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East Asian analogues for early Alpine orogenesis

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Abstract

The Alpine orogeny is a consequence of the collision of Africa with Eurasia, which eliminated the Western Tethys Ocean. Processes similar to those that would have taken place early in that collision can today be seen operating in the islands of the Indo-Pacific gateway between Southeast Asia and Australia and have the potential to offer insights into the beginnings of orogenesis in the Alps. Studies of the gateway area emphasise the importance of the impact on subduction zones of topography on the downgoing plate, and of the effects of flows in the asthenosphere on lithosphere tectonics.

Keywords Alpine orogenesis, Indonesia, Melanesia, Philippines, Subduction, Collision

1 Introduction

The Alpine orogen, which includes the Carpathians, the Dinarides and the Hellenides as well as the Alps themselves, was formed during closure of the Western Tethys Ocean as a consequence of convergence between Africa and Eurasia. Collision began at about 65 Ma and continues to this day, but the early stages of evolution have proved difficult to unravel because the critical evidence is all too often obscured by the overprint of later events. Nor is the theory of plate tectonics in its simplest form of any real assistance, because none of the observations on which it was originally based directly addressed the existence of fold and thrust mountain belts. Specifically, as far as the Alpine orogen is concerned, the interactions of rigid crustal plates are insufficient as explanations for the high curvatures of many of the mountain chains involved.

The oft-repeated mantra, first stated by Charles Lyell (1830), of the present being the key to the past, suggests that studies of a collision orogen at a much earlier stage of development would be of value when seeking to understand the Alps. Happily, just such a real-world model exists today in the archipelagoes of Indonesia, Melanesia and the Philippines (Fig. 1). In the discussion that follows, this region is referred to as the Indo-Pacific gateway, a term borrowed from the physical oceanographers who study the interchange of waters between the two oceans. The western boundary of the gateway is marked by the island of Sumatra, the active margin of the Southeast Asian block that encompasses also the islands of Borneo and Java. The eastern boundary is formed by the island of New Guinea, which is the active margin of the Australian continent (e.g. Davies, 2012, and references therein). The gateway is closing as Australia advances to oblique collision with Asia, but the two continents are still separated by more than a thousand kilometres of seas and islands. Western Tethys may also have contained numerous islands during the early stages of its closure, and the enigmatic (van Hinsbergen et al., 2014) Adria block that has been crucial to the formation of the Alps (van Hinsbergen et al., 2020) must have been similar in some ways to one or more of the larger island blocks within the gateway domain. One important observation is that while many of these blocks were created by island-arc or oceanic magmatic processes, others are fragments of the converging continents. Australia has contributed the greater part, with Australia-derived terranes now

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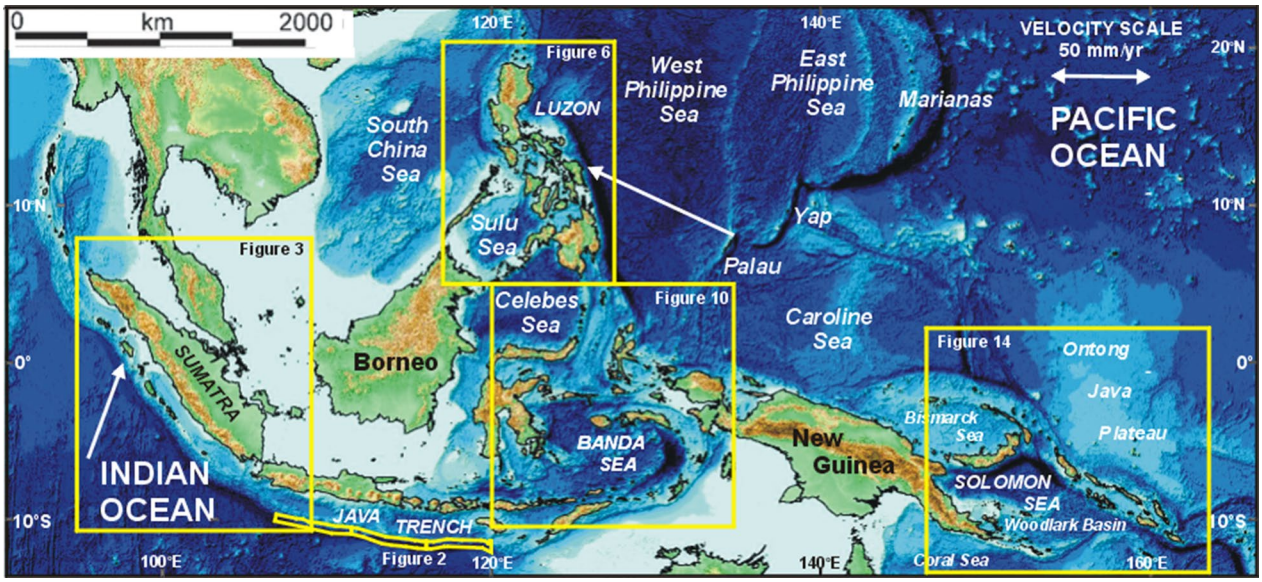

Fig. 1 The Indo-Pacific Gateway. Place names in italic capitals indicate the areas discussed in the text, which are further defined by yellow outlines and accompanying figure numbers. The white arrows show plate-movement directions and magnitudes across the Sumatra and Philippine trenches. Base map: GEBCO

occurring as far north and west as the eastern half of Sulawesi (Milsom, 2000; Charlton, 2000, and references therein).

With one exception (the Banda Arc and its suggested Carpathian counterpart), no attempt has been made in what follows to draw direct comparisons between specific parts and processes of the Alpine orogeny and possible counterparts in the gateway region. The aim of this paper is a much more limited one: it is to present the gateway to Alpine geologists, and it is for them to apply any lessons that can be learned to their own areas of study, should they find it useful to do so. The focus is on five selected regions of increasing complexity, identified here as the Java Trench, Sumatra, Luzon, Banda Sea and Solomon Sea regions. In each case the section headings focus on the processes exemplified rather than on the areas themselves. In two cases (Sumatra and the Banda Sea) the location maps used show gravity rather than bathymetry and topography, and a gravity map is included in the Luzon section. Maps of this type provide alternative ways of looking at geology, and can be a source of fresh ideas and insights.

2 Seamount subduction (Java Trench)

The Indo-Pacific gateway is still open, and at its southern edge, where the Indian Ocean is being orthogonally subducted at the Java Trench, plate tectonics can be seen operating in its simplest form. Java, the largest island in the Sunda Arc, embodies a transition from active continental margin in the west to oceanic island arc in the east, and the Indian Ocean to the south is host to an unusual number of seamounts with lateral dimensions of the order of a few tens of kilometres. As part of Cruise CD30 of the British research vessel RRS Darwin, the effect of such features on subduction was examined using the GLORIA long-range sidescan sonar system to image the floor of the trench and the front of the accretionary wedge (Masson et al., 1990). Additional information on the area between 109° 05′ E and 111° 25′ E has been provided by Kopp et al. (2006) but, because of the limited range of the swathe bathymeter deployed, there are large gaps between the strips of detailed coverage for which they presented images.

The images obtained during CD30 were interpreted as showing extensional faulting of both the normal oceanic crust and the seamounts as they descended into the subduction zone, and seamount subduction was everywhere accompanied by 'amphitheatres' of downslope-concave spoon-shaped indentations in the wedge, backed by oversteepening of its lower slope (Fig. 2). However, the volumes of material on the trench floor adjacent to these areas appear to be considerably smaller than the missing volume within the amphitheatres, raising the possibility that a significant fraction of the wedge material has been thrusted and folded landward. This in turn suggests that at least the upper parts of the seamounts are being accreted to the forearc rather than being subducted, and the bathymetry of the wedge, which is shown in the lowermost image in Fig. 2, is consistent with this having occurred in the past. Kopp et al. (2006) came to no firm

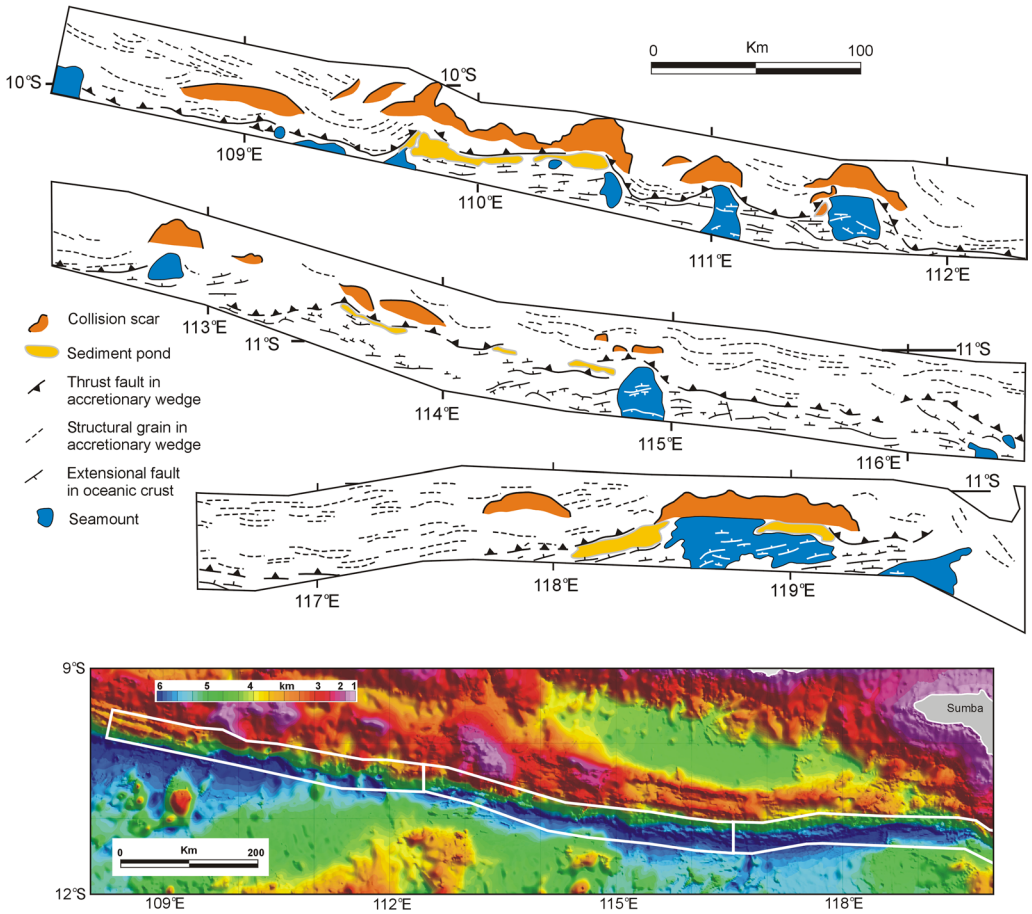

Fig. 2 Interpretations of Gloria imagery obtained during a traverse of the RRS Charles Darwin along the Java Trench. Coloured version of Fig. 3 of Masson et al. (1990). The lowermost image shows the swathe location overlaid on bathymetry derived from satellite altimetry (Sandwell et al., 2021). The bathymetric highs in the forearc north of the GLORIA coverage were discussed by Kopp et al. (2006). Some or all may be relics of past seamount subduction

conclusion in this respect, but imagery from the Japan Trench, where the forearc is non-accreting and therefore less easily deformed, suggests that the same processes operate there but that significant deformation occurs only when the seamount is much closer to the wedge (Lallemand & LePichon, 1987). Japan has long been at the forefront of the study of carbonate sequences originally deposited on oceanic seamounts and now exposed onshore in former accretionary wedges (e.g. Peybernes et al., 2020), and these are now being studied globally for the evidence they provide on conditions in pre-Jurassic oceans.

