Extension during late Neogene collision in east Indonesia and New Guinea

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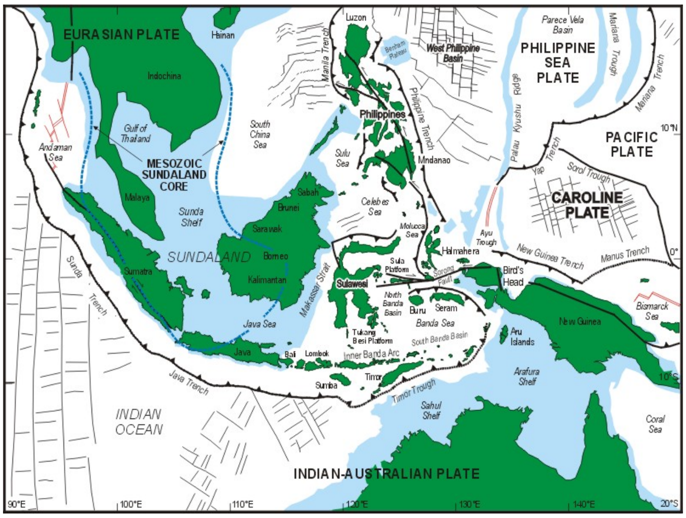
Abstract: Computer animations of a plate tectonic model for the Cenozoic development of the region of SE Asia and the SW Pacific illustrate the importance of extension during collision. In the past 10 Ma plate boundaries have shifted rapidly, and GPS measurements provide a snapshot of the changing tectonic setting. From about 25 Ma the New Guinea passive margin collided with the Philippines-Halmahera-South Caroline Arc, the Australian margin began to collide with the SE Asian margin in Sulawesi, and the Ontong Java Plateau collided with the Melanesian Arc. These collisions caused a major change in the character of plate boundaries between about 25 and 20 Ma. Until about 12 Ma much of the sector between Sulawesi and Fiji was dominated by strike-slip faulting and local subduction but this situation changed at about 12 Ma as old oceanic lithosphere entered the trench west of New Guinea, and new subduction zones developed east of New Guinea. The Banda Sea and Woodlark Basin illustrate the speed of change, the unexpected interplay of convergence and extension, and the importance of subduction as the cause of change. Immediate causes of extension within the orogenic system include strike-slip movements, effects of hinge roll-back, and pull forces of subducting slabs. High resolution dating is required to identify extensional events but the animations portray almost simultaneous contraction and extension which may be characteristic of many orogenic belts.

Table of Contents

Introduction

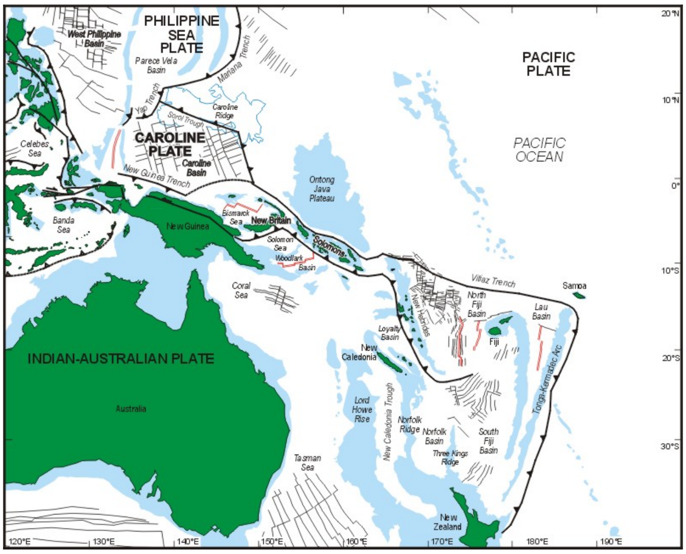
SE Asia and the SW Pacific include two major continental regions, Sundaland-Eurasia (Figure 1) and Australasia (Figure 2), separated by oceanic plates (Hamilton, 1979; Yan and Kroenke, 1993). The western Pacific is a mosaic of oceanic plates and within the very wide plate boundary zones are numerous small fragments of oceanic, arc and continental character. These include true plates, for example those formed at spreading centres, as well as microplates and tectonic blocks which have been fragmented by collision, subduction-related processes, strike-slip faulting, and extension within the convergent regions. Many authors have looked to this region for examples of processes that may have contributed to development of ancient orogenic belts (e.g. Silver and Smith, 1983; Snyder and Barber, 1997; van Staal et al., 1998),, and those working in the region require a context for the tectonic processes they observe. However, a grasp of the development of this region is extremely difficult to acquire because of the number of plates and smaller tectonic fragments and the speed and complexity of their motions. Animations can help to provide context, explanation and insights into the development of the region. They may in particular help understand the setting of magmatic activity which has in places led to economic mineral deposits but elsewhere has not. In New Guinea the origin of several of the large young centres of mineralisation remains enigmatic (e.g. Richards et al., 1990; MacDonald and Arnold, 1994; Mertig et al., 1997; Meinert et al., 1997; Macpherson and Hall, 1999). Rapid changes in the tectonic configuration of plate boundaries during the Cenozoic may have affected the nature of magmas and the character of fluids moving through the crust.

