INDONESIA, GEOLOGY

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Indonesia is a geologically complex region situated at the southeastern edge of the Eurasian continent. It is bordered by tectonically active zones characterized by intense seismicity and volcanism resulting from subduction. Western Indonesia is largely underlain by continental crust, but in eastern Indonesia there is more arc and ophiolitic crust, and several young ocean basins. The Indonesian archipelago formed over the past 300 million years by reassembly of fragments rifted from the Gondwana supercontinent that arrived at the Eurasian subduction margin. The present-day geology of Indonesia is broadly the result of Cenozoic subduction and collision at this margin.

PRESENT-DAY TECTONIC SETTING

Indonesia is an immense archipelago of more than 18,000 islands extending over 5000 km from east to west between 95° and 141° E, and crossing the equator from 6° N to 11° S (Figs. 1 and 2). It is situated at the boundaries of three major plates: Eurasia, India-Australia, and Pacific-Philippine Sea (Fig. 1). In western Indonesia, the boundary between the Eurasian and Indian plates is the Sunda Trench. Parallel to this in Sumatra is the right-lateral strike-slip Sumatran Fault, which results from the partitioning of oblique plate convergence into normal convergence at the trench and trench-parallel movement further north. Most active deformation in Sumatra occurs between the trench and the Sumatran fault. In contrast, east of Java, active deformation occurs within a complex suture zone up to 2000 km wide, including several small plates and multiple subduction zones; plate boundaries (Fig. 1) are trenches and another major strike-slip zone, the left-lateral Sorong Fault, which runs from New Guinea into Sulawesi. Global Positioning System (GPS) measurements indicate very high rates of relative motions, typically more than several centimeters per year, between tectonic blocks in Indonesia.

Volcanism and Seismicity

The subduction zones are mainly well defined by seismicity extending to depths of about 600 km (Fig. 3) and by volcanoes (Fig. 1). There are at least 95 volcanoes in Indonesia that have erupted since 1500, and most are situated between 100 and 120 km above descending lithospheric slabs. Thirty-two have records of very large eruptions with a volcanic explosivity index (VEI) of greater than 4; 19 have erupted in the last 200 years, including Tambora in 1815 (VEI = 7) and Krakatau in 1883 (VEI = 6). Tambora, on the island of Sumbawa, is known for its impact

