Subduction history in the Melanesian Borderlands region, SW Pacific

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Keywords: Coral Sea, Melanesia, subduction, seafloor-spreading, SW Pacific, tectonics, geodynamics

Abstract

The easternmost Coral Sea region is an underexplored area at the northeasternmost corner of the Australian plate. Situated between the Mellish Rise, southern Solomon Islands, northern Vanuatu and New Caledonia, it represents one of the most dynamic and tectonically complex submarine regions of the world. Interactions between the Pacific and Australian plate boundaries have resulted in an intricate assemblage of deep oceanic basins and ridges, continental fragments and volcanic products; yet there is currently no clear conceptual framework to describe their formation. Due to the paucity of geological and geophysical data from the area to constrain plate tectonic models, a novel approach has been developed whereby the history of subduction based on a plate kinematic model is mapped to present-day seismic tomography models. A plate kinematic model, which includes a self-consistent mosaic of evolving plate boundaries through time is used to compute plate velocity fields and palaeo-oceanic age grids for each plate in 1 million year intervals. Forward geodynamic models, with imposed surface plate velocity constraints are computed using the 3D spherical finite element convection code *CitcomS*. A comparison between the present-day mantle temperature field predicted by these geodynamic models with seismic tomography suggests that the kinematic model for the subduction history in the eastern Coral Sea works well for the latest Cenozoic but fails to predict seismically fast material in the lower mantle (indicative of cold, subducted material) imaged in seismic tomography models. This implies that the location and nature of the plate boundaries in the eastern Coral Sea used in these models requires further refinement. A quantified tectonic framework and subduction history of the region will assist in assessing hydrocarbon and mineral resource potential of northeastern Australia and Australia's Pacific island neighbours, the eastward extent of Australian continental lithosphere and will help place further constrains on the subsidence and uplift history of Australia's eastern sedimentary basins and carbonate-capped plateaus.

Introduction

The SW Pacific is characterised by a series of marginal basins, submerged continental slivers and back-arc—arc—forearc complexes which are largely controlled by the interaction of the Australian and Pacific plates since the Mesozoic (Crawford et al., 2003, Schellart et al., 2006, Sdrolias et al., 2003, Yan and Kroenke, 1993) (Figure 1). Most studies limit the northern extent of SW Pacific plate reconstructions to the easternmost Coral Sea, in the "Melanesian Borderlands" region, an underexplored area of around 50,000 km^2 with poorly interpreted submarine features. The lack of knowledge of the area is due, in part, to the inherent complexity of seafloor structures over a small oceanic area; overprinting due to its close proximity to one of the world's most dynamic subduction zone systems; and the scarcity of marine geophysical data and geological samples. However, this area is critical for plate reconstructions of both the SW Pacific and SE Asia as it occupies a pivotal position along the western Pacific plate boundary, linking and providing plate boundary continuity between these two tectonically complex regions. This gap in our fundamental knowledge of the seafloor in the easternmost Coral Sea restricts our capacity to construct accurate plate kinematic models of both SE Asia and the SW Pacific, which in turn leads to an incomplete record of subduction, a fragmented map of volcanic arc and back-arc environments and an uncertain eastward extent of Australian continental lithosphere beyond the Mellish Rise, all of which are critical for assessing the resource potential of northeastern Australia and that of Australia's Pacific island neighbours.

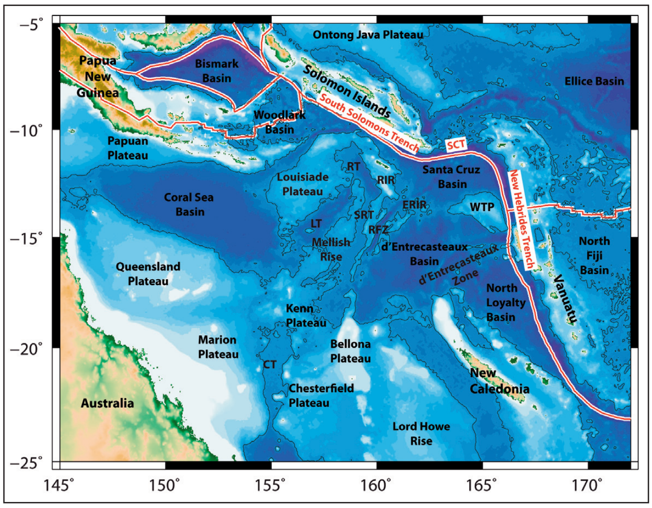

Figure 1. Regional digital elevation model (ETOPO2) of the eastern Coral Sea. CT = Cato Trough, ERIR = East Rennell Island Ridge, LT = Louisiade trough, RFZ = Rennell Fracture Zone, RIR = Rennell Island Ridge, RT = Rennell trough, SCT = San Cristobal Trench, SRT = South Rennell Trough, WTP = West Torres Plateau. Red lines denote present day plate boundaries (Bird, 2003). Thin back lines denote the 3500 m bathymetric contour.

To partly overcome the sparse regional data coverage and to move towards better-constrained plate kinematic and geodynamic models of the region, a new methodology has been developed that links the history of subduction predicted by a plate kinematic model to present-day mantle structure imaged in seismic tomography models. This methodology allows an assessment of the validity

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of plate reconstructions in an area, as each model produces a unique mantle structure. The input plate kinematic model used in this geodynamic model (Seton et al., 2012) was created using the plate reconstruction software *GPlates* (Boyden et al., 2011) and is accompanied by a series of dynamically evolving plate boundaries and plate polygons through time (Gurnis et al., 2012), velocity fields of each plate and maps of the age-area distribution of the ocean floor in one million year intervals. The forward geodynamic models with imposed surface plate velocity were computed using the 3D spherical finite element convection code *CitcomS* (Zhong et al., 2008).

Regional Setting

The easternmost Coral Sea is located east of the Coral Sea Basin and Kenn Plateau, south and southwest of the Solomon Islands, west of northern Vanuatu and north of New Caledonia (Figure 1). The present day plate boundary configuration in this region is dominated by subduction of the northward migrating Australian plate beneath the westward migrating Pacific plate along the South Solomon/San Cristobal Trench (south of the Solomon Islands). To the east, lithosphere from the easternmost Coral Sea is consumed at an eastward-dipping subduction zone along the New Hebrides Trench (Figure 1).

The seafloor fabric of the eastern Coral Sea contains a series of submerged plateaus, linear depressions, elongated ridges, oceanic basins and seamounts (Figure 1-3). The submerged plateaus to the west, the Louisiade Plateau and Mellish Rise, are inferred to be floored by Australian continental lithosphere based on the similarity in seismic character to the Queensland and Kenn plateaus where continental basement has been confirmed (Taylor and Falvey, 1977, Exon et al., 2006). The Louisiade Trough, which reaches depths of over 5500 m separates the Louisiade Plateau and Mellish Rise and is believed to have accommodated seafloor spreading during the opening of the Tasman and Coral Seas as evidenced by the identification of magnetic anomalies (Gaina et al., 1999) and rift-related structures along the margins (Exon et al., 2006) (Figure 1).