Figure 1. Region covered in the SE Asia reconstruction



Principal geographical features of the region covered in the SE Asia reconstructions. The blue shaded areas are the continental shelves of Eurasia and Australia drawn at the 200 m isobath and elevated but deeper bathymetric features in the Philippine and Caroline Sea. Red lines are active spreading centres.

Figure 2. Principal geographical features of the region covered in the SW Pacific reconstructions.



The blue shaded areas are the continental shelf of Australia drawn at the 200 m isobath and elevated but deeper bathymetric features in the Pacific. Red lines are active spreading centres.

Click for Larger Image.

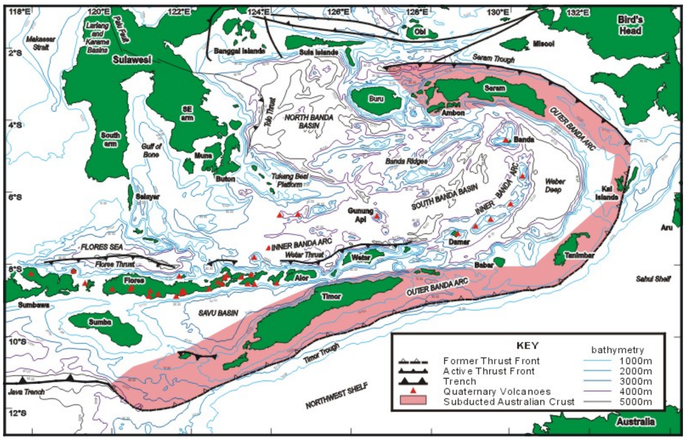
Present Tectonics of the North Australian margin

The present geometry of subduction around the north Australian margin is very complex and there are numerous slabs with very varied orientations (e.g. Cardwell and Isacks, 1978; Pegler et al., 1995; Spakman and Bijwaard, 1998). There are now about ten years of accumulated GPS observations from this complex region (e.g. Puntodewo et al., 1994; Tregoning et al., 1998; Larson et al., 1999; Rangin et al., 1999a; Kreemer et al., 2000). They show that within the region there are many plate boundaries and plates with very high rates of motion. Seismicity (McCaffrey, 1996), tomography (Spakman and Bijwaard, 1998), palaeomagnetism and the distribution of volcanic activity indicate the existence of numerous microplates, some of which formed rapidly, were destroyed during short time intervals, and in many cases rotated rapidly in similar short time intervals. Spreading rates of these small oceanic microplates are often very high, for example, the Bismarck Sea and the Woodlark Sea opened rapidly in the last few million years. Convergent rates in many areas in the region are amongst the highest on the present-day globe, as at the southern end of the Philippine Trench and at the New Britain Trench. Some ocean basins, such as the Woodlark Basin, are even subducted as they spread. Many of the small oceanic basins and plates have life expectancies of less than 15 Ma. Even volcanic arcs may have disappeared during collision as illustrated by overriding of the Halmahera Arc by the Sangihe Arc in the Molucca Sea.

Banda Sea

In the Banda Sea region (Figure 3) seismicity indicates a complex subduction situation with an Indian Ocean slab dipping north extending to more than 600 km, and a second subducted slab dipping southwest beneath Seram which extends to at least 300 km depth (McCaffrey, 1989). The BirdÕs Head of New Guinea is now broadly moving with the Pacific Plate. There are very high rates of convergence between the BirdÕs Head and Seram by underthrusting at the Seram Trough. The Australia-Asia boundary is a complex region of disconnected fractures in the Banda Sea and there is south-dipping thrusting in the Wetar region (McCaffrey, 1988; McCaffrey et al., 1995). The present Australian-SE Asia Plate boundary appears to be on the north side of the volcanic arc extending from the Flores Sea through to the north of Wetar. The South Banda Basin formed very recently and there is increasing evidence for a Neogene age from interpretation of magnetic anomalies (Hinschberger et al., 1999) and dredging (Honthaas et al., 1998). Heatflow (van Gool et al., 1987) and dredged samples (RŽhault, 1994) also indicate a young age for the North Banda Basin. On the south side of the Banda Sea the Banda volcanic arc collided with the Australian margin in the Pliocene terminating northward subduction in the Timor sector (Audley-Charles, 1986; Harris, 1991). Plate boundaries have clearly changed rapidly in this region in the last few million years.

