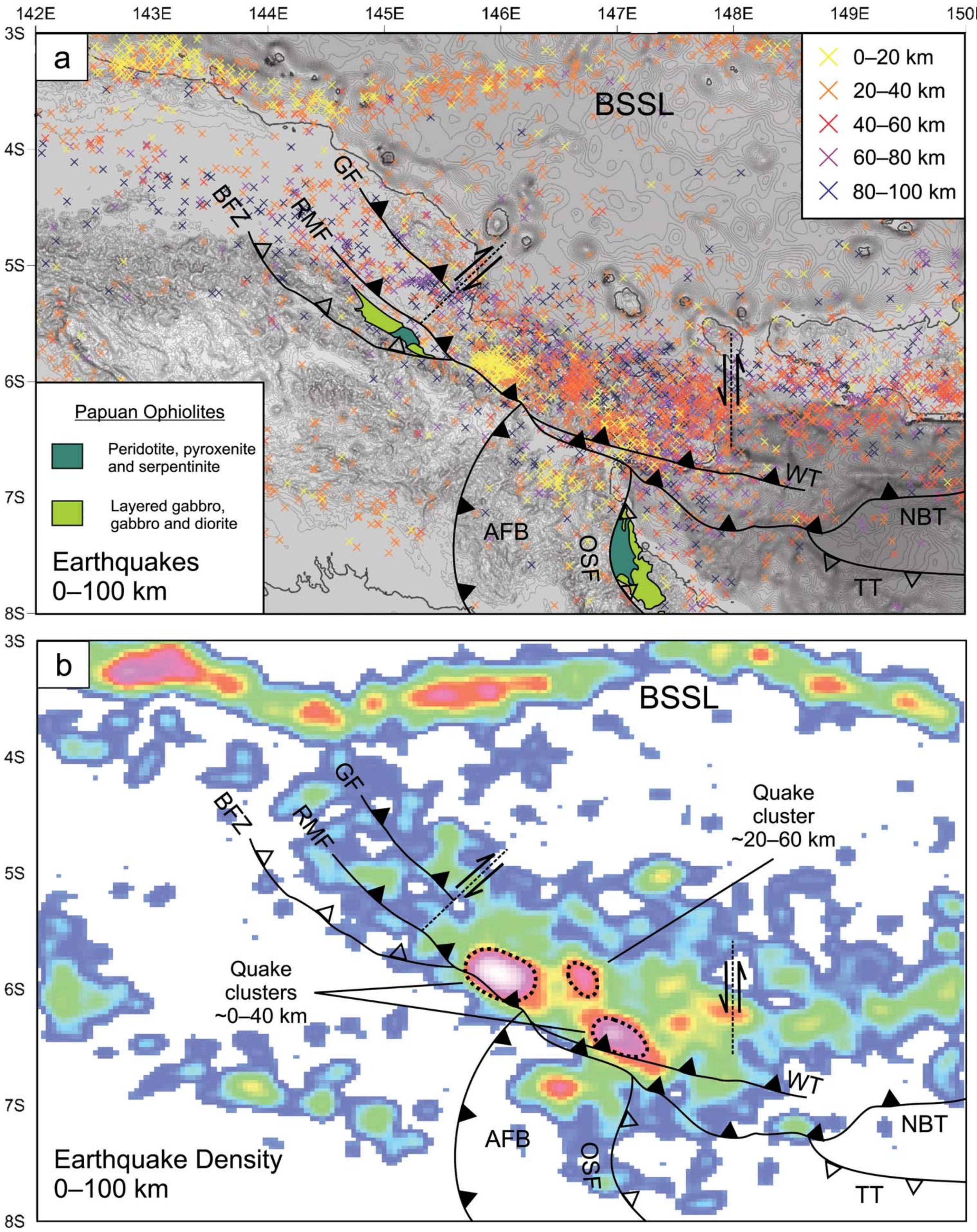

Figure 2 Seismicity and major structure of northwest Papua New Guinea. Earthquakes are derived from the NEIC earthquake database (1990–2010) for the 0–100 km depth bin. (a) Seismicity, structure and geology of the southwest Bismarck Sea–Huon Peninsula region. Structures and labels follow Figure 1b; see text for discussion of geology. (b) Earthquake density distribution map for the same region. Earthquake densities are contoured from high density (white) to low density (blue). We note there are high-density earthquake clusters adjacent to the point where the Bundi Fault Zone and Owen Stanley Fault intersect and under-thrust the Ramu-Markham Fault.

the USGS National Earthquake Information Center (NEIC) database for the period between 1973 and 2010 (Figure 2). In addition, Centroid-Moment-Tensor (CMT) earthquake solutions were derived from the Harvard Global CMT database (1976–2010) and plotted within ArcScene in ArcGIS using the USGS 3D Visualisations of Earthquake Focal Mechanisms extension. The NEIC earthquake database and CMT database include all earthquakes with moment magnitude values (Mw) greater than Mw 4.5; the EHB database utilises earthquakes greater than Mw 4.3.

The earthquake hypocentre data were scrutinised using a variety of software and techniques. Initially, the data were imported into the 4DEarth model (GOCAD) where slab surface models were derived. Details of the slab model are presented below. In order to estimate earthquake abundance distributions and clustering (Figure 2), a simple gridding function was used to derive a map highlighting the number of earthquakes within grid cells with dimensions of $0.04 \times 0.04^\circ$ latitude and longitude. This grid cell size allowed the minimum number of cells to be chosen without biasing towards the generation of many separate but isolated clusters or points. In addition, the use of equi-dimensional cell size removed any directional bias; therefore, the trends observed in the density distribution maps represent a true cluster orientation. The results are presented as a series of density distribution maps which are plotted for depth bins of 0–40 km, 40–100 km and 100–300 km (depths of 0–20, 20–40, 40–60, 60–80, 80–100, 100–120 and 120–140 km are contained within the Supplementary Papers).

Seafloor gravity and topography

Seafloor gravity data for the Bismarck Sea (Figure 3) are sourced from the Australian Bureau of Mineral Resources (1970). The gravity model provided has been corrected for a uniform ocean thickness.

Topography and bathymetry data derived from the National Oceanic and Atmospheric Administration ETOPO1 1-minute global relief model (Amante & Eakins 2009) provide an additional framework for correlation and interpretation.

Geochemical data

Woodhead *et al.* (1998, 2010) created an extensive geochemical dataset for the New Britain and West Bismarck arcs based on new and existing geochemical data from New Britain from Johnson & Chappell (1979) and Woodhead & Johnson (1993). The majority of these geochemical data were produced for major and trace elements by X-ray fluorescence (XRF) and limited use of spark-source mass spectrography (SSMS; Johnson & Chappell 1979; Woodhead & Johnson 1993; and references therein). Woodhead & Johnson (1993) and Woodhead *et al.* (1998, 2010) used inductively coupled plasma mass spectrometry (ICPMS) and Pb, Sr, Nd and Hf isotope analyses to develop the best compilation of data for eastern Papua New Guinea. Woodhead *et al.* (2010) investigated along-arc geochemical changes in Bismarck arc, and we re-evaluate these data in the context of the new tectonic model presented here.

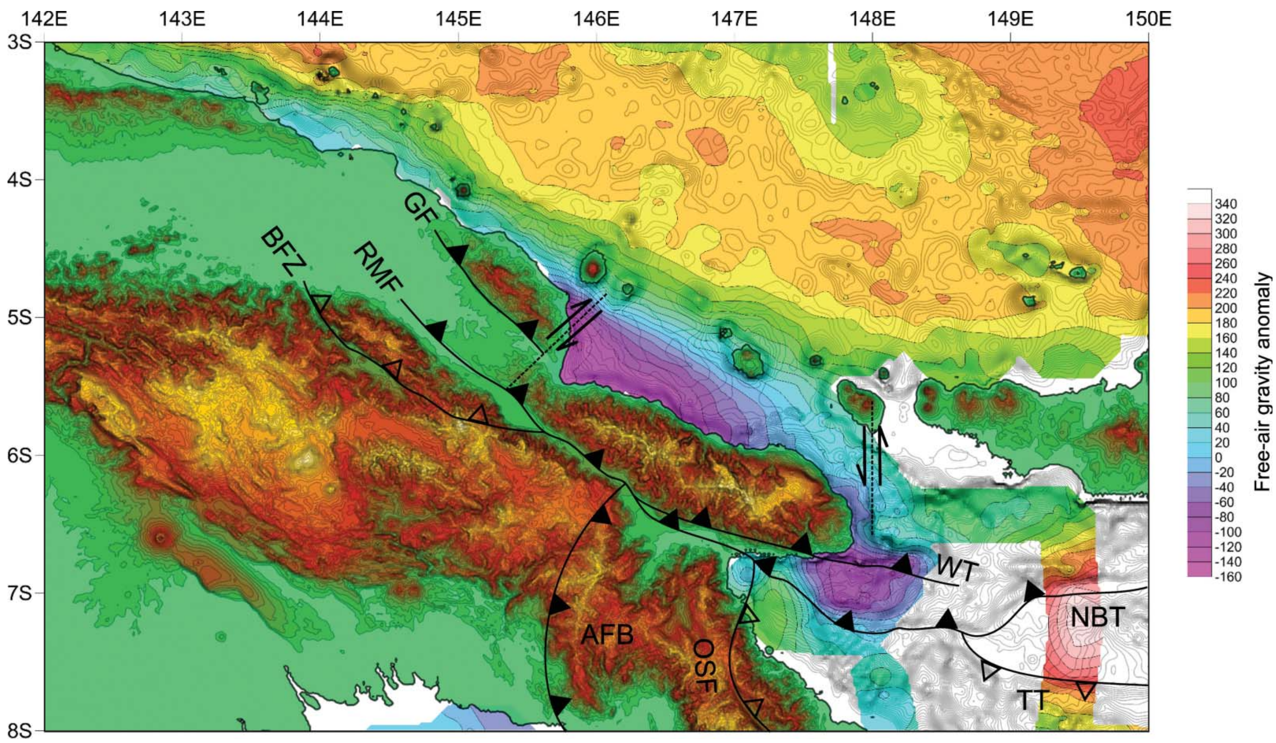

Figure 3 Seafloor free-air gravity anomaly map for the southwest Bismarck–Huon Peninsula region (Data from Australian Bureau of Mineral Resources 1970).