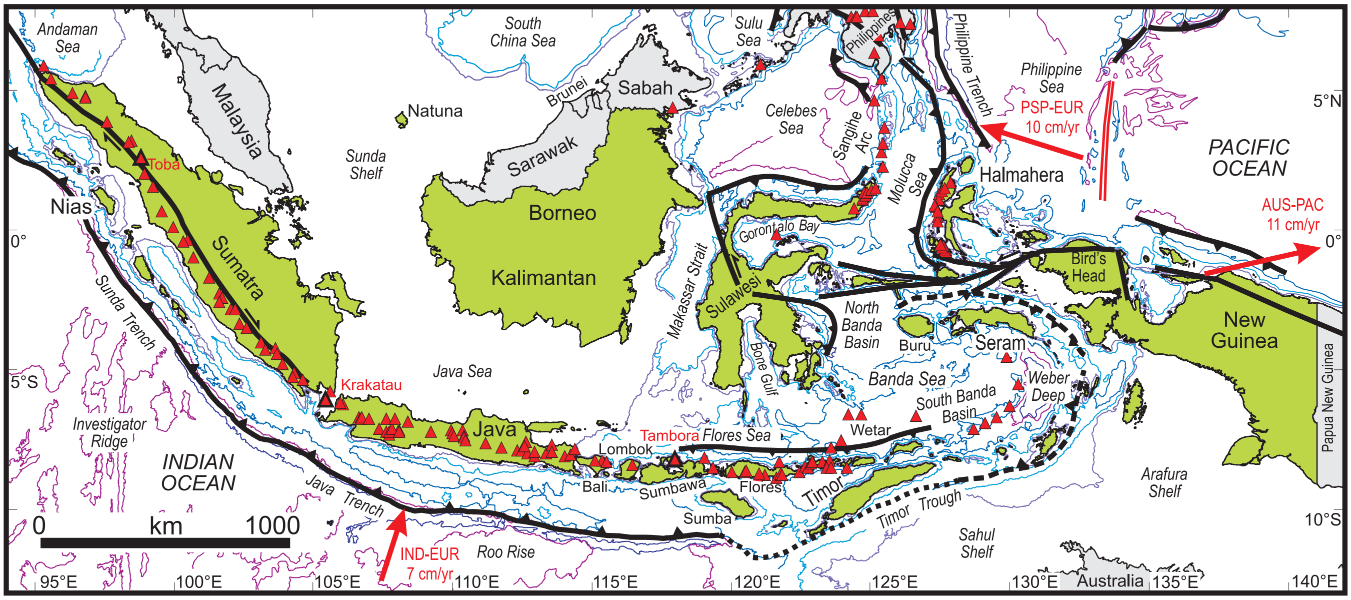

FIGURE 1 Geography of Indonesia and surrounding regions showing present-day tectonic boundaries and volcanic activity. Indonesia is shaded green, and neighboring countries are shaded in pale grey. Bathymetric contours are at 200 m, 1000 m, 3000 m, 5000 m, and 6000 m. The location of the three most famous explosive eruptions known from Indonesia are shown in red text. Red arrows show plate convergence vectors for the Indian plate (IND-EUR) and the Philippine Sea plate (PSP-EUR) relative to Eurasia, and for the Australian plate relative to the Pacific plate (AUS-PAC). There is little thrusting at the Timor trough. The Seram trough and Flores-Wetar thrusts are the sites of active thrusting.

