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Subducted slabs beneath the eastern Indonesia–Tonga region: insights from tomography

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Abstract

Tomographic images of mantle structure beneath the region north and northeast of Australia show a number of anomalously fast regions. These are interpreted using a recent plate tectonic reconstruction in terms of current and former subduction systems. Several strong anomalies are related to current subduction. The inferred slab lengths and positions are consistent with Neogene subduction beneath the New Britain and Halmahera arcs, and at the Tonga and the New Hebrides trenches where there has been rapid rollback of subduction hinges since about 10 Ma. There are several deeper flat-lying anomalies which are not related to present subduction and we interpret them as former subduction zones overridden by Australia since 25 Ma. Beneath the Bird's Head and Arafura Sea is an anomaly interpreted to be due to north-dipping subduction beneath the Philippines–Halmahera arc between 45 and 25 Ma. A very large anomaly extending from the Papuan peninsula to the New Hebrides, and from the Solomon Islands to the east Australian margin, is interpreted to be the remnant of south-dipping subduction beneath the Melanesian arc between 45 and 25 Ma. This interpretation implies that a flat-lying slab can survive for many tens of millions of years at the bottom of the upper mantle. In the lower mantle there is a huge anomaly beneath the Gulf of Carpentaria and east Papua New Guinea. This is located above the position where the tectonic model interprets a change in polarity of subduction from north-dipping to south-dipping between 45 and 25 Ma. We suggest this deep anomaly may be a slab subducted beneath eastern Australian during the Cretaceous, or subducted north of Australia during the Cenozoic before 45 Ma. The tomography also supports the tectonic interpretation which suggests little Neogene subduction beneath western New Guinea since no slab is imaged south of the New Guinea trench. However, one subduction zone in the tectonic model and many others, that associated with the Trobriand trough east of Papua New Guinea and the Miocene Maramuni arc, is not seen in the tomographic images and may require reconsideration of currently accepted tectonic interpretations.

Keywords: tomography; subduction; slabs; Southwest Pacific; plate tectonics

1. Introduction

The northern Australia plate boundary (Fig. 1) is a complex and actively deforming region within which are some of the fastest relative plate mo-

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tions on Earth [1,2]. Plate motion models [3,4] indicate that Australia has moved rapidly north since the Eocene, accompanied by subduction and collision between Indonesia and New Zealand. To reconstruct the region in the past requires interpretation of a range of geological and geophysical data but subduction and collision destroy much of the evidence, so distinguishing between different tectonic models can be difficult.

Tectonic reconstructions predict where lithosphere has been subducted and how much has been consumed in plate convergence zones. Seismic tomography can provide information which can test and improve such reconstructions. The record of subduction preserved in the mantle can be made visible, within spatial resolution limits, because subducted lithosphere produces a strong temperature anomaly [5]. This causes slabs to be detectable as regions with relatively fast seismic wave speeds. Such interpretation of anomalously fast regions is straightforward if the subducted slabs are seismically active. However, interpretation of aseismic regions with relatively fast seismic wave speeds as remnants of subducted slabs is more problematic since it is possible that these anomalous regions may result from other mantle processes. Interpretation is further complicated by a variety of possible imaging errors, some of which are extremely difficult to identify. Nevertheless, comparing the predictions of tectonic reconstructions with imaged mantle structure is a powerful tool. The tomographic models provide an independent source of information to test tectonic reconstructions [6–8] and conversely, plate tectonic models can help to suggest interpretations of imaged mantle structure, e.g. [9–11].

Here we discuss tomography and tectonic interpretations of a region extending from the Molucca Sea eastward to Tonga, and from the Australian craton north into the Pacific, and compare predictions of subduction derived from a recent tectonic reconstruction [12] to imaged mantle structure for this region. Australia separated from Antarctica in the Cretaceous but until about 45 Ma the rate of separation was low [4,13]. Since the Eocene the southern ocean has grown considerably and thousands of kilometres of lithosphere were subducted north of Australia. Even in regions with little seismicity the amount of subduction means that most slabs should be visible on tomographic images, and because of intense seismicity the scale of anomalies which can be detected is quite small close to the active plate boundaries.

2. Present tectonics

Currently the Australia–Pacific plate boundary [14] is marked by shallow seismicity stretching from the Bird's Head of New Guinea to the Tonga–Kermadec arc (Fig. 1). To the north of this boundary are the Philippine Sea, the Caroline and Pacific plates. To the south is the Australian plate but within its boundary zone with the Pacific are a number of small plates, spreading centres and backarc basins.

At the eastern edge of the Australian plate the Pacific plate is subducting west beneath the Tonga–Kermadec arc, behind which are spreading centres of the Lau basin. Further west is the New Hebrides arc where subduction is in almost the opposite direction, towards the NE. Between the New Hebrides and the Tonga arcs are spreading centres of the North Fiji basin. In the sector between the Solomons and eastern New Guinea subduction is essentially north-directed, at a high rate beneath the New Britain arc and at a lower rate beneath the Solomons. South of this subduction zone, within the Australian plate, is the actively spreading Woodlark basin (Fig. 1). North of the New Britain arc is the Bismarck Sea and its spreading centre links east to a strike-slip boundary in the Solomons, between the Pacific and Australian plates, and west into a diffuse zone within northern New Guinea which continues west to the Bird's Head.

At present the region is tectonically complex and in some places there are no clear connections between plate boundaries. At the eastern end of New Guinea (Fig. 1), in the Bismarck Sea and Solomon Sea region, there are several bathymetric troughs which have been interpreted as active and inactive trenches [2,15–19]. The New Britain trench is associated with seismicity down to several hundred kilometres but other bathymetric

