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The Banda Sea: continental collision at the eastern end of Tethys

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Abstract: Continental collision in the Himalayan and Mediterranean segments of the Tethyan domain has produced regions of dramatic local extension within overall compressional environments. In the Mediterranean, deep basins have been created which are partly enclosed by orogenic belts forming arcs with total curvatures approaching 180°. These basins are floored either by attenuated continental crust (Alboran and Aegean seas) or by oceanic crust (parts of the Tyrrhenian Sea),

The eastern Indonesia (Banda Arc) segment of the Tethyan collision zone has not usually been considered in terms of continent-continent collision because attention has been focussed on the present-day impact of Australia. There is, however, much evidence for earlier collisions of fragments of the Australasian continent with this margin of Eurasia, and there are striking resemblances to the Mediterranean region. High standing ridges in the centre of the Banda Sea include continental material but water depths in excess of 5 km testify to the presence of oceanic crust in the North and South Banda basins. The 180° loop of the Banda Arc can be considered an end member in the spectrum of Tethyan collisional orogens, at the limit at which oceanic influences (in the form of the uncollided Indian Ocean west of Australia) remain important.

INTRODUCTION

The Indo-Australian, Eurasian and Pacific plates interact in eastern Indonesia in a diffuse triple junction buffered by a number of independent microplates (Hamilton, 1979; Silver *et al.*, 1985). The Pacific Plate exerts its influence indirectly via the loosely associated Molucca, Philippine and Caroline seas, with motions relative to Eurasia which can be broadly summarised as convergence at the Philippine Trench and shear along the Sorong Fault Zone (Fig. 1). Relative motion between the Caroline Sea and Indo-Australia is now absorbed by deformation in New Guinea, and between Indo-Australia and Eurasia by Sunda Arc subduction and Banda Arc collision (Hamilton, 1979). The Banda Arc collision has been intensively studied (Bowin *et al.*, 1980; Richardson, 1993), but interpretation has been hindered by uncertainties as to the origin of the Banda Sea, where water depths in excess of 5 km testify to the presence of oceanic crust in the North and South Banda basins but where high-standing ridges include continental material (Silver *et al.*, 1985). It has been suggested that the sea is underlain by trapped Mesozoic crust (McCabe *et al.*, 1993) but the magnetic anomaly matching on which this hypothesis is based is suspect because of the irregular shape of the oceanic area, and has not been supported dredging, which has recovered only Middle Miocene or younger rocks (Rehault *et al.*, 1994). Since there is compelling evidence for Middle Miocene collision in the Sulawesi region, at the western margin of the sea (Bergman *et al.*, 1996), a Banda Sea origin as a post-collisional collapse basin, on the Mediterranean model, seems more probable. Evidence in favour of this interpretation is reviewed below.

THE BANDA ARC

The Sunda volcanic arc, beneath which the Indian Ocean is being uncontroversially subducted from Sumatra to Flores, continues without noticeable offset into the Banda volcanic arc but with a marked eastward decrease in the age of the oldest identifiable volcanic events (Abbott and Chamalaun, 1981). Volcanism on Sumatra and Java can be traced back to at least the Paleogene but the oldest igneous rocks in the SW Banda Arc are Middle Miocene and there may not have been any activity in the Banda islands until the Pliocene. Eruptions are still common on these eastern islands but appear to have now ceased on Alor and Wetar, north of Timor (Hamilton, 1979). Throughout the arc the volcanic products testify to the subduction of continental crust, which is thought to have entered the Banda subduction zone at about 3.5 Ma in the Timor region (Vroon, 1992). Seismic reflection surveys have imaged continental margin sediments being thrust beneath Timor (Hughes *et al.*, 1996; Snyder *et al.*, 1996), Tanimbar (Schlüter and Fritsch, 1985) and Seram (Hamilton, 1979) and indicate that oceanic crust has now been eliminated around virtually the entire collision region.