To the northeast of the Mellish Rise lies a short, narrow depression, the Rennell Trough, with water depths exceeding 5000 m (Figure 1) and a gravity anomaly low of -780 mGals (Figure 2), similar in amplitude to the nearby South Solomon Trench. The origin of the trough is unknown, however previous models speculate that it was the site of east-dipping subduction during the Eocene (Daniel et al., 1978, Weissel and Watts, 1979, Yan and Kroenke, 1993), which accommodated the opening of the Coral Sea basin from ~61 Ma.

An elongated ridge structure north and east of the Rennell Trough, the Rennell Island Ridge (Figure 1), is characterised by normal faulting on its western side, based on seismic reflection profiles (Landmesser et al., 1974). Along the ridge, the exposed Rennell and Bellona Islands belong to one of the world's largest exposed raised coral atoll, consisting of a thick (up to 500 m) sequence of coral reefs and dolomites (Taylor, 1973). The nature of the basement comprising the ridge is unknown, however airborne gravity and magnetic signatures are similar in character to the Cretaceous uplifted oceanic crust found on the Malaita Islands, southern Solomon Islands (Hughes and Turner, 1977). This would imply that the Rennell Island Ridge may be an uplifted sliver of oceanic basement, but this interpretation is at odds with the Eocene subduction zone model for the Rennell Trough proposed

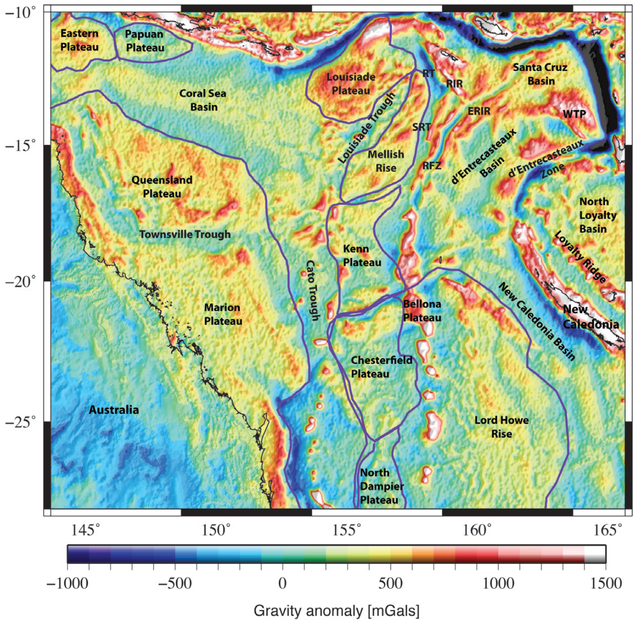

Figure 2. Combined onshore and offshore gravity anomaly grid from Geoscience Australia with the tectonic elements defined by Gaina et al. (1998, 1999) outlined in purple. ERIR = East Rennell Island Ridge, RFZ = Rennell Fracture Zone, RIR = Rennell Island Ridge, RT = Rennell Trough, SRT = South Rennell Trough, WTP = West Torres Plateau.

by others (Daniel et al., 1978, Weissel and Watts, 1979, Yan and Kroenke, 1993) that would result in the establishment of a volcanic arc along the Rennell Island Ridge rather than in a fragment of uplifted oceanic lithosphere. An alternative suggestion, based on seismic reflection profiles, is that the Rennell Island Ridge may represent a fragment of Mesozoic continental lithosphere derived from the Australian continental margin (Landmesser et al., 1974), which was rifted off the Louisiade Plateau. In this scenario, the Rennell Trough would be an abandoned spreading centre and not a remnant deep-sea trench. As there are no basement outcrops present on the exposed Rennell and Bellona Islands and dredge samples are not available, the true character of both the Rennell Trough and Rennell Island Ridge remain unknown. The Quaternary uplift of the Rennell Island Ridge has been linked to the proximal northeast-dipping subduction along the South Solomon Trench.

South and southwest of the Rennell Island Ridge and east of the Mellish Rise reside a series of long and narrow troughs and ridges on the eastern margin of the Mellish Rise (Figure 1). These include the South Rennell Trough, the Rennell Fracture Zone and the East Rennell Island Ridge (Figure 1-2). Based on seismic reflection profiles, the Rennell Fracture Zone and/or South Rennell Trough are thought to have formed along a transform fault (Landmesser et al., 1974) with subsequent seafloor spreading during the late Oligocene (Daniel et al., 1978, Larue et al., 1977). The East Rennell Island Ridge extends northward, arcing eastwards into the Santa Cruz/Torres Basin (Figure 1-2) confirming that the activation of this boundary post-dates the formation of the Santa Cruz/Torres Basin. The Santa Cruz/Torres Basin itself has been postulated to be floored by oceanic lithosphere that is interpreted to have formed during the Cretaceous (Kroenke, 1984, Schellart et al., 2006), coincident with the inferred Cretaceous opening of the d'Entrecasteaux Basin to the south. Other models propose opening during the Oligocene (Larue et al., 1977, Wells, 1989) coincident with extension along the South Rennell Trough. There are no published magnetic anomaly interpretations for the basin, which may have aided in interpreting the age of the basin formation, primarily due to poor magnetic profile coverage over the basin.

South of the Santa Cruz/Torres Basin but north of the d'Entrecasteaux Zone lies the West Torres Plateau, a shallow submarine plateau (between 900-2000 m water depth) of unknown origin (Figure 1). The two alternative models for the nature of basement include a continental origin (Schellart et al., 2006), such as a continental raft from eastern Gondwanaland, or a mantle plume origin with the eruption of the associated Large Igneous Province (LIP) in the Oligocene (Yan and Kroenke, 1993). Incorporating a continental origin for the West Torres Plateau would require an approximately east-west spreading direction in the d'Entrecasteaux Basin, unless significant north-south translation has occurred after an earlier period of east-west extension.

The d'Entrecasteaux Basin that lies to the west of the West Torres Plateau and north of the d'Entrecasteaux Zone (Figure 1) has been interpreted as floored by oceanic lithosphere even though there are no direct in-situ samples. A tenuous interpretation based on limited magnetic anomaly profiles yielded a Cretaceous age (between anomalies 30-34, 65-84 Ma) for the basin formation (Lapouille, 1982) from roughly NW-SE directed spreading. The spreading direction is confirmed from a single swath bathymetry track over the basin, which shows NE-SW seafloor fabric in the eastern part of the basin. Several authors have questioned the prevailing interpretation, however no alternative interpretation of the magnetic lineations has been published. The majority of models for the evolution of the SW Pacific incorporate a Cretaceous opening model for the d'Entrecasteaux Basin.