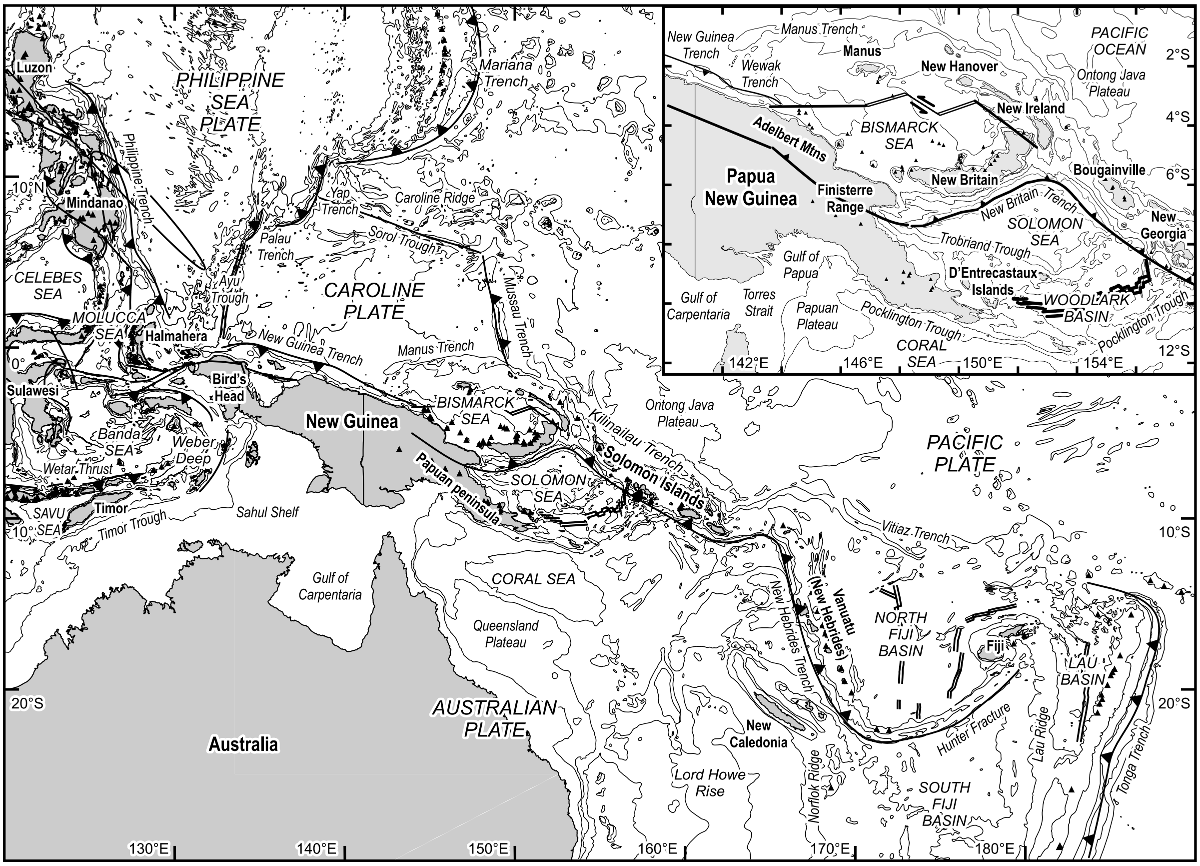
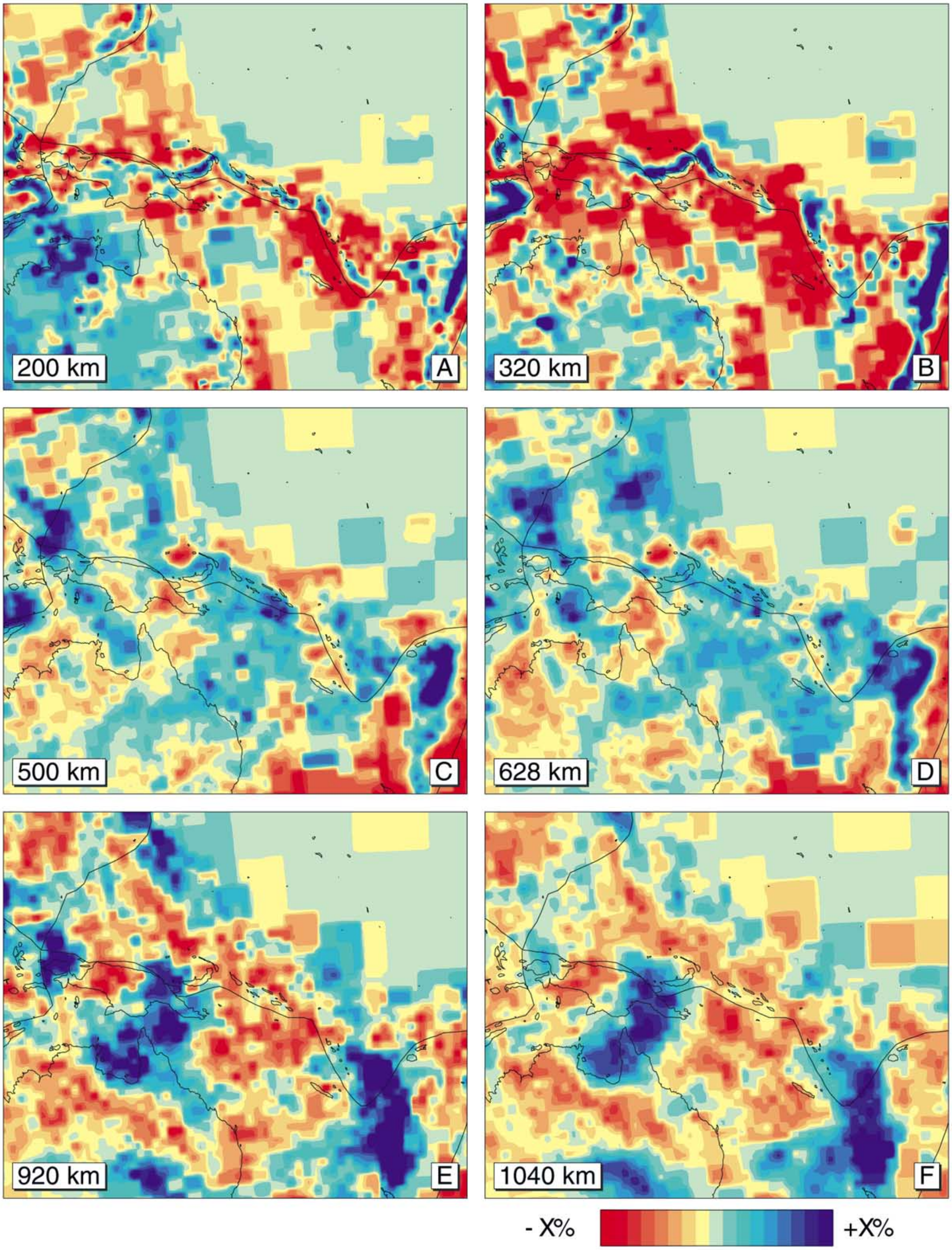