The Australasian origin of most of the rocks exposed on Timor, the most intensively studied of the outer arc islands, had long been recognised (Audley-Charles, 1968) but presented no geological problems until, with the advent of plate tectonics, Timor and Australia were assigned to different plates. Since then there have been numerous and often contradictory attempts to identify and explain relationships between formations and events on either side of the collision zone. Dismissal of Australasian material in the outer arc as mélange accreted to the forearc during the last stages of subduction (Hamilton, 1979) discounted the existence of systematically mappable (even if often intensively imbricated) formations which outcrop over areas of many tens of square kilometres (Barber, 1978). Mélanges, of varied origin (Barber *et al.*, 1986), appear to be of only minor significance on most islands. Alternative models have invoked the supposed coexistence on the larger islands of two distinct stratigraphies, one (the allochthon) representing a pre-collision Banda forearc, the other comprising more recently emplaced para-autochthonous thrust sheets of Australian margin sediments (Carter *et al.*, 1976). This distinction has, however, been questioned (Brown, 1992) and even where accepted has provoked controversy, sometimes within a single paper (Audley-Charles *et al.*, 1979), as to which formations should be assigned to which unit. It is, however, possible on many of the islands to deduce a history of Triassic continental margin sedimentation, Jurassic rifting and subsequent drift characterised by the deposition of cherts and deep water limestones in environments remote from sources of clastic sedimentation. Crucially, this same pattern is repeated at the western margin of the Banda Sea on Buton island (Davidson, 1991), where sediments could not have been transferred from Australia to Eurasia during the Banda collision since Buton and Australia lie on opposite sides of the volcanic arc.

Around the Outer Banda Arc, structural studies have emphasised the importance of factors other than the 3.5 Ma collision. For example, the main phase of thrusting on Timor has been dated as Middle Miocene, with the Pliocene and Pleistocene dominated by normal faulting (Berry and Grady, 1981). Buton is critically important in this context also, since it also suffered Miocene deformation and imbrication (Davidson, 1991). On nearby Sulawesi, the Middle Miocene was a time of orogeny associated with widespread volcanic activity and the emplacement of extensive ophiolite sheets. Bergman *et al.* (1996) obtained radiometric ages for

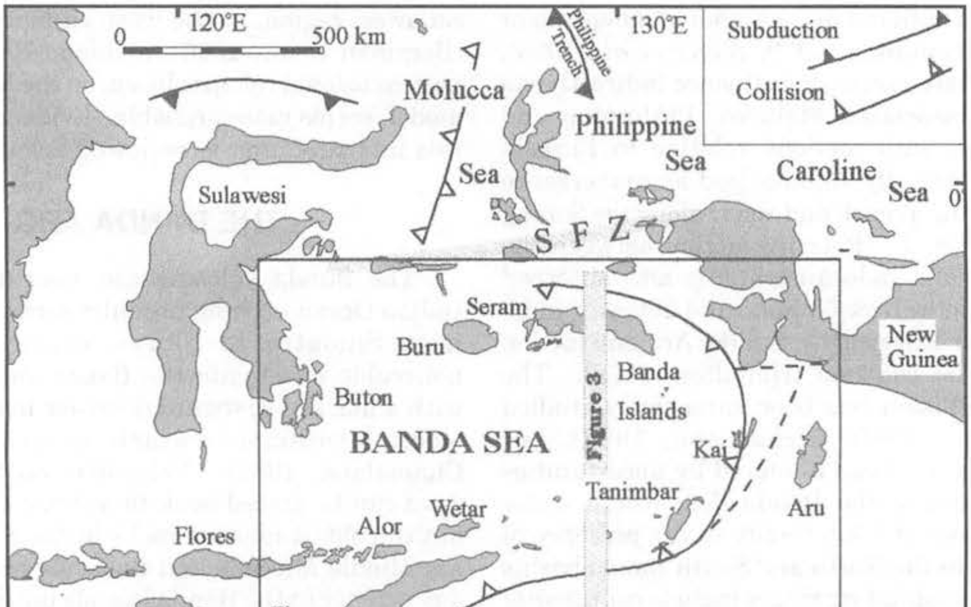

Figure 1. Eastern Indonesia. The dotted lines show the essentials of the two-plate solution to Banda Arc tectonics, which is rejected in this paper.

basaltic to dacitic volcanics in western Sulawesi ranging from 18 to 3 Ma but concentrated between 11 and 5 Ma, and attributed the later stages of activity to extensional collapse of a collision orogen. On Buton the post-orogenic period was marked by the deposition of deep-water chalks and marls above synorogenic molasse (Davidson, 1991). Because the Australasian rocks of Buton were clearly involved in the Sulawesi orogeny, the Middle Miocene collision must have been with one or more microcontinents which preceded Australia in its drift northward. Australasian crust would therefore be expected in any forearc which developed following this collision.