The observations from both the Java and Japan trenches indicate that seamount subduction is not an easy process, and that partial accretion to the forearc wedge is likely. Some part of the seamount will, however, be subducted and it is possible that the presence of such material in the subducted plate results in enhanced partial melting and that it influences the distribution of volcanoes in the overlying arc. This is not a speculation that can be tested in the Java Trench because the seamounts in that part of the Indian Ocean are randomly distributed and there is no way of determining the positions of those that have already been subducted. In Sumatra, in the western portion of the Sunda Arc, the situation is rather different.

3 Strain partitioning (Sumatra)

In much of the relevant literature, the basic processes of plate tectonics are illustrated by cross-sections showing oceanic crust being generated at a mid-ocean rift and subducted back into the mantle at a trench flanking a continent or island arc. While such depictions are inevitable, there is a risk that their two-dimensional nature will encourage thinking limited to situations in which the direction of movement of the oceanic crust is at right angles to the trench. In the real world, this is seldom the case. The island of Sumatra (Fig. 3) has made an outstanding contribution to plate tectonics by providing

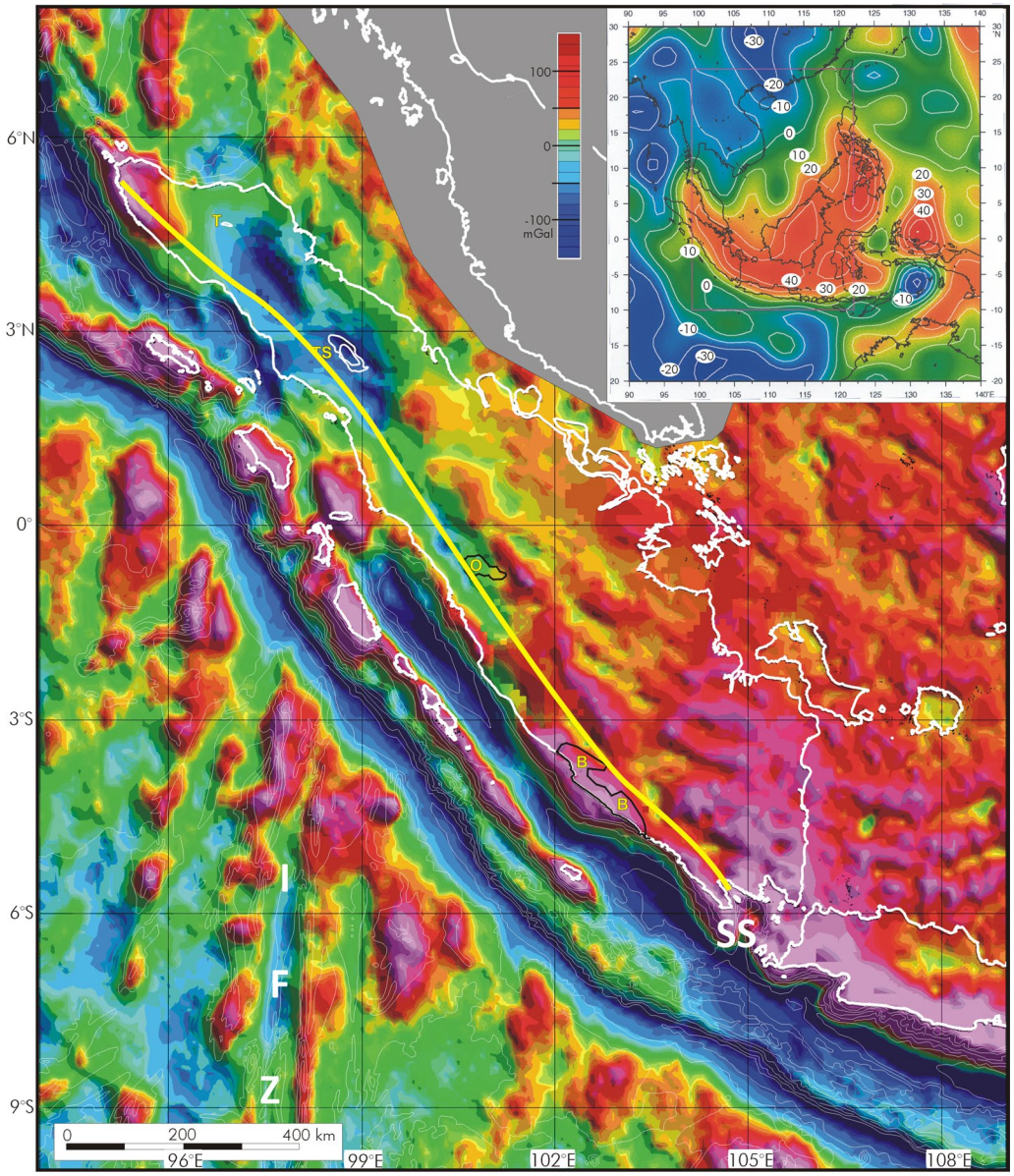

Fig. 3 Sumatra, with the Indian Ocean to the south and west and continental Southeast Asia to the north and east. The map shows free-air gravity derived from satellite altimetry offshore (Sandwell et al., 2021) and Bouguer gravity onshore. Bouguer gravity is largely controlled by crustal geology and crustal thickness, free-air gravity adds additional emphasis to bathymetric features such as the Sumatra Trench because the sediment cover, although denser than sea water, is significantly less dense than the basement rocks. The thin white lines are bathymetric contours, the thick yellow line is the trace of the Sumatra Fault System. IFZ: investigator Fracture Zone; SS: Sunda Strait. The inset shows the long-wavelength gravity field in the western and central parts of the Indo-Pacific gateway and is dominated by a gravity high that is interpreted as a consequence of the abundance of unassimilated relics of subduction within the asthenosphere. Illustration from Milsom & Walker (2005, Fig. 3.1)

one very clear example of what happens when an oceanic plate converges on a trench at an oblique angle.

Sumatra is an island but not an island arc. The seas to the northeast are shallow and underlain by thick crust, while the Indian Ocean to the southwest is a true ocean and the part that has been subducted at the well-defined trench is traceable as a seismogenic Wadati-Benioff zone (WBZ) to depths of several hundred kilometres. This, then, is an active continental margin. It is oriented roughly NW–SE, but the Indian Ocean is moving to the NNE (Fig. 4) and the mechanical constraints imposed by oblique collision have led to partitioning of strain into trench-parallel and trench-normal components. In the simplest models, the trench-parallel component

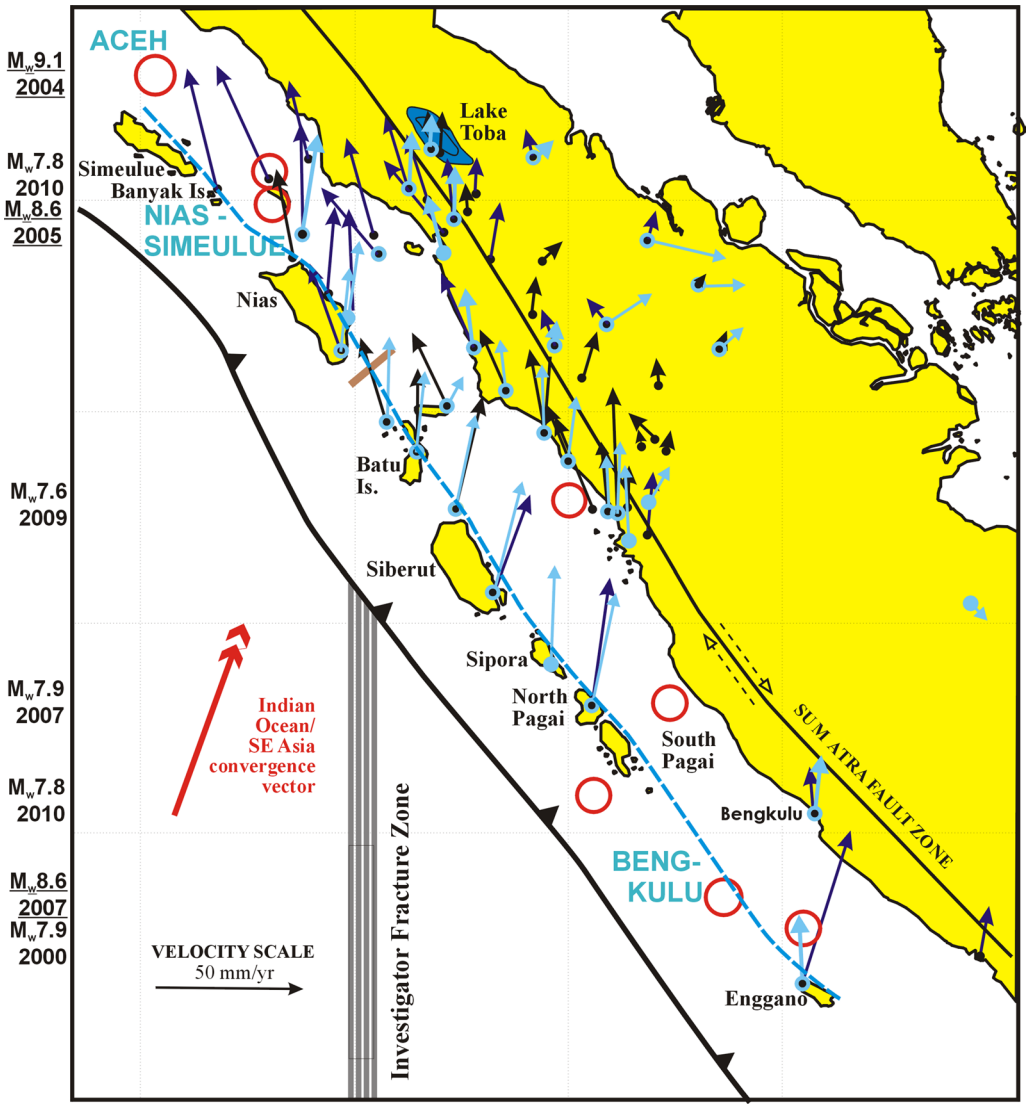

Fig. 4 GPS measurements in Sumatra and its forearc. The black arrows show the annual movement vectors relative to Southeast Asia estimated by Prawirodirdjo et al. (1997) for the period 1989–1993, the blue arrows the vectors from measurements made by Bock et al. (2003) in 1991–1997 and 2001, close to the beginning of a series of megathrust earthquakes spanning a period of seven years. Red circles mark the epicentres of earthquakes listed in the catalogues of the National Earthquake Information Center as having magnitudes (Mw) of more than 7.5. Magnitudes and dates are shown to the left of the margin. Events named in blue (e.g. ACEH) are those with magnitudes of more than 8, cited in the text. The earthquake search period was from 2000 to 2020, but there were no events satisfying the search criteria during its second half. More recent GPS studies (Feng et al., 2015) have concentrated on estimating short-term post-seismic displacements that are unlikely to be identifiable as such in the geological record. The thick brown line oriented roughly NE-SW south of Nias marks the location of the seismic section shown in Fig. 5. The dashed blue line marks the trace of the Mentawai Fault imaged in Fig. 5. Illustration modified from Fig. 2.4 of Milsom (2005a)

is accommodated along the right-lateral Sumatra Fault System (McCarthy & Elders, 1997), with only the trench-normal component taken up at the trench as in classical subduction. If this were actually the case, the contact between the Indian Ocean and the strip of crust sandwiched between the subduction thrust and the transcurrent fault would be a pure thrust, without any lateral horizontal motion on the thrust plane. This strip, wedged between major plates as a result of strain partitioning, and much longer than it is wide, has been referred to in the literature as a sliver plate or, alternatively, as a forearc sliver (Haq & Davis, 2010).