Fig. 1. Tectonic map of the Australia–Pacific plate margin. Barbed lines are active subduction zones, double lines are active spreading centres, and other lines are faults. Black triangles are volcanoes from the Smithsonian database (http://www.nmnh.si.edu/gvp/). Bathymetry from the GEBCO digital atlas [69] with contours at 200 m, 2000 m, 4000 m and 6000 m. Inset shows geographical features of the Bismarck Sea, Woodlark basin and surrounding regions.

features such as the Manus trench, the Trobriand trough and the Moresby–Pocklington trough appear not to be currently active plate boundaries. At the western end of New Guinea there is a similar uncertainty. North of the Bird's Head there is active spreading between the Philippine Sea plate and the Caroline plate in the Ayu trough, but south of this there is a wide zone of intra-plate deformation without a simple clear plate boundary. The New Guinea trench is a sediment-filled feature which is much shallower than a normal oceanic trench and associated with a poorly defined, broadly south-dipping, zone of diffuse seismicity which extends only to depths of 100–200 km. GPS measurements [20,21] suggest that the Bird's Head is now moving with the Pacific plate and therefore the Australia–Pacific boundary must pass through New Guinea south of the Bird's Head. The tectonic complexity of the present Pacific–Australia plate boundary reflects the creation of new plates, short-lived subduction of small plates, and intra-plate deformation.

3. Seismic tomography models

Recent developments in data analysis and tomographic techniques have led to a new generation of global models which are capable of resolving details of mantle structure [22–27]. In particular, the P-wave speed model [24], based


200 km
A
320 km
B
500 km
C
628 km
D
920 km
E
1040 km
F
- X%
+X%

on a well located data set [28], shows details of slab morphology comparable to those previously seen only in studies of smaller regions of Australia and the SW Pacific [9,29]. Imaging small details on a global mantle scale has been possible by using a special cell-parameterisation technique which allows the variation of cell dimensions as a function of the local degree of data density [30]. The smallest cells used have dimensions of 0.6° laterally and 35 km in depth. In this paper we use an improved tomographic model [26] which was obtained by incorporating in addition three-dimensional (3-D) ray tracing in the tomographic analysis in an attempt to account for focussing and defocusing effects due to 3-D mantle structure.

4. Anomalies in the tomographic images

The tomographic results of the region are displayed as selected layer sections down to a depth of 1040 km in Fig. 2. Sensitivity tests have been conducted for a variety of models in which a synthetic pattern of isolated blocks (spikes) is compared with the patterns recovered by tomography after inverting the synthetic data [24,26,31]. The sensitivity tests are extremely important in identifying the parts of the tomographic model and the spatial scales for which interpretation can be attempted. These tests (see the **background data set**[1]) show that spatial resolution is highly variable in the mantle volume of interest. Details on the scale of 1.2° are detectable in the shallow mantle below the Pacific plate boundary from New Guinea to Tonga. In contrast, no resolution exists below the Pacific because of lack of data sampling. Tests with different spike sizes show the scale of structures in a particular depth range that can be resolved. For instance, below the Coral Sea and Australia detail on the scale of 2.4° is hardly detectable near the bottom of the upper mantle whereas structures on the scale of 4.2° are well detected. In the lower mantle structure is well resolved on scales of 3–4°.

For the purposes of description and discussion the principal positive anomalies identified from tomographic images are numbered (Fig. 3). From the sensitivity tests we infer that all the anomalies are spatially sufficiently resolved to warrant interpretation. Vertical depth sections are shown in Fig. 4. Several anomalies are associated with existing subduction (A1 to A4). A number of more enigmatic wave speed anomalies (A5 to A8) are found in the deeper parts of the upper mantle and lower mantle. We first identify the anomalies and then discuss their interpretation.

4.1. Principal P-wave velocity anomalies

A1. Positive P-wave speed anomalies associated with subduction are well resolved in the Tonga–Kermadec region where the slab is visible to depths of 1500 km. The slab has a flat-lying portion below Tonga which is seismically active (Figs. 2C,D and 4F). West of the flat-lying segment the subducted slab can be followed into the lower mantle [9] where it has a north–south strike.

A2. Subduction at the New Hebrides trench yields a fragmented image but the slab is well delineated by intermediate and deeper seismicity. To the NE, below the North Fiji basin, a flat-lying positive anomaly in the upper mantle corresponds to a region of deep seismicity (Figs. 2C,D and 4E). Weak positive anomalies are imaged below 700 km but spatial resolution is not adequate to show if the slab penetrates into the lower mantle or not.

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Fig. 2. Six depth images for the SW Pacific–Australia region from the global tomographic model [26] with depths indicated in the lower left corner of each panel. Colour contours depict the anomalous P-wave speed relative to the average speed at depth. The reference model is ak135 [70]. Negative anomalies are red and positive anomalies are blue and represent slow or fast regions respectively compared to average ak135 propagation speeds. The contour scale varies between $-X\%$ and $+X\%$ where $X=2.5$ (A), 1.5 (B–D), and 0.75 (E, F).

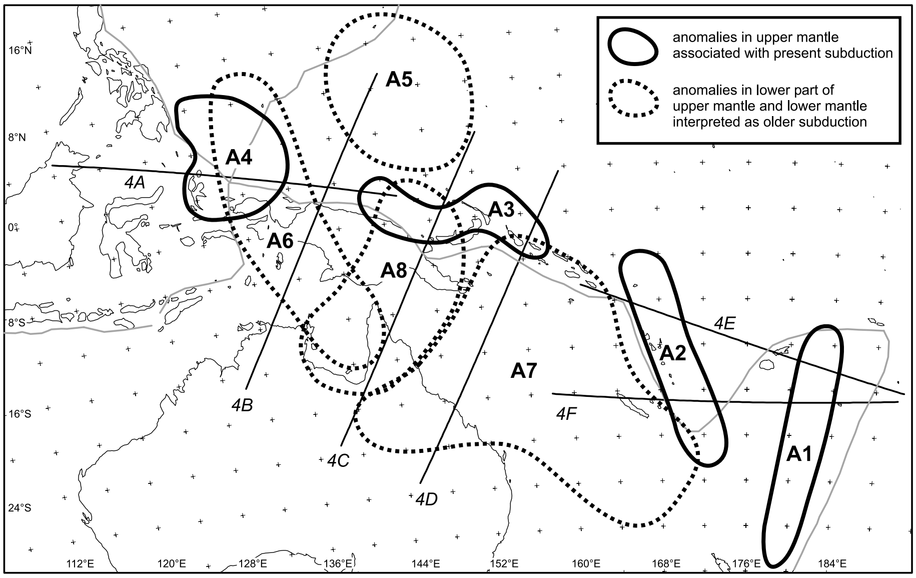

Fig. 3. Anomalies discussed in the text. A1 to A4 are dipping anomalies in the upper mantle, A5 to A7 are broadly flat anomalies near the base of the upper mantle, and A8 is a strong anomaly in the lower mantle. Grey lines: major plate boundaries; black lines numbered 4A to 4F: vertical sections of Fig. 4.