INTERPRETATION AND RESULTS

Subduction zone and slab architecture

Previous work in the region focused on establishing an accepted plate boundary model using information such as seismicity and instantaneous GPS motions (e.g. Denham 1969; Johnson & Molnar 1972; Ripper 1982; Abers & Roecker 1991; Pegler *et al.* 1995; Wallace *et al.* 2004). It is widely accepted that multiple subduction zones have existed since the beginning of crustal amalgamation of Papua New Guinea, however the details pertaining to the geometry and type of crust subducting along the northeastern Papua New Guinea coast and western New Britain are unresolved, despite its infancy.

Construction of new 3-D subducted slab models, up to 600 km depth in the mantle, build on earlier work by O'Kane (2008). Earthquake hypocentre data (Engdahl *et al.* 1998; Engdahl 2006) are primarily used to generate the 3-D models of subducted slab with all earthquakes below 100 km assumed to occur within the subducting plate (Isacks *et al.* 1968). The method for constructing slabs follows that outlined in Richards *et al.* (2007, 2011). The Global CMT database is examined in 3-D to assist in interpreting the geometry of the slab. The final interpreted slab geometry of the composite Australian plate (Solomon Sea plate, Woodlark Basin and Australian plate) subducted at the New Britain and San Cristobal trenches, and termed the Solomon slab, is presented in Figure 4. Miller *et al.* (2006) used a similar method of analysing slab geometries in conjunction with earthquake failure solutions beneath the southern Mariana Arc.

Overall, the Solomon slab exhibits a moderate dip between the surface and ~100 km depth; below this depth, the slab is steeply dipping. West of the New Britain trench–Trobriand trough triple-junction, the Solomon slab currently resides at a depth of ~100 km, and remains close to this depth until it terminates in the west beneath central Papua New Guinea. Furthermore, a north-dipping slab component is modelled in the west which extends to ~250 km depth below west New Britain and continues to the west at shallower depths (Figure 4), consistent with findings from Johnson & Molnar (1972), Johnson & Jaques (1980), and Abers & Roecker (1991). A restricted south-dipping slab component is also imaged but this is limited to the region adjacent to the Huon Peninsula, accounting for observations made by Ripper (1982), Cooper & Taylor (1987), Pegler *et al.* (1995), and Woodhead *et al.* (2010). The lack of a definitive modern seismic or tomographic signature for either an extensive slab at depth or plate interface seismicity at the trench (Hall 2002; Hall & Spakman 2002) suggests that there is very little evidence for substantial southward subduction at the Trobriand trough (Johnson & Molnar 1972; Johnson & Jaques 1980; Abers & Roecker 1991) in agreement with the slab map present here. A small tear in the slab is interpreted below the eastern margin of the Huon Peninsula; this fundamentally separates the western slab domain from the remaining Solomon slab in the east.

Adjacent to east New Britain and New Ireland, the curvature of the trench and subducted slab, and associated subduction of an originally flat oceanic crustal sheet have resulted in the development of a vertical tear

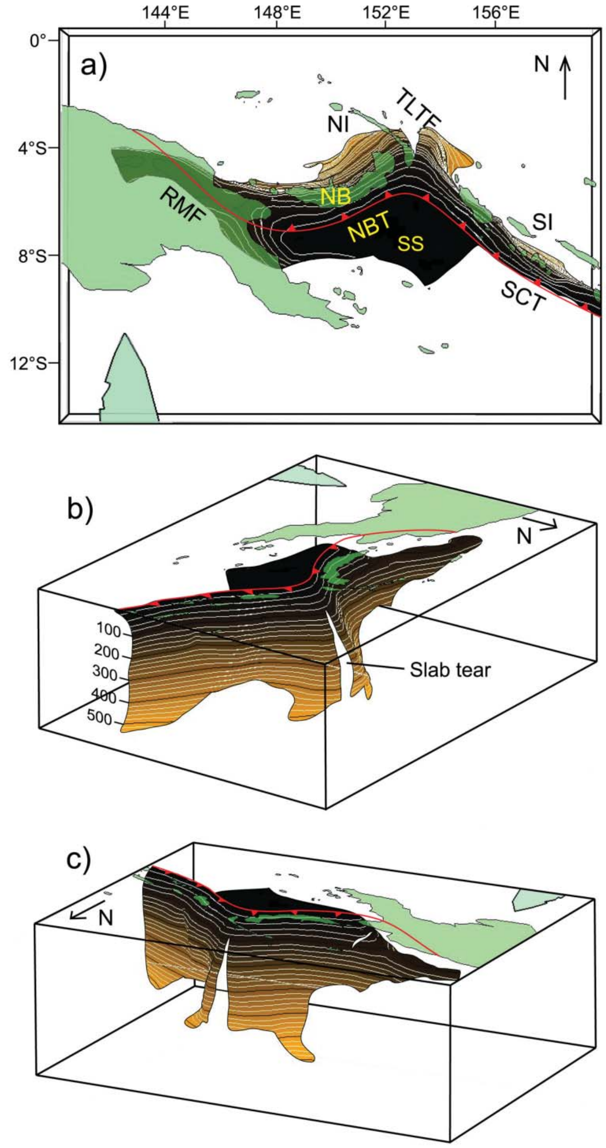

Figure 4 3-D model of the Solomon slab comprising the subducted Solomon Sea plate, and associated crust of the Woodlark Basin and Australian plate subducted at the New Britain and San Cristobal trenches. Depth is in kilometres; the top surface of the slab is contoured at 20 km intervals from the Earth's surface (black) to termination of slab-related seismicity at approximately 550 km depth (light brown). Red line indicates the locations of the Ramu-Markham Fault (RMF)–New Britain trench (NBT)–San Cristobal trench (SCT); other major structures are removed for clarity; NB, New Britain; NI, New Ireland; SI, Solomon Islands; SS, Solomon Sea; TLTF, Tabar–Lihir–Tanga–Feni arc. See text for details.

in the slab (Figure 4); in line with findings suggested by Cooper & Taylor (1989). At present, the tip of the tear terminates beneath southern New Ireland and exhibits a western and an eastern flank propagating beneath the Tabar–Lihir–Tanga–Feni arc; the western flank propagated beneath Lihir (where the slab lies some 550 km below owing to the steep dip). The tear here is significant because it provides a window where the asthenosphere can penetrate from the rear of the slab to the front. To the east, the Solomon slab is dipping beneath the Solomon Islands and reaches a maximum interpreted depth of 500 km. The subducted slab here exhibits less 'structure' than the slab to the west; however, research focused on mapping the subducted extent of the Woodlark Basin rift is ongoing.

Gravity and seismicity correlation

At the relatively shallow sub-crustal depths (in the order of 50–100 km), upper crustal features can mask seismic tomography and earthquake distribution. We instead utilise regional seafloor gravity free-air anomaly data obtained during the 1970 Hamme Cruise (Figure 3; Australian Bureau of Mineral Resources 1970) to help interpret crustal boundaries. In particular, we focus on the region adjacent to the Huon Peninsula and north coast of Papua New Guinea (Figure 1). Figure 5 presents the gravity data together with seismicity and the interpreted slab model. A large gravity-low anomaly is observed trending sub-parallel to the northern coast of Papua New Guinea defined by negative gravity values (Figure 3). The gravity low is particularly intense to the north of the Huon Peninsula (Davies *et al.* 1987; Honza *et al.* 1987). This anomalous gravity-low also corresponds with the location of intense seismicity beneath the Huon Peninsula at depths of between 0 and 100 km (Figure 5). Gravity and seismicity anomalies of the two datasets correlate extremely well suggesting a relationship between the two, to a depth of up to 100 km. This level of seismicity has been attributed to the presence of Australian lithosphere at up to 100 km depth (Pegler *et al.* 1995; Woodhead *et al.* 2010); however, this has only been explored in 2-D sections adjacent to the eastern Huon Peninsula without consideration given to the 3-D extent of the seismicity.