Figure 3. Banda Sea

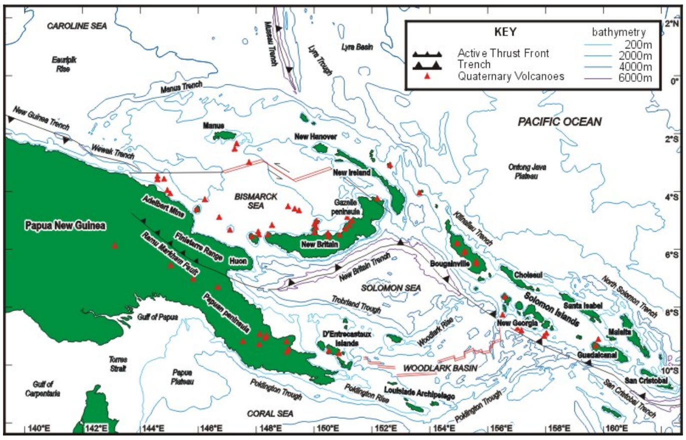


Geography and principal tectonic features of the Banda Sea and surrounding regions with volcanoes from the Smithsonian database.

Halmahera and Sangihe Arcs and Molucca Sea

The Philippine Arc terminates southwards in the Molucca Sea collision zone where the opposed Halmahera and Sangihe Arcs are actively converging (Figure 4). The Molucca Sea Plate dips east under Halmahera and west under the Sangihe Arc in an inverted U-shape (McCaffrey et al., 1980). Seismicity indicates approximately 200-300 km of lithosphere subducted beneath Halmahera and the west-dipping slab can be identified to a depth of at least 600 km beneath the Sangihe Arc. Tomography suggests possibly greater lengths for the subducted slabs (Spakman and Bijwaard, 1998; Rangin et al., 1999b). North of Halmahera the Philippine Sea Plate is subducting to the west (Cardwell et al., 1980) in a young subduction zone; here too plate boundaries have moved rapidly in the last few million years.

Figure 4. Molucca Sea

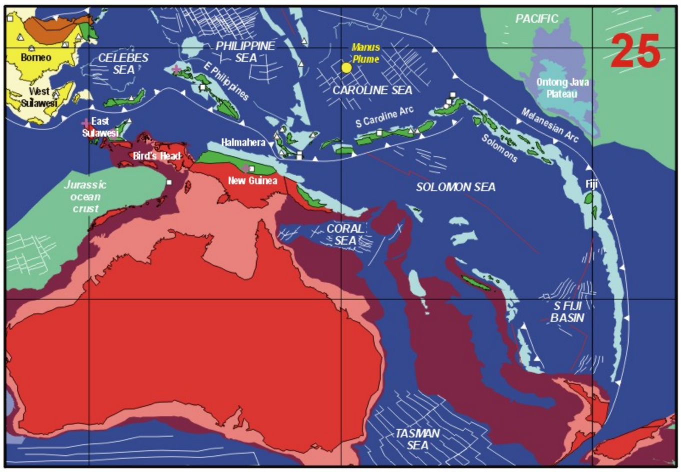


Geography and principal tectonic features of the Molucca Sea and surrounding regions with volcanoes from the Smithsonian database.

Eastern New Guinea

Up to five separate plates have been postulated in the region between the Manus Trench and the Pocklington Trough (Figure 5). GPS measurements indicate the existence of the South Bismarck, Woodlark and Solomon Sea Plates (Tregoning et al., 1998), and the Manus Trench and Trobriand Trough may mark former plate boundaries. Active and very rapid northward subduction of the Solomon Sea is occurring beneath the South Bismarck Plate to form the New Britain Arc. West of the Solomon Sea seismicity suggests an over-ridden double subduction zone similar to that of the Molucca Sea beneath New Guinea (Cooper and Taylor, 1987; Pegler et al., 1995). At the northern end of the New Britain Arc a complex pattern of strike-slip faults link the Bismarck Sea spreading centre to the Pacific Plate boundary. Both the Woodlark Basin and Bismarck Sea are actively spreading oceans. Once again, a notable feature of the Bismarck-Woodlark region is the rapid changes in tectonic boundaries during the last 5-6 Ma.