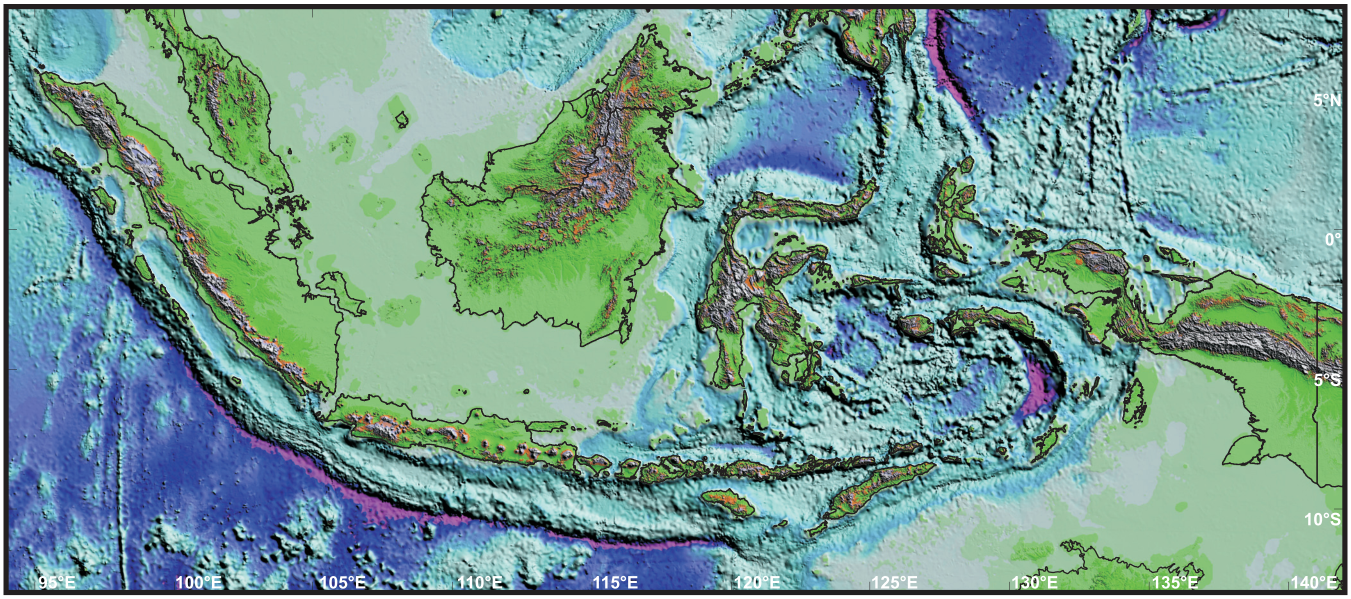

FIGURE 2 Digital elevation model showing topography and bathymetry of the Indonesian region. Compare to Fig. 1 for tectonic and geographic features.

on global climate, and its 1815 eruption resulted in the Northern Hemisphere's 1816 "year without a summer," when crops failed, causing famine and population movements. The eruption of Toba on Sumatra 74,000 years ago was even bigger (estimated VEI of 8) and is the largest eruption known on Earth in the last 2 million years.

Sundaland

The interior of Indonesia (Fig. 2), particularly the Java Sea, Sunda Shelf, and surrounding emergent, but topographically low, areas of Sumatra and Kalimantan (Indonesian Borneo), is largely free of seismicity and volcanism (Figs. 1 and 3). This tectonically quiet region forms part of the continental core of the region known as Sundaland (Fig. 4).

Sundaland extends north to the Thai-Malay Peninsula and Indochina, and formed an exposed landmass during the Pleistocene. Most of the Sunda Shelf is shallow, with water depths considerably less than 200 m (Fig. 2), and its lack of relief has led to the misconception that it is a

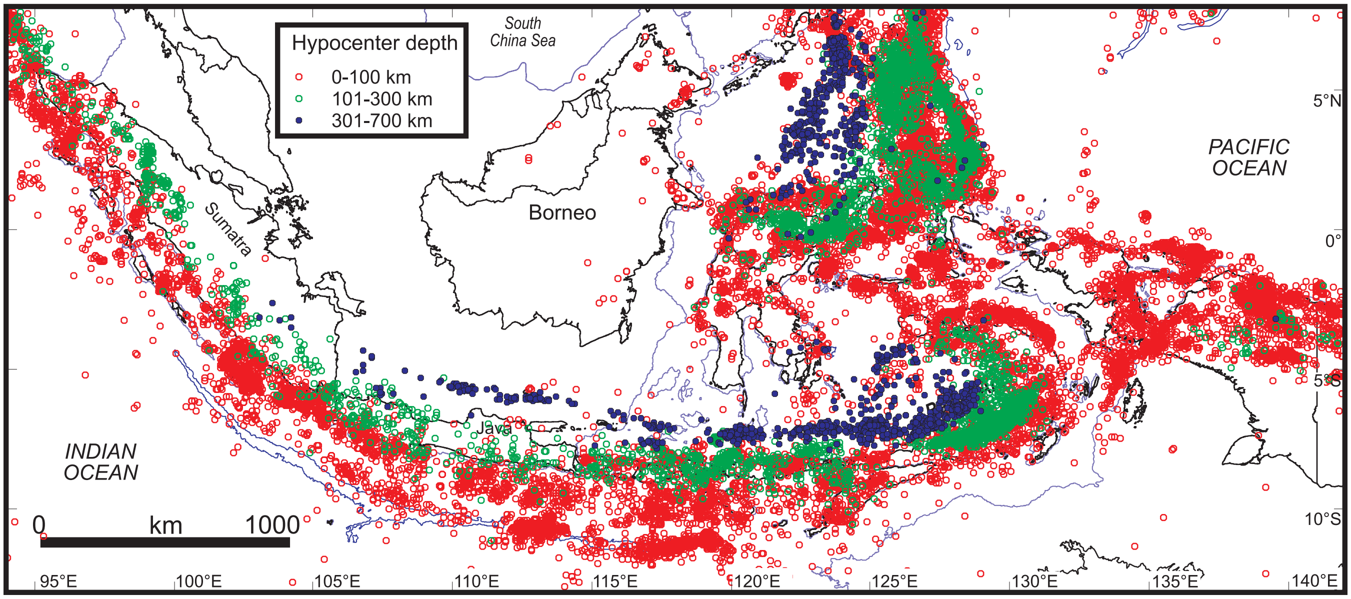

FIGURE 3 Seismicity in the Indonesian region between 1964 and 2000. Bathymetric contours are shown at 200 m and 6000 m.