An additional component of the anomalous gravity low is present to the southeast of our interpreted upper

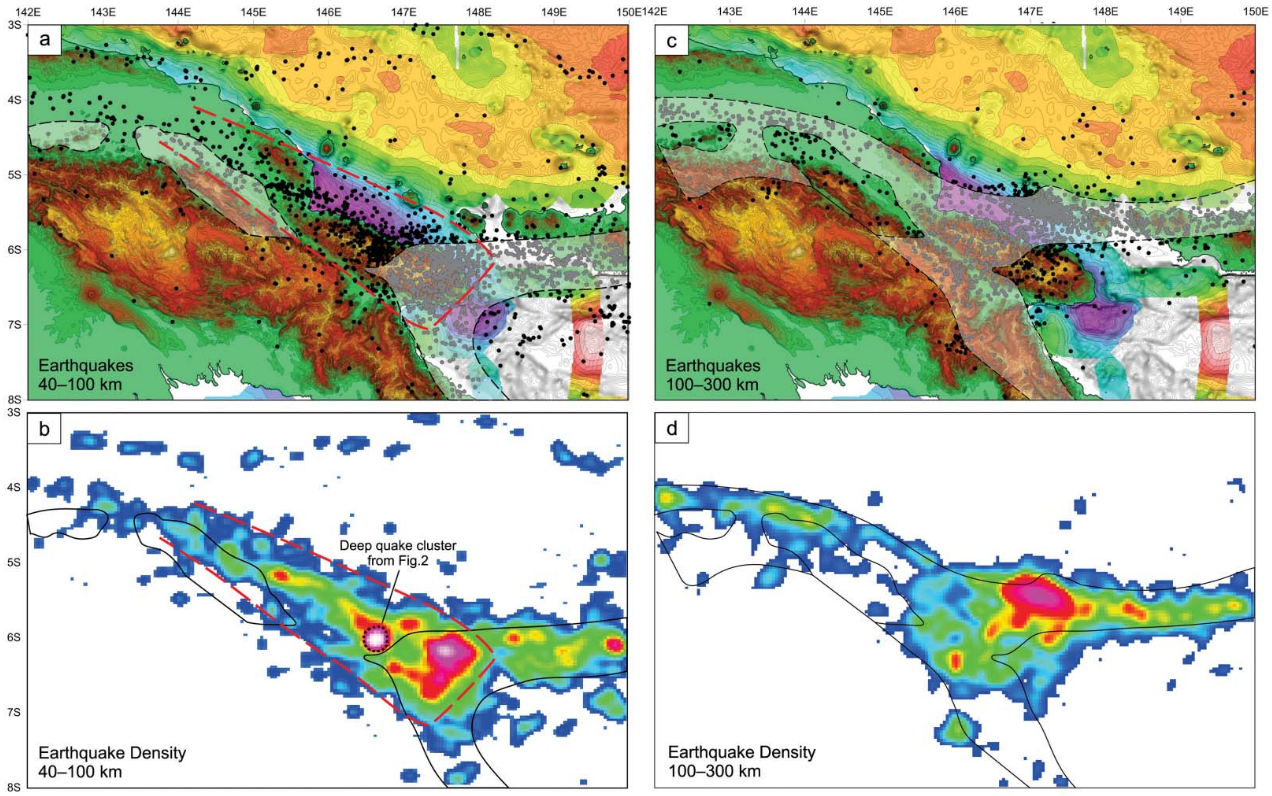

Figure 5 Gravity and seismicity correlation for the southwest Bismarck–Huon Peninsula region. All earthquakes illustrated are from the NEIC earthquake database (1990–2010) and projected on the Bismarck Sea seafloor gravity anomaly map and topography (a, c); and associated earthquake density distribution maps (b, d). (a, b) Gravity and seismic correlation between 40 and 100 km depth; the top surface of the slab map above 100 km depth is shown as a white shaded area (a) and area outlined in black (b). A large area of anomalously high earthquake density trending east-southeast–west-northwest and outlined by the red dashed line does not show a relationship with the defined windows for slab-related seismicity (a, b); furthermore, this anomalous seismic region correlates well with the negative (low; purple) gravity anomaly to the north of- and beneath the Huon Peninsula. We make note of the two highest density earthquake clusters; the largest in extent of the two lies at the southeast tip of the Huon Peninsula, this is a region of overlap between both the slab map and anomalous seismicity/gravity correlation implying multiple earthquake sources superimposed; the second is located at the approximate centre of the Finisterre Terrane and holds the greatest observed density. (c, d) Gravity and seismicity correlation between 100 and 300 km depth; the top surface of the slab below 100 km to termination is shown according to the previous description; as this surface represents the top of the slab, where the top surface is above 100 km depth, earthquakes occurring below this depth and within the slab are not atypical. Seismicity in this depth range correlates well with the outlined slab map and show little relationship with gravity anomaly trends. A zone of intense, high density seismicity is present north of the Huon Peninsula, this has previously been referred to as the 'Finisterre Nest' (Abers & Roecker *et al.* 1991).

mantle crustal anomaly. This is not as seismically active as the remainder of the anomalous zone and falls within the normal bounds of slab-related seismicity for the region. This anomaly is also consistent with elevated bathymetry at the surface, and can therefore be attributed to thickened crust between the Ramu-Markham Fault–New Britain trench and the Wonga Thrust.

Previous interpretations of geochemistry

Woodhead *et al.* (2010) concluded that the West Bismarck and New Britain arcs are both 'typical' subduction-related volcanic arcs, and although contiguous along strike, exhibit very different geochemical characteristics. The arc was divided into two parts, the West Bismarck arc and New Britain arc with the line separating the two drawn between the western-most volcanoes of New Britain (Cape Gloucester, Langila, Aimaga, Tangi and Gloucester) and the remainder of New Britain in the east (Woodhead *et al.* 2010). In the most general terms, the distinction between New Britain and West Bismarck arcs equates to a tholeiitic–calc-alkaline transition (Jakes & Gill 1970; Woodhead *et al.* 1998, 2010), and may reflect underlying differences in the nature and composition of the mantle wedge or subducting plate, or the processes of mass transfer between the two, or alternatively is a consequence of collisional processes during accretion of the Adelbert and Finisterre Terranes (Woodhead *et al.* 2010).

Along-arc geochemical trends of elements, ratios, and isotopic variation utilising a compilation of data from both Woodhead *et al.* (1998, 2010) are shown in Figure 6. Further characteristics of this arc will be discussed below. Woodhead *et al.* (2010) identified important differences between the geochemistry of the two arcs. Arc lavas from the New Britain volcanic front are derived from a mantle source highly depleted in many incompatible trace elements (Woodhead *et al.* 1998), while the least evolved West Bismarck arc lavas generally have higher HFSE contents than the New Britain volcanic front. Extreme element depletion in the New Britain lavas is typically attributed to prior melt extraction in the back-arc Manus Basin, however, the same process does not operate to the same extent on the mantle source of the West Bismarck lavas (Woodhead *et al.* 1993, 2010). The Sm/La ratios (Figure 6), which are higher in New Britain, suggest a depleted mantle source when compared with the West Bismarck arc lavas. Furthermore, the decrease in the Sm/La ratio to the west together with a decrease in the size of volcanic edifices and eruption rate (Johnson 1977) suggests the degree of mantle melting falls dramatically from east to west (Woodhead *et al.* 2010).

In addition, Woodhead *et al.* (2010) finds Th/La ratios in the West Bismarck arc are lower than that of bulk