This form of accommodation was suggested early in the history of plate tectonics (Fitch 1972) and is, inevitably, an oversimplification. The general picture has been confirmed by GPS measurements made at points

on the mainland and the islands to the west (Fig. 4), but these have also shown it to be a less than perfect solution to the frictional-geometrical problems posed by oblique convergence. Subduction in this region is notable for fault-locking, stress build-up and eventual stress release in very large earthquakes, and there appears to be a direct relationship with the very considerable relief on the upper surface of the underthrusting plate. The Indian Ocean south-west of Sumatra is notable for the presence of major north-trending bathymetric features, the most prominent of which, the Investigator Fracture Zone (Figs. 3, 4), is currently impacting the trench in the vicinity of the equator. At the trench this zone is some 70 km wide and consists of four parallel ridges with relief of 1000 to 2000 m (Lange et al., 2010), and one visible effect of its subduction is the presence of a bathymetric high that cuts across the forearc basin and is capped by the Batu Islands (Fig. 4). A second, less coherent, ridge system a little further to the west has a similar effect, producing the rise capped by the Banyak Islands, and each of these rises appears to be associated with a blocking zone on the thrust plane.

The GPS measurements illustrated in Fig. 4 show that between 1989 and 1993 the movements of forearc islands north of the Batu Islands were very similar to the arc-parallel component of the movement of the Indian Ocean Plate, in accord with sliver-plate theory. Further south, however, the forearc appears to have been locked to the Indian Ocean during this period, with only minor differences between the vectors determined on the individual islands and the regional convergence vector. This is not a sustainable situation, and the four years covered by these measurements provide little more than a snapshot of what is, or was, happening in a complex and evolving geological system. The later measurements also shown in Fig. 4 illustrate this pattern less clearly but cover a period leading up to extreme earthquake activity. In the decade 2000–2010 there were three mega-thrust earthquakes with magnitudes (Mw) greater than 8, pointing to episodic readjustment in the forearc. GPS measurements made during this period in a collaboration between the Tectonics Observatory at Caltech and the Indonesian Institute of Sciences (LIPI) have mapped short-term changes associated with these events and demonstrated patterns of deformation that call into question the whole concept of a single sliver plate (Chlieh et al., 2008). In reality, the forearc sliver is divided into segments with boundaries defined by the Banyak and Batu island groups that cut across the forearc basin, and deformation due to failure in any one of these segments barely propagates into any of the others. Most spectacularly, the rupture associated with the tsunami-generating Magnitude (Mw) 9.1 Aceh earthquake of December 2004 extended some 1200 kms to the north-west but only as far as the Banyak islands to the south-east (Tanioka et al., 2006), and the Mw 8.6 Bengkulu earthquake in September 2007 ruptured only the region south of the Batu Islands (Konca et al., 2008). The Mw 8.6 Nias-Simeulue earthquake of 2005 was a little different. It appears to have been sourced within the Banyak blocking zone and was described by Konca et al. (2007) as having nucleated under both Simeulue and Nias, and therefore propagating in both segments. These observations show that the subduction of a major topographic feature such as the Investigator Fracture Zone is likely to be reflected in major changes in the upper plate.

The 1989–1993 GPS campaign also indicated a large discrepancy in the sector south of the Batu Islands between the movements of the forearc islands and the adjacent mainland, implying the presence of a significant fault or fault zone within the forearc sliver. This zone, now known as the Mentawai Fault, is generally an offshore feature but is exposed onshore in eastern Nias (Samuel & Harbury, 1996). Elsewhere it defines the generally linear east coasts of the major forearc islands and has been imaged by seismic reflection surveys both in this southern sector (Diament et al., 1992) and further north (Fig. 5). GPS data suggest that during the period of the observations it was barely active in the northern sectors, while seismic images such as that shown in Fig. 5 document a fault zone accommodating complex movements during which extensional, compressional and transcurrent faulting has occurred at different times.

Subduction-related magmatism in Sumatra has a surface expression in the 1700 km long Barisan mountains, which are up to 3800 m high. Primarily volcanic, their topography has been modified by uplift and subsidence associated with transpression and transtension in

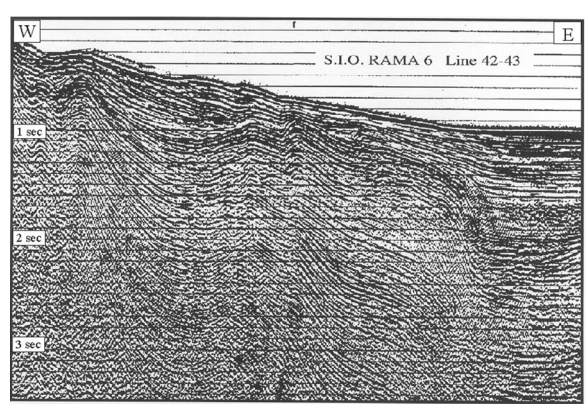

Fig. 5 Seismic image of the Mentawai Fault between Nias and the Batu Islands. Scripps Institution of Oceanography Cruise Rama-6. Extract from Fig. 2.6 of Milsom (2005a). Location shown in Fig. 4

the Sumatra Fault System, which exploits the zone of weakness represented by the volcanic line (McCarthy & Elders, 1997), and there is evidence of an association between volcanism and the relief on the subducted plate. The Investigator Fracture Zone, which must presumably be as much a feature of the previously subducted crust as it is of the crust that has yet to be subducted, would have reached depths conducive to magma generation when vertically beneath the location of the Toba super-volcano, which last erupted some 74,000 years ago (Chesner & Rose, 1991).

Before leaving Sumatra behind, it is worth pointing to one additional, and intriguing, feature of Fig. 3. The east coast of Sumatra is oriented north–south and is remarkably straight. Immediately offshore is a series of linear free-air gravity highs and lows with roughly east–west orientation but with slight south-facing convexity. These are not, however, purely marine features but persist onshore as Bouguer gravity features that have no apparent effect in the geology as mapped.

Surveys of the Java-Sumatra junction region have been concentrated in the Sunda Strait rather than in the area to the north (e.g. Malod et al., 1995), and the origin of these features therefore remains unexplained. They can, however, reasonably be taken as evidence for a pattern of rotational strain associated with the change in the orientation of Java relative to Sumatra, as hypothesized by Advokaat et al. (2018).

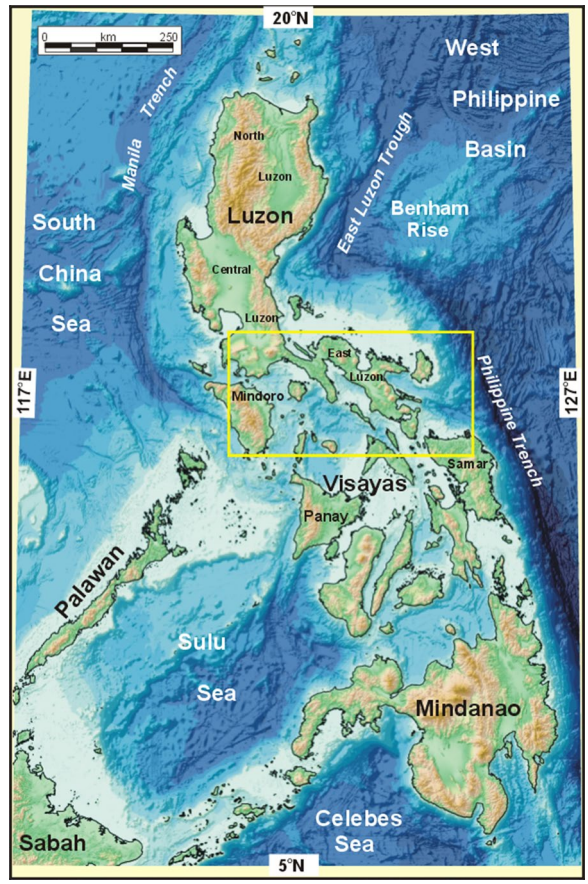

Fig. 6 The Philippine Archipelago. Base map: GEBCO, re-projected to UTM Zone 51N in Global Mapper. The yellow rectangle identifies the syntaxis area illustrated in Fig. 9

4 Syntaxis (Luzon)

A definition

Syntaxis: An abrupt major change in the dominant orientation of the main fold and thrust structures in an orogenic belt (Bates & Jackson, 1987).

The type-example of such a feature is the eastern syntaxis in Myanmar, southwestern China and eastern Tibet, formed as a consequence of the collision of India with Asia. It has a western counterpart at the Iranian end of the collision zone, but not all syntaxes require such massive colliders.

Situated at the northern apex of the 'gateway' triangle, the Philippine archipelago (Fig. 6) has already become involved in the Australia-Asia collision, but its present features have been determined only marginally, if at all, by the northward drift of Australia, and to a much greater extent by the semi-independent movement of the Philippine Sea Plate, which is located immediately east of the Philippine archipelago (Queano et al., 2007). The islands can be divided into four main groups. Palawan and Mindoro are composed of Asian continental crust, overthrust in places by an ophiolitic forearc (e.g. Yumul et al., 2008), but the other three groups are almost entirely the products of arc volcanism. They are collectively referred to in this section as a 'Philippine Arc' that specifically does not include the Palawan-Mindoro block. The southernmost group of this arc is dominated by the large island of Mindanao, the northernmost one by the equally large island of Luzon (see Fig. 6). Between these two groups is a region of comparable size occupied by a cluster of smaller islands known collectively as the Visayas. Luzon itself can be further subdivided into three parts, these being North Luzon, to the north of the important and topographically prominent Aurora Fault (Fig. 7), Central Luzon, the site of the active Taal volcano and the capital city, Manila, and East Luzon, a peninsula created by very recent volcanism that would have been included in the Visayas had not accidents of volcaniclastic deposition and current sea level provided land bridges between what would otherwise have been separate islands.