Figure 5. Bismarck Sea and Woodlark Basin



Geography and principal tectonic features of the Bismarck Sea and Woodlark Basin and surrounding regions with volcanoes from the Smithsonian database.

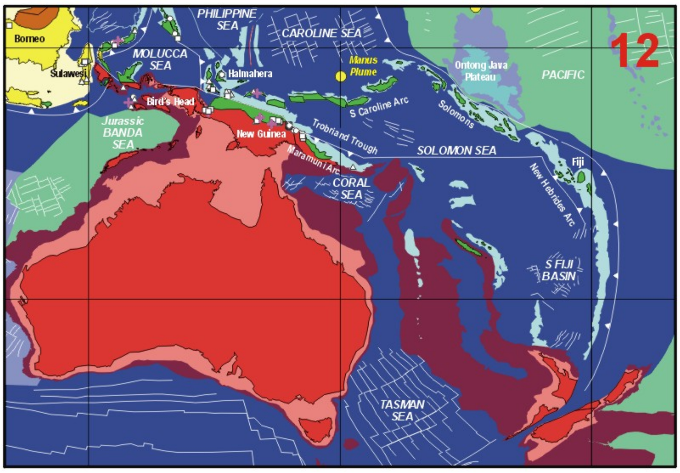
Plate tectonic reconstruction and animation

The model discussed here was initially developed for SE Asia (Hall, 1996, 1997a), extended to include the SW Pacific (Hall, 1997b, 1998) and is being continually updated to include new data. A complete account of the most recent plate tectonic model accompanied by animations is in press (Hall, 2001) in which there is an extensive bibliography. The reconstructions were made using the ATLAS computer program (Cambridge Paleomap Services, 1993). The model now includes approximately 120 fragments in SE Asia and the SW Pacific. It has been animated using 1 Ma time-slices.

Fragments and colours

Present coastlines are used in the reconstructions and most fragments retain their current size so that they remain recognisable. In some regions, such as extended continental margins and volcanic arcs, changes in area and volume of crust are likely to be significant. During collision, contraction may have also changed dimensions of fragments. The model simulates such changes an approximate way by modelling deforming areas as multiple fragments, allowing overlap of fragments, and represented some in a stylistic manner to convey the processes inferred. The colour scheme indicates the nature of the crust and principal regional features (Figure 6). One aspect of the use of colour needs to be emphasised. Dark blue is the default background colour. Reconstructing backwards from the present creates space, for example, by undoing the effects of subduction ÔunsubductedÕ crust is coloured dark blue. However, most fragments do not change size or shape and gaps may open up between fragments which are coloured dark blue but may not represent ocean crust. In some cases gaps have been filled by allowing fragments to overlap, but it is important to be cautious in inferring the nature of the crust between fragments merely on the basis of the colour used in the reconstructions.

Figure 6. Key to principal colours and symbols

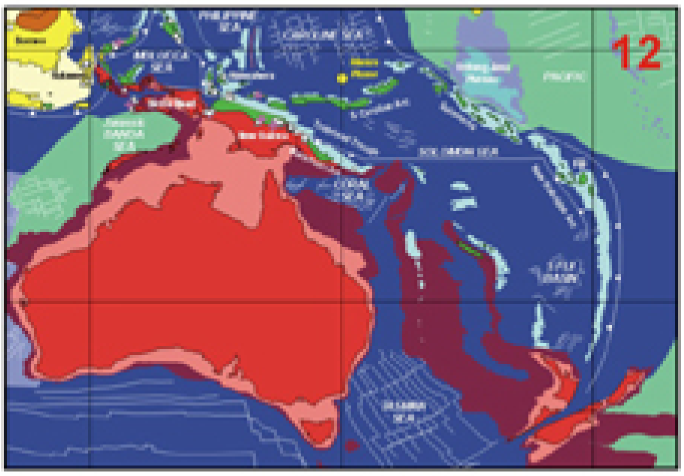


Key to principal colours and symbols used on Figures 7 to 10 and the animations.