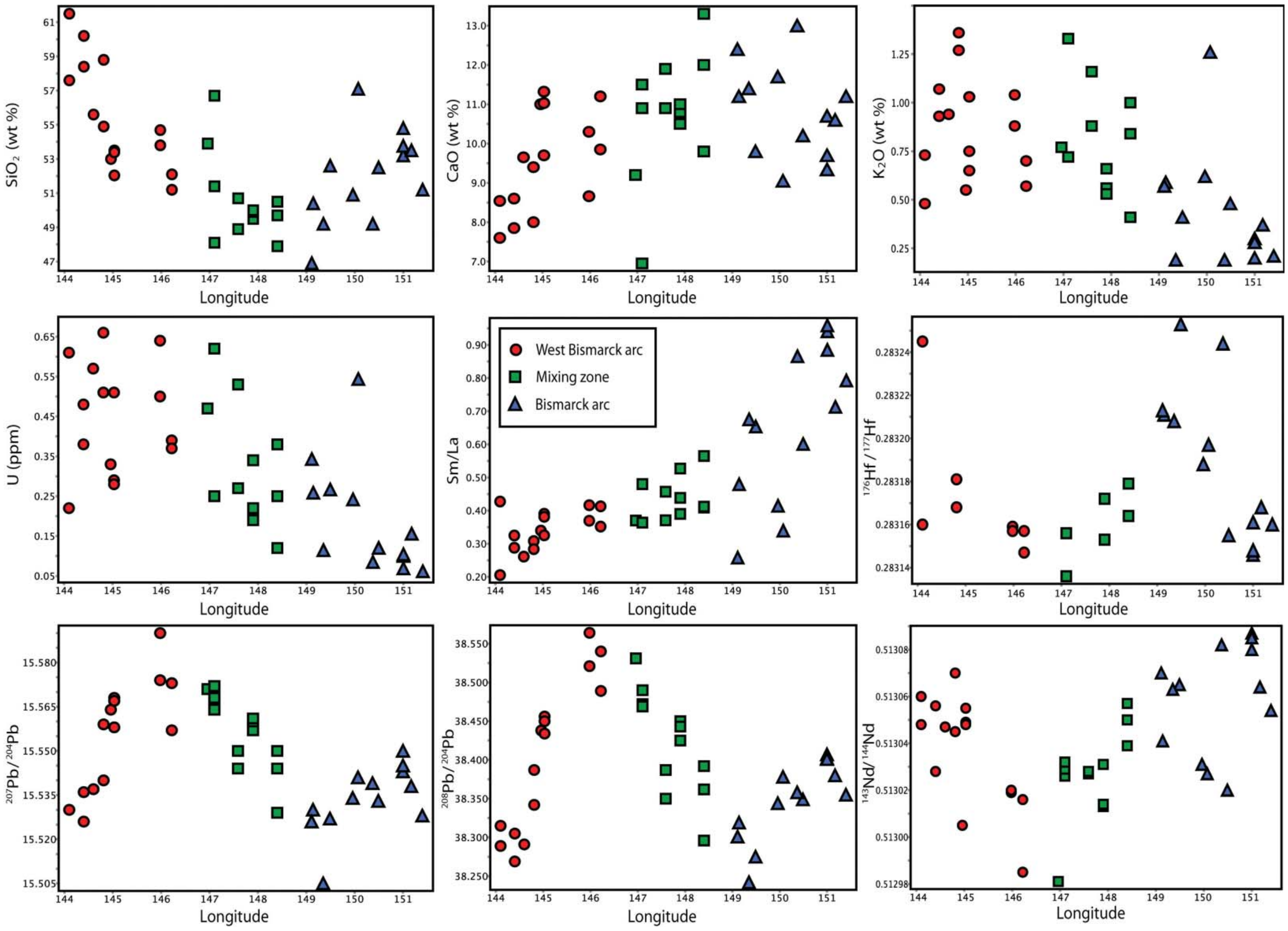

Figure 6 Along-arc geochemical variation in selected major and trace elements, trace element ratios, and isotopic ratios for the West Bismark and New Britain arcs (data from Woodhead *et al.* 1998, 2010). See text for further discussion.

continental crust and the ‘average arc’ (Plank 2005) suggesting that a sedimentary component is apparent in the West Bismarck arc lavas. Woodhead *et al.* (2010) noted that prior to collision with the South Bismarck plate, the Australian plate likely carried high Th/La sediments derived from mainland Papua New Guinea. This is supported by the similar Th/La ratios to average sediments from the Solomon Sea (Woodhead *et al.* 1998), which also contain a substantial volcaniclastic input derived from the Papua New Guinea Highlands (Crook 1987). Moreover, Pb-isotopic compositions of the West Bismarck lavas, which contain relatively radiogenic Pb compared with Manus Basin MORB (Figure 6), suggest a strong ‘crustal’ signature is evident, again similar to Pb compositions found in the Solomon Sea sediments. Hafnium and Nd isotope ratios show opposite but similar trends exhibiting the highest ratio values in the New Britain arc and decreasing in the West Bismarck arc; Woodhead *et al.* (2010) interpreted this as a response to arc–continent collision where increased proximity to a crustal source dramatically increased the proportion of continent-derived detritus delivered to the subducting slab. These geochemical observations are important and differentiate the New Britain arc magmas, predominantly mantle derived but with a very small sedimentary component, from the West Bismarck arc where the sedimentary component is interpreted to be much greater.

DISCUSSION

Crustal architecture

The seismological activity or inactivity of major structures and plate boundaries should be apparent over a regional-scale, even taking into account the relatively short geological window of earthquake recording. The principal cause of seismicity in the Bismarck Sea region is subduction at the New Britain trench; this has long been recognised and accepted as the origin for shallow through to deep earthquakes. On the same regional-scale, additional earthquake trends related to major structure and plate boundary activity are those of the Bismarck Sea seismic lineation and New Guinea trench in the north and northwest, and the Papuan Fold and Thrust Belt to the southwest (Figures 1, 2). These major tectonic structures have long been defined and are well understood. However, shallow to intermediate depth seismicity of the northeast Papua New Guinea mainland is characterised by a somewhat chaotic distribution of earthquakes (Figure 2). While much of the shallow seismicity has previously been correlated with upper crustal structure (Cooper & Taylor 1987; Abers & McCaffrey 1994; Stevens *et al.* 1998), it is evident that a significant proportion cannot be clearly related to any recognised structural control (Figures 2, 5).

As presented in this study, the anomalous seismicity is focused beneath the Finisterre Terrane and immediate adjacent areas (Figures 2, 5). This zone is defined by an uncharacteristically high abundance of earthquakes compared with ‘typical background’ seismicity (Figure 5), and defines a zone extending from the surface to approximately 100 km depth beneath northeast Papua New Guinea. Furthermore, this feature correlates with a negative gravity anomaly that cannot be easily related to any near surface geological phenomena (Figure 3). Similar gravity lows observed adjacent to trenches are commonly interpreted as subducted low-density crust (Morales *et al.* 1999; Mishra *et al.* 2000), or alternatively, as crustal thickening and stacking of low-density crust during orogenesis (Stern 1995; Casas *et al.* 1997). Both scenarios are typical of convergent margin settings much like the recent history of the Bismarck Sea region. We propose the anomalous gravity-low in combination with anomalous seismicity is the expression of a previously undefined crustal block underthrust beneath the Adelbert and Finisterre Terranes during collision with the Papua New Guinea margin. In addition, this crustal block is interpreted to be continental crust that is the underthrust and subducted leading edge of Papua New Guinea (Figure 7). This is significant in that the nature of the continental margin has not previously been considered in the context of the northern Papua New Guinea accreted terranes and holds implications for the dynamics of terrane collision processes. The extent of the underthrust margin is further supported by CMT solutions. These are illustrated in Figure 7 for between 40 and 90 km depth and highlight a regional compressional stress field orientated WNW–ESE, consistent with the trend of the underthrust margin; this regional stress distribution has previously been recognised in Australian lithosphere by Woodhead *et al.* (2010). At the eastern boundary of the underthrust margin, we see evidence for more complex deformation occurring through translational source mechanisms and an additional dilational regime, rotated into a generally northeast–southwest orientation (Figure 7).

If we infer the underthrust Papua New Guinea margin is similar in extent to the margin prior to terrane accretion, we can begin to add detail to this crustal block and place it in the context of the surrounding structure and geology expressed at the surface. Within the seismic signature of the underthrust block (Figures 2, 5) there are earthquake clusters typified by an increase in the density of seismic activity that are confined to the north side of the Ramu-Markham Fault–New Britain trench plate boundary. The regional context of these clusters, and likewise the source regions, has not previously been investigated. It is clear from Figure 2 that these clusters are proximal to major structures; the Bundi Fault Zone, Aure Fold Belt, and Owen Stanley Fault, where the structures are currently being underthrust beneath the Finisterre Terrane at the Ramu-Markham Fault. We interpret this seismicity as possible reactivation of the former structural suture zones during their passage beneath the Finisterre Terrane. It is reasonable to assume this structure will continue to depth in the downgoing crustal block, and likewise can be defined by a similar earthquake cluster at greater depths as observed between approximately 20 and 60 km (Figures 2, 5). Furthermore, we propose that based on this premise, and similarities in geological context, that is, ophiolite belts of similar interpreted age adjacent to, and exhibiting analogous structural and tectonic relationships to major suture zones, that the Bundi Fault Zone and Owen Stanley Fault can be correlated as the same structural discontinuity (Figure 7). This provides