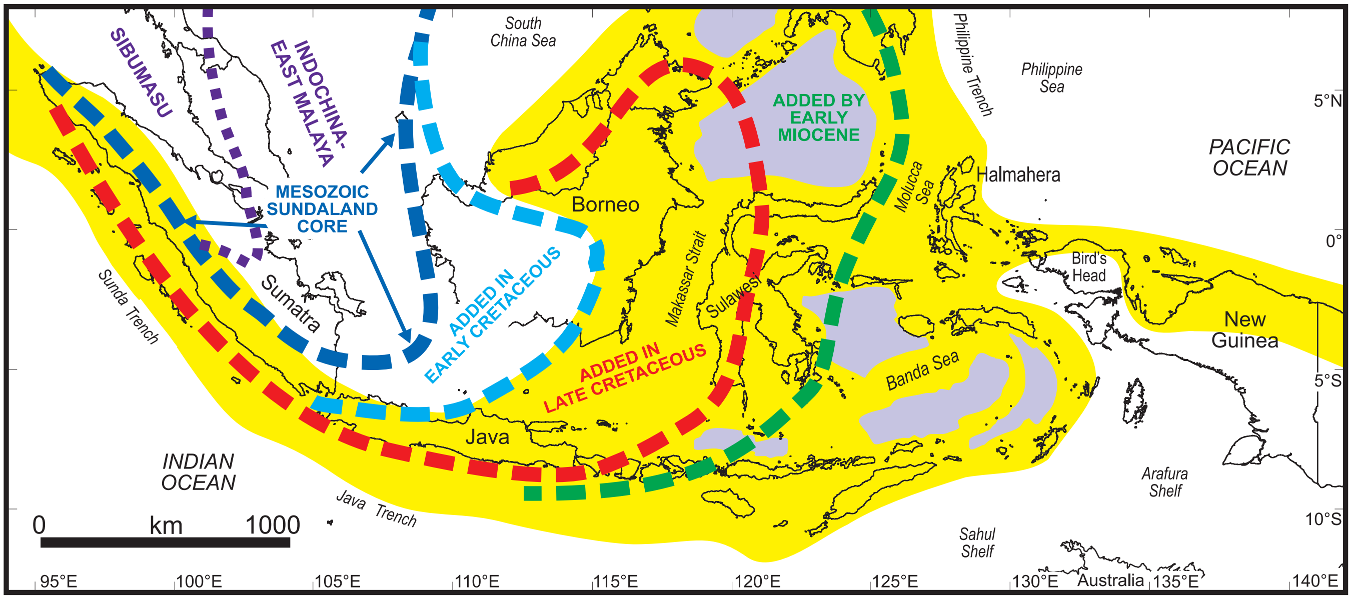

FIGURE 4 Growth of the Indonesian region. Collision between the Sibumasu and East Malaya-Indochina blocks occurred in the Triassic. Additional crust has been added to this Sundaland core, largely by later collisions of continental blocks. The present-day zone of active deformation is shaded yellow. Grey areas within this complex plate-boundary zone are areas underlain by Cenozoic ocean crust.