Animations of the model

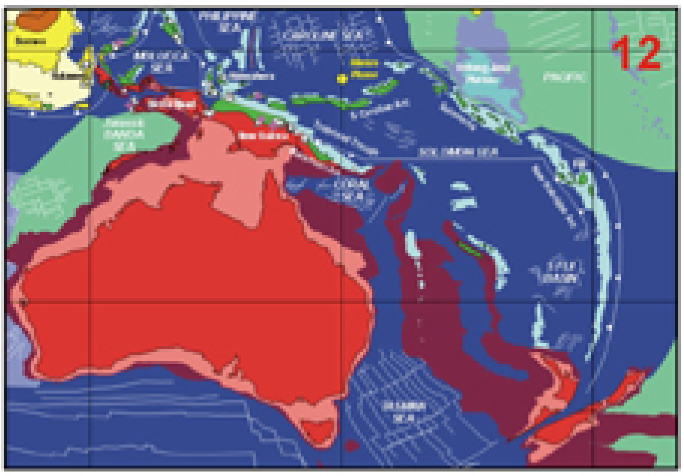
The reconstructions are produced using the PC-based ATLAS (formerly at http://www.atlas.co.uk/cpsl/) palaeogeographic mapping program which draws each map with the appropriate projection. Producing the final animation has a number of further steps. The maps are generated as Postscript files to which most plate boundaries are added by hand in CorelDraw. VisualBasic programs in CorelDraw are used to generate rapidly the multiple images required for an animation. For this paper, bitmaps were used to produce QuickTime Movies and animated gifs. Bitmap movies are relatively small files, and can be very quickly advanced and reversed, but are limited to fixed display resolutions. Other animations, such as Powerpoint, are larger and slower but have the advantage that a vector format can be used for individual images which are then independent of display resolution and can be copied and pasted into publications without loss of quality. The filenames here indicate the resolution and type of the animation (e.g swp_xvga.mov). They have a number of screen resolutions: VGA (640x480), SVGA (800x600) and XVGA (1024x768) indicated by a suffix. Quicktime movies have the file extension .mov. and animated gifs have the extension .gif.

Figure 1. Computer animation XVGA (1024x768)



The studied area matches the last frame of the computer animation found at Figure 3. See text for explanation.

Figure 2. Computer animation VGA (640x480)



The reconstructions are produced using the PC-based ATLAS (formerly at http://www.atlas.co.uk/cpsl/) palaeogeographic mapping program which draws each map with the appropriate projection. The studied area matches the last frame of the computer animation found at Figure 3. See text for explanation.

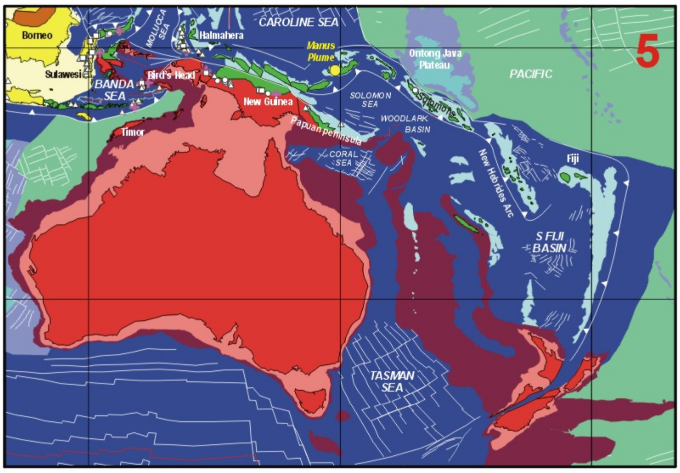
Summary of the history of the last 25 Ma

Important plate motion changes occurred in SE Asia and the West Pacific at about 45 Ma, 25 Ma and 5 Ma. Of these the 25 Ma reorganisation is the most important and the animation begins at that time. Before then Australia had been moving north in an apparently simple way, with north-dipping subduction beneath SE Asia and the Philippine-Halmahera-Caroline arcs. East of Australia there was subduction of the Pacific plate, broadly to the west and SW, associated with slab rollback and considerable backarc extension forming the Solomon Sea and Fiji basins. Viewing of the animation should accompany the following brief summary of the development of the north Australian margin between east Indonesia and the Pacific since 25 Ma.