Tectonic framework

The eastern Australian margin was dominated by a period of long-lived subduction throughout the Mesozoic (Veevers, 2006, Cluzel et al., 2010), expressed by andesitic volcanism that occurred along the Queensland margin north to Papua New Guinea (Jones and Veevers, 1983) and Aptian-Albian andesitic volcanogenic detritus in east Australian continental basins (e.g. Eromanga and Surat Basins) (Hawlader, 1990, Veevers, 2006). At 100-99 Ma, a major change in the tectonic regime is recorded in eastern Australia (Veevers, 2006). Sedimentation in the east Australian basins changed from volcanogenic-dominated to quartzose sandstone (Veevers, 2006), the basins structural system changed from a prolonged period of subsidence to uplift (Matthews et al., 2010) and volcanism became alkalitic (Veevers, 2006). In addition, the eastern margin commenced a period of extension and passive margin formation (e.g. extension in the Lord Howe Rise and New Caledonia Basins and dispersal of continental blocks from eastern Gondwana), which is believed to have formed adjacent to a strike-slip/transpressional margin defining the boundary between Panthalassa and eastern Gondwana (Veevers, 2006, Jones and Veevers, 1983). A hiatus in subduction-related volcanism in eastern Australia, New Caledonia and New Zealand is recorded between 95-83 Ma (Cluzel et al., 2010). This major tectonic regime change is coincident with a reorganization of the plates associated with the break-up of the Ontong Java, Manihiki and Hikurangi plateaus (Chandler et al., 2012, Seton et al., 2012), which bordered the eastern Gondwanaland margin at this time.

Break-up in the southern area between Australia and the Lord Howe Rise initiated at 90 Ma, before seafloor spreading was

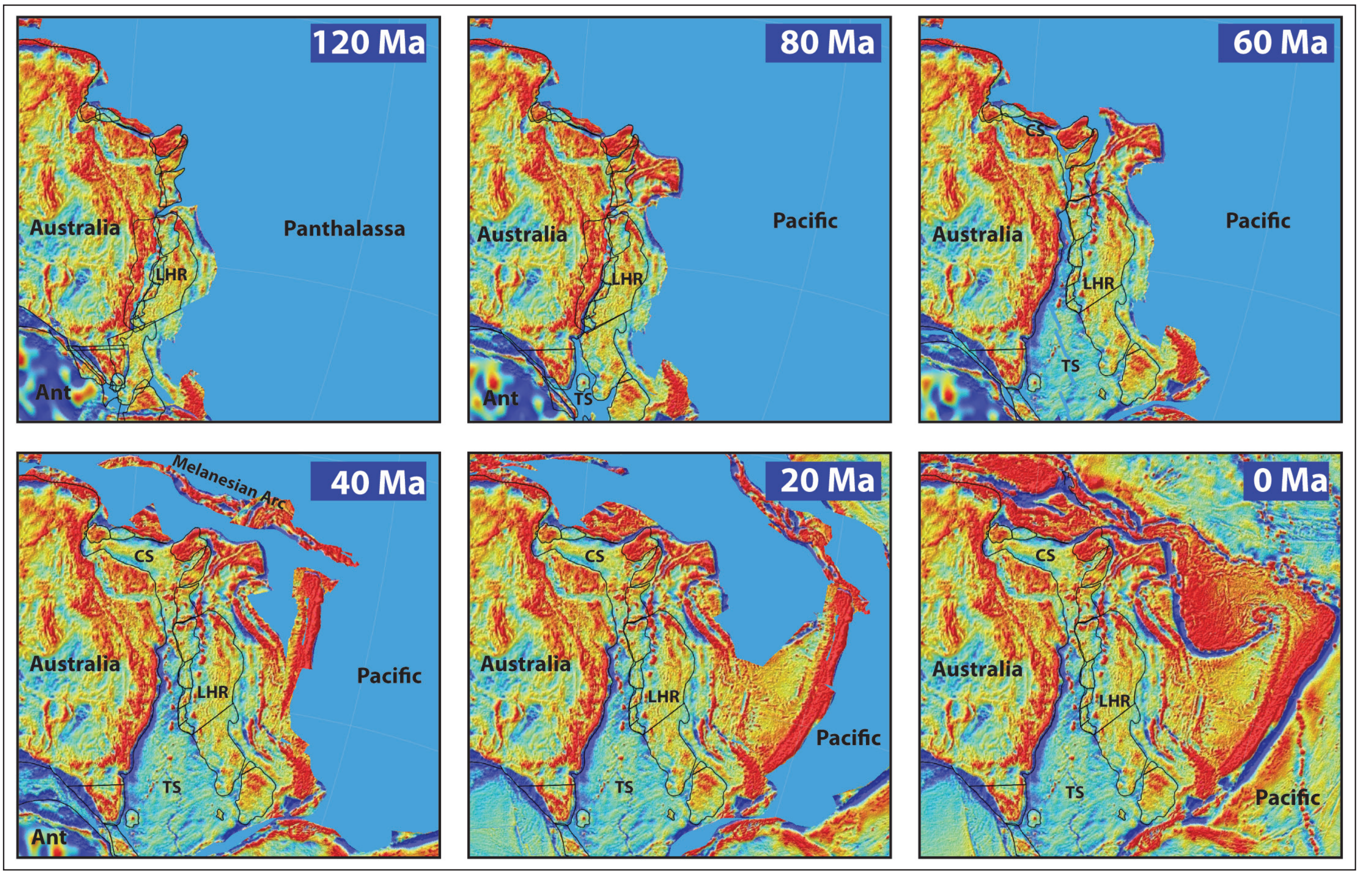

Figure 3. Reconstructed raster of the gravity anomalies highlighting the issues with prevailing models of the eastern Coral Sea, particularly in the context of the greater SW Pacific. Blue areas indicate areas that have no present day record (i.e. subducted oceanic lithosphere).

established at 83 Ma (Gaina et al., 1998). Spreading propagated into the Coral Sea and Louisiade Trough by 61 Ma leading to the separatation of the Louisiade, Kenn and Papuan Plateaus and the Mellish Rise from the Australian continent and establishing a triple junction between the Australian-Lord Howe-Louisiade plates (Gaina et al., 1999) (Figure 3). Regional plate tectonic models invoke Cretaceous spreading in the d'Entrecasteaux, Santa Cruz/Torres Basins and/or South Loyalty Basin (e.g. Schellart et al., 2006, Crawford et al., 2003) behind a west-dipping subduction zone between the Australian and Pacific plates (Figure 3-4). These models necessarily imply that the d'Entrecasteaux, Santa Cruz/Torres Basins and/or South Loyalty Basin were formed by back-arc spreading. Spreading in the Tasman and Coral Seas and Louisiade Trough ceased by 52 Ma (Gaina et al., 1998, Gaina