Paleomagnetic measurements, which could critically test the collision-collapse hypothesis, have been limited in number. The results obtained (Haile, 1981) suggest northward latitudinal drifts of the Outer Banda Arc islands of 10° to 25° since the Late Triassic, with a small CCW rotation of Timor and a much larger (and largely post Late Miocene) CCW rotation of Seram. This is certainly compatible with the Middle Miocene thrusting on Timor having taken place near Sulawesi when it was still separated from Australia proper by oceanic crust, and with the involvement of both Timor and Seram in the extensional collapse of a Middle Miocene Sulawesi orogen.

GRAVITY FIELD

In pioneering marine gravity surveys, Vening Meinesz (1932) defined belts of negative free-air and isostatic anomaly extending from the Sumatra forearc in the west and around the loop of the Banda Arc to Buru. There is only one minor discontinuity, west of Timor. The subsequent delineation of similar belts associated with virtually all subduction zones diverted attention from some peculiarities of Banda Arc gravity which have been increasingly emphasised by more detailed surveys. Differences between the Sunda and Banda gravity fields are most obvious onshore. On the forearc islands west of Sumatra, Bouguer gravity increases steadily towards the trench (Milsom *et al.*, 1991) but on the islands of the Outer Banda Arc the gradient is generally much steeper and in the opposite sense. On both Timor (Milsom and Richardson, 1976) and Seram (Milsom, 1977), the most rapid changes, culminating in values in excess of +100 mGal, are concentrated within 30 km of the coasts facing the volcanic arc.

In offshore work it is usual to omit the rather artificial Bouguer correction, which replaces sea water with a layer of rock which never has and never could exist, and map free-air gravity, adjusted only for instrumental effects and for latitude. However, the Bouguer correction can be justified as a filter which suppresses the effects of the strong density contrast at the seafloor and emphasises deeper sources. Its application in the Banda Arc demonstrates that the source of the steep onshore gradients is not confined to the islands but is continuous and persistent around the arc (Fig. 2). The Bouguer low, which lies slightly inboard of the isostatic and free-air lows, can be explained by the presence of a low-density forearc wedge, but accounting in a geologically plausible manner for the high values between the volcanic and outer arcs is more difficult. Published interpretations of profiles across various parts of the arc (Chamalaun *et al.*, 1976; Schlüter and Fritsch, 1985; Milsom and Audley-Charles, 1986; Richardson, 1993), while differing in detail, all involve abrupt (steep, vertical or even overturned) transitions from thick crust beneath the outer arc to thin oceanic crust beneath the inter-arc gap. This oceanic strip evidently terminates abruptly west of Timor.

Although gravity data from the Banda region are not compatible with the presence of continental crust between the outer and volcanic arcs, thrust sheets on both Timor and Seram which are directed away from the inter-arc gap include metamorphic rocks apparently derived from all levels of continental crust (Barber, 1978). Similar rocks have been reported from smaller islands which also lie within the region of steep Bouguer gradients (Hamilton, 1979). The nearest geologically plausible source area is southern Sulawesi, on the far side of the volcanic arc, where there are also flysch sediments which have been recognised as "remarkably similar" (Carter *et al.*, 1976) to Palelo Series sediments on Timor.

SEISMICITY

Deep earthquakes in the Banda region (Fig. 3) define a continuous, scoop-shaped Wadati-Benioff zone (WBZ) which extends to a depth of about 500 km and which dips north beneath Timor, south beneath Seram and west beneath the Kai islands (Richardson, 1993). The continuity of this surface would necessarily be illusory if subduction had taken place beneath a static and rigid upper plate, since at least two independent subducted slabs would be required to produce convergence over the full 180° of arc curvature. Two-slab solutions have, in fact, been widely invoked, one common version (Fig. 1) involving strike-slip displacement of the collision trace into the Seram Trough from the northern end of the Aru Trough (Hamilton, 1979). However, seismic reflection surveys have shown the Aru Trough to be extensional and have imaged the collision trace describing an almost uninterrupted