At the present time the Philippine Arc as a whole trends NNW-SSE, but palaeomagnetic investigations have shown that this has not always been the case and

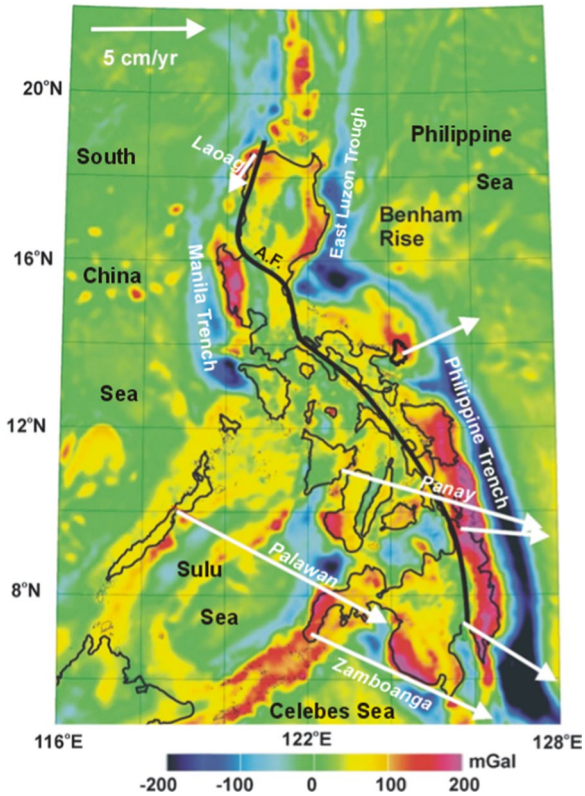

Fig. 7 Gravity field of the Philippines (Bouguer gravity onshore, free-air gravity offshore) computed from a combination of conventional and airborne gravity onshore and satellite altimetry offshore (Gatchalian et al., 2017). White arrows show motion vectors relative to the West Philippine Basin derived from the GEODYSSEA GPS programme (Rangin et al., 1999). The three unlabelled vectors record motions close to major fault zones and are considered to be heavily influenced by local tectonics. Subsequent GPS studies reported by Hsu et al. (2016) have confirmed the effective locking of North and Central Luzon to the Philippine Sea Plate but did not extend far enough south to define their relative motion with respect to the rest of the archipelago. The heavy black line shows the location of the Philippine Fault System as proposed by Barrier et al. (1991) and is generally similar to the locations suggested by most other authors. The NW–SE segment marked A.F. that separates North from Central Luzon is the Aurora Fault. In the south, between 120 and 128°E, the area covered by this figure adjoins the area covered by Fig. 10

that the archipelago, while possibly not very different in shape, was formed with a very different orientation. The work done so far has been insufficient to resolve the conflicts between a number of competing scenarios (e.g. Deschamps & Lallemand, 2002; Milsom et al., 2006; Queano et al., 2007), but it is generally accepted that the West Philippine oceanic basin was initiated just south of the equator at around 50 Ma by sea-floor spreading at the Central Basin Fault Rift located east of North Luzon (Fig. 8), and that the Philippine Arc was created at that time as its active southwestern margin. Spreading ceased at about 30 Ma, at which point the oceanic crust on either side of the spreading ridge became part of a single Philippine Sea Plate that had begun to move north and undergo clockwise rotation. During this phase in its history the Philippine Arc continued to act as the plate's active western margin, although there is evidence for episodic and limited convergence at its eastern side also. From 10 Ma onwards a highly oblique collision with the Palawan-Mindoro block led to the disruption of the western subduction zone and development of the northward-propagating Philippine Trench on the eastern side of the archipelago. This phase was terminated when subduction ceased in the northernmost segment of this trench (the present-day East Luzon Trough; Lewis & Hayes, 1989). Both the East Luzon Trough and the Philippine Trench are marked in Fig. 7 by deep free-air gravity lows.

Because the WNW-ESE convergence across the Philippine Trench is oblique to its strike, there is a Philippine analogue of the transcurrent Sumatra Fault System in the form of the left-lateral Philippine Fault System (Fig. 7). The trench ends rather abruptly in the vicinity of East Luzon, where the archipelago as a whole suffers an abrupt westward shift that is associated with the termination of east-facing subduction east of Luzon and probably an increased rate of subduction at the Manila Trench. The fault is usually shown, as in Fig. 7, as taking a NW path through the northern Visayas before ending, via a succession of segments, in the main cordillera of North Luzon (e.g., Aurelio, 2000). This continuity may, however, be illusory.

An important, although rather subdued, feature of the gravity map of Fig. 7 is the free-air gravity high in the ocean some 150 km east of North Luzon that marks the position of a very large subsea feature generally known as the Benham Rise, although very recently renamed the Philippine Rise. The regional bathymetry of the West Philippine Basin, supplemented by detailed high-precision bathymetric surveys reported by Barretto et al. (2019), indicates that this rise was generated by hotspot magmatism close to the spreading centre (the Central Basin Fault Rift on Fig. 8). On the north-east side of the spreading axis, and at a similar distance from it, is a counterpart to the Benham known as the Urdaneta Plateau, and still further north-east there is another plateau, the Oki Daito Rise. This, however, has not, and cannot have, a counterpart south-west of the Benham, because the crust that would have included any such feature has been subducted at the Philippine Trench (see Fig. 8).

The hypothetical subducted plateau, for which the name Anagolay, the Tagalog goddess of lost things, is suggested, does, however, have a ghostly presence in

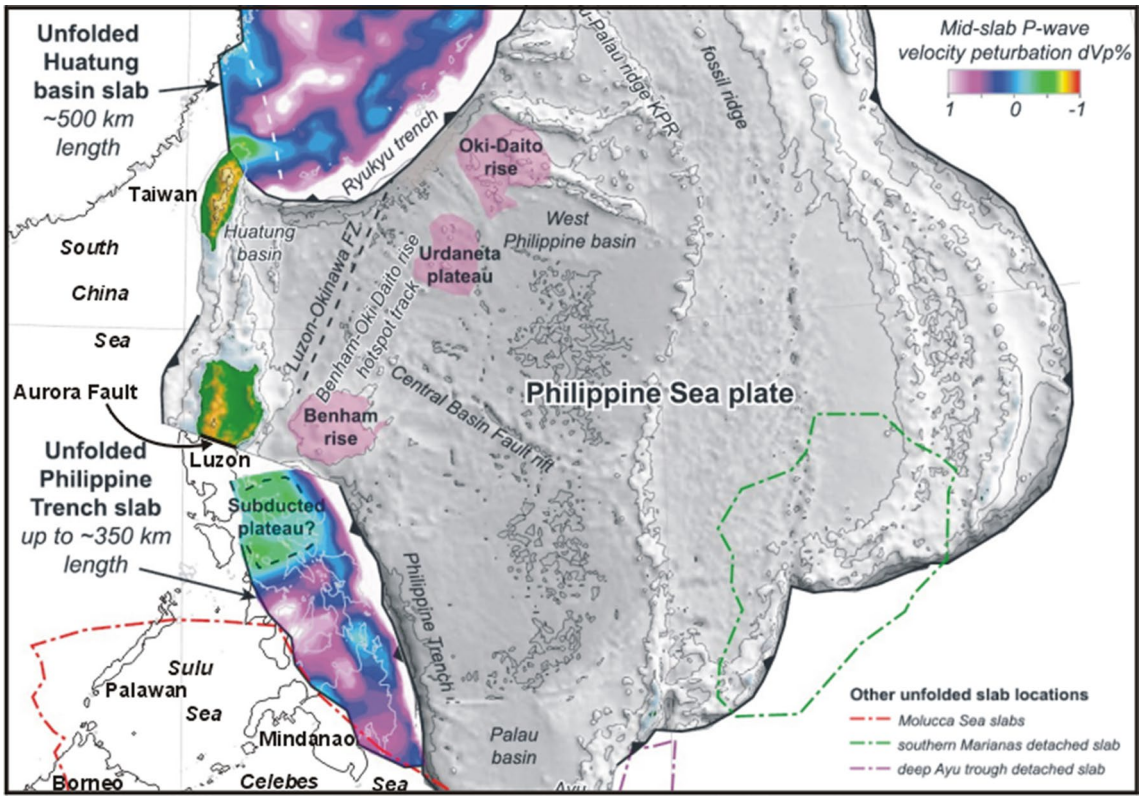

Fig. 8 The West Philippine Basin, showing the tomographically-determined locations of its subducted parts depicted as unfolded slabs (i.e. slabs restored to their original horizontal extents), coloured according to the P-wave velocity perturbation. The tomographic image also includes the low-velocity Anagolay Plateau, identified in this image simply as a 'Subducted Plateau?'. Annotated image from Fig. 14 of Wu et al. (2016), reproduced here under the terms of Creative Commons Attribution-NonCommercial-NoDerivs Licensing. Note the role suggested here for an extended Aurora Fault

seismic tomography. In the map of Fig. 8, which is reproduced from Wu et al. (2016), it appears as a low-velocity region (green area in Fig. 8) replacing the high velocity anomaly produced by the subducted Philippine Sea lithosphere elsewhere. It seems that the material of which it is formed, being less dense than normal oceanic crust, proved indigestible. Hence it terminated west-directed subduction and necessitated enhanced development of the Manila Trench, which is situated off the west coast of Luzon (see Figs. 6 and 7) and subducts the South China Sea.

The GPS motion vectors shown in Fig. 7 are too few and too widely separated to well define displacements within the Philippines. The most striking feature is the very large difference between the motion vector recorded at the Laoag station on North Luzon and all other stations. Inevitably, with the ending of subduction at the Philippine Trench east of Luzon, North and Central Luzon were incorporated into the West Philippine Sea Plate and have since shared its westward motion relative to the rest of the archipelago. This observation, together with the geometric and mechanical constraints, seems incompatible with the existence of a continuous transcurrent fault system that includes both the Philippine Fault System through Mindanao and the Visayas and the N-S faults in North Luzon. There is, moreover, no direct evidence for the hypothesised segment of the Philippine Fault situated offshore to the east of central Luzon. Mapping by Lagmay et al., (2005; 2009) has defined a cluster of transcurrent faults in East Luzon and the extreme northern Visayas with orientations roughly parallel to the Panay, Palawan and Zamboanga convergence vectors shown in Fig. 7. The broad transcurrent system through this area (Fig. 9) forms a diffuse link between the northern end of the Philippine Trench and the southern end of the Manila Trench that can justifiably be termed a syntaxis. It seems that, in contrast to the seamounts entering the Java Trench, which are being largely incorporated into the accretionary prism, and to the Investigator Fracture Zone, which appears to have had a significant but relatively minor influence on the pattern of islands in the Sumatra forearc, the Anagolay Plateau is large enough for its attempted subduction to cause major changes over a wide area of the Philippine archipelago.