25-12 Ma

Australia and SE Asia made contact at about 25 Ma (Figure 7). Collision-related deformation in Sulawesi dates from the late Oligocene-early Miocene. Sub-ophiolite metamorphic rocks indicate late Oligocene intra-oceanic thrusting and early Miocene subduction (Hall and Wilson, 2000). Ophiolites were clearly obducted in SE Sulawesi during the early Miocene and unconformable contacts indicate emergence. There was collision between the Philippines-Halmahera-South Caroline Arc with the New Guinea margin at about 25 Ma (Dow, 1977; Jaques and Robinson, 1977; Pigram and Davies, 1987; Hill and Raza, 1999) which required a change in plate boundaries at the southern edge of the Philippine Sea Plate (Hall et al., 1995). Northward subduction of the oceanic crust ceased and a major left-lateral strike-slip boundary developed through northern New Guinea. From this time arc terranes were translated westwards along the margin within the strike-slip system and fragments of continental crust were sliced from the BirdÕs Head and moved west to collide in Sulawesi. The Ontong Java Plateau also collided with the Melanesian Arc after 25 Ma (Petterson et al., 1997, 1999). The reconstructions show the final contact at about 18 Ma but the full extent of the Ontong Java Plateau before termination of subduction is not known. The term Ôsoft collisionÕ has been used to describe shortening of the leading edge of the Ontong Java Plateau and thrusting of part of the plateau into the Solomon Islands which took place before 18 Ma. From 25 Ma the arcs extending from Melanesia to the Philippines became effectively coupled to the Pacific Plate. The arc terranes moved in a clockwise direction and the Philippine Sea and Caroline Sea Plates rotated around the western Pacific at the margin of what is effectively a great Pacific Plate as suggested by some of the mobilist pioneers (Carey, 1958; Holmes, 1965).

Figure 7. Reconstruction at 25 Ma.



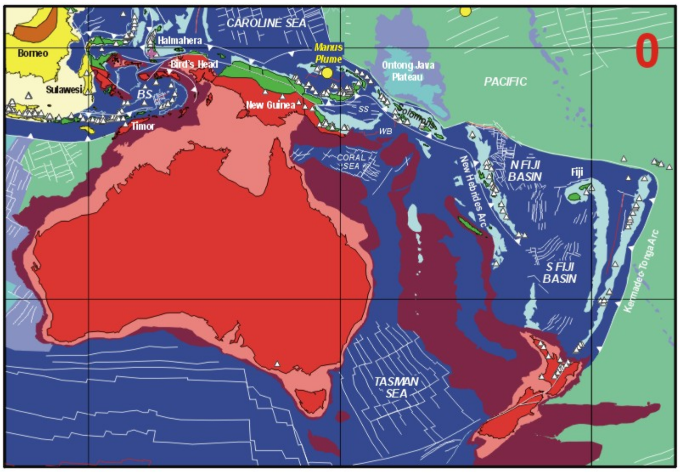
The East Philippines-Halmahera-South Caroline Arc collided with the Australian Plate at the north New Guinea margin and the Ontong Java Plateau began to collide with the Melanesian Arc. On Figures 7 to 10 the filled white circles, triangles and squares are isotopic ages of igneous rocks from our database which includes Indonesia, New Guinea and the Philippines. Magenta crosses are isotopic ages from metamorphic rocks. Horizontal grid lines are the equator and 30¡S, and vertical grid lines are 120¡E, 150¡E and 180¡E.

From 25 Ma until about 12 Ma much of the sector between Sulawesi and Fiji was dominated by strike-slip faulting and local subduction. Although Australia was moving northwards, the clockwise rotation of the Philippine Sea and Caroline Sea Plates to the north meant that the boundary remained essentially zone of strike-slip. Because of the position of the rotation poles the strike-slip boundary was moving north at the same rate as Australia. Localised transpression and transtension in this zone are likely but cannot yet be reconstructed because of our inadequate knowledge of the regional geology. Very small changes in positions of Euler poles, non-rigid behaviour of fragments, and other sources of errors could allow even more complexity than already in the model which is likely to be an over-simplification.

12-5 Ma

This situation changed dramatically at about 12 Ma (Figure 8). West of New Guinea Jurassic ocean crust reached the Sunda trench and began to subduct. The great age of the ocean crust north of the NW Shelf compared to that subducting further west (mainly Cenozoic with some Cretaceous crust) caused the Sunda trench to propagate rapidly east as the Jurassic slab fell away into the mantle. The subduction hinge retreated rapidly as the slab rolled back, and the rollback induced major extension in the upper SE Asian plate. Extension had begun by 10 Ma, and led to melting (Linthout et al., 1996, 1997) which I interpret as a response to rapid decompression, extension-related metamorphism, initial arc volcanism contaminated by continental crust (Honthaas et al., 1999), arc splitting and finally backarc basin spreading forming the South Banda Sea from about 6 Ma.

Figure 8. Reconstruction at 12 Ma.