A3. Below most of the Solomon Islands, tomographic evidence for a subducting slab is absent above 500 km. Positive anomalies appear only below 500 km in the SE, associated with seismicity. There is clear evidence for an upper mantle slab beneath the NW Solomons region where slab geometry mimics the cusp in the plate boundary near the New Britain arc (Figs. 2A–D and 4C). The subducting Solomon Sea slab dips north and is seismically active down to 600 km. Laterally, it terminates abruptly beneath central New Guinea and no upper mantle slab is imaged below west New Guinea (Fig. 2A–C).

A4. Subduction of the Molucca Sea below Halmahera to the east, and the Sangihe arc to the west, produces anomalies (Fig. 4A) with a clear inverted U-shape [32]. Below the Caroline plate the Halmahera anomaly broadens with depth towards a large anomaly in the lower mantle (Fig. 4A). The Sangihe slab dips to the NW and its anomaly also approaches a deeper positive anomaly which underlies a large part of SE Asia [24,32,33].

A5. A prominent positive anomaly below the Caroline Ridge (Fig. 2C–E) broadens with depth and is mainly in the upper mantle except to the north where it merges with anomalies associated with deep Pacific subduction beneath the Mariana arc.

A6. An extensive elongate positive anomaly at depths between 500 and 700 km extends from north of the Bird's Head, beneath the Arafura Sea, to the Gulf of Carpentaria (Figs. 2C,D and 4B).

A7. A large positive anomaly imaged below 500 km, predominantly in the upper mantle, extends from the Papuan Peninsula to the New Hebrides and from the Solomon Islands to the east Australian margin (Fig. 2C,D). Because of the large lateral extent of this flat anomaly it can be identified in many other global mantle models including those with a nominally lower spatial resolution [25,27].

A8. There is a huge positive anomaly between about 700 and 1100 km which extends from beneath the Gulf of Carpentaria to Papua with a broadly NNE–SSW trend (Fig. 2E,F and 4C).

5. Cenozoic tectonic models

In order to interpret the tomographic images of the region it is helpful to have tectonic models to which the images can be compared. Below we summarise the principal features of different models of the Cenozoic tectonic development and divide the Australian margin into two major segments. The New Guinea segment includes New Guinea and extends to the east of the Papuan peninsula, and the Melanesian segment extends from the Solomons eastwards to the Tonga–Kermadec arc.