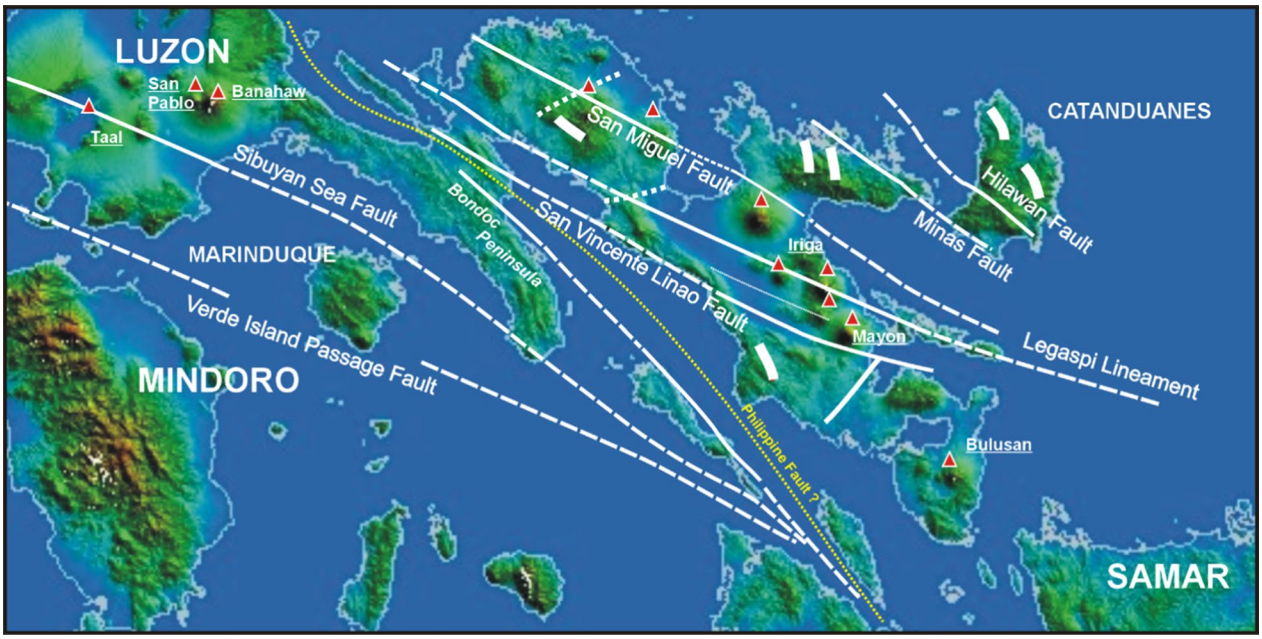

Fig. 9 The East Luzon Syntaxis. Faulting from Lagmay et al., (2005, 2009). Short thick lines indicate extensional faults, thinner lines are left-lateral transcurrent faults, dashed where based on interpretations of bathymetry. Red triangles are Late Neogene volcanoes, named where there is a record of historic eruption. The yellow dotted line marks the current consensus location of the main fault of the Philippine Fault System. Topography from the Shuttle Radar Topographic Mission (SRTM) 3 arc-second grid, visualised in Global Mapper

One objection that might be raised to this hypothesis is that the Philippine Trench as it exists today ends at the northern side of the syntaxis zone, not at the southern side as would seem to be required. It is, however, entirely possible that the trench began to propagate north again after the attempted subduction of Anagolay. A process of this kind has been suggested by Nichols et al. (1990) for the southern end of the trench, which is now propagating down the eastern side of the island of Halmahera, which resists subduction (see Fig. 10).

5 Orocline (Banda Sea)

One place where there is an apparently direct and close resemblance between the gateway region and a part of the Alpine orogenic system is the Banda Sea (Fig. 10), which occupies the space between the large islands of Sulawesi and New Guinea (Réhault et al., 1994; Honthaas et al., 1998; Hinschberger et al., 2001). Within this space, but separated by a complex area of extended continental crust known as the Banda Ridges, are two small oceanic basins (the North and South Banda Basins, outlined by black dashed lines in Fig. 10). The South Banda Basin is flanked to the south and east by a chain of volcanic islands representing a continuation of the Sunda Arc but which from Flores eastwards is known as the Inner Banda Arc. The region immediately to the east of this arc is occupied by the remarkably deep Weber forearc basin. These five distinct geological provinces are confined to the south, east and partially to the north within the loop of the non-volcanic Outer Banda Arc, a chain of often mountainous islands of which the largest are Buru and Seram in the north and Timor in the south.

The geometric similarity between this area and the arcuate Carpathian mountains enclosing the Pannonian Basin is hard to ignore. In purely geographic terms, parallels can immediately be drawn between the North Banda Basin and the Vienna Basin—Little Hungarian Plain, between the South Banda Basin and the Great Hungarian Plain south of the Transdanubian Mountains (a possible Banda Ridges analogue), and between the Weber and Transylvania basins. Parallels can also be suggested with other highly arcuate orogens that enclose extensional basins, such as the Hellenic, Tyrrhenian and Alboran arcs of the Mediterranean, and the Scotia Arc, and to some extent also the Antilles Arc, of the Americas. The repetition of such features on the Earth's surface has led to their being given a special name. They are called oroclines (Van der Voo, 2014).

There are, of course, significant and important differences between Pannonia and the Banda Sea. The Pannonian Basin is undoubtedly extensional, but nowhere has extension reached the point at which new oceanic crust has been created; the difference has undoubtedly dictated the differences in the topography of the upper

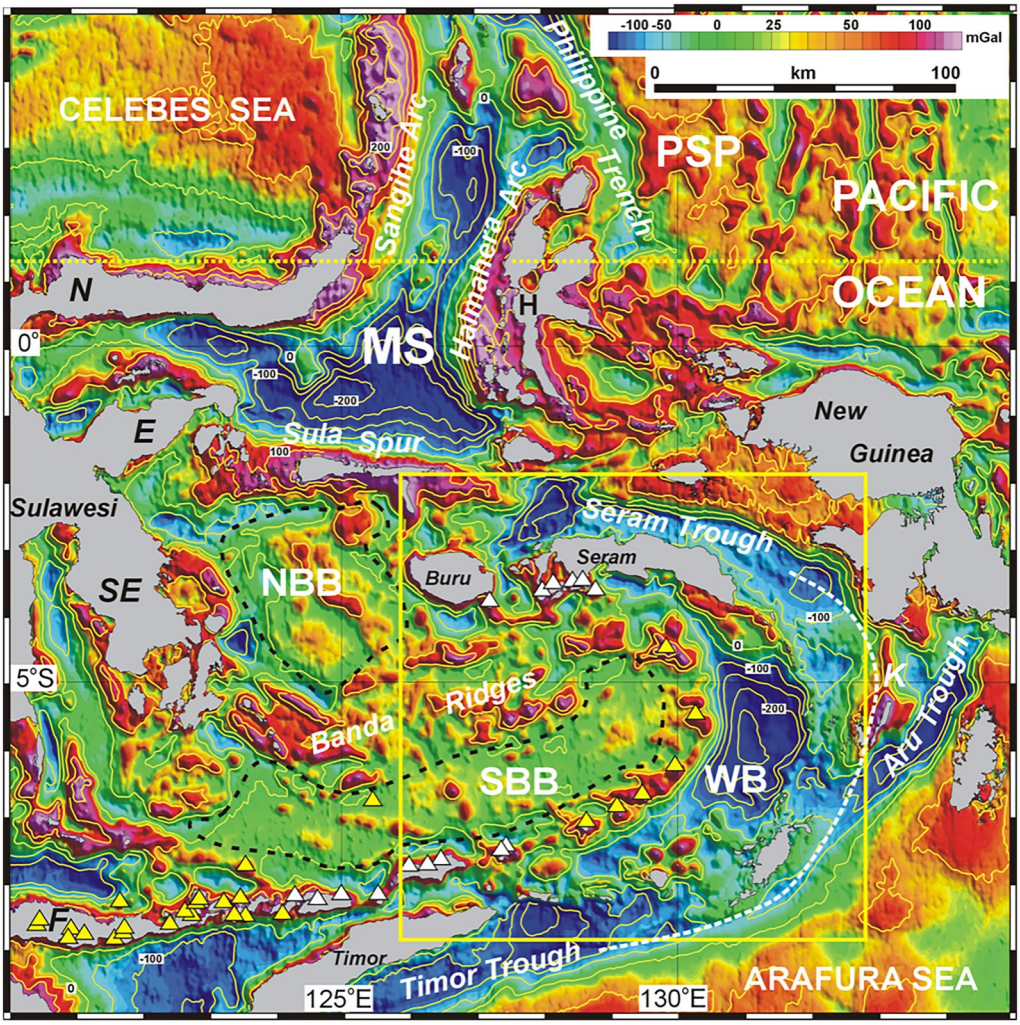

Fig. 10 Free air gravity map of the Banda Sea and Banda Arcs. The Outer Banda Arc consists of the large islands of Timor, Seram and Buru, as well as numerous smaller islands. The arc is composed principally of sedimentary rocks of Australasian (not Asian) affinity, and is in contact with the Australian continental margin in the north, south and east. The contact is a collision front, marked by the dashed white line through the deep free-air gravity lows that coincide with the Timor and Seram troughs in the south and the north but which in the east passes between the two largest islands of the Kai archipelago (Milsom et al., 1996). The gravity low in the Molucca Sea is a consequence of the coalescence of the subduction trenches associated with the converging Halmahera and Sangihe arcs (see Fig. 13). Active volcanoes on the inner arc ridge are indicated by yellow triangles, and inactive volcanic centres by white triangles. The yellow rectangle indicates the area of the seismicity plots of Fig. 11 and the dashed yellow line indicates the location of the tomographic cross-section of Fig. 13 (which extends beyond the limits of this map to both east and west). F: Flores. K: Kai archipelago, MS: Molucca Sea, NBB: North Banda Basin, PSP: Philippine Sea Plate, SBB: South Banda Basin, WB: Weber Basin. In the north, between 120 and 128°E, the area covered by this figure adjoins the area covered by Fig. 7. The base map was constructed from free-air gravity grids of re-tracked satellite altimetry (Sandwell et al., 2021). Contour interval 50 mGal

surfaces of the basements in the two areas, evident in the bathymetry in the case of the Banda Sea and in the very variable depth to sediment base described by Balázs et al. (2012) in the Carpathian Basin. Nor does there appear to be any significant present-day Carpathian analogue of the volcanic activity in the Inner Banda Arc, although the possibility of future eruptions in the 100 km-long Neogene volcanic chain along the eastern flank of the Transylvanian Basin cannot be entirely discounted (Harangi et al., 2010). When, however, the differences in the geological settings are taken into account, with one basin internal to a continent and the other in a quasi-oceanic domain, the congruencies can still be considered remarkable.

For the Banda region to be useful as an early analogue for Pannonia, mere similarity is not enough. Fresh insights must be provided, and for a considerable time the necessary understanding of the Banda area was

inhibited by the division of the orogen, in much of the literature, into separate Northern and Southern arcs. There is no doubt that the two are different in many ways, and most noticeably in the absence of any present-day volcanic activity in the north, where the formerly volcanic islands are, with one exception, restricted to a limited region south of western Seram. This fact, coupled with the absence of large islands in the eastern part of the arc, was cited in support of the idea that the apparently continuous arc had been created by coincidental juxtaposition of the eastern extension of the Sunda Arc and a much shorter and independent north-facing arc (e.g. Das 2004, and references therein). It was, however, an interpretation that became difficult to sustain after plots of earthquake hypocentres were shown to define a scoop-shaped seismogenic zone (Milsom, 2001). Over a distance of more than 700 kms, and with just a few scattered and possibly mis-located exceptions, the deepest earthquakes define a line dipping west at an angle of about 40° (Fig. 11A). Along all N-S sections, of which one example is shown in Fig. 11B, the maximum depths of events associated with south-facing subduction are identical to the maximum depths of events associated with north-facing subduction. In Fig. 11B the north and south zones merge at a depth of around 400 km.