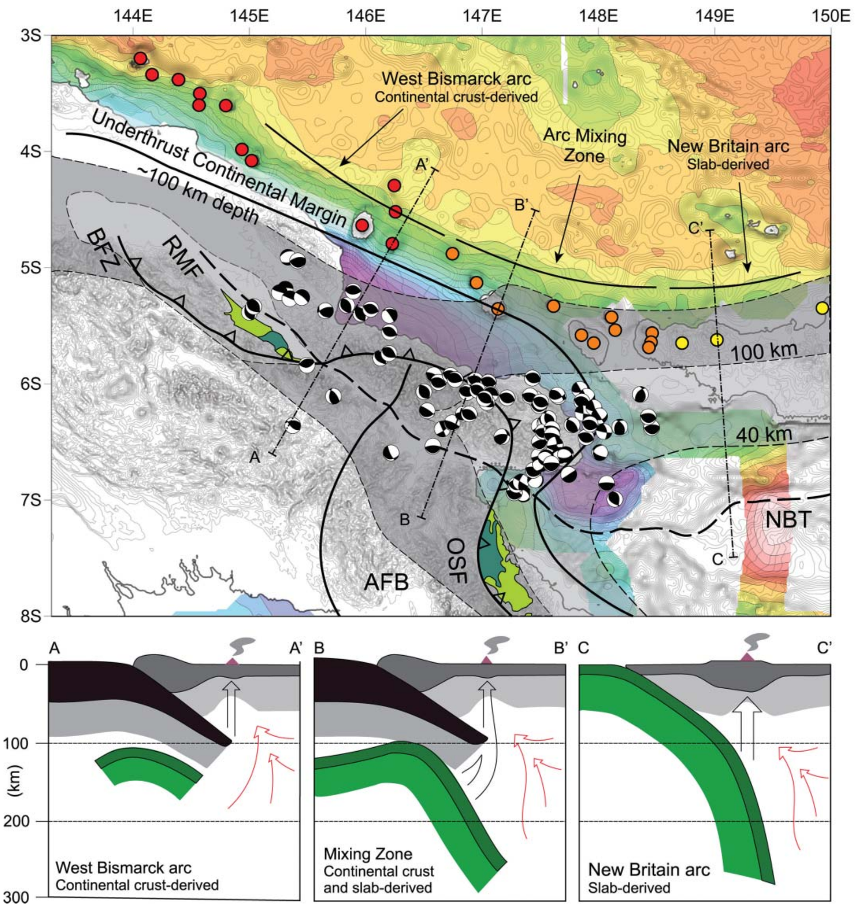

Figure 7 Interpretation of present-day tectonic plate configuration and magmatic arc distribution in northeastern Papua New Guinea. Gravity anomaly map is provided as a base map. Bold black outlines illustrate the extent of the under-thrust continental crust, formerly the leading edge of the Papua New Guinea mainland; and the associated correlation of the Bundi Fault Zone and Owen Stanley Fault in the under-thrust crust. CMT solutions are shown for the under-thrust margin between 40 and 90 km depth. Below the under-thrust margin, the distribution of subducted oceanic crust of the Solomon slab is shown for comparison, and is contoured at 40 and 100 km until termination to the slab. The 'Bismarck arc' is divided into the West Bismarck arc, New Britain arc, and mixing zone between the two; these are derived from continental crust, oceanic slab, and a combination of the two respectively. Cross-sections through the plate arrangement are provided to illustrate the 3-D framework of the new plate arrangement and context of corresponding fluid sources of the equivalent magmatic arc. See text for discussion.

a new context for major structures within Papua New Guinea as regionally significant suture zones rather than discrete and unrelated geological phenomena.

Along-arc geochemical variation

Given the constraint provided by the new crustal architecture model presented here, we can begin to address the implications of these findings and re-evaluate current geological models of northeastern Papua New Guinea. Most significantly, we can reinterpret the geochemical signatures of the currently active New Britain and West Bismarck arcs within a robust tectonic framework. It becomes clear from the Solomon slab map that the New Britain arc is related to the Solomon slab adjacent to the island of New Britain (Figure 7). However, in the western Bismarck Sea, the north-dipping limb of the subducted slab is located to the south of the West Bismarck arc and beneath the accreted Finisterre and Adelbert Terranes and the Papua New Guinea mainland (Figure 7), spatially removed from the active West Bismarck arc. This observation immediately brings into question the relationship between the West Bismarck arc and the subducted Solomon slab proposed in previous studies. Instead, we suggest that the source of fluids and potential crustal melts is readily available in the form of the underthrust edge of Papua New Guinea crust (Figure 7).

The extent of the underthrust margin at depth is outlined by both gravity and seismic signatures, consistent with the interpretations of Davies *et al.* (1987), Honza *et al.* (1987) and Woodhead *et al.* (2010). At a depth of approximately 100 km in the mantle, the underthrust continental margin is likely to be undergoing dewatering processes and contributing fluids to the mantle wedge. Given these fluids are derived from a continental-crustal source rather than oceanic crust, this accounts for the high sediment-signature input into the magmas and comparatively reduced slab influence addressed above, in contrast to the New Britain arc in the east. This concept is further supported by the frontal edge of the underthrust margin correlating spatially with the overlying arc (Figure 7). Therefore, we define the New Britain and West Bismarck arc as two distinct entities with different source regions and different geochemical affinities. These two arcs are the expression of either slab-derived fluids (New Britain arc) or continental crust-derived fluids (West Bismarck arc). There is, however, the added complication that the two arcs form a single, more or less morphologically continuous volcanic arc. Therefore, a zone must be present where fluids derived from both subducted slab and underthrust continental crust are mixing and both contribute to arc magmatism (Figure 7). This model is consistent with an observed continuum in the geochemical signatures between the two arcs, transitioning from a slab signature-dominated melt in the east through to the crustal signature-dominated melt in the west (Figure 6). This influence of slab-derived fluids is apparent up to approximately 146.5°E at which point the slab becomes removed to the south beneath the underthrust continental margin and effectively blocked from any further contribution of fluids in the arc building process (Figure 7). This explains the delay in the apparent peak crustal signatures in arc geochemistry up to this point as observed by Woodhead *et al.* (2010).

It is also worth noting that further to the northwest along the trend of the West Bismarck arc and towards the Bismarck Sea seismic lineation, we see a geochemical trend that is consistent with a return to more mantle-like signatures. We suggest the Bismarck Sea seismic lineation behaves as a leaky transform in line with findings from Llanes *et al.* (2009) resulting in variable continental-derived fluid contribution to arc magmatism.

Geodynamic evolution of the Bismarck Sea

Given the regional significance of the findings outlined in this study, we propose a new plate tectonic reconstruction for the Bismarck Sea region that builds on previous reconstructions of the region (e.g. Abbott 1995; Hill & Raza 1999; Weiler & Coe 2000; Hall 2002) and incorporates the new tectonic elements introduced in this paper. Reconstructions of the Australian plate include all previously accreted terranes. GPS measurements of current, geologically instantaneous plate motions (Tregoning *et al.* 1998, 1999; Tregoning 2002; Wallace *et al.* 2004) form the basis for this new Bismarck Sea reconstruction while the published timing for events and sea floor magnetic anomalies from Taylor (1979), Goodliffe *et al.* (1997), Taylor *et al.* (1999) and Gaina & Müller (2007) are used to infer the direction and rate of seafloor spreading. Paleomagnetic rotation data for the Finisterre Terrane from Weiler & Coe (2000) is used to further constrain reconstructions.

New reconstructions highlighting the significance of the leading Australian continental margin are shown in Figure 8. Between 3 and 4 Ma the Australian plate collided with the Adelbert-Finisterre Terrane, closing the western New Britain trench and forming the Ramu-Markham Fault (Abbott *et al.* 1994; Abbott 1995). This is coincident with decoupling and the initial formation of the North Bismarck plate, South Bismarck plate and associated Bismarck Sea seismic lineation (Martinez &