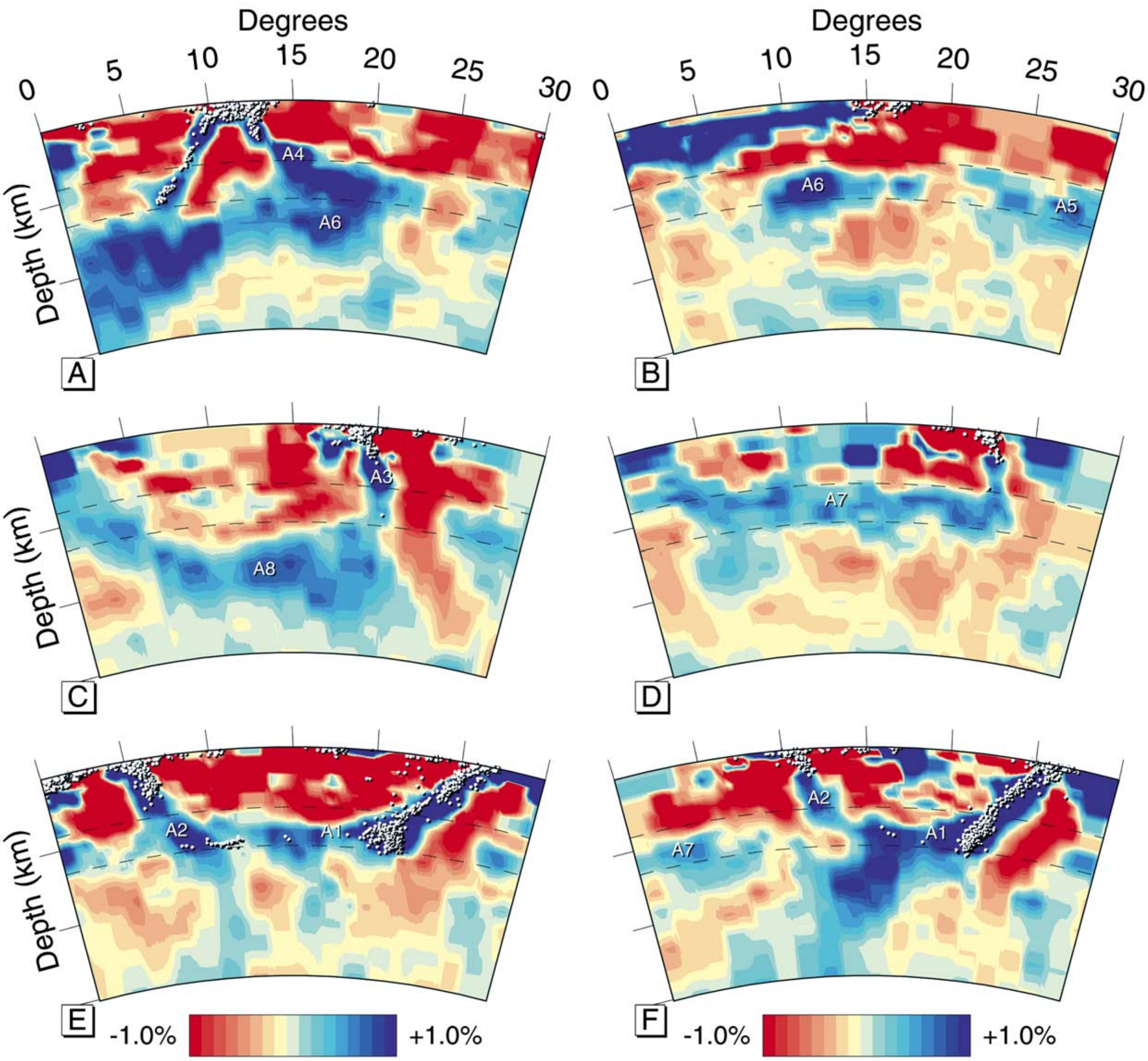

Fig. 4. Six vertical sections through the tomographic model [26] to a depth of 1500 km on great circle segments of 30°, located on Fig. 3. As in Fig. 2 colours denote the anomalous P-wave velocity structure. Anomaly amplitudes vary with depth from many percent in the top of the mantle to typical peak values around 0.5% at 1000 km or deeper [26]. All sections are however contoured between −1% and +1% and relatively strong colours in the uppermost mantle or weak colours in the lower mantle should not be interpreted as an indication of significance of imaged structure. White dots in the sections represent hypocentres [28] of earthquakes that occurred within 50 km of the section plane. On slices C and D sensitivity tests (see **background data set**[1]) show that apparent north-dipping slabs at the left hand side are resolution artefacts, as is the strong blue dot above A7 on D.

5.1. Cenozoic tectonics

Plate tectonic models for the region fall into three groups. Firstly, there are regional models which show the major plates of SE Asia, the western Pacific and Australia [12,16,17,34–43]. Secondly, there are many local plate models concerned with smaller areas or limited time intervals, e.g. [15,44–51]. Finally, there are publications showing maps and cross-sections of subduction zones at different times, but which do not give a complete history, e.g. [52–56].

5.2. The New Guinea segment

Tectonic models for the New Guinea segment can be divided into two broad categories. The majority of models advocate northward subduction of oceanic crust north of Australia beginning in the early Cenozoic, followed by collision of the Australian passive margin with a south-facing arc in the late Cenozoic. The second category of models proposes that the northern Australian margin was an active margin and there was southward subduction beneath this margin before it collided with an arc in the late Cenozoic.

Many models show a single arc-continent collision, often postulated to have led to subduction polarity reversal [16,57]. Variations include the opening of marginal basins within the Australian margin and their subsequent subduction, and multiple subduction zones. In some models these subduction zones have a consistent polarity, some suggest more than one subduction zone north of Australia dipping north, e.g. [12,36], but other models have subduction zones with opposing polarities, e.g. [35,39,41,45,47]. Several models propose or imply multiple arc-continent collisions, e.g. [39,41,53], although at different times, with accretion of arc fragments to the northern New Guinea margin during the Cenozoic.

A common theme in many of the models, particularly those which involve multiple subduction zones and collisions, is the diachronous collision of a volcanic arc with the northern New Guinea margin. This is generally agreed to have started earliest in the west and progressed eastwards to the present collision between the New Britain–Finisterre arc and New Guinea. The collision is interpreted to have followed subduction to both north and south leaving a doubly vergent subducted oceanic slab [15,18] beneath Papua similar to the inverted U-shape of the Molucca Sea slab [16,58,59]. The Solomon Sea is usually interpreted as the remnant of this ocean [39,41,54]. Beneath Papua the SW-dipping part of this interpreted subduction system has been named the Maramuni arc [60].

5.3. The Melanesian segment

There are fewer models for the Melanesian segment [12,17,34,35,38,40,43] and many show only cross-sections or parts of the region, e.g. [49,61]. There is broad agreement that from the early Cenozoic there was south- or SW-directed subduction beneath the Solomons until the Solomon arc collided with the Ontong Java Plateau. Pacific–Australia plate convergence by subduction then ceased in the Solomons region and transferred to other locations. The main difference between models is in the proposed site of initiation of the arc, and the timing of arc collision with the Ontong Java Plateau. Some models suggest that the Melanesian arc was rifted away from the Australian continental margin by backarc spreading due to southward subduction in the early Cenozoic [12,34,43], whereas others suggest the arc was initiated in an intra-oceanic setting by southward subduction north of Australia [40]. Initiation of subduction at the Australian margin would have led to formation of a large marginal basin behind the Melanesian arc and implies very significant rollback of the subduction hinge during the Paleogene. In the alternative intra-oceanic arc model, rollback would be smaller. In both models almost all ocean crust was subducted during the Neogene. The intra-oceanic initiation model implies this crust was Mesozoic–Early Eocene whereas the Australian margin initiation model implies it was all Eocene–Oligocene.

Most models accept that arc-plateau collision took place in the Miocene but may have occurred over an extended period. The early stage is thought to have shortened part of the leading edge of the Ontong Java Plateau margin [55] and was followed by thrusting of the Solomons arc over the plateau. The Solomons were transferred, or partially coupled, to the Pacific plate and therefore the boundary ceased to be a subduction zone and instead became a broadly strike-slip fault zone with possible later local subduction to the SW or to the NE on each side of the Solomons. In the last 10–12 Ma there was initiation of NE-dipping subduction beneath the New Hebrides arc, the relatively rapid rotation of the New Hebrides arc to form the North Fiji basin, and significant rollback of the subduction hinge as the Pacific plate was subducted west beneath the Tonga–Kermadec arc [12,40,43,49].

5.4. The New Guinea–Melanesian boundary

Most reconstructions focus on either the New Guinea or the Melanesian regions and there has been little attention paid to the implied change of polarity in subduction between the New Guinea and the Melanesian segments although it is shown schematically in some models [36,41]. Alternatively, it has been suggested that before 45 Ma there was SE-dipping subduction beneath the New Britain–New Ireland arc [61] which bent round into the SW-dipping subduction beneath the Solomons shown in other models. Rapid rotation of the New Britain–New Ireland section of the arc at about 30 Ma, followed by development of NE-dipping subduction, is interpreted to have produced the present configuration. This model [61] is the only one which proposes a subduction zone orthogonal to the Australian margin.