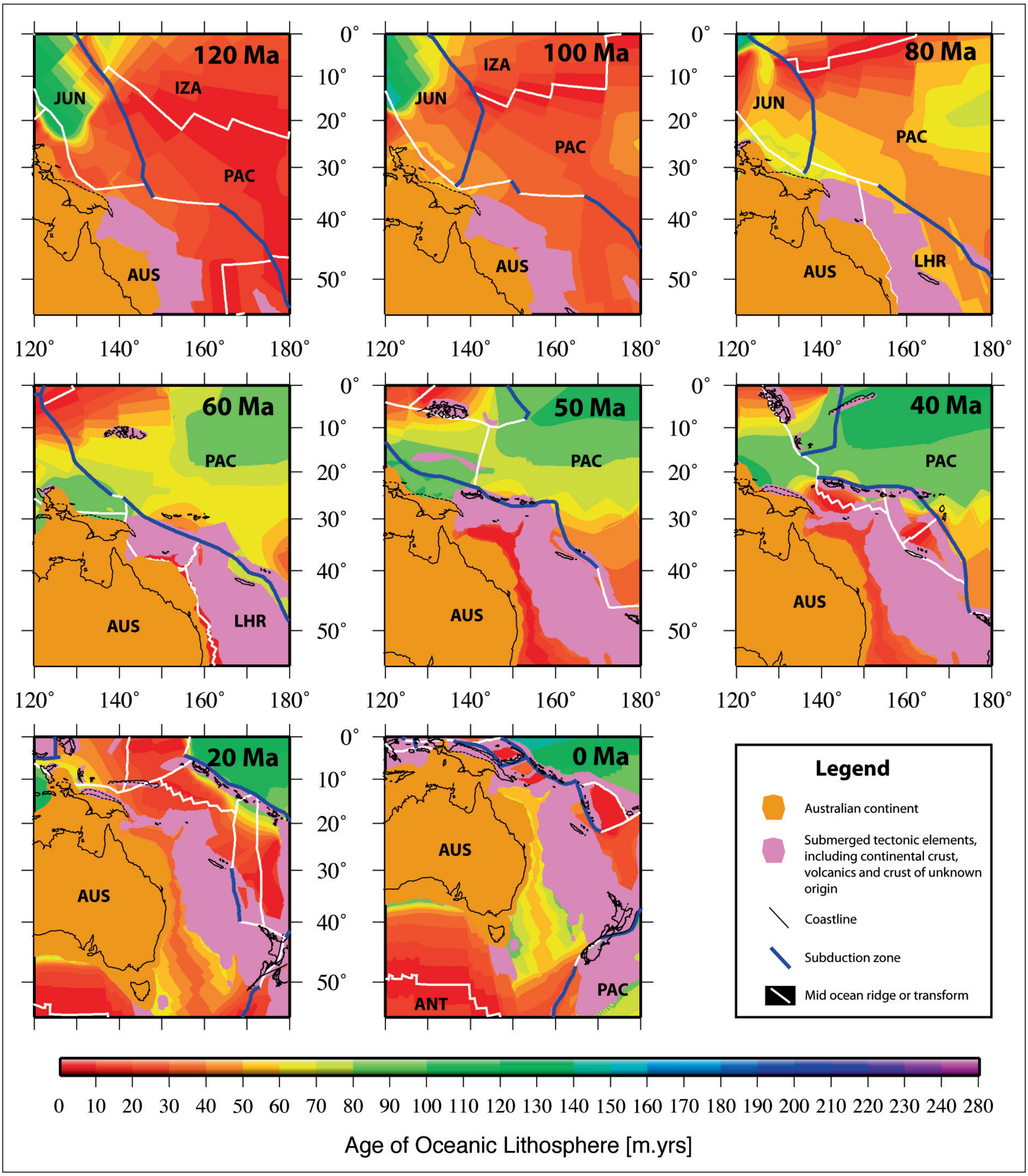

Figure 4. Plate reconstructions, plate boundary locations and palaeo-age grids of the SW Pacific at 120, 100, 80, 60, 50, 40, 20, 0 Ma. These data are created in one million year time intervals and are used as surface boundary constraints into our forward geodynamic models.

et al., 1999). Some models invoke subduction along the Rennell Trough in the area adjacent to the Coral Sea basin during this time.

Southward-dipping subduction is interpreted to have initiated along the Melanesian Arc in the Eocene (~45-50 Ma) continuing southward along a proto-Tonga-Kermadec Ridge (Hall, 2002, Gaina and Müller, 2007, Schellart et al., 2006, Sdrolias et al., 2003). Schellart et. al. (2006) invoked simultaneous eastward-dipping subduction along the western margin of New Caledonia leading to the opening of the North Loyalty Basin and the formation of the d'Entrecasteaux Zone as a transform margin accommodating basin opening. Most models invoke the initiation of the Melanesian Arc from intra-oceanic convergence (Yan and Kroenke, 1993), although there is no direct evidence to support this view.

The dominant tectonic regime in the SW Pacific after the Eocene was subduction roll-back and episodic back-arc basin opening, including the North Loyalty, South Fiji, North Fiji and Lau back-arc basins (Sdrolias et al., 2003, Schellart et al., 2006, Yan and Kroenke, 1993). Evidence for seafloor spreading along the South Rennell Trough/Rennell Fracture Zone and possible opening of the Santa Cruz Basin during the Oligocene may indicate that further plate boundaries were present north of the South Fiji Basin. How these plate boundaries fit into the broader tectonic framework is unknown but they may have initiated at the time of a major plate reorganisation in the SW Pacific, expressed as a kink in the motion of the Australian plate (Knesel et al., 2008).

At around 25-20 million years ago, the Ontong Java Plateau arrived at the North Solomon/Vitiaz Trench (Figure 4). The arrival is assumed to be marked by an initial "soft collision" with no major associated uplift (Petterson et al., 1997). Continued convergence subsequently caused major uplift and compression along the Melanesian Arc. In the late Miocene (~12 Ma), a reversal in the polarity of subduction occurred (Petterson et al., 1997) as continued subduction of the Ontong Java Plateau clogged the subduction zone during hard collision. Subduction was subsequently initated along the present day South Solomon/San Cristobal Trench, leading to the subduction of the Australian plate beneath the Pacific plate and the destruction of crust from the easternmost Coral Sea (Figure 1 and 4).

Methodology

The tectonic evolution of the eastern Coral Sea is largely unconstrained due to the paucity of data regarding the nature and age of the crust that underlies the area. In the absence of new data, an innovative approach is required to constrain the type and location of plate boundaries through time. This new approach couples plate reconstructions with a forward model of mantle flow using the plate reconstruction software *GPlates* (Boyden et al., 2011), and a 3D spherical finite-element mantle convection code, *CitcomS* (Zhong et al., 2008, Tan et al., 2007). The geodynamic modeling approach consists of assimilating plate kinematics, the thermal structure of the oceanic lithosphere and the shallow thermal structure of slabs into the forward model in one million year increments e.g. (Zahirovic et al., 2012). The plate motions are imposed as kinematic boundary conditions on the top surface of the spherical domain and are taken from the model of Seton et al. (2012). In this global kinematic model, the SW Pacific is implemented based on the model of Sdrolias et al. (2003) for the Cretaceous and Di Caprio et al. (2009) for the Cenozoic. The model includes a set of continuously closed plate polygons, as described in Gurnis et al. (2012), in one million year time intervals from which we extract plate velocity vectors.