Figure 11 suggests a scoop- shaped subducted slab beneath the Banda Sea, formed from the lithosphere of an oceanic embayment that could reasonably be termed a proto-Banda Sea. The existence of such a slab has been confirmed by subsequent seismic tomography (Spakman & Hall, 2010; Wu et al., 2016). The extreme extension that accompanied the eastward advance of a formerly only gently curved N-S oriented subduction zone immediately east of Sulawesi, and the consequent exposure in places on Seram of the world's youngest-known (16 Ma) ultra-high-temperature granulite, has been discussed by Pownall et al. (2013). The development of the forearc Weber Basin (Fig. 12), has been described by Pownall et al. (2016).

The sequence of events leading up to this rather remarkable situation has been a complex one. Limited palaeomagnetic evidence for large (~45°) counter-clockwise rotation of western Sulawesi prior to 13 Ma (Sasajima et al., 1980) lends support to the idea that this part of the island once formed part of an extension of the Sunda Arc east of Java. The trigger for the rotation seems to have been the impact on the subduction zone of a large block of detached Australian continental crust (see discussion in Advokaat et al., 2018), which has since fragmented to form the eastern and south-eastern Sulawesi peninsulas, the large islands of Buru and Seram and the extended continental crust of the Banda Ridges.

Following this collision, subduction presumably continued at a new trench outboard of this block, which began to break up with the formation of the North Banda Basin in a back-arc position at about 12.5 Ma (Réhault et al., 1994). After about 6 million years, extension transferred to the South Banda Basin and then, at about 3 Ma, to the Weber forearc basin (Hinschberger et al., 2001). For any of this to happen, there must have been an oceanic area into which arc roll-back could take place, and it is the subducted lithosphere of this 'proto-Banda Sea' that has now been mapped tomographically. The illustration reproduced in Fig. 12 implies a surface area to this slab that is considerably greater than the area occupied by the present-day Banda Sea, and for this to be the case the lithosphere must either have been squeezed downwards into the deep 'U' by N-S contraction, or have undergone rigid body fragmentation, or ductile extension or, quite possibly, all three.

Why should any of this happen? All these are processes that would require a considerable driving force and, given the mechanical constraints imposed by geometry, the mere presence of oceanic crust in a small basin trapped within a collision zone does not seem a sufficient explanation for the development of an orocline. Gravity-driven orogenic collapse has been suggested as one possible driver (Milsom et al., 2001) but as far as the Banda Sea is concerned there is another possibility, because the Molucca Sea to the north is being subducted to both east and west (Silver & Moore, 1978; McCaffrey et al., 1980). On the western side, the slab beneath the Sangihe Arc is seismogenic to a depth of 600 kms, while in the east a shorter slab is defined beneath Halmahera (see Fig. 13). This poses difficulties both for theories in which subduction is driven largely by ridge push (a problem, because there is no ridge) and for those in which it is driven by slab pull (a problem because the two subducting parts of the single oceanic slab are pulling in opposite directions). One thing, however, is clear; as the space between the Halmahera and Sangihe arcs is reduced by continuing subduction, large volumes of the asthenospheric mantle occupying that space must be escaping either to the north or to the south, or both. The tomographic image presented by Wu et al. (2016) shows exceptionally low velocity in this region at depths of between 300 and 500 km (Fig. 13). This potentially mobile material, if forced south by the contraction of the Molucca Sea, might well enter behind the Banda 'scoop' and force it east. Collision of the Banda Arc with New Guinea is now closing off this escape route and major rearrangements of plate boundaries are inevitable throughout the region during the next few million years.

The progressive halting of subduction by collision is made visible by the patterns of volcanic activity in the

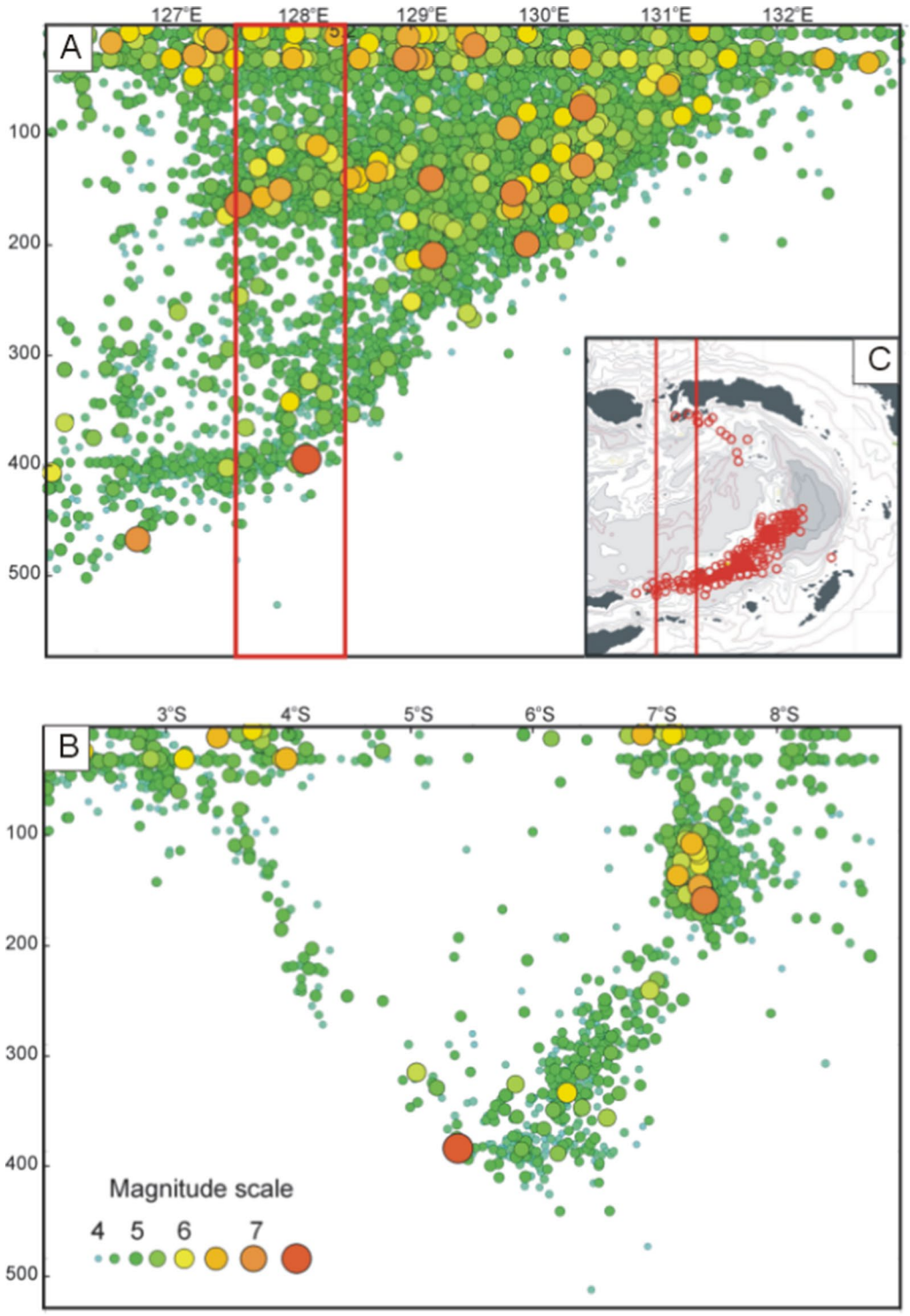

Fig. 11 Seismicity in the Banda Sea, utilising all earthquakes with magnitudes greater than 4 in the National Earthquake Information Center catalogue for the period 1990–2020. Colours and sizes of circles vary according to magnitude. **A** Plot of all events within the area defined in (**C**), viewed from the south. **B** Plot of all events within the swathe defined by the red N-S lines in (**C**), viewed from the west. **C** Events within the depth range 125–150 km, emphasising the concentration of deep earthquakes in the south-east bend of the orocline. The majority of the more intense shocks occur in this region. Note also the similar, but weaker, zone in the north-east bend

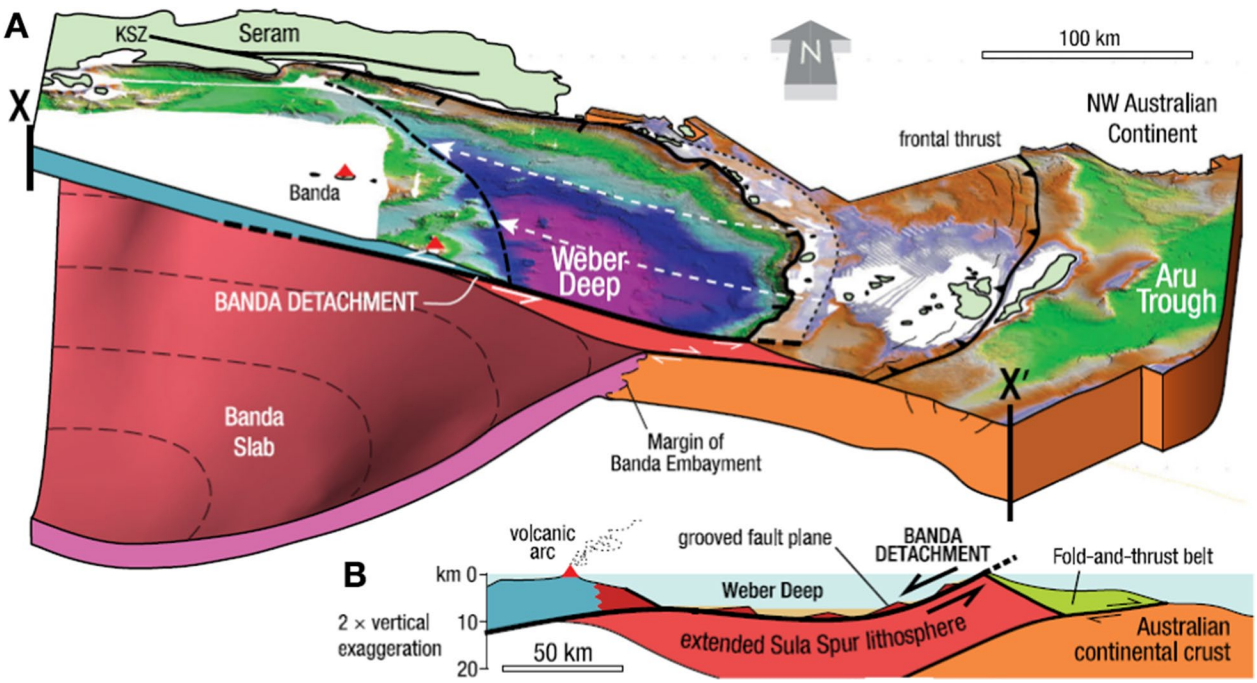

Fig. 12 The Banda subduction scoop. Figure 5 from Pownall et al. (2016). Copyright Geological Society of America. Used with permission