5.5. Plate tectonic model

The plate tectonic model used here [12,43] covers the whole of the region of interest in this paper, from the Molucca Sea to the Tonga–Kermadec arc. It synthesises a range of data, from spreading histories obtained from small ocean basins to more qualitative information such as that obtained from land geology. It therefore incorporates features of many of the models outlined above but differs from them all in postulating a mainly strike-slip plate boundary zone in northern New Guinea during the Neogene. Because the model [12] can be examined at 1 Ma steps its predictions can be compared easily with features observed in tomographic images. Its essential features are as follows.

From the Mesozoic the north Australian margin was a passive continental margin produced by Jurassic rifting. There was diachronous arc-continent collision of intra-Pacific arcs with this passive margin emplacing ophiolitic rocks between New Guinea and New Caledonia in the Eocene. At about 45 Ma, after the collision, there was a plate reorganisation, and new north-dipping subduction began about 2000 km north of Australia beneath the Philippines–Halmahera arc. At the same time southward subduction began at the eastern Australian margin forming the Melanesian arc between New Britain and Tonga (Fig. 5).

Subduction beneath the Philippines–Halmahera arc continued until about 25 Ma. During this period the Philippines–Halmahera arc remained in approximately the same position. In the Melanesian segment, rollback of the subduction hinge between 45 and 25 Ma (Fig. 5) led to the formation of a wide backarc basin from the Solomon Sea to the South Fiji basin. The subduction direction changed to SW-dipping as the Melanesian arc rotated north. From about 40 Ma the Caroline Sea opened as a backarc basin by rollback of the Pacific subduction hinge at the eastern margin of the Philippine Sea plate. The arc east of this backarc basin was the site of formation of terranes now found in northern New Guinea.

At about 25 Ma there was collision of the Philippines–Halmahera arc with the Australian margin and this terminated the north-dipping subduction. The zone of arc-continent collision stretched from Sulawesi to eastern New Guinea. At about the same time the Ontong Java Plateau collided with the Melanesian arc. This led to termination of SW-dipping subduction.

After these collisions the arcs between the Philippines and Melanesia became broadly a single system which rotated clockwise at the leading edge of the Pacific plate, accommodated by subduction at the eastern edge of the Philippine Sea plate. The arc terranes now found in north New Guinea moved along the north Australian margin

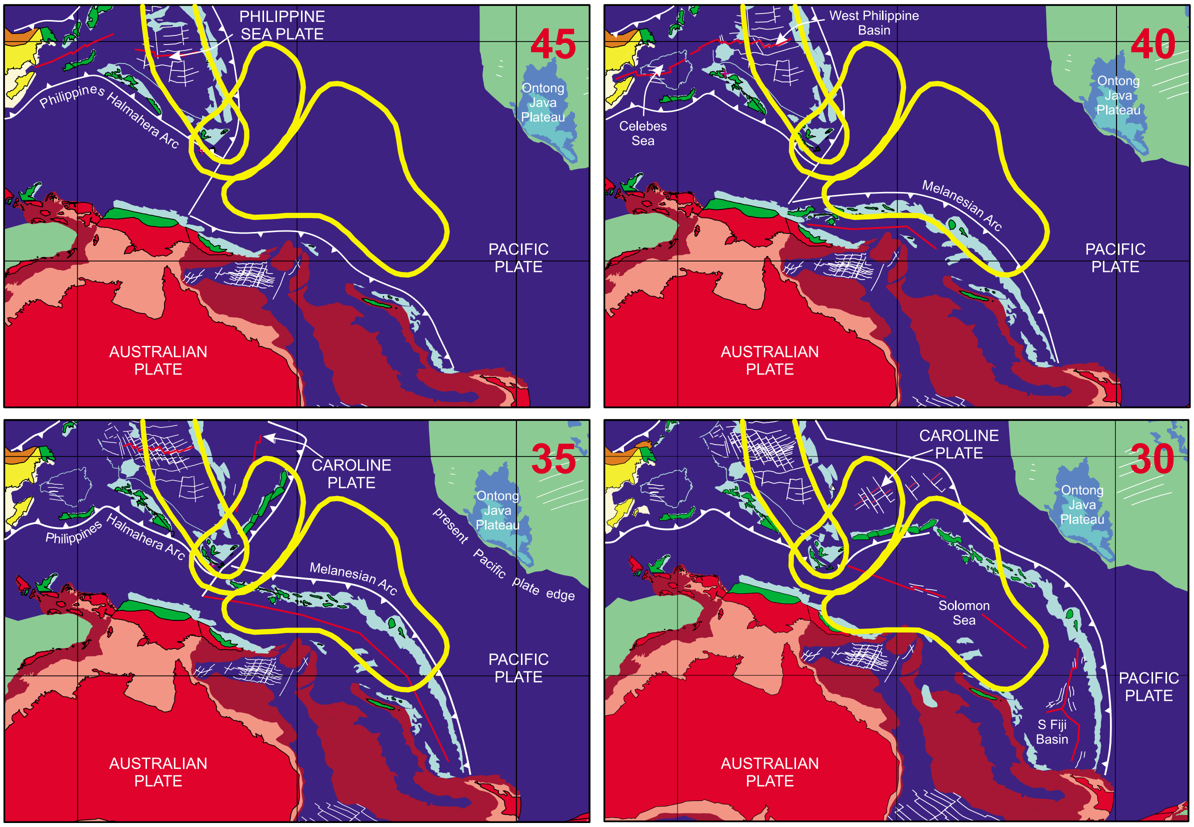

Fig. 5. Tectonic reconstructions from 45 to 30 Ma [12]. On each map the present positions of the deep mantle anomalies (A6 to A8) are shown in yellow. Anomaly A6 corresponds to the predicted position of a slab produced by north-dipping subduction beneath the east Philippines–Halmahera arc between 45 and 25 Ma. Anomaly A7 occurs at the predicted position of a slab produced by south-dipping subduction beneath the Melanesian arc between 45 and 25 Ma. Older subduction at the position of A8 may have influenced the position of younger plate boundaries since the anomaly is located in the region where there must have been a change in polarity of subduction between 45 and 25 Ma.

in a strike-slip zone. There was therefore no significant subduction at the north Australian margin in Irian Jaya. Further east, Pacific–Australia convergence was accommodated by development of new subduction zones: there was SW-dipping subduction beneath east Papua forming the Maramuni arc and NE-dipping subduction beneath the New Hebrides. The two opposed subduction systems were linked by a transform crossing the Solomon Sea.