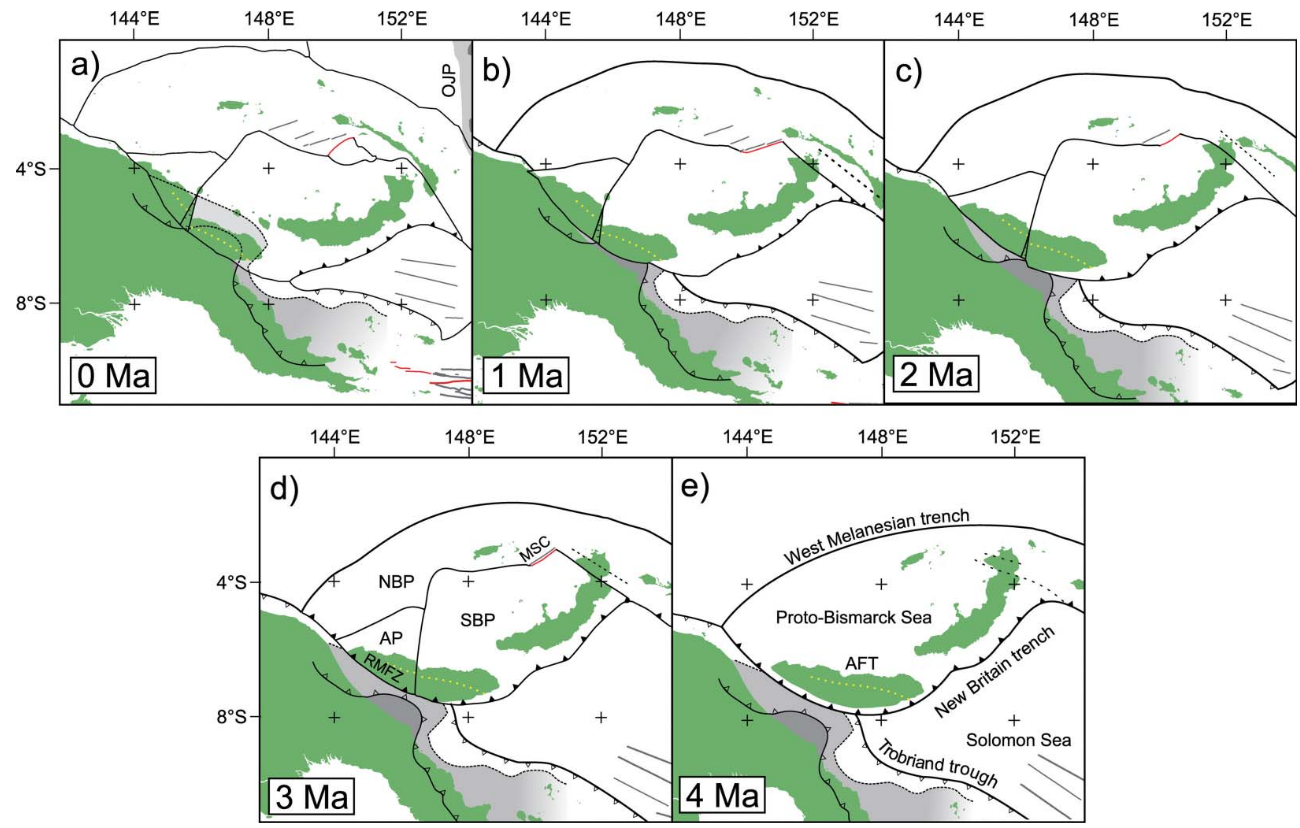

Figure 8 Tectonic reconstruction of the Bismarck Sea region. The inferred Papua New Guinea northeastern continental margin is shown in grey, and highlights the continuation of the Bundi–Owen Stanley suture and the seaward continental shelf; yellow dotted line represents the Finisterre Volcanics of the Adelbert and Finisterre Ranges. Magnetic isochrons and spreading centres are included for the Woodlark Basin (Taylor *et al.* 1999), Solomon Sea (Gaina & Müller 2007) and Manus Basin (Taylor 1979). Filled triangles and open triangles indicate normal and slow or extinct subduction respectively. AFT, Adelbert-Finisterre Terrane; SBP, South Bismarck Plate; NBP, North Bismarck Plate; AP, Adelbert microplate; MSC, Manus Spreading Centre; RMFZ, Ramu-Markham Fault Zone; OJP, Ontong Java Plateau. Reconstructions are presented in a fixed hot spot reference frame.

Taylor 1996). Continued advance of the Australian plate impinging on the western South Bismarck plate resulted in the onset of clockwise rotation of the South Bismarck plate (e.g. Weiler & Coe 2000). Furthermore, the South Bismarck plate became decoupled from the North Bismarck plate and the subducting Solomon Sea plate, allowing the South Bismarck plate to rotate freely about a pole southeast of the Finisterre Terrane (Tregoning *et al.* 1999). Rotation of the South Bismarck plate resulted in retreat of the New Britain trench in the east and rifting and sea-floor spreading at the Manus spreading centre from 3 Ma (Taylor 1979; Martinez & Taylor 1996). Fragmentation of the South Bismarck plate in response to collision with the thickened crust of the Bundi–Owen Stanley suture zone formed the independent Adelbert microplate. Right lateral offset of the Oligocene–Lower Miocene Finisterre Volcanics in the Adelbert and Finisterre Terranes is interpreted to have resulted from crustal displacement along the Adelbert microplate–South Bismarck plate boundary. Continued north-northeast motion of the Australian plate combined with clockwise rotation of the South Bismarck plate resulted in ongoing subduction of the Solomon Sea plate and initiation of rifting adjacent to the Manus spreading centre with opening the Manus microplate from *ca* 1 Ma (Martinez & Taylor 1996).

The concept of a separate Adelbert microplate, although presented here for the first time in a regional context, is not a new idea and initially arose from geological observations of the volcanic island-arc terranes in the Adelbert and Finisterre Ranges (e.g. Jaques & Robinson 1977; Abbott *et al.* 1994; Wallace *et al.* 2004). A physical boundary between the Adelbert and Finisterre Ranges was interpreted in early mapping of cross faulting in the Finisterre Ranges (Jaques & Robinson 1977; Abbott *et al.* 1994), however, dextral translational faults defined by Abers & McCaffrey (1994) (Figure 1) have been adopted as the Adelbert-Finisterre boundary in this study. The most apparent contrast between the Adelbert microplate and South Bismarck plate is a dramatic difference in elevation (Figure 1; Abbott 1995). Abbott (1995) interpreted that the Gowop Limestone cap both the Adelbert and Finisterre Ranges and that the contrast in elevation of the Adelbert Range is due to less total uplift of the Adelbert block, and cannot be attributed to erosion in the Adelbert Range. This contrast is likely to be the result of differential plate motion with northward motion and clockwise rotation of the Adelbert microplate relative to the South Bismarck plate resulting in a lower rate of convergence with the Australian plate. Such differential motion also explains the observed offset of the Finisterre Volcanics common to both ranges (Figure 8; Jaques & Robinson 1977; Abbott *et al.* 1994). Moreover, the nature of the continental crust underthrust beneath the Adelbert and Finisterre Terranes likely holds implications for the degree of uplift. Reconstructions show the Finisterre Terrane was forced over, and currently overlies the thickened crust of the Bundi–Owen Stanley suture zone, in contrast to the marginal continental crust beneath the Adelbert Terrane, thus resulting in reduced total uplift compared with the Finisterre Ranges. This is a new approach to explain differential uplift of the Adelbert and Finisterre Terranes where the nature and geometry of the prior continental margin, in combination with collision obliquity, controls accretion dynamics.

It is also apparent from previous reconstructions and those presented here that arc–continent collision in northeast Papua New Guinea was a consequence of oblique collision between the larger Australian and Pacific plates. This process ‘zipped’ shut the intervening Solomon Sea between the Papua New Guinea mainland and the outboard Adelbert and Finisterre Terranes (Figure 8; Abbott 1995; Hill & Raza 1999). However, the zipping process continues to the present-day along this margin, therefore, collision is considered time transgressive and will continue to migrate eastwards. Figure 9 presents forward-looking tectonic reconstructions where continued subduction of the Solomon Sea plate at the New Britain trench will ultimately consume the Solomon Sea leading to arc–continent collision between the Papuan Peninsula (Australian plate) and New Britain. We estimate it will take approximately 5 m.y. to consume the Solomon Sea at present plate motion rates. As in the previous instance of the Finisterre Terrane, we predict slab pull forces acting on the subducted Solomon Sea slab coupled to the Australian plate at the point of collision will lead to drawdown and underthrusting of the leading edge of continental crust. This process initiates a plate configuration where New Britain is allowed to overthrust the continental margin. Throughout this process we predict the apparent continual outboard migration of the associated subduction-derived magmatic arc as the accreting plate overrides the loci of slab dewatering (Figure 9).

The tectonic process of arc–continent accretion is not unique to the tectonic evolution of Papua New Guinea. In the geological record, there are many recognised arc–continent collision episodes (e.g. Teng 1990; Rosenbaum *et al.* 2002; Whattam 2009; Najman *et al.* 2010), and similarly occurrences of continental crust entering a trench and failing to subduct (e.g. New Caledonia; Aitchison *et al.* 1995; Rawling & Lister 2002; Spandler *et al.* 2005). These collision events are typically distinguished in field studies by the presence of ultra-high-pressure metamorphic terranes and/or obduction of ophiolite sequences, however, these observed rock types are not present en masse in northeast Papua New Guinea, and it seems apparent that the processes of terrane accretion and partial subduction of continental crust remain active. In the distant future, we can reasonably expect some exhumation of subducted continental crust will occur in line with findings in ancient arc–continent collision events. Recognising this process in the recent geological past, and in the near future for New Britain, provides valuable insight into the dynamics and tectonic settings that give rise to such geological phenomena. Furthermore, the role of subducted continental crust as a potential source of fluids in magmatic arc generation, in this case the West Bismarck arc, is a relatively new avenue of geological research and will only occur under exceptional tectonic circumstances. Nevertheless, recognition of the expression of continental crust-derived arcs at the surface and an understanding of the tectonic events leading up to the generation of such apparent geological anomalies will be invaluable in unravelling complex tectonic regions globally.