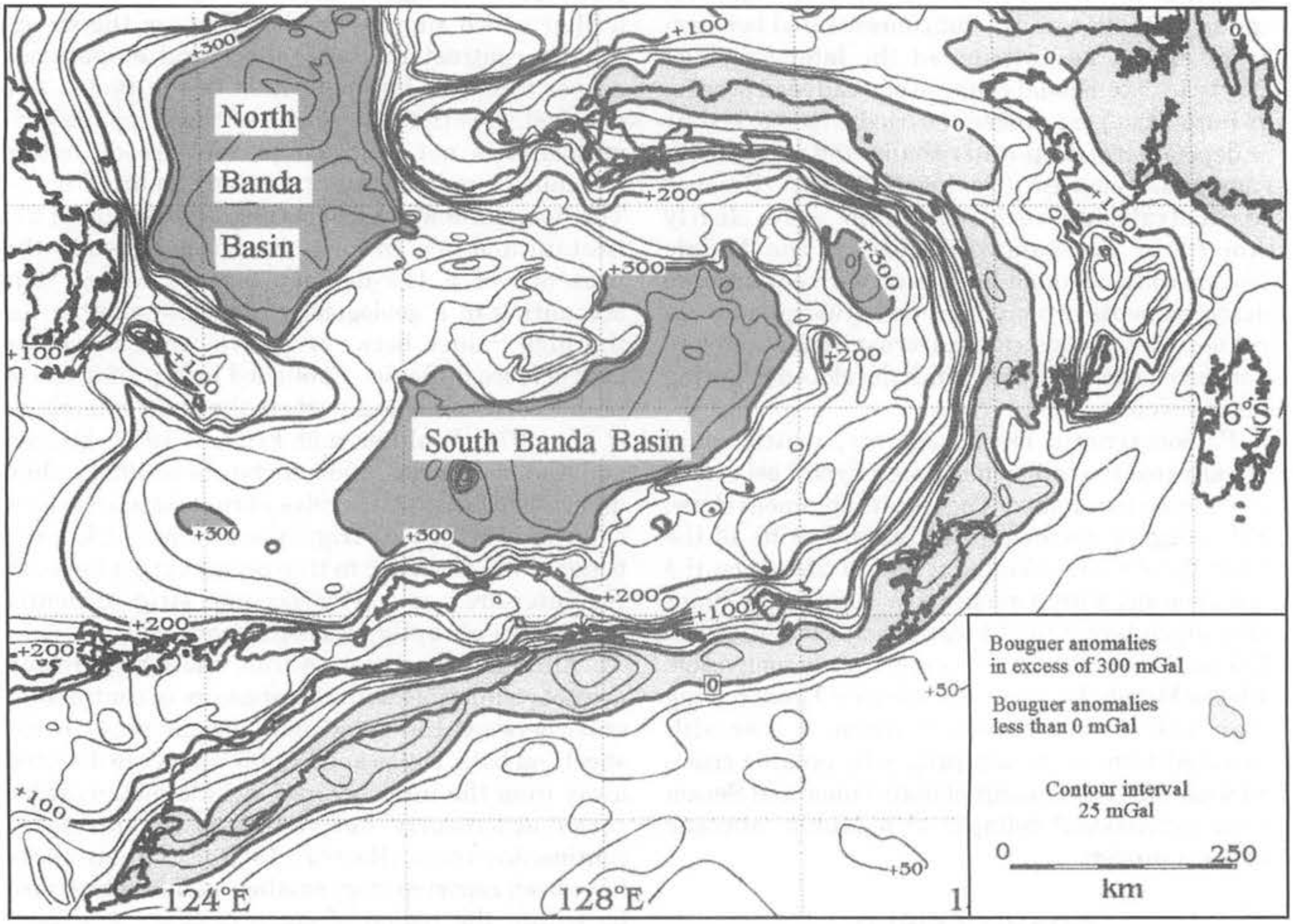

Figure 2. Bouguer anomalies in the Banda Sea, modified after Bowin *et al.* (1980).