Jurassic ocean crust arrived at the trench south of Sulawesi. Eastward subduction of the Molucca Sea had begun. The New Guinea terranes moved in a wide left-lateral strike-slip zone. Subduction of the Solomon Sea was underway beneath eastern New Guinea margin to form the Maramuni Arc. To the east of New Guinea subduction began on the east side of the Solomon Sea to initiate the New Hebrides Arc.

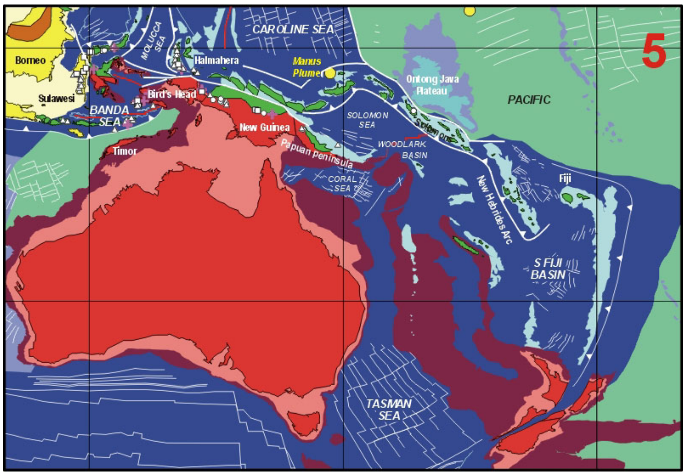
To the east of New Guinea a new subduction zone developed on the east side of the Solomon Sea beneath the New Hebrides. It is not clear why this subduction zone developed in the opposite direction to the already subducting Pacific slab. Another important east-dipping subduction zone developed at about the same time, beneath Halmahera, when west-directed subduction of the Molucca Sea (part of the Philippine Sea Plate) was already established. It may be that the westward motion of the Philippine Sea and Caroline Sea Plates to the north of Australia were impeded by collision in the strike-slip zone in New Guinea, or at its western end in the Sulawesi-Banda region, or by initiation of subduction of the Jurassic Banda Sea. Whatever the cause, east-dipping subduction began at the New Hebrides Trench, and there was extension in the North Fiji region as the Solomon Sea slab rolled back with rotation of the New Hebrides arc (Musgrave and Firth, 1999). By 10 Ma the older southwest-directed subduction of the Solomon Sea at the Marumuni arc in eastern New Guinea was linked by a transform fault crossing the Solomon Sea to the new east-dipping subduction which produced the New Hebrides Arc. The Solomon Sea was then rapidly reduced in size by subduction on both its east and west sides. Development of the New Hebrides Arc led to a complex pattern of oceanic spreading in the North Fiji Basin (Auzende et al., 1995). There were ridge jumps, rotation of the Fiji Islands, and later rifting at the northern end of the Kermadec-Tonga Arc.

Within a short period the New Hebrides Trench propagated north to initiate subduction beneath the Solomons and the New Britain Arc. Subduction ceased along its southern edge leaving the Trobriand Trough as a relict trench. Subduction was now primarily at the northern side of the Solomon Sea beneath the New Britain Arc which was converging on the eastern New Guinea margin. This left the inverted U-shaped slab in the mantle beneath eastern New Guinea. The changing balance of forces on the Solomons Sea Plate caused spreading to initiate at or close to the former transform fault leading to spreading in the Woodlark Basin. The Woodlark rifting propagated rapidly west (Benes et al., 1994; Taylor et al., 1995; 1999) along the centre of the former arc, ripping open the Papuan peninsula and forming core complexes in advance of the propagating tip (Baldwin et al., 1993).

5 Ma to present

There was another regional change in plate motions at about 5 Ma (Figure 9) although the cause is obscure. South of the Bird's Head the rapid hinge retreat continued and there was movement of the trench towards the Australian margin which maintained the extension of the Banda Sea region. The active volcanic arc was split as the South Banda Sea began spreading as a backarc basin. At about 3 Ma the volcanic arc came into collision with the Australian margin in the region of Timor. Spreading ceased in the South Banda Sea and the volcanic arc became coupled to the Australian margin in the Outer Banda Arc region around Timor. After collision, new plate boundaries developed north of the arc in the Flores-Wetar Sea and to the north of the South Banda Sea.

Figure 9. Reconstruction at 5 Ma.