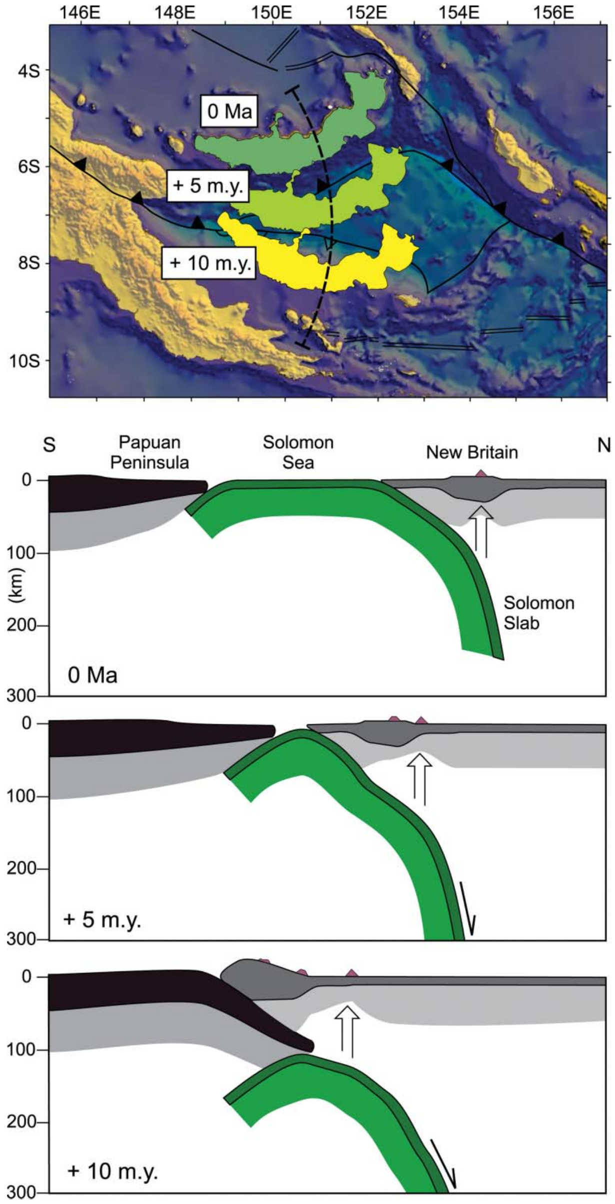

Figure 9 Forward tectonic reconstruction of progressive arc collision and accretion of New Britain to the Papua New Guinea margin. (a) Schematic forward reconstruction of New Britain relative to Papua New Guinea assuming continued northward motion of the Australian plate and clockwise rotation of the South Bismarck plate. (b) Cross-sections illustrate a conceptual interpretation of collision between New Britain and Papua New Guinea.

CONCLUSIONS

We re-evaluate the tectonics of northeastern Papua New Guinea and the South Bismarck Sea region, and present a new and robust model for the 3-D architecture of the crust and upper mantle in this region. The new tectonic plate model accounts for all the observed geological phenomena including geology, geophysics, seismicity, arc geochemistry, topography, bathymetry, landscape morphology, and a newly developed slab model of crust subducted at the New Britain trench, while also drawing from studies and concepts introduced by numerous workers over decades of research. Compilation and re-evaluation of these data reveal a previously unrecognised crustal block at depth beneath the Finisterre Terrane on the northern Papua New Guinea coast, defined by anomalous seismicity and a correlative negative gravity anomaly. We interpret this as the leading edge of Australian continental crust, which has become partially subducted beneath the Adelbert and Finisterre Terranes during arc–continent collision and terrane accretion. This continental crust extends to a depth of approximately 100 km in the mantle where it is currently undergoing dewatering reactions and contributing fluids to the upper plate resulting in formation of the West Bismarck arc adjacent to the northeastern Papua New Guinea coastline. The West Bismarck arc is a distinct arc, separate from the slab-derived New Britain arc to the east, however, a mixing zone exists between the two where fluids derived from both normal subduction processes and also partially subducted continental crust are contributing to arc magmatism. In light of these findings we present a new tectonic reconstruction for the recent development of the Bismarck Sea in conjunction with a forward-looking reconstruction to highlight the role of marginal continental crust in the dynamics of arc–continent collision and accretion. Furthermore, we stress the importance of the recognition of continental crust and marginal provinces in collisional tectonic settings and their potential to contribute in arc building processes.

ACKNOWLEDGEMENTS

We would like to thank Nautilus Minerals for providing data from the Hamme Cruise. We also thank Carl Spandler, Thorsten Becker, Patrice Rey, Gideon Rosenbaum and Robert Hall and an anonymous reviewer for helpful criticisms and suggestions.

REFERENCES

Abbott L. D. 1995. Neogene tectonic reconstruction of the Adelbert-Finisterre–New Britain collision, northern Papua New Guinea. *Journal of Southeast Asian Earth Sciences* **11**, 33–51.

Abbott L. D., Silver E. A. & Galewsky J. 1994. Structural evolution of a modern arc–continent collision in Papua New Guinea. *Tectonics* **13**, 1007–1034.

Abers G. A. & McCaffrey R. 1994. Active arc–continent collision: Earthquakes, gravity anomalies, and fault kinematics in the Huon–Finisterre collision zone, Papua New Guinea. *Tectonics* **13**, 227–245.

Abers G. A. & Roecker S. W. 1991. Deep structure of an arc–continent collision: Earthquake relocation and inversion for upper mantle P and S wave velocities beneath Papua New Guinea. *Journal of Geophysical Research* **96**, 6379–6401.

Aitchison J. C., Clarke G. L., Meffre S. & Cluzel D. 1995. Eocene arc–continent collision in New Caledonia and implications for regional southwest Pacific tectonic evolution. *Geology* **23**, 161–164.

Amante C. & Eakins B. W. 2009. *ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis*. NOAA Technical Memorandum NESDIS National Geophysical Data Center, Colorado, USA.

Australian Bureau of Mineral Resources 1970. *Geophysical survey in Gulf of Papua*. Bismarck Sea, cruise id: HAMME70, BMR survey 5, Australian Bureau of Mineral Resources, Canberra.

Casas A., Kearey P., Rivero L. & Adam C. R. 1997 Gravity anomaly map of the Pyrenean region and a comparison of the deep geological structure of the western and eastern Pyrenees. *Earth and Planetary Sciences Letters* **150**, 65–78.

Cooper P. & Taylor B. 1987. Seismotectonics of New Guinea: a model for arc reversal following arc–continent collision. *Tectonics* **6**, 53–67.

Cooper P. & Taylor B. 1989. Seismicity and focal mechanisms at the New Britain trench related to deformation of the lithosphere. *Tectonophysics* **164**, 25–40.

Crook K. A. 1987. Petrology and mineral chemistry of sedimentary rocks from the western Solomon Sea. *Geo-Marine Letters* **6**, 203–209.

Davies H. L. 2012. The geology of New Guinea—the cordilleran margin of the Australian continent. *Episodes* **35**, 87–102.

Davies H. L., Lock J., Tiffin D. L., Honza E., Okuda Y., Murakami F. & Kisimoto K. 1987. Convergent tectonics in the Huon Peninsula region, Papua New Guinea. *Geo-Marine Letters* **7**, 143–152.

Denham D. 1969. Distribution of Earthquakes in the New Guinea–Solomon Islands region. *Journal of Geophysical Research* **74**, 4290–4299.

Engdahl E. R. 2006. Application of an improved algorithm to high precision relocation of ISC test events. *Physics of the Earth and Planetary Interiors* **158**, 14–18.

Engdahl E. R., van der Hilst R. & Buland R. 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. *Bulletin of the Seismological Society of America* **88**, 722.

Gaina C. & Müller D. 2007. Cenozoic tectonic and depth/age evolution of the Indonesian gateway and associated back-arc basins. *Earth Science Reviews* **83**, 177–203.

Goodliffe A. M., Taylor B., Martinez F., Hey R., Maeda K. & Ohno K. 1997. Synchronous reorientation of the Woodlark Basin Spreading Center. *Earth and Planetary Science Letters* **146**, 233–242.

Hall R. 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. *Journal of Asian Earth Sciences* **20**, 353–431.

Hall R. & Spakman W. 2002. Subducted slabs beneath the eastern Indonesia–Tonga region: insights from tomography. *Earth and Planetary Science Letters* **201**, 321–336.

Hendrix M. S., Dumitru T. A. & Graham S. A. 1994. Late Oligocene–early Miocene unroofing in the Chinese Tian Shan: An early effect of the India–Asia collision. *Geology* **22**, 487–490.

Hill K. C. & Raza A. 1999. Arc–continent collision in Papua Guinea: Constraints from fission track thermochronology. *Tectonics* **18**, 950–966.

Honza E., Davies H. L., Keene J. B. & Tiffin D. L. 1987. Plate boundaries and evolution of the Solomon Sea region. *Geo-Marine Letters* **7**, 161–168.

Isacks B., Oliver J. & Sykes L. R. 1968. Seismology and the new global tectonics. *Journal of Geophysical Research* **73**, 5855–5899.

Jakes P. & Gill J. B. 1970. Rare earth elements and the island arc tholeiite series. *Earth and Planetary Science Letters* **9**, 17–28.

Jaques A. L. & Robinson G. P. 1977. The continent–island arc collision in northern Papua New Guinea. *BMR Journal of Australian Geology and Geophysics* **2**, 289–303.

Johnson R. W. 1977. Distribution and major element chemistry of late Cenozoic volcanoes at the southern margin of the Bismarck Sea, Papua New Guinea. *Australian Bureau of Mineral Resources Report*, vol. 188.