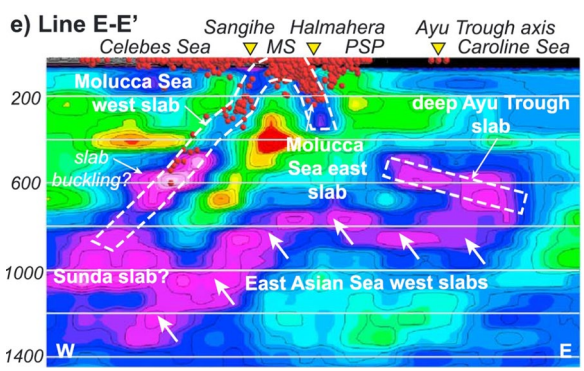

Fig. 13 East–west tomographic section across the Molucca Sea (Fig. 21e of Wu et al., 2016, reproduced under the terms of Creative Commons Attribution-NonCommercial-NoDerivs Licensing). Red circles are projected locations of earthquake hypocentres within 50 km of the plane of cross-section whose position is indicated on Fig. 10. Seismic velocity anomaly contours range from − 1% (red) to + 1% (purple)

inner arc. Volcanism has ceased not only in the northern part of the arc, which is now in contact with the continental shelf of New Guinea, but also in the south, where the submerged margin of northwest Australia is entering the trench south of Timor, forcing eastern Timor north across the forearc basin. Volcanic activity has ceased on the arc islands immediately north of Timor but not on those to the west or further to the east. It seems likely that in both the northern and the southern arms of the arc the magma conduits have been severed during collision.

With the acceptance of this overall picture come other observations with potential application to the more highly evolved Alpine orogen and in particular, to its Carpathian-Pannonian segment. The similarity between the locations of the North Banda Basin and the Vienna Basin/Little Hungarian Plain in relation to the adjacent orogens suggests that the descriptions by Pownall et al. (2013) of extreme extension in Seram may resonate with students of Alpine/Carpathian relationships. The fact that the Mesozoic sediments of the outer arc islands and eastern Sulawesi are of Australasian, not Southeast Asian, origin (Milsom, 2000) demonstrates yet again the permeability of supposedly impassable plate boundaries; it is direct evidence that subduction may not be entirely halted in a collision but, if it is possible to do so, may be re-established outboard of the original trench, effectively transferring blocks of crust from one plate to the other.

There is one additional and intriguing observation that may have very direct relevance to the Carpathians, where deep earthquakes are restricted to a vertical, roughly cylindrical, zone at depths of between 90 and 160 km beneath Vrancea in the south-eastern bend of the arc (Craiu et al., 2022). Earthquakes are far more widely distributed in the still active Banda arc and define an extensive seismogenic region, but,

as already noted, and as shown in Fig. 11C, there are remarkable concentrations coupled with almost aseismic gaps, suggesting that the extreme extension is breaking up the formerly continuous slab. Extension in the Pannonian Basin was ending at about the same time as it was commencing in the Banda Sea and a similar process may there have advanced to the point where only a single seismogenic fragment remains, now sinking into the lithosphere (Milsom, 2005b). The fact that both this seismogenic fragment and the most recent volcanic events in the Carpathians are further east than would be expected from a simple subduction model is consistent with eastward flow continuing in the sub-lithospheric mantle after collision of the overlying lithospheric blocks.

6 Small oceanic basins (Solomon Sea)

The complexity of the geology of Sumatra, the western boundary of the Indo-Pacific gateway, can only be appreciated when it is examined in detail. The complexity of the eastern boundary, the island of New Guinea, is all too apparent (Davies, 2012), and nowhere more so than around the Solomon Sea in the extreme east. The region between latitudes 3˚N and 13˚S and between longitudes 145˚E and 165˚E constitutes only a tiny fraction of the surface of the Earth but, as shown in Fig. 14, it contains within its boundaries an astonishing variety of geological features. Among these is a small ocean basin with an active spreading centre and a well-defined spreading fabric (1: Woodlark Basin); a second, slightly older basin with a somewhat less well-defined fabric (2: Bismarck Sea); a third, considerably older oceanic basin with no obvious fabric (3: Solomon Sea); two orthogonally-arranged trenches backed by volcanically-active island arcs that overlie Wadati-Benioff zones that extend to depths of some 600 km near their junction and which are therefore among the deepest in the world (4: New Britain and Bougainville Trenches), a chain of high-potash andesitic volcanoes with only rare underlying deep seismicity but with a clear association with the propagation of a spreading rift into continental crust (5: the eastern Papuan Peninsula), an active oceanic rift impacting at

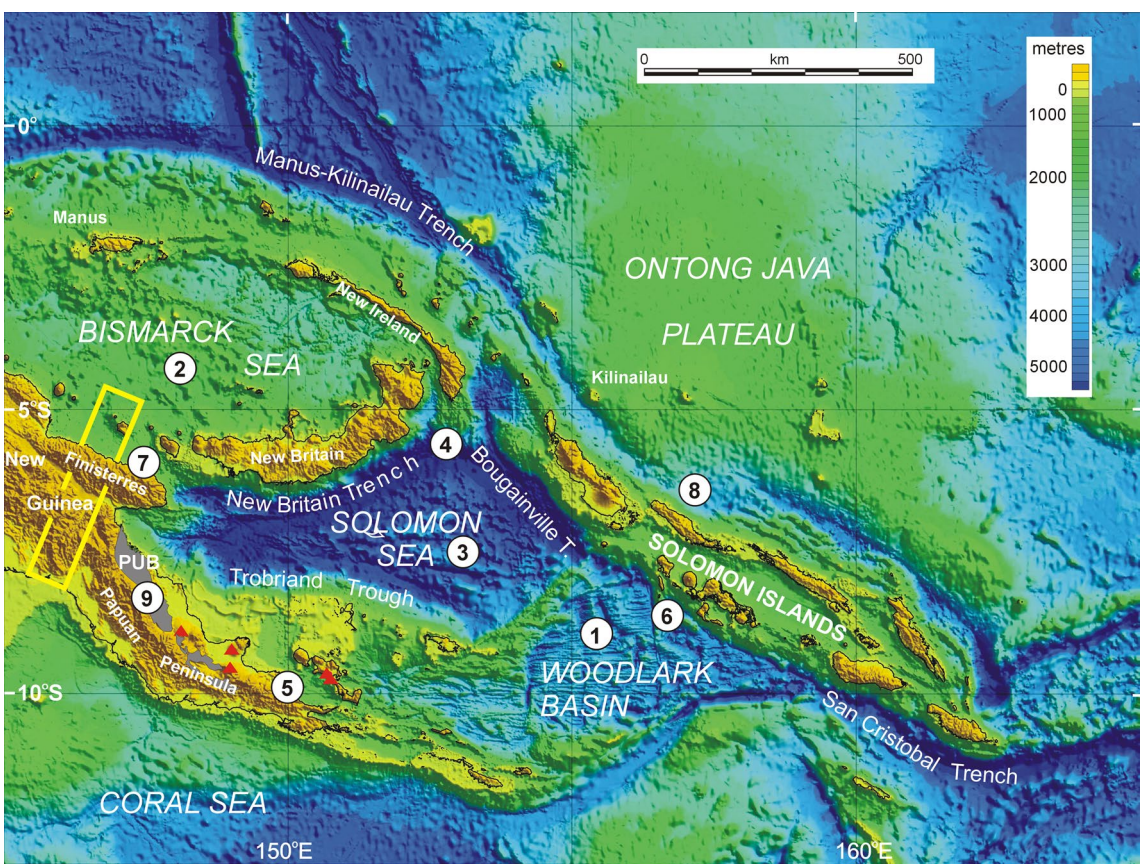

Fig. 14 The Solomon region. The Papuan Ultramafic Belt (PUB) in the north-eastern part of the Papuan Peninsula is shaded light grey and numbered 9. Active volcanoes of the peninsula and the adjacent small islands are indicated by red triangles. The yellow rectangle indicates the location of the earthquake cross-section plotted in Fig. 15. Base map: GEBCO

right angles on an island arc (6: central Solomon Islands), an island arc part-way through collision with a continental margin (7: Finisterre Ranges), a vast oceanic plateau that has impacted on a former arc (8: Ontong Java Plateau), and one of the most impressive of the 'large slab' ophiolites that are now generally interpreted as forearc fragments thrust-emplaced on continental crust (9: Papuan Ultramafic Belt, or PUB). None of these features existed before the beginning of the Cenozoic, and all developed in the context of the steady northward movement of Australia. That development can best be summarised in terms of six distinct phases, decreasing in timespan and increasing in resolution and confidence as the present day is approached.

Phase 1: The oldest rocks in the region are the felsic metamorphics that form the high mountains along the 'spine' of the Papuan Peninsula, interpreted as a metamorphosed continental-margin sequence now detached from its continent by the opening of the Coral Sea in the Late Cretaceous. This event, and the partly simultaneous opening of the Tasman Sea to the south, has had multiple consequences for the history of the western Pacific (Gaina et al., 1999; Bulois et al., 2017) but will not be considered further here.

Phase 2: Following its separation from the Australian mainland, the margin sequence was metamorphosed, generally to greenschist facies, during the thrust emplacement on its north-eastern flank of a 'large slab' ophiolite (Dewey & Casey, 2013) known as the Papuan Ultramafic Belt (PUB) (Davies, 1971; Davies & Smith, 1971). Potassium-argon ages obtained from the metamorphic sole of the thrust are clustered around 58 Ma, with a scatter of older values up to about 65 Ma but with none younger than 57 Ma (Lus et al., 2004).

It is now widely accepted that ophiolites that display the full igneous stratigraphy from mantle peridotites to pillow basalts and include island arc elements are former forearcs, and the presence of the PUB therefore implies that in the Paleocene or Early Eocene the northern margin of Australia encountered a south or south-west facing subduction zone. That in turn implies that somewhere in the vicinity there should be the remnants of a Paleocene volcanic arc. No such rocks have yet been identified, but Late Eocene arc volcanics form the exposed basement of New Britain (Ryburn, 1975). A very broad-brush interpretation of these observations is that the early Palaeogene saw one or more collisions between northern Australia and an arc or arcs at the margin of the Pacific. This still poorly understood period can be considered the second phase in the evolution of the Solomon Sea region.