The mantle flow model is a forward global convection model starting at 200 Ma. The thermal structure of the lithosphere within the oceans is assimilated into the convection model using the depth-dependent method described in Matthews et al. (2010) with an assimilation depth parameter of 65 km. The thermal structure assimilated uses the lithospheric half-space cooling model (Turcotte and Schubert, 1982) in which oceanic crustal age is derived from a set of palaeo-age grids (Figure 4). In addition, at each time step the thermal structure was progressively assimilated the thermal structure within 350 km of subducting slabs using the method of Bower et al. (in prep). The model consists of ~ 12.5 x 10^6 nodes, achieving an average surface resolution of ~ 50 km and an average radial resolution of 45 km. A series of models were run with alternative mantle parameters and the two preferred models are called SPW1 and SPW2. Both models have a Rayleigh number of ~ 4 $\times 10^7$, with temperature-dependent viscosity and a viscosity of the lower mantle 100 times greater than that of the upper mantle. Model SPW2 includes the effect of a phase change at 670 km depth with a Clapeyron slope of -2 MPa K-1 and a 7 % density increase (Billen, 2008).

Seismic tomography provides a three-dimensional image of the heterogeneities in the earth's mantle and is often used as a proxy for mantle temperature anomalies: seismically slow material representing hot, buoyant material such as mantle upwellings and seismically fast material representing cold, dense material such as subducted slabs. Even though not all seismic velocity perturbations can be related to geological structures – for example thermo-chemical heterogeneities in the mantle can also produce such perturbations (Trampert et al., 2004) – the long wavelength signals are well resolved. The present day mantle structure as predicted by the new geodynamic models was compared to two P-wave models (MIT-P (Li et al., 2008) and GyPSuM (Simmons et al., 2010)) and the S-wave model of Grand (2002).

Results

A first-order comparison between the present-day mantle temperature field predicted by our geodynamic models with seismic tomography suggests that prevailing kinematic models for the subduction history in the eastern Coral Sea work well for the latest Cenozoic but fail to predict the seismically fast material in the mid and lower mantle imaged in seismic tomography models. Geodynamic model output results were examined along a set of profiles corresponding to the present day location of Melanesian subduction (i.e. where the eastern Coral Sea is presently subducting beneath the Pacific plate). Although several profiles were studied, we present the results centered on 130˚E, 35˚S and 175˚E, 5˚S. For a detailed description of the SW Pacific along profiles further south see Matthews et al. (this volume).

Geodynamic models

Mesozoic plate reconstructions of the SW Pacific are dominated by west-dipping subduction along eastern Gondwanaland, consuming oceanic lithosphere from the proto-Pacific or Panthalassic Ocean (Figure 4), continuing northward along the

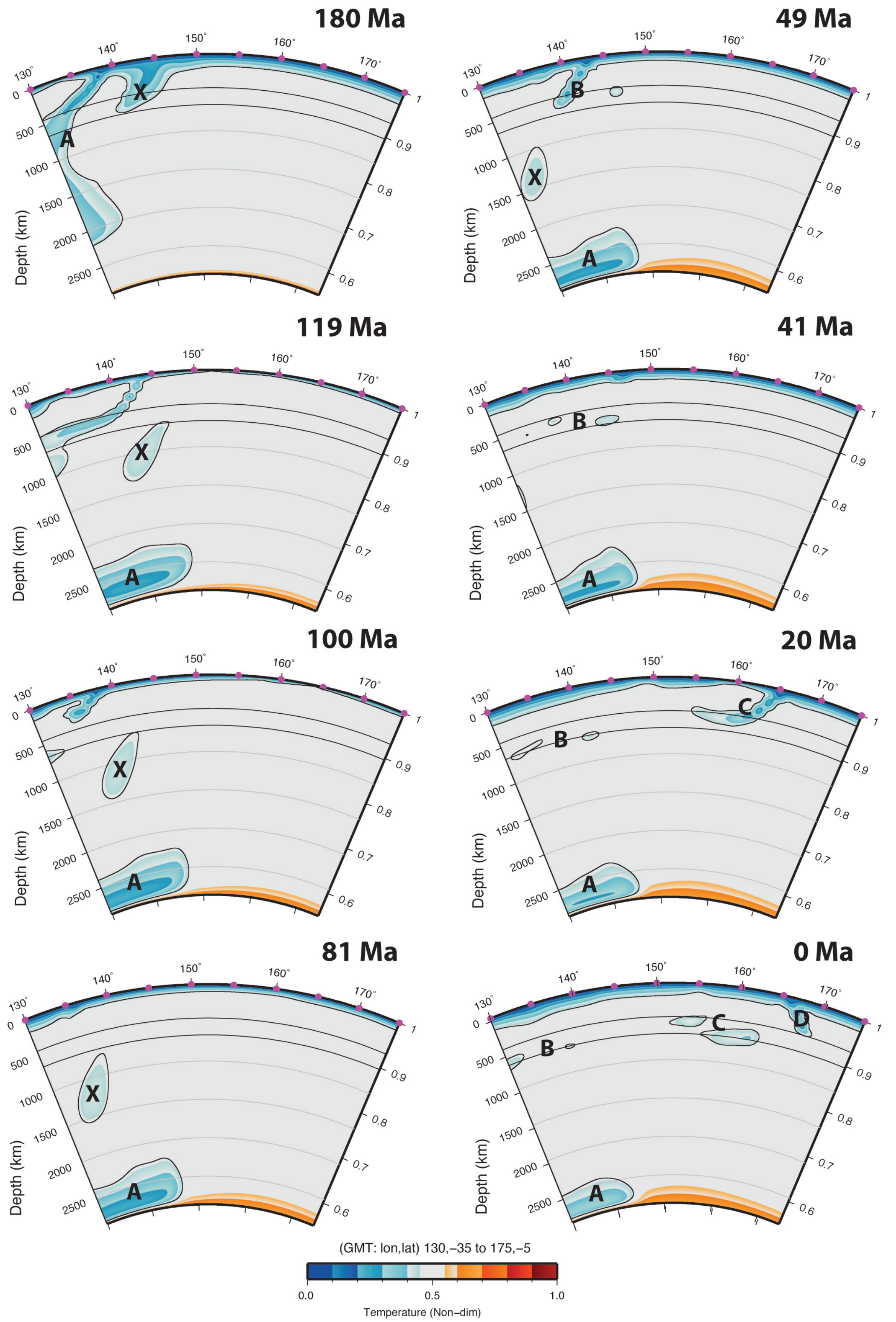

Figure 5. Forward model output for our preferred model (SPW1) along profile 130˚E, 35˚S to 175˚E, 5˚S at 180, 119, 100, 81, 49, 41, 20, 0 Ma showing the progression of subduction and changes in slab material entering the mantle at different times. Black outlines are slab contours, which represent material 60 % colder than the ambient mantle temperature. Letters are described in text.