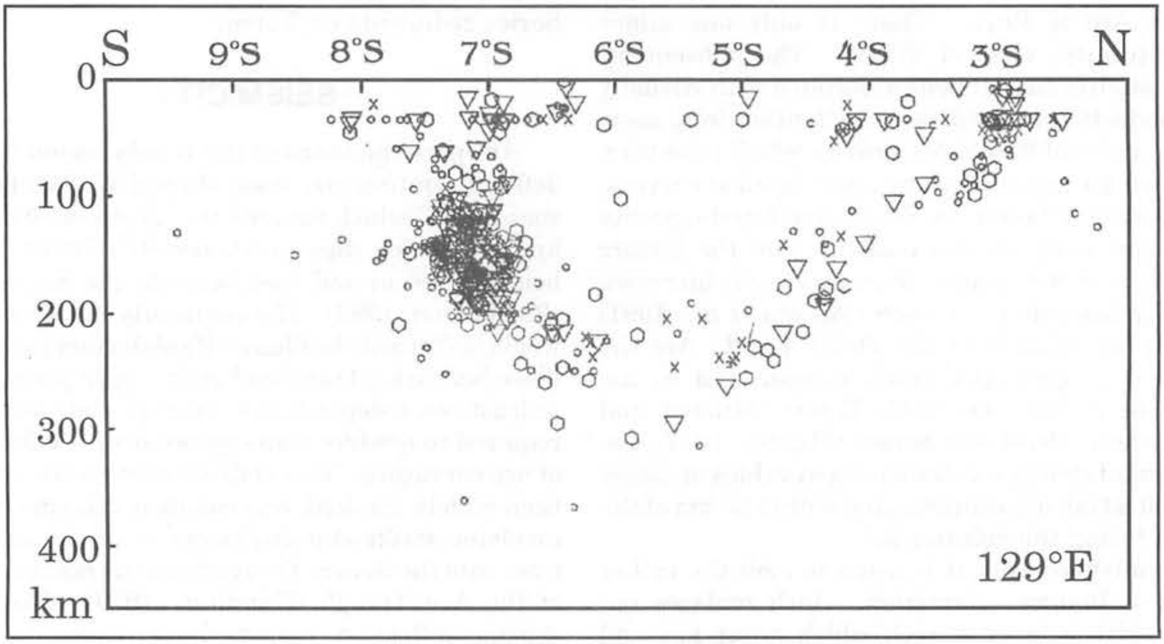

Figure 3. Earthquake hypocentres in a N-S 55 km swathe across the Banda Sea at 129°E.

curve through the Kai islands (Milsom *et al.*, 1996). The earthquake pattern is thus more readily explained in terms of a subducted slab which has rolled back, forcing expansion of the upper plate. The patterns of bathymetry and Bouguer gravity in the Banda Sea region (Fig. 2) suggest that this expansion was partly accommodated by major fractures which trend approximately NE between Seram and Kai and approximately SW on either side of Tanimbar.

Shallow earthquakes in the region are not confined to the WBZ but are widely distributed, although more numerous in the east (McCaffrey and Abers, 1991). Fault plane solutions indicate predominantly strike-slip displacements with a variety of orientations (McCaffrey and Abers, 1991). Only in the northeast are thrusts common and, although one large extensional earthquake has been recorded near the western margin of the Weber Basin, normal fault solutions are generally rare.

MEDITERRANEAN ANALOGIES

A Late Neogene origin for the Banda Sea appears anomalous in requiring rapid local extension during a period dominated by collisions. However, it is now widely accepted that continental collision in the Mediterranean produced deep basins, floored by attenuated continental crust in the Alboran and Aegean seas and by oceanic crust in parts of the Tyrrhenian Sea (Dewey, 1988). These basins resemble the Banda Arc not merely in size (Fig. 4) but also in being partly enclosed by orogens with total curvatures approaching 180°. Thrusts are directed radially outwards and are thus in places at high angles to slip vectors between the adjacent major plates. Thrusting and extension seem to have been generally contemporaneous and to have occurred following collision with continental fragments originally dispersed within the Tethys ocean (Dewey, 1988; Platt and England, 1993; Lonergan and White, 1997). These observations have led to hypotheses involving post-collisional collapse driven by the excess gravitational potential energy of the elevated orogen. Since the surface elevations that can be produced by collision alone seem insufficient, thickening of the lithospheric mantle as well as the crust is often invoked. Such thickening would produce a cold, dense root, the removal of which, by delamination or convective erosion, would dramatically increase uplift and gravitational potential energy, and hence promote extension (Platt and England, 1993).

Gravitationally-driven extension could continue only until the potential energies of the interior and exterior zones were equalised. Following collision, however, a subduction trace would be expected to re-form outboard of the collision region, providing a region with very low potential energy into which expansion could continue. Lonergan and White (1997) have suggested that the Alboran Sea was formed by very rapid westward roll-back of a subduction zone and have illustrated their hypothesis with a sketch very reminiscent of the Banda Sea. Ultimately, if space allowed, small oceans would be formed, floored by basalts with back-arc basin geochemistry but differing from non-collisional back-arc basins in the inclusion of fragments of continental material.