stable area. Sundaland is often described as a shield or craton, but geological observations, heat flow, and seismic tomography show that this is not the case. There has been significant deformation during the Cenozoic with the formation of deep sedimentary basins and the localized but widespread elevation of mountains. Unlike well-known shields or cratons (e.g., Baltic or Canadian), Sundaland is not underlain by a thick, cold lithosphere formed in the Precambrian. Its interior has high surface heat flow values, typically greater than 80 mW/m^2. At the Indonesian margins, high heat flows reflect subduction-related magmatism, but the hot interior of Sundaland appears to be the consequence of high upper-crustal heat flow from radiogenic granites and their erosional products, the insulation effects of sediments, and a high mantle heat flow. P- and S-wave seismic tomography show that Sundaland is an area of low velocities in the lithosphere and underlying asthenosphere, in contrast to the colder and thicker Indian and Australian continental lithosphere to the northwest and southeast. Such low mantle velocities are commonly interpreted in terms of elevated temperature, and this is consistent with regional high heat flow, but they may also partly reflect a different composition or elevated volatile contents.

Consequences of Long Subduction History

The upper mantle velocities and heat flow observations suggest the region is underlain by a thin and weak lithosphere. In contrast, in the lower mantle beneath Indonesia, there is a high velocity anomaly, suggesting the accumulation of subducted lithosphere.

These features are the consequence of long-term subduction at the Indonesian margins. The active margins are the site of magmatism, heating, and weakening, but the region of weak lithosphere extends many hundreds of kilometers from the volcanic margins. The character of the lithosphere has been a major influence on the development of Indonesia, combined with repeated collisions at the subduction margins that have led to continental growth.

PRE-CENOZOIC HISTORY OF INDONESIA

Western Indonesia, notably the islands of Sumatra and Borneo, contains most of the oldest rocks in Indonesia.

Sumatra: Basement

Sumatra represents the geological continuation of the Malay Peninsula and contains the most extensive outcrops of Paleozoic and Mesozoic rocks. The oldest rocks at the surface are Carboniferous sediments, but possible Devonian rocks have been reported from petroleum boreholes in the Malacca Straits, and granites from boreholes in central Sumatra have been dated as Silurian. Xenoliths in dykes, granite clasts in sediments, and various high-grade metamorphic rocks from different parts of Sumatra suggest a pre-Carboniferous crystalline basement similar to that beneath the Malay Peninsula, which is Proterozoic at depth.

Sumatra: Cathaysian and Gondwana Blocks

In western Sumatra there are Paleozoic sediments that range in age from Carboniferous to Triassic, and Permian volcanic rocks with Cathaysian affinities. These are interpreted to form part of an Indochina–East Malaya block (Fig. 4) that separated from Gondwana in the Devonian and by the Carboniferous was in warm tropical low latitudes where a distinctive flora developed.

In contrast, in eastern Sumatra, Carboniferous sediments include pebbly mudstones interpreted as diamictites that formed in a glacio-marine setting. These indicate cool Gondwana affinities. The Carboniferous rocks and associated Permian and Triassic sediments belong to the Sinoburmalaya or Sibumasu block (Fig. 5), which was at high southern latitudes during the Carboniferous, separated from Gondwana in the Permian, and collided with the Indochina–East Malaya block, already amalgamated with the South and North China blocks, in the Triassic.

Sumatra: Triassic Collision

The collision of the Sibumasu and Indochina–East Malaya blocks was the first stage in the geological development of Indonesia. The widespread Permian and Triassic granites of the Thai-Malay tin belt extend into western Indonesia and are the products of subduction and post-collisional magmatism associated with this event.

Sumatra: Mesozoic

The Mesozoic sedimentary record is very limited but suggests that much of Sundaland, including most of its Indonesian margin, was emergent. During the Mesozoic, there is interpreted to have been reorganization of Sumatran crustal blocks, possibly by strike-slip faulting at an active margin. Isotopic dating in Sumatra indicates that there were several episodes of granite magmatism, interpreted to have occurred at an Andean-type margin, during the Jurassic and Cretaceous. Marine sedimentary rocks were deposited in an intra-oceanic arc that collided with the Sumatran margin in the Middle Cretaceous. The collision added arc and ophiolitic rocks to the southern margin of Sumatra.