Johnson R. W. & Chappell B. W. 1979. Chemical analyses of rocks from the late Cenozoic volcanoes of north-central New Britain and the Witu Islands, Papua New Guinea. *Australian Bureau of Mineral Resources Report*, vol. 209.

Johnson R. W. & Jaques A. L. 1980. Continent–arc collision and reversal of arc polarity: new interpretations from a critical area. *Tectonophysics* **63**, 111–124.

Johnson T. & Molnar P. 1972. Focal mechanisms and plate tectonics of the southwest Pacific. *Journal of Geophysical Research* **77**, 5000–5032.

Johnson R. W., Mutter J. C. & Arculus R. J. 1979. Origin of the Willaumez-Manus Rise, Papua New Guinea. *Earth and Planetary Science Letters* **44**, 247–260.

Kley J. & Voigt T. 2008. Late Cretaceous intraplate thrusting in central Europe: Effect of Africa–Iberia–Europe convergence, not Alpine collision. *Geology* **36**, 839–842.

Llanes P., Silver E., Day S. & Hoffman G. 2009. Interactions between a transform fault and arc volcanism in the Bismarck Sea, Papua New Guinea. *Geochemistry, Geophysics, Geosystems* **10**, Q06013.

Madsen J. A. & Lindley I. D. 1994. Large-scale structures on Gazelle Peninsula, New Britain: Implications for the evolution of the New Britain Arc. *Australian Journal of Earth Sciences* **41**, 561–569.

Mann P. & Taira A. 2004. Global tectonic significance of the Solomon Islands and Ontong Java Plateau convergent zone. *Tectonophysics* **389**, 137–190.

Martinez F. & Taylor B. 1996. Backarc spreading, rifting, and microplate rotation, between transform faults in the Manus Basin. *Marine Geophysical Research* **18**, 203–224.

Miller M. S., Gorbatov A. & Kennett B. L. N. 2006. Three-dimensional visualization of a near vertical slab tear beneath the southern Mariana Arc. *Geochemistry, Geophysics, Geosystems* **7**, Q06012.

Mishra D. C., Singh B., Tiwari V. M., Gupta S. B. & Rao M. B. S. V. 2000. Two cases of continental collisions and related tectonics during the Proterozoic period in India—insights from gravity modeling constrained by seismic and magnetotelluric studies. *Precambrian Research* **99**, 149–169.

Morales J., Serrano I., Jabaloy A., Galindo-Zaldívar J., Zhao D., Torcal F., Vidal F. & González Lodeiro F. 1999. Active continental subduction beneath the Betic Cordillera and the Alborán Sea. *Geology* **27**, 735–738.

Najman Y., Appel E., Boudagher-Fadel M., Bown P., Carter A., Garzanti E., Godin L., Han J., Liebke U., Oliver G., Parrish R. & Vezzoli G. 2010. Timing of India–Asia collision: Geological, biostratigraphic, and palaeomagnetic constraints. *Journal of Geophysical Research* **115**, B12416.

O'Kane T. 2008. *3-D structure and tectonic evolution of the Papua New Guinea and Solomon Islands region and its relationship to Cu–Au mineralization*. Unpublished Honours thesis, Research School of Earth Sciecnes, The Australian National University.

Pegler G., Das S. & Woodhouse J. H. 1995. A seismological study of the eastern New Guinea and the western Solomon Sea regions and its tectonic implications. *Geophysical Journal International* **122**, 961–981.

Petterson M. G., Babbs T., Neal C. R., Mahoney J. J., Saunders A. D., Duncan R. A., Tolia D., Magu R., Qopoto C., Mahoa H. & Natogga D. 1999. Geological-tectonic framework of Solomon Islands, SW Pacific: crustal accretion and growth with an intra-oceanic setting. *Tectonophysics* **301**, 35–60.

Plank T. 2005. Constraints from thorium/lanthanum on sediment recycling at sub- duction zones and the evolution of the continents. *Journal of Petrology* **46**, 921–944.

Rawling T. J. & Lister G. S. 2002. Large-scale structure of the eclogite-blueschist belt of New Caledonia. *Journal of Structural Geology* **24**, 1239–1258.

Richards S., Holm R. & Barber G. 2011. When slab collide: A tectonic assessment of deep earthquakes in the Tonga–Vanuatu region. *Geology* **39**, 787–790.

Richards S., Lister G. & Kennett B. 2007. A slab in depth: Three-dimensional geometry and evolution of the Indo-Australian plate. *Geochemistry Geophysics Geosystems* **8**, Q12003.

Ripper I. D. 1982. Seismicity of the Indo-Australian/Solomon Sea plate boundary in the southeast Papua region. *Tectonophysics* **87**, 355–369.

Rosenbaum G., Lister G. S. & Duboz C. 2002. Relative motions of Africa, Iberia and Europe during Alpine orogeny. *Tectonopysics* **359**, 117–129.

Sobel E. R. & Dumitru T. A. 1997. Thrusting and exhumation around the margins of the western Tarim basin during the India–Asia collision. *Journal of Geophysical Research* **102**, B3, 5043.

Spandler C., Rubatto D. & Hermann J. 2005. Late Cretaceous–Tertiary tectonics of the southwest Pacific: Insights from U–Pb sensitive, high resolution ion microprobe (SHRIMP) dating of eclogite facies rocks from New Caledonia. *Tectonics* **24**, TC3003.

Stern T. A. 1995. Gravity anomalies and crustal loading at and adjacent to the Alpine Fault, New Zealand. *New Zealand Journal of Geology and Geophysics* **38**, 593–600.

Stevens C., McCaffrey R., Silver E. A., Sombo Z., English P. & van der Kevie J. 1998. Mid-crustal detachment and ramp faulting in the Markham Valley, Papua New Guinea. *Geology* **26**, 847–850.

Taylor B. 1979. Bismarck Sea: Evolution of a back-arc basin. *Geology* **7**, 171–174.

Taylor B., Goodliffe A. M. & Martinez F. 1999. How continents break up: Insights from Papua New Guinea. *Journal of Geophysical Research* **104**, 7497–7512.

Teng L. S. 1990. Geotectonic evolution of Late Cenozoic arc–continent collision in Taiwan. *Tectonophysics* **183**, 57–76.
Tregoning P. 2002. Plate kinematics in the western Pacific derived from geodetic observations. *Journal of Geophysical Research* **107**, B1 2020.
Tregoning P., Jackson R. J., McQueen H., Lambeck K., Stevens C., Little R. P., Curley R. & Rosa R. 1999. Motion of the South Bismarck Plate, Papua New Guinea. *Geophysical Research Letters* **26**, 3517–3520.
Tregoning P., Lambeck K., Stoltz A., Morgan P., McClusky S. C., van der Beek P., McQueen H., Jackson R. J., Little R. P., Laing A. & Murphy B. 1998. Estimation of current plate motions in Papua New Guinea from Global Positioning System observations. *Journal of Geophysical Research B: Solid Earth* **103**, 12181–12203.
Wallace L. M., Stevens C., Silver E., McCaffrey R., Loratung W., Hasiata S., Stanaway R., Curley R., Rosa R. & Taugaloidi J. 2004. GPS and seismological constraints on active tectonics and arc–continent collision in Papua New Guinea: Implications for mechanics of microplate rotations in a plate boundary zone. *Journal of Geophysical Research* **19**, B05404.
Weiler P. D. & Coe R. S. 2000. Rotations in the actively colliding Finisterre Arc Terrane: paleomagnetic constraints on Plio–Pleistocene evolution of the South Bismarck microplate, northeastern Papua New Guinea. *Tectonophysics* **316**, 297–325.
Whattam S. A. 2009. Arc–continent collisional orogenesis in the SW Pacific and the nature, source and correlation of emplaced ophiolitic nappe components. *Lithos* **113**, 88–114.
Woodhead J. D. & Johnson R. W. 1993. Isotopic and trace element profiles across the New Britain island arc, Papua New Guinea. *Contributions to Mineralogy and Petrology* **113**, 479–491.
Woodhead J. D., Eggins S. M. & Gamble J. G. 1993. High field strength and transition element systematics in coupled arc–back arc settings: evidence for multi-phase melt extraction and a depleted mantle wedge. *Earth and Planetary Science Letters* **114**, 491–504.
Woodhead J. D., Eggins S. M. & Johnson R. W. 1998. Magma genesis in the New Britain island arc: Further insights into melting and mass transfer processes. *Journal of Petrology* **39**, 1641–1668.
Woodhead J., Hergt J., Sandiford M. & Johnson W. 2010. The big crunch: Physical and chemical expressions of arc/continent collision in the Western Bismarck arc. *Journal of Volcanology and Geothermal Research* **190**, 11–24.

Received 7 June 2012; accepted 8 July 2013

SUPPLEMENTARY PAPER

Earthquake density distribution maps for depth bins of 0–20, 20–40, 40–60, 60–80, 80–100, 100–120 and 120–140 km. Earthquake densities are contoured from high density (white) to low density (blue).