subduction zone bordering the Junction plate (Figure 4). The slab material associated with this margin is thought to have been quite voluminous due to the extended duration of subduction (active for > 150 million years), the advanced age of the downgoing oceanic lithosphere (average age of between 90-120 million years; Figure 4) and the high convergence rates predicted between the Australian and Phoenix plates (average rate of 11 cm/yr). This is reflected in our geodynamic model output, which confirms voluminous slab material was inserted into the mantle around longitude 139˚E, producing a well-developed Benioff zone underlying the submarine plateaus and rises in the eastern Coral Sea (Figure 5). We observe a continuous slab from the upper to lower mantle at 180 Ma with minimal flattening at the 660 km discontinuity, consistently with plate reconstruction models that do not include a rapid rollback of the subduction hinge. A secondary subduction zone is observed in the geodynamic model output at a longitude of 145˚E (Figure 5) due to a minor amount of intra-oceanic convergence at 190 Ma, resulting in slab material entering the mantle eastward of the dominant east Gondwanaland/Junction subduction zone. The intra-oceanic convergence only existed for a period of 10 million years but the material produced during this period resides in the upper mantle for about 70 million years, and subsequently sinks in the lower mantle (Figure 5). Subduction continued along eastern Gondwanaland and the Junction plate until 120 Ma (Seton et al. 2012) and the model output at 119 Ma (Figure 5) shows an increase in the flattening of the slab at the 660 km discontinuity and an eastward migration of the subduction hinge by ~700 km. The observed flattening of the slab results from the increase in the eastward hinge roll-back during the opening of the South Loyalty back-arc basin, which occurred between 140-120 Ma (Seton et al. 2012) (Figure 4).

Geological observations indicate that there was a major change in tectonic regime east of Australia after 120 Ma (e.g. (Veevers, 2006, Matthews et al., 2010, Cluzel et al., 2010)), with the cessation of subduction predicted some time between 110-90 Ma. Further north, subduction continued along the Junction plate and connected to the eastern Gondwanaland subduction zone via a transform fault (Figure 4). The new geodynamic model output, which is focused in the area around the Junction plate, shows a waning of subduction at ~100 Ma (Figure 5), reflecting the formation of the transform connecting the eastern Gondwanaland and Junction plate subduction zones in our plate model. Additionally, this is coincident with a change in spreading direction associated with the break-up of Ontong Java Nui in the westernmost proto-Pacific ocean (Chandler et al. 2012), which has been incorporated into the plate model. The plate kinematic model of Seton et al. (2012) proposes that subduction was re-established east of Australia as an east-dipping system around 85 Ma (Figure 4). The geodynamic model output in our area of interest corresponds to the region where the transform fault connected eastern Gondwanaland and the Junction plate, explaining the absence of material entering the mantle at this location in the new geodynamic models.

The Melanesian subduction zone or Vitiaz trench, representing subduction of the Pacific plate under the Australian plate, was initiated at 50 Ma in our reconstructions. The initiation of subduction is reproduced in the new geodynamic model output as a west-dipping slab in the upper mantle (Figure 5). The plate reconstructions suggest that convergence continues along this boundary until at least 12 Ma (Figure 4). However, by 40 Ma, the geodynamic model output does not reflect active subduction at this location; instead only a small volume of slab material resides in the upper mantle (Figure 5). This may indicate either that we are underestimating the sinking velocities in the upper mantle (3 cm/yr) and/or that the duration of subduction is under-estimated and therefore reflects an artifact in the initial boundary conditions of our model and can be confirmed via seismic tomography. By 20 Ma, subduction is clearly observed in the model output in the upper mantle (Figure 5). This was followed by the cessation of southwestward dipping subduction due to the hard docking of the Ontong Java Plateau to the Melanesian subduction zone around 12 Ma and the establishment of northeast dipping subduction on the leeside of the Melanesian Arc, as reproduced in the geodynamic model output (Figure 5).

The present day mantle temperature field predicted by the new geodynamic models shows four distinct regions of remnant slab material. The first region (A in Figure 5) is currently located at the core-mantle boundary. It represents material from the voluminous Cretaceous subduction east of Australia, which migrated westward and currently underlies the western Australian continent, pooling at the core-mantle boundary. The second region (B in Figure 5) is located in the upper mantle, between the 440 and 660 km transition zone, and represents remnant slab material from subduction that occurred with the establishment of the Melanesian/Vitiaz subduction zone in the Eocene. The amount of material inserted into the mantle during this period is severely underestimated in the model as it does not predict a continuous subducted slab throughout the entire duration of subduction along the Melanesian Arc even though there is evidence that subduction was continuous since the Eocene. As stated earlier, this may be a combination of under-estimated upper mantle sinking rates and the timing of subduction initiation. Importantly, there is a complete absence of material in the upper mid-mantle. The third region (C in Figure 5) is currently located between the 440 and 660 km transition zones at longitudes between 152-162˚E and stems from the later stage of the southwest dipping subduction along the Melanesian/Vitiaz subduction zone. The remnant slab, although discontinuous, does appear to have flattened at the transition zone. The fourth region (D in Figure 5) is the recently developed northeast dipping subduction along the leeside of the Melanesian Arc. Subduction was initiated here in the last 10 million years with opposite polarity to the previous subduction and is actively consuming the crust of the Santa Cruz/Torres Basin and the crust that exists to the north of the Rennell Island Ridge. Thw slab associated with this youngest period of subduction has yet to reach the transition zone.

Seismic Tomography

A snapshot of present-day mantle structure is imaged via seismic tomography and can be compared to the predicted present-day mantle temperature structure from the new forward geodynamic models. An examination of three seismic tomography models reveals five main pervasive seismically fast regions in the mantle in the area of interest that is interpreted to correspond to different periods of subduction.