Borneo: Mesozoic Collisions

Southwestern Borneo (Fig. 4) may be the eastern part of Triassic Sundaland, or it could be a continental block added in the Early Cretaceous, at a suture that runs south from the Natuna Islands. The Paleozoic is represented mainly by Carboniferous to Permian metamorphic rocks, although Devonian limestones have been found as river boulders in eastern Kalimantan. Cretaceous granitoid plutons, associated with volcanic rocks, intrude the metamorphic rocks in the Schwaner Mountains of southwestern Borneo. To the north, the northwestern Kalimantan domain, or Kuching zone, includes fossiliferous Carboniferous limestones, Permo-Triassic granites, Triassic marine shales, ammonite-bearing Jurassic sediments, and Cretaceous melanges. In Sarawak, Triassic floras suggest Cathaysian affinities and correlations with Indochina. The Kuching zone may mark a subduction margin continuing south from East Asia, at which ophiolitic, island arc, and microcontinental crustal fragments collided and were deformed during the Mesozoic.

Sumatra, Java, Kalimantan, Sulawesi: Cretaceous Active Margin

A Cretaceous active margin is interpreted to have run the length of Sumatra into western Java and then continued northeast through southeastern Borneo and into western Sulawesi, as suggested by the distribution of Cretaceous high pressure–low temperature subduction-related metamorphic rocks in central Java, the Meratus Mountains of southeastern Kalimantan and western Sulawesi. Western Sulawesi and eastern Java (Fig. 4) are underlain in part by Archean continental crust, and geochemistry and zircon dating indicates derivation of this crust from the west Australian margin. Subduction ceased in the Late Cretaceous following collision of this block with Sundaland.

Sundaland: Cretaceous Granites

Cretaceous granites are widespread in the Schwaner Mountains, in western Sarawak, on the Sunda Shelf, and on the Thai-Malay Peninsula. They have been interpreted as the product of Andean-type magmatism at active margins but are spread over a large area and are far from any likely subduction zones. They probably represent post-collisional magmatism following Cretaceous addition of continental fragments in Borneo, eastern Java, and western Sulawesi.

CENOZOIC HISTORY OF INDONESIA

Cenozoic rocks cover most of Indonesia. They were deposited in sedimentary basins in and around Sundaland. There are products of volcanic activity at subduction margins, and there are ophiolites, arc rocks, and Australian continental crust added during collision.

Little is known of the Late Cretaceous and Paleocene because of the paucity of rocks of this age. From Sumatra to Sulawesi, the southern part of Sundaland was probably mostly emergent during the Late Cretaceous and Early Cenozoic, and there was widespread erosion; the oldest Cenozoic rocks typically rest unconformably on Cretaceous or older rocks. There is little evidence of subduction, although there was minor volcanic activity in southern Sumatra and Sulawesi. At the beginning of the Cenozoic, there were probably passive margins around most of Indonesia.

Eocene Subduction Initiation

India moved north during the Cretaceous to collide with Asia in the Early Cenozoic but passed to the west of Sumatra. Australia began to move rapidly northward from about 45 million years ago, in the Eocene. At this time, northward subduction resumed beneath Indonesia, producing widespread volcanic rocks at the active margin. The Sunda arc stretched from Sumatra, through Java and the north arm of Sulawesi, and then continued into the western Pacific. From the Eocene to the Early Miocene, the Halmahera arc was active in the western Pacific, far north of Australia, above a north-dipping subduction zone.

Also in the Eocene, southward subduction of the proto–South China Sea began on the northern side of Sundaland. Sediment carried north from southwestern Borneo was deposited in deep marine fans at this active margin. Early Cenozoic volcanic activity in Kalimantan is not well dated or characterized but appears to be related to this subduction.