When Maramuni subduction ceased the New Hebrides trench propagated from west to east to start new north-directed subduction beneath the Solomons and New Britain arcs. Slab-pull forces at the New Britain trench then led to the formation of the Woodlark spreading centre at the former Solomon Sea transform. Very young Woodlark basin lithosphere is now being subducted at the South Solomon trench. Throughout this period west-dipping subduction of the Pacific plate continued at the Tonga–Kermadec trench with rapid rollback of the subduction hinge in the last 10 Ma.

6. Tectonic interpretation of tomographic anomalies

We first comment on anomalies clearly related to present-day subduction, and then discuss other mantle anomalies which we interpret in terms of older subduction.

6.1. Young and current subduction systems

A1. At the Tonga trench the Pacific plate subducts west at a high rate, with the rate decreasing southwards towards New Zealand. The age (> 120 Ma) of the subducted lithosphere and high rate of subduction (> 10 cm/a) result in a deep negatively buoyant slab of lithosphere [9]. The slab dips uniformly at about 50°, becomes almost horizontal in the transition zone and uppermost lower mantle, and then sinks into the lower mantle several hundred kilometres further west. This shape is proposed [9] to be due to rapid rollback of the subduction hinge at the northern end of the Tonga–Kermadec arc where at least 2100 km of slab is imaged, in contrast to slower rollback at the southern end of the arc where < 1000 km of slab is visible. Comparison of the tectonic model [12] with these dimensions suggests that the anomalies are due to subduction since 25 Ma and that most rollback occurred since about 10 Ma. Thus, tomography defines the position of the Australia–Pacific plate boundary back to at least 25 Ma.

A2. Beneath the North Fiji basin the subducted slab dips steeply NE and becomes almost horizontal in the transition zone. The resolution is insufficient to say if the slab penetrates into the lower mantle. Beneath the northern part of the North Fiji basin deep earthquakes at 550–650 km have been attributed to events in a flat-lying slab [62] interpreted as the remnant of a slab subducted at the Vitiaz trench [63] about 5–8 Myr ago. However, observations on land and in the North Fiji basin do not support the suggestion of subduction at the Vitiaz trench at this time [17,49,64], nor is this suggestion consistent with Pacific–Australia plate motions. Instead, the seismicity and tomography suggest a similar interpretation to that of the Tonga subduction with rapid rollback causing development of a kink and flat segment in the subducted slab. The tectonic model [12] predicts about 1000 km of subduction since 15 Ma at the New Hebrides trench. The imaged slab length and orientation are consistent with subduction at the New Hebrides trench since about 12 Ma, and clockwise rollback of the subduction hinge.

A3. Beneath the Solomons there is no seismic or tomographic evidence of a significant length of subducted slab. Seismicity to depths of 200–300 km suggests local subduction to north and south on both sides of the Solomons. There are a few scattered events at depths greater than 500 km. At the western end of the Solomons the subducted slab beneath the New Britain arc becomes visible and is associated with seismicity to depths of 450 km. At about 153°E there is a marked arcuate kink in the high velocity anomaly below 200 km which becomes smoother at greater depths. This may be due to deformation of the slab in the mantle. The New Britain subduction is interpreted [12] to have propagated NW from the New Hebrides trench after subduction ceased at the Maramuni trench. An alternative possibility suggested by the tomographic images is that subduction initiated beneath the New Britain arc and propagated east with the eastern Solomon Sea remaining partly coupled to the Pacific. This would account for the absence of seismicity and a high velocity anomaly beneath the Solomons. However, the absence of seismicity and anomaly beneath the Solomons may be due to the very young age of the Woodlark basin crust; the spreading centre is being subducted below New Georgia and therefore the subducted slab may be thermally similar to the mantle into which it is sinking. North of the Woodlark Rise, where a high velocity anomaly is very clear, the subducted slab descending beneath Bougainville is significantly older, and is probably Oligocene.

A4. In the Molucca Sea region high velocity anomalies to the west and east have been interpreted [32,37] as the Molucca Sea slab subducted during the Neogene. Seismicity shows the west-dipping Sangihe slab is identifiable to at least 650 km and the east-dipping Halmahera slab to about 200 km [58,59]. Tomographic images suggest the Halmahera slab extends to about 400 km. The total length of subducted lithosphere is about 1500 km, very close to that predicted [12] since subduction began on the Sangihe side of the Molucca Sea at 25 Ma. In places the Molucca Sea slab anomalies appear to merge with deeper anomalies and it has been proposed that both the Sangihe and Halmahera slabs can be traced deep into the mantle [33], to a broad high velocity zone beneath the Celebes Sea at depths below 700 km, and to another broad high velocity zone beneath the Bird's Head at depths greater than 400 km. This would require about 3500 km of subducted slab which would be much greater than the amount predicted by any tectonic models [12,37]. In contrast, we interpret these broad and flat anomalies as the remnants of an older slab subducted beneath the Philippines–Halmahera arc between 45 and 25 Ma (A6, below).

6.2. Older subduction systems

A5. The broad high velocity anomaly at depths between 550 and 700 km centred on the Caroline Ridge is the southern end of a Pacific high velocity anomaly trending approximately N–S which continues to the north beneath the eastern Philippine Sea plate. We interpret this to be the result of Pacific subduction beneath the eastern margin of Philippine Sea plate since 25 Ma [12].

A6. This extensive elongate high velocity anomaly at depths between 500 and 700 km approaches the young Halmahera slab anomaly east of the Molucca Sea. The Halmahera slab has a clear consistent dip to the east whereas the deeper anomaly is flat-lying and extends much further south. It also becomes deeper to the north, to the north of Halmahera. We interpret this anomaly to be the result of northward subduction between 45 and 25 Ma beneath the Philippines–Halmahera arc north of Australia, where approximately 2000 km of oceanic lithosphere was subducted between 45 and 25 Ma [12]. The length of slab estimated from the tomographic cross-sections is also approximately 2000 km.

A7. We interpret this very large flat anomaly between depths of 500 and 700 km to be the result of south- and SW-directed Pacific subduction at the Melanesian arc between 45 and 25 Ma. The formation of a large marginal basin behind the Melanesian arc implies very significant rollback of the subduction hinge during the Paleogene. By analogy with the present Tonga arc, rapid rollback would produce an extensive area of flat-lying slab which would be expected to sink to the base of the mantle after subduction ceases. All models predict hinge rollback but this large high velocity anomaly favours those models with the most rollback [12,34,43]. This interpretation implies that a flat-lying slab can survive for many tens of millions of years at the bottom of the upper mantle. Slowly increasing buoyancy due to temperature increase may prevent slumping into the lower mantle. If it were to remain in the upper mantle and become thermally completely assimilated all that would remain would be a geochemical reservoir of anomalous composition.