The first region (A in Figure 6) is located at the core-mantle boundary west of 140˚E and is observed in both P- and S-wave seismic tomography models but less pronounced in the northernmost profiles of the MIT-P model (Figure 6). The remnant slab material is correlated to be from long-lived Mesozoic subduction, which has reached and pooled at the core-mantle boundary. The majority of the material from this period of subduction is located further westward underneath the southwestern Australian continent. The second seismically fast region observed in the seismic tomography models (B in Figure 6) is located at depths of between

700-1500 km in all seismic tomography models. It is difficult to discern whether this anomaly comprises two discrete anomalies or whether it was produced by a single subduction episode. Either way, the geodynamic model output fails to accurately account for this slab material. The new models only show a small amount of slab material at depths between 400-700 km, which stems from the initial Eocene subduction along the Melanesian Arc. The profiles showing the time progression of the forward models (Figure 5) indicates that a continuous and long-lived slab was not modeled, likely due to incorrect initial boundary starting conditions which led to an underestimation of the amount of slab material inserted into the mantle. By adjusting the surface boundary conditions and therefore, increasing the amount of slab material, an increase in the amount and depth of cold material is expected to be seen in the model. The third region (C in Figure 6) is related to the Oligocene-Miocene subduction along the Melanesian Arc and can be observed in seismic tomography models at depths between 300-1200 km in both P-wave and S-wave models but appears to be best resolved in the MIT-P model at depths of 500-900 km (Figure 6). A flattening of material along the 660 km discontinuity is observed, related to slab roll-back characteristic of western Pacific subduction zones. Again, the amount of slab material entering the mantle has been under-estimated, which is likely a function of the convergence rate imposed in the models for this subduction system. The fourth region (D in Figure 6) is clearly related to the present day northeast-dipping subduction along the South Solomons/San Cristobel trench with a good match to the new geodynamic model output. The South Solomons/San Cristobel Benioff zone is best resolved in the MIT-P model and appears to be steeply-dipping, reaching a depth of 500 km. The fifth seismically fast region (E in Figure 6) is located at depths of between 1500-2500 km between 130-145˚E and observed in all seismic tomography models but

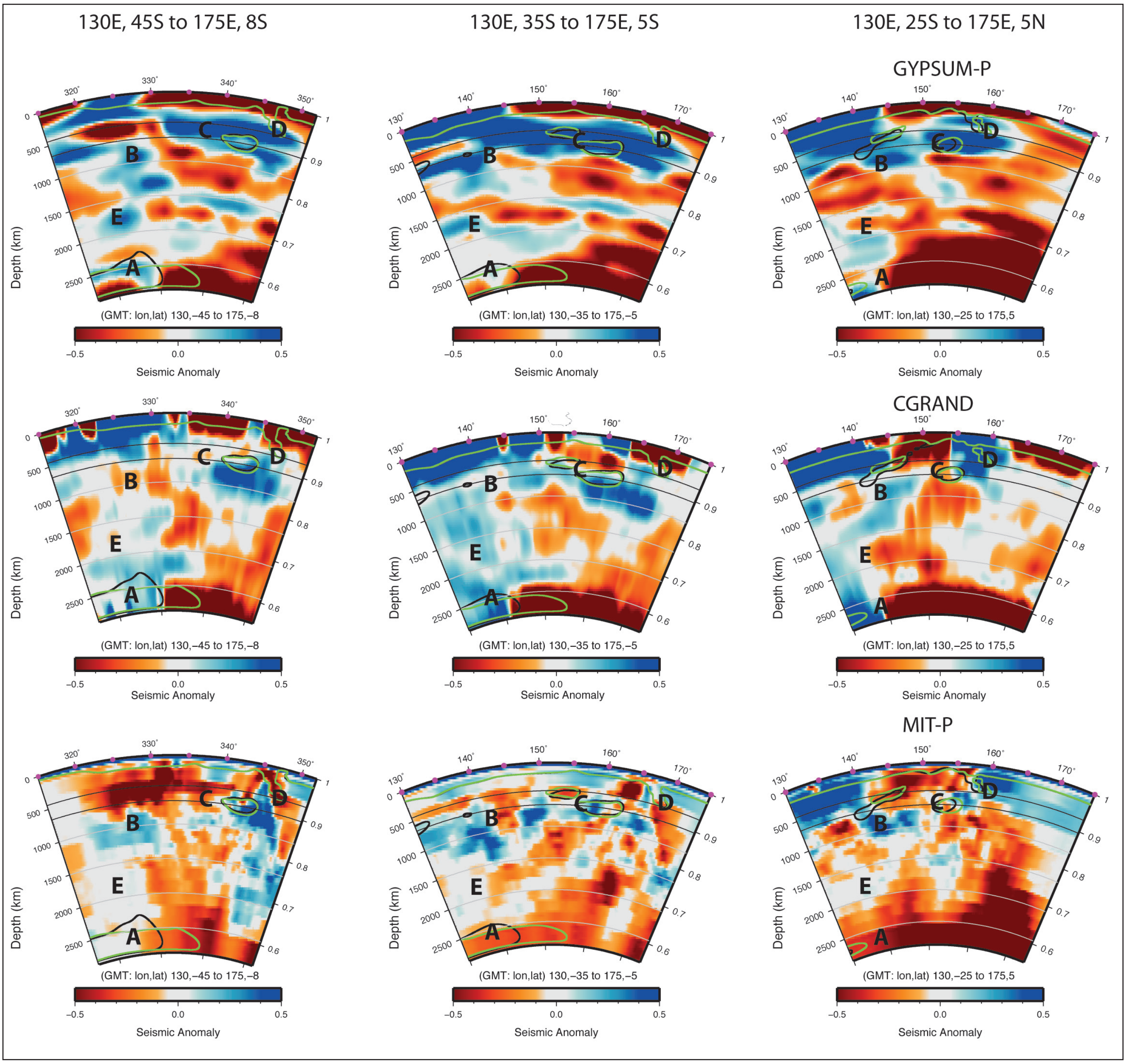

Figure 6. Present day model output for three profiles across the Melanesian arc compared to several seismic tomography models highlighting the mismatch between our model results, particularly for the mid- and lower mantle. Geodynamic model output is shown for comparison as slab contours (black = SPW1, green = SPW2). Slab contours represent material 60% colder than the ambient mantle temperature for each model run.

best resolved in the GyPSuM P-wave model (Figure 6). The source of this material is unknown, however the new geodynamic model output fails to predict any slab material at this location at these depths. However, the time progressive forward model profiles (Figure 5) reveal that no slab material is inserted into the mantle in the late Cretaceous, even though plate kinematic models of the SW Pacific necessitate that subduction was occurring at this time (Crawford et al., 2003, Schellart et al., 2006, Sdrolias et al., 2003, Yan and Kroenke, 1993). Importantly, the presence of slab material in all seismic tomography models at mid-mantle depths, provides extra support for the existence of subduction along eastern Gondwanaland during the Cretaceous (see Matthews et al. this volume).

Discussion

Reconstructions of the eastern Coral Sea

The new coupled plate kinematic-mantle convection modeling approach provides a method of assessing the validity of plate reconstructions in a particular region, as each model produces a unique mantle structure that can be compared to present day mantle structure from seismic tomography. While the latest results highlight several deficiencies in the prevailing models for the subduction history around the eastern Coral Sea, they provide an important basis for the refinement of plate kinematic models in the absence of additional geological constraints.