Eocene Rifting

In the interior of Sundaland, widespread rifting began at a similar time as subduction and led to the formation of numerous sedimentary basins. These basins, some more than 10-km deep, are filled with Cenozoic sediments and are rich in hydrocarbons. The largest of these are in Sumatra, offshore Java, and eastern Kalimantan. In southeastern Sundaland, Eocene rifting led to the separation of Borneo and western Sulawesi, forming the Makassar Straits (Fig. 2), and by the Oligocene, much of eastern Kalimantan and the straits was an extensive area of deep water. In western Sulawesi, shallow water deposition continued, and there are extensive platform limestones in the south arm. The southern part of the straits is relatively shallow (about 1 km) and underlain by continental crust. The northern straits are connected to the oceanic Celebes Sea, but it is not known whether they are underlain by oceanic or stretched continental crust because there is up to 14 km of sediment below the 2.5-km-deep sea floor. The Makassar Straits are today a major passageway for water and heat from the Pacific to the Indian Ocean and have been an important influence on biogeography. The Wallace Line, marking an important boundary between Asian and Australasian faunas, follows the Makassar Straits south to pass between the islands of Bali and Lombok.

Miocene: Continental Collisions

At the beginning of the Miocene, ophiolites were emplaced by collision between the Australian and the Sundaland continents in Sulawesi, and between the Australian continent and the Halmahera arc much further to the east in the Pacific. The ophiolites of Sulawesi are remnants of fore-arc and oceanic crust between Sundaland and the Australian plate, whereas those of the North Moluccas are fragments of Philippine Sea plate arcs. Later in the Early Miocene, there was collision in north Borneo with the extended passive continental margin of South China. These collisions led to mountain building in eastern Sulawesi and in Borneo. The first Australian continental crust was added in eastern Indonesia (Fig. 5), but as northward movement of Australia continued, there was a change in eastern Indonesia to extension, complicated by minor collisions as microcontinental blocks moved along strike-slip faults. In the Sunda arc, volcanic activity declined in Java for a few million years before a late Miocene increase from Sumatra to the Banda arc.

Neogene: Java-Sumatra

In the Java–Sulawesi sector of the Sunda arc, volcanism greatly diminished during the Early and Middle Miocene, although northward subduction continued. The decline in magmatism resulted from Australian collision in eastern Indonesia, causing rotation of Borneo and Java. Northward movement of the subduction zone prevented replenishment of the upper mantle source until rotation ceased in the late Middle Miocene. Then, about 10 million years ago, volcanic activity resumed in abundance along the Sunda arc from Java eastward. Since the Late Miocene, there has been thrusting and contractional deformation in Sumatra and Java related to arrival of buoyant features at the trench, or increased coupling between the overriding and downgoing plates. Both islands have been elevated above sea level in the last few million years.

Neogene: Borneo

The rise of mountains on Borneo increased the output of sediment to circum-Borneo sedimentary basins. In eastern Kalimantan, thick Miocene to recent sediments filled accommodation space created during Eocene rifting. Most was derived from erosion of the Borneo highlands and inversion of older parts of the basin margins to the north and west, which began in the Early Miocene.

Sedimentation continues today in the Mahakam delta and in the offshore deepwater Makassar Straits.

In parts of central Kalimantan, there was some Miocene magmatism and associated gold mineralization, but volcanic activity largely ceased in Kalimantan after collision. Minor Plio-Pleistocene basaltic magmatism in Borneo may reflect a deep cause such as lithospheric delamination after Miocene collisional thickening.

Neogene: Sulawesi

Sulawesi is inadequately understood and has a complex history still to be unraveled. In eastern Sulawesi, collision initially resulted in thrusting of ophiolitic and Australian continental rocks. However, contractional deformation was followed in the Middle Miocene by new extension. There was Miocene core complex metamorphism in north Sulawesi, extensional magmatism in south Sulawesi, and formation of the deep Gorontalo Bay and Bone Gulf basins between the arms of Sulawesi.