Of all the Mediterranean examples, the Tyrrhenian Sea, which includes areas of oceanic crust and high-standing blocks of continental crust, most closely resembles the Banda Sea. Analogue modelling, with sand representing the brittle upper crust, silicone putty the ductile lower crust and lithospheric mantle and glucose syrup the asthenosphere, has been used to assess the relative importance to the observed E-W extension and N-

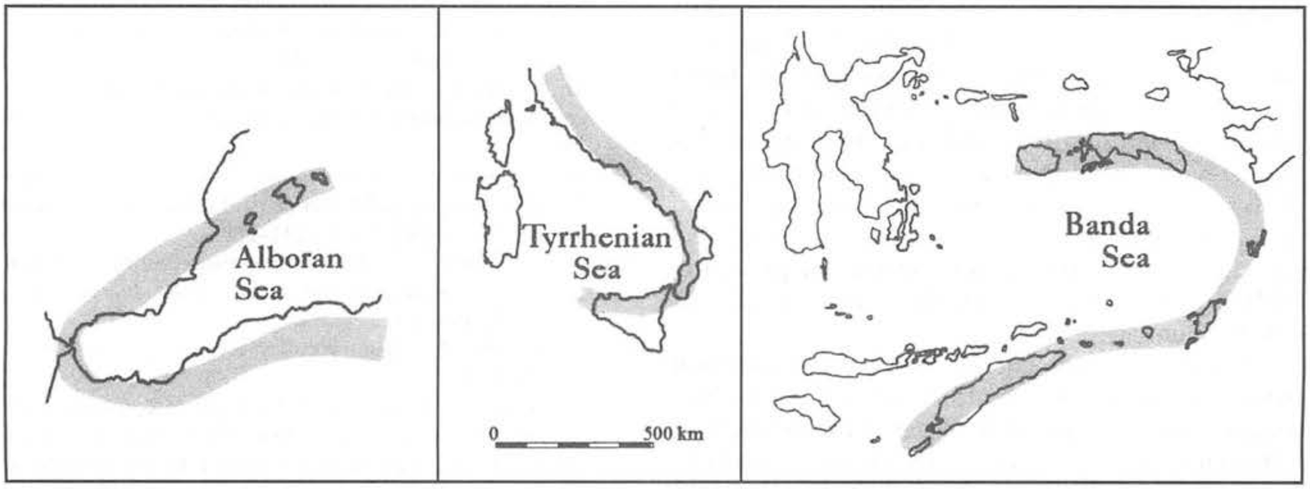

Figure 4. Tethyan oroclines compared.

S compression of (a) the advance of Africa, (b) orogenic collapse and (c) subduction roll-back of the Ionian Sea (Faccena *et al.*, 1996). Only when all three factors were allowed to operate was there a satisfactory result. The advance of Africa was required to initiate subduction, the initial stages of expansion were driven by the excess potential energy of the thickened crust, and subduction roll-back became dominant once the length of the subducted slab reached the equivalent of about 150 km. Because the 'African piston' and 'European backstop' prevented N-S expansion, an arcuate thrust orogen developed enclosing a region in which extensional basins alternated with blocks of thicker crust. Strike-slip faulting played a crucial role, an observation very relevant to the mechanisms and distribution of shallow earthquakes in the Banda Sea.

CONCLUSIONS

The Banda Sea, in eastern Indonesia, strikingly resembles some of the Mediterranean sub-basins. In all cases, strongly arcuate orogenic belts characterized by outward directed thrusts enclose extensional regions some 10^5 km^2 in area which have expanded rapidly within contexts of overall compression. The similarities imply essential similarities in the underlying processes. A necessary condition has been the presence within the subducting Tethys ocean of small continental fragments which created, on arrival at the active margin, local orogenies ahead of the main collision. Collapse of these orogens may have been triggered by detachment of underlying roots of deep lithospheric mantle, producing further uplift and excess potential energy, but post-collision subduction must have been equally important. New subduction traces developing outboard of the local orogens provided regions of very low potential energy into which expansion could continue until halted by the destruction of all available subductable oceanic crust. The final thicknesses of the basin crusts have therefore been determined by the initial boundary conditions and not the processes themselves. Examples such as the Banda Sea, from outside the Mediterranean region, testify to the general nature of these processes and also contribute to a better understanding by providing additional examples, at different stages of development.

The new oceanic basins produced by roll-back in the Banda Sea have depths typical of much older oceanic crust. One possible reason is the differential extension of crust and lithospheric mantle. Extensional forces in thickened continental lithosphere will be concentrated in the uplifted crustal layers, which may therefore suffer the most extension. Since, however, lithospheric mantle is denser than the asthenosphere, it will tend to subside unless thinned to the same extent as the crust. Subsidence of the Banda Sea oceanic basins to anomalously great depths can thus be understood.

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