The absence of predicted slab material in the mid-lower mantle in the new geodynamic models (Figure 5), despite extensive evidence in seismic tomography models for slab material at mid-mantle depths, implies either that the absolute location of subduction in the region or that the type of plate boundary imposed in the new models requires further refinement. Based on a conservative sinking velocity of 3 cm/yr for the upper mantle and 1.3 cm/yr for the lower mantle (as proposed for the South Loyalty Basin in Schellart et al. (2009)), the slab material currently residing at depths of 1500-2500 km beneath central Australia would have formed at the surface prior to and during the dispersal of the microcontinental blocks off eastern Australia and opening of the Tasman and Coral Seas. The location of the proposed subduction zone must have been further eastward than the location of the transform boundary in the plate reconstructions of Seton et al. (2012) (Figure 4) in order to account for the presence of the slab material between longitudes 130-145˚E (see Matthews et al. this volume). We propose that this subduction zone was associated with the opening of the d'Entrecasteaux Basin (~65-84 Ma) (Lapouille, 1982) as a back-arc basin and invoke contemporaneous opening of the Santa Cruz/Torres Basin associated with the same system.

One of the most enigmatic features in the eastern Coral Sea is the origin of the Rennell Trough (Figure 1-2). The suggestion that the Rennell Trough was the site of subduction in the late Cretaceous-early Cenozoic facilitating the opening of the Coral Sea basin is difficult to reconcile with mantle tomography, as in this scenario the slab material at a depth of ~1500 km would be expected further west than 140˚E. Subduction along the Rennell Trough would also require plate reconstructions of the area to include two proximal and contemporaneous subduction zones, dipping in the same direction. If the Rennell Trough does not represent a palaeo-trench, the implication is that it may instead have been the site of active rifting, as proposed by Landmesser et al. (1974). In this scenario, the basement of the Rennell Island Ridge would be expected to be correlated to the Louisiade Plateau and not include island arc volcanics.

The initiation of subduction along the Melanesian Arc during the Eocene is captured in the new models, but as a minor subduction event, even though the interpretation of seismic tomography indicates that Eocene subduction was more voluminous than predicted. This inconsistency may be due to an age of subduction initiation that is too young and slow upper mantle sinking rates. The material predicted in the new models is located at similar longitudes to the slab material in the seismic tomography, suggesting that the absolute position of the plate boundary is our model for the initiation of subduction along he Melanesian Arc is well resolved, even though the amount of subduction may be under-estimated. The flattening that is observed suggests extensive slab roll-back starting in the Eocene, which may have facilitated the opening of a small back-arc basin behind the Melanesian Arc. This back-arc basin was likely subducted during the subduction polarity reversal, the remnant of which now resides in the Solomon Sea (Gaina and Müller, 2007).

A major event that affected the eastern Coral Sea was the proposed "hard docking" of the Ontong Java Plateau to the Melanesian subduction zone between 20-25 Ma (Petterson et al., 1999), which is believed to have clogged the subduction zone. This event affected Australia's plate motion (Knesel et al., 2008) and eventually led to a subduction polarity reversal along the Melanesian Arc (Petterson et al., 1999). As this event had regional consequences, this should be reflected in the adjacent eastern Coral Sea. The Rennell Fracture Zone and associated ridges and trough crosscut many existing features in the eastern Coral Sea suggesting that these features formed at a later stage. The reversal in subduction polarity along the Melanesian Arc from southwest-dipping to northeast-dipping along the South Solomon/San Cristobal Trench is well resolved in both the new geodynamic model output and seismic tomography implying that the timing and sinking rates predicted by the model are reasonable (Figure 6).

Relevance to resource exploration

The hydrocarbon potential of the frontier basins east of Australia was recently assessed in the context of stratigraphy and palaeogeography using updated geophysical datasets by Norvick et al. (2008). The study of Norvick et al. (2008) focused on sedimentary basins along the Lord Howe Rise and correlations to basins onshore, which have known hydrocarbon accumulations. The Mellish Rise and Louisiade Plateau in the eastern Coral Sea are composed of Australian continental basement, forming the northermost extent of the "Lord Howe microcontinent", which rifted off east Australia during eastern Gondwanaland break-up. In addition, the Rennell Island Ridge and West Torres Plateau are hypothesized to be floored by Australian continental lithosphere and were also likely attached to the Lord Howe microcontinent but underwent additional rifting episodes. Although the study of Norvick et al. (2008) did not extend north of the Kenn Plateau, these fragments in the eastern Coral Sea should be included in any frontier basin exploration assessment.

The history of subduction is a fundamental component to understanding the effect of the deep Earth on surface processes. The new geodynamic modelling results feed directly into examining the vertical motion history of hydrocarbon-bearing basins on the Australian continent and carbonate platforms in the western Coral Sea, using a similar approach to Di Caprio et al. (2009) and Matthews et al. (2010). By refining the location and timing of subduction, a predictive tool has been provided for understanding the subsidence/uplift history of these regions not related to traditional basin modeling methods.

Lastly, the temporal and spatial information on the location of subduction and their associated back-arc-arc-forearc complexes, which currently reside in the SW Pacific will provide a valuable tool for mineral exploration as volcanic arc complexes form one of the most important plate tectonic environments for mineral resources (Cooke et al., 2005, Solomon, 1990, Groves and Bierlein, 2007).

Conclusions

The coupled plate kinematic-geodynamic modeling approach has enabled an assessment of current plate kinematic models in the eastern Coral Sea. A comparison between the present-day mantle temperature field predicted by the new geodynamic models with seismic tomography suggests that kinematic models for the subduction history in the eastern Coral Sea work well for much of the Cenozoic but fail to predict the seismically fast material in the lower mantle (indicative of cold, subducted material) imaged in seismic tomography models. This implies that the absolute location of the plate boundaries in the eastern Coral Sea imposed in the models prior to and during the dispersal of the microcontinental blocks off eastern Australia and opening of the Tasman and Coral Seas requires further refinement.

In particular, based on the modeling results we propose that subduction was active during the Late Cretaceous, as microcontinental blocks were dispersed within the eastern Coral Sea and that subduction was located much further east than previously inferred. We propose that the d'Entrecasteaux and Santa Cruz/Torres basins formed contemporaneously as back-arc basins associated with this subduction system. We find no evidence in seismic tomography to support the existence of the Rennell Trough as the site of subduction in the late Cretaceous/early Cenozoic. The establishment of the Melanesian Arc in the Eocene and the subsequent reversal in subduction polarity at ~12 Ma are predicted in the new models, although the amount of slab material is underestimated in these models.

This new methodology, aimed at refining plate reconstructions from information hidden in the deep earth, can assist in assessing the history of basins in northeastern Australia and Australia's Pacific island neighbours in particular where geological and geophysical data are sparse. The revised reconstructions also help to better define the eastward extent of Australian continental lithosphere in the eastern Coral Sea and place further constrains on the subsidence and uplift history of Australia's eastern sedimentary basins and carbonate-capped plateaus.

Acknowledgements

Maria Seton and Dietmar Müller were funded through Australian Research Council grants DP0987713 and FL0992245, respectively. Nicolas Flament was funded through a Statoil industry research grant. Models were run on the Sun Constellation VAYU Cluster at the National Computational Infrastructure.

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