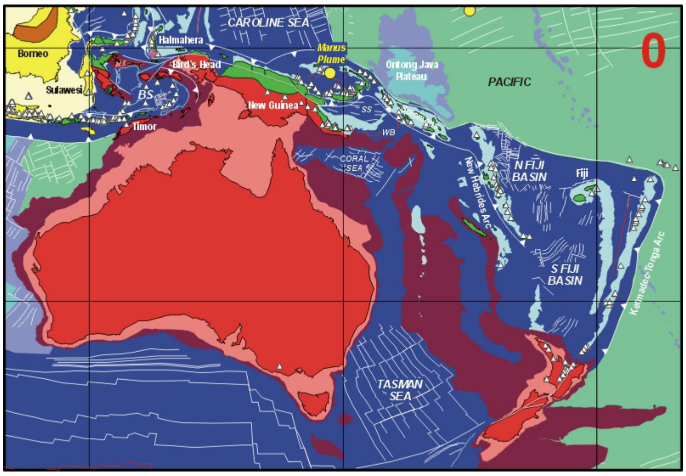


The arrival of Jurassic ocean crust at Sunda-Java trench caused rapid hinge rollback in eastern Indonesia, resulting in young volcanism in the Inner Banda Arc, and oceanic spreading in the Banda Sea. Bismarck Sea opening began. Slab pull forces caused spreading in the Woodlark Basin. Hinge retreat at the New Hebrides Trench was accompanied by the rotation of Fiji.

In north New Guinea the arc terranes were close to their present-day (Figure 10) positions, requiring little but rotation and minor translation (e.g. Abbott, 1995; Weiler and Coe, 2000) within a transpressional left-lateral fault zone. The limited and poorly-defined subduction at the New Guinea Trench and Manus Trench probably dates only from this time. At present much of the convergence between the Pacific and Australia is absorbed by distributed deformation over a very wide zone. The regions close to the BirdÕs Head are among the most complex and are still relatively poorly understood. The very limited knowledge of the Cenderawasih region, east of the BirdÕs Head, suggests another episode of rapid extension (Dow et al., 1985). Part of Cenderawasih Bay may have opened by ocean spreading at this stage and there is a suggestion from very young metamorphic ages in the area of the BirdÕs Neck (Bladon, 1988) of core complex formation during the last 5 Ma.

To the east of New Guinea slab-pull by the subducting Solomon Sea slab was the cause of Woodlark Basin spreading. Ironically, this subduction, which produced the Woodlark spreading, is also subducting the Woodlark Basin, and may lead to its complete elimination. It may well be difficult to infer the existence of the Woodlark Basin in another 5 Ma. To the north the Manus plume (Macpherson et al., 2000) arrived at approximately its present-day position within the New Guinea sinistral fault system at around 5 Ma (Macpherson and Hall, 2001) and the conjunction of plume and strike-slip faulting may have promoted rapid spreading in the Bismarck Sea which began at about 5 Ma (Taylor, 1979) in a setting which resembles a large pull-apart.

Figure 10. Present tectonic configuration.



Arc-continent collision in the Timor region has caused subduction reversal north of Timor and between Seram and the BirdÕs Head. East of New Guinea the Woodlark Basin spreading centre propagates west but the basin is being subducted at its eastern edge at a similar rate.

Key conclusions

The regions around New Guinea illustrate the importance of extension in a convergent setting. In all areas the ultimate driving force is subduction although local mechanisms may be different in different places. The Woodlark Basin has opened due to slab-pull forces caused by subduction beneath New Britain, and is being subducted beneath the Solomons almost as fast as it is forming. In the Banda Sea extension of the upper plate, induced by rollback of an old slab, has proceeded from caused continental rifting to arc-continent collision. In both regions this has occurred within a period of about ten million years. There is tenuous evidence of extension during the same period in other areas of New Guinea region which may indicate that extension and convergence are typical of the whole orogenic system. The sequence of events varies from place to place but may include rapid extension with core complex formation, arc magmatism, arc splitting, ocean crust formation and subduction reversal. Subduction can eliminate very young ocean crust and there may be large and rapid local rotations.

Some of the extension may be related to strike-slip movements within the New Guinea margin. In this situation there may have been even more rapid and frequent changes from extension to contraction, related to fault geometry and plate boundary conditions which are very sensitive to small movements in rotation pole positions. These in turn are likely to be a response to changing plate boundary conditions, in particular, changing slab lengths at subduction zones.

The speeds of all these processes are very high and at present it is difficult to predict where and when extensional events could occur. The lesson from the Indonesia-New Guinea collision zone is that extension may be typical of collisional orogenesis, that the speed of processes means that high precision dating is required to recognise such events, and that extension and contraction may be effectively simultaneous.

Acknowledgements

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