A8. This distinctive anomaly has a NNE–SSW trend and is visible between 900 and 1100 km. No active subduction zone in the region penetrates so deep except beneath Tonga where the very high rate of subduction and the great age of the subducted Pacific lithosphere may be the cause of such deep penetration [9]. The depth suggests this anomaly could be a remnant of Cretaceous subduction. A N–S seismic anomaly beneath the Australian–Antarctic discordance south of Australia has been proposed [65] to be a slab, now in the lower mantle, subducted east of Australia during the Cretaceous and subsequently overridden by Australia. Anomaly A8 is at a similar depth and along strike from Australian–Antarctic discordance anomaly and may therefore be the same slab if the Cretaceous subduction zone had continued north with a similar orientation. Another possibility is that the anomaly is a remnant of early Cenozoic subduction. Palaeomagnetic evidence has been used to suggest [61] that before 45 Ma there was SE-dipping subduction orthogonal to the Australian margin. This would be consistent with the depth and the orientation. The slabs postulated here to have been subducted between 45 and 25 Ma (anomalies A5 to A7) do not extend significantly into the lower mantle. However, it is possible that the anomaly represents a slab subducted between 45 and 25 Ma which has sunk to a greater depth than other slabs subducted during the same period. The Tonga region shows that penetration into the lower mantle is possible. However, since a flat slab near the base of the upper mantle is likely to be associated with hinge rollback (cf. anomaly A7), a steeply dipping slab in the lower mantle suggests a relatively stationary trench with a broadly NNE–SSW orientation, which is not easy to reconcile with any tectonic model. We therefore prefer the interpretation of a pre-45 Ma subduction zone and speculate that the position of an old slab in the mantle may have influenced the position of younger plate boundaries since the anomaly is located below the region where there was a change in polarity of subduction [12] between 45 and 25 Ma (Fig. 5).

6.3. Subduction systems which are not seen

As reviewed above, most authors postulate north-dipping subduction north of Australia during the Paleogene. If there had been south-dipping subduction, as suggested in some interpretations, there should be large high velocity anomalies beneath western Australia in the lower part of the upper mantle. Their absence and the presence of high velocity anomalies further north (anomaly A6) cause us to prefer north-dipping subduction with subducted slabs now overridden by Australia. There is also no evidence of continuation of New Britain arc subduction very far to the west. This implies the 'doubly vergent system' of the Solomon Sea did not extend significantly west of Papua New Guinea and there was no Neogene subduction beneath western New Guinea. This is consistent with the absence of subduction-related volcanic activity in Irian Jaya [12], the unusual chemical character of the volcanic rocks that are known [66], and favours the strike-slip model [12].

A second postulated subduction zone not seen in the tomographic images is the SW-dipping subduction commonly suggested to have occurred during the Miocene beneath the Papuan peninsula to produce the Maramuni arc [50,60,67] or more recent subduction at the Trobriand trough [15,19]. The Australian plate would have overridden the subducted slab since about 20 Ma as it moved north. It would therefore be expected that the subducted slab would become flat-lying in the upper mantle and the slab should be visible at relatively shallow depths beneath the Coral Sea and Queensland plateau, as it is beneath New Britain. We recognise that the absence of features in the tomographic images may reflect inadequacies in the data set or variations in ray path sampling. However, the resolution of tomographic model in this region is of the order of 4° and therefore the 1000 km of slab predicted [12] should be detectable. If the subducted slab was young it might not be visible, like subducted Woodlark basin, but the age of the subducted lithosphere is expected to be Oligocene or older [12,40] and subduction of the same marginal basin produces a clear anomaly beneath the New Britain arc. Other explanations require modifications to tectonic models: for example, subduction was of shorter duration than that suggested by the few K–Ar dates from volcanic rocks [68], the volcanic activity interpreted as subduction-related was due to extension [46,50], or most of Solomon Sea subduction occurred beneath the New Britain arc and little on the south side at the Maramuni arc [48].

7. Conclusions

The rapidly improving tomographic images offer significant opportunities to distinguish between, test and improve tectonic interpretations of the region if the models can be examined at closely spaced intervals of time. We have compared the tomographic images to the predictions of one model [12] and in general found good agreement. The positions of most subduction zones, and the predicted slab lengths, suggested by the tectonic model are consistent with the positions of high velocity mantle anomalies. We see no evidence for significant subduction beneath most of New Guinea in the last 25 Ma. This is consistent with the strike-slip model of [12] and with much geological evidence, for example, the absence of Neogene subduction-related volcanic activity in Irian Jaya. For the period between 45 and 25 Ma the tomographic images support the suggestion of north-directed subduction north of New Guinea beneath the Philippines–Halmahera arc, and do not favour models which interpret south-directed subduction beneath New Guinea. They also support the interpretation of a change in subduction polarity at about 150°E during the same period, from north-dipping Philippines–Halmahera subduction to south-dipping subduction beneath the Melanesian arc, with rapid rollback of the Melanesian subduction hinge. The interpretation of the anomaly underlying the Coral Sea as the result of this rollback implies that a flat-lying slab can survive for many tens of millions of years at the bottom of the upper mantle. If this flat-lying slab does not sink into the lower mantle then it will eventually become completely thermally assimilated and be detectable only as a geochemical reservoir of anomalous composition. We suggest that the very deep anomaly which extends from the Gulf of Carpentaria to Papua may be a remnant of pre-45 Ma subduction beneath Australia.

The tectonic model is very useful in helping to interpret the anomalously fast regions in the mantle and the tomographic images also provide an independent test of the model. The agreement between the two is encouraging. In addition, tomography can make an important contribution by questioning assumptions in a region where there is still a relatively limited knowledge of the surface geology. One widely accepted subduction zone, the Maramuni arc of Papua New Guinea, expected from suggestions of young or significant Miocene subduction at the Trobriand trough [15,19] is not visible on the tomographic images. A reconsideration of evidence used to interpret the history of the Papuan peninsula suggests explanations other than SW-dipping subduction [46,48,50], or significantly reduced amount of subduction, may require revision of this [12] and other tectonic models for this part of the region.

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