Phase 3: The development of the Solomon Sea, which now separates the arc rocks of New Britain from the PUB ophiolite by hundreds of kilometres of oceanic crust. Dating of this sea is very uncertain, but heat flow and basin depth data have been interpreted as suggesting dates in the range 24–44 Ma (Joshima & Honza, 1986) and magnetic anomalies have been assigned dates in the range 28–34 Ma (Joshima et al., 1986), placing its formation long after ophiolite emplacement and very possibly after the ending of Phase 2 volcanic activity in New Britain. After this activity ceased, the continuing northward advance of Australia must have been accommodated by subduction of the Pacific at the north-facing Manus–Kilinailau Trench, to which the Solomon Sea would have been back-arc. Late Oligocene igneous rocks exposed on New Britain (Ryburn, 1975) and New Ireland (Hohnen, 1976) and the Late Eocene to Oligocene rocks of the Solomon Islands Volcanic Province described by Coleman (1970) have been interpreted as parts of a continuous arc associated with this trench (Petterson et al., 1999). Back arc extension is common in the Western Pacific, which is where it was first recognised in the course of marine surveys in the late 1960s (Karig, 1970; 1971), and there is therefore nothing inherently implausible about a former unity of the PUB and New Britain or their subsequent separation along a zone of weakness created by subduction-related volcanism.

Phase 4: Subduction at the Manus–Kilinailau Trench was halted in the Early Pliocene by the arrival north-east of the Solomon Islands of the world's largest subsea igneous province, the Ontong Java Plateau (Mann & Taira, 2004; Obayashi et al., 2021). Reduced activity elsewhere was marked by a period of quiescence and carbonate deposition in New Britain and New Ireland that occupied almost the whole of the Miocene and part of the Pliocene.

Phase 5: The blocking of the trench north-east of the Solomons transferred the islands to the Pacific Plate, and a new subduction zone developed along their Solomon Sea margin to accommodate the continuing convergence. This led in its turn to plate reorganisation throughout the area, with the opening of the Bismarck Sea between New Britain and the Manus-New Ireland segment of the Manus–Kilinailau arc (Taylor, 1979) initiating subduction of the Solomon Sea at the New Britain Trench. The lengths of the seismogenic zones beneath New Britain and the Solomons bear witness to the subduction of least half of the original crust of the Solomon Sea, in the course of which the western part of the New Britain arc was emplaced on the New Guinea margin to form the Finisterre Ranges (Abbot, 1995). For reasons that have yet to be satisfactorily explained, the Finisterre block is offset south of the direct New Britain trend but the active volcanic line is not, being present as a chain of volcanic islands off the coast north of the Finisterres. The collision zone is marked at the surface by a broad flat valley, and plots of the distribution of earthquake hypocentres

beneath it show the continuation of the New Britain WBZ dipping north at an angle of about 35° from subcrop in the valley to a depth of about 75 km (Fig. 15).

Deep earthquakes in this region are not, however, confined to this relatively shallow zone. Earthquake hypocentres at depths below 100 km define a separate zone in the shape of an inverted and asymmetric U with a shallow-dipping southern arm and an almost vertical northern arm (Fig. 15). Pegler et al. (1995) concluded that there must have been earlier subduction to both north and south, and that both arms are still to some extent active. The eastward extension of the south-dipping arm can be linked to the Trobriand Trough, a poorly defined trench or trench-like feature along the southern margin of the Solomon Sea, and there have been rare earthquakes at depths of over a hundred kilometres beneath the historically, and lethally, active volcanoes of the Papuan Peninsula (Smith, 1982).

Phase 6: With the partial blocking of subduction at the New Britain Trench, the drag of the subducted lithosphere produced extension at the opposite side of the Solomon Sea, and the Woodlark Basin began to open. This may well be the smallest oceanic basin on the planet that displays the full oceanic suite consisting of an active spreading ridge, a ridge-parallel bathymetric fabric, fracture zones at right angles to that fabric and dateable magnetic anomalies. First suggested as a locus of sea-floor spreading on the basis of partial but in some places very detailed bathymetry (Milsom, 1970), the basin quickly attracted the attention of marine geophysical institutes and was eventually targeted by Leg 180 of the Ocean Drilling Program (Robertson et al, 2001; Taylor & Huchon, 2002). Of particular interest is the fact that, while the newly-generated oceanic crust is being absorbed at the Solomons subduction zone at the eastern end of the basin, with the production of a distinctive volcanic suite on the islands of the central part of the Solomons chain, at its western end the spreading axis is propagating into the thick crust of the Papuan Peninsula (Goodliffe & Taylor, 2007). Metamorphic core complexes have been exposed, small but deep fault-bounded extensional basins have been formed, and it is possible that the volcanic activity of the Papuan Peninsula and adjacent islands, although presumably sourced from a subducted slab, has been triggered by the ongoing extension.

To be able to examine so many different processes and their consequences in such a small area is a real geological bonus, but also a warning to those who study more highly evolved orogens. It is remarkable how much can happen in a relatively small area in a geologically very short period of time.

7 Summary

Inevitably, this overview omits many of the details of the observations on which the current understanding of the evolution of the Indo-Pacific gateway is based. Those details are to be found in the references cited, but it is

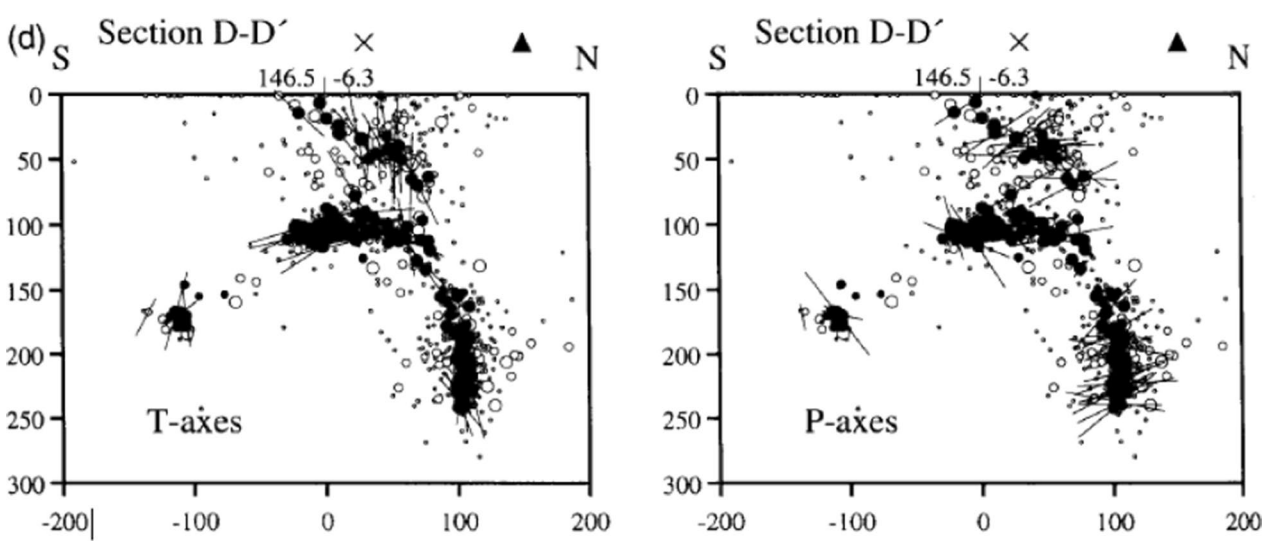

Fig. 15 Earthquake hypocentres in a swathe at right-angles to the Finisterre Range of mainland Papua New Guinea, showing extensional and compressional axes (Pegler et al., 1995). See Fig. 14 for location. Tomography tells much the same story and suggests that the south dipping subduction phase was either very brief, very slow, or very recent, since the tomographic expression of the slab extends to little more than 200 km (see Hall & Spakman, 2003, Fig. 9e)

not claimed that they will necessarily and in every case have any relevance to Alpine studies. Nor is it the place of someone whose research has been largely concentrated in the gateway region to produce interpretations of Alpine evolution. It is for the people who have engaged in long and thoughtful study of the Western Tethys collision to decide whether the exploitation of volcanic lines as zones of weakness by transcurrent and extensional faulting occurred also in the Alpine orogeny, whether the evolution of the Banda Sea has anything to tell them about the evolution of Pannonia-Carpathia, whether the Philippine syntaxis has anything to say about shifts in subduction polarity during Alpine collision, whether there were ever 'large slab' forearc ophiolites analogous to the Papuan Ultramafic Belt emplaced in the Alpine chain and whether the Solomon Sea—Woodlark Basin region can tell them anything useful about the generation and destruction of small oceanic and back-arc basins in a collision setting.

It must also be emphasised that not every interpretation offered here is uncontroversial. The unravelling of the past history and present-day tectonics of the gateway is still very much work in progress. It resembles in some respects a vast jigsaw, with multiple players simultaneously attempting to assemble separate parts, and it is not uncommon for one of those players to recognise that a particular piece exactly fits into their part of the puzzle, only to see it used by another player for another purpose. Opinions have also changed with time. The ground-breaking regional reconstruction of the history of the entire area presented by Hall (2002), which had its origins in very local palaeomagnetic studies in northern Indonesia, has since been much modified, in some cases by its own author when incorporating into it the results of collaboration with the seismic tomographers (Hall & Spakman, 2013). Alternative reconstructions have been presented, often to address problems in one specific area and sometimes without due regard for the problems the solution created in other areas. The reconstructions presented by Mann & Taira (2004, their Fig. 6), which are surely correct as far as the focus area of the Ontong Java Plateau is concerned, also show the island of New Britain with the same orientation throughout the Miocene and Pliocene, despite the presence on one side of the island of a trench connected to a seismogenic zone reaching in places to depths of over 600 kms, and on the other side of an oceanic basin that probably did not exist before the beginning of the Pliocene.

As far as the present paper is concerned, the denial of the commonly accepted extension of the Philippine Fault System into northern Luzon would be anathema to many, and the proposed role of a forerunner of the Benham—Philippine Rise in shaping the island of Luzon and driving the termination of subduction at the East Luzon Trough has yet to appear in the peer-reviewed literature. Nor is the suggestion that Banda Sea extension was driven, in part at least, by asthenospheric flow routinely accepted. The historical outline presented for the Solomon Sea region is merely a framework, undoubtedly over-simplified and very possibly incorrect in places. For example, the paper by Benyshek & Taylor (2021), which is accompanied by an extensive reference list, suggests that extension in the Woodlark Basin preceded the Finisterre collision. This does not, however, mean that these situations are not worth bearing in mind when considering the complexities of Alpine orogenesis. The aim of this paper is to present them to workers in the Alpine regions, and so bring to their attention the problems being faced, and the solutions being developed, in an area which, while similar to theirs in many respects, preserves much of the vital information un-obscured by later overprint.

Of the conclusions that might be drawn from this overview, two seem especially important. The first is that, while the long-term effects on the upper plate of the subduction of isolated seamounts remain uncertain, the effects of the subduction or attempted subduction of long bathymetric ridges and large oceanic plateaus will always be locally, and sometimes regionally, significant.

The second is that the possible influence of the topography of the base of the lithosphere, both when in situ and when subducted, on flow in the asthenosphere, and also the effects of such flows on lithospheric tectonics, should always be taken into account when considering orogenic processes. It is all too easy to think of plate tectonics in terms of rigid plates sliding smoothly over a fluid substrate, but the very considerable thickness variations in the lithosphere in orogenic areas, and the additional constraints represented by subducted lithosphere, imply that this cannot possibly be the case.

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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The author declares he has no competing interests.

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Publisher's Note

John Milsom is a retired geophysicist with a background in academic, commercial and government-sponsored investigations in the areas described.