Compressional deformation began in the Pliocene, partly as result of the collision of the Banggai-Sula microcontinent in east Sulawesi, which caused contraction and uplift. Geological mapping, paleomagnetic investigations, and GPS observations indicate complex Neogene deformation in Sulawesi, including extension, block rotations, and strike-slip faulting. There are rapidly exhumed upper mantle and lower crustal rocks, and young granites, near to the prominent Palu-Koro strike-slip fault (Fig. 1). During the Pliocene, coarse clastic sedimentation predominated across most of Sulawesi as mountains rose. The western Sulawesi fold-thrust belt has now propagated west into the Makassar Straits. At present, there is southward subduction of the Celebes Sea beneath the north arm of Sulawesi and subduction on the east side of the north arm of the Molucca Sea toward the west (Fig. 1).

Neogene: Banda

The Banda arc is the horseshoe-shaped arc that extends from Flores to Buru, including Timor and Seram, with islands forming an outer non-volcanic arc and an inner volcanic arc. It is an unusual region of young extension that developed within the Australian-Sundaland collision zone and formed by subduction of an oceanic embayment within the northward-moving Australian plate.

In the Middle Miocene, Jurassic ocean lithosphere of the Banda embayment began to subduct at the Java Trench. The subduction hinge rolled back rapidly to the south and east, inducing massive extension in the upper plate. Extension began in Sulawesi in the Middle Miocene. As the hinge rolled back into the Banda embayment, it led to formation of the Neogene Banda volcanic arc and the opening of the North Banda Sea, the Flores Sea, and later the South Banda Sea. About 3–4 million years ago, the volcanic arc collided with the Australian margin in Timor, causing thrusting. Remnants of the Asian margin and Paleogene Sunda arc are found in the uppermost nappes of Timor and other Banda islands.

After collision, convergence and volcanic activity ceased in the Timor sector, although volcanic activity continued to the west and east. New plate boundaries developed north of the arc between Flores and Wetar (Fig. 1), and to the north of the South Banda Sea, associated with subduction polarity reversal. The Banda region is now contracting. During the last 3 million years, there have been significant shortening and probable intra-continental subduction at the southern margins of the Bird's Head microcontinent south of the Seram trough (Fig. 1).

Neogene: North Moluccas

In eastern Indonesia, the Halmahera and Sangihe arcs (Fig. 1) are the only arcs on Earth currently colliding. Both of the currently active volcanic arcs formed during the Neogene. The Sangihe arc is constructed on Eocene oceanic crust and initially formed at the Sundaland margin in the Early Cenozoic. The modern Halmahera arc is built upon older arcs, of which the oldest is a Mesozoic intra-oceanic arc that formed in the Pacific. Early Miocene arc–Australian continent collision terminated northward subduction, and the north Australian plate boundary became a major left-lateral strike-slip zone in New Guinea. Volcanism ceased, and there was widespread deposition of shallow marine limestones. Arc terranes were moved westward within the Sorong fault zone. At the western end of the fault system, there was subduction beneath the Sangihe arc and collision in Sulawesi of continental fragments sliced from New Guinea.

Initiation of east-directed Halmahera subduction probably resulted from locking of strands of the left-lateral Sorong fault zone at its western end in Sulawesi. The present-day Molucca Sea double subduction system was initiated in the Middle Miocene, and volcanism began in the Halmahera arc about 11 million years ago. The Molucca Sea has since been eliminated by subduction at both its eastern and western sides. The two arcs first came into contact about 3 million years ago, and this contact was followed by repeated thrusting of the Halmahera fore-arc and back-arc toward the active volcanic arc. Collision has formed a central Molucca Sea (Fig. 1) melange wedge, including ophiolite slices from the basement of the Sangihe arc. There are small fragments of continental crust between splays of the Sorong fault.

Neogene: New Guinea

In New Guinea, there was rifting from the Late Triassic onward to form a Mesozoic northern passive margin of the Australian continent, on which there was widespread carbonate deposition during the Cenozoic. To the north of the passive margin were a number of small oceanic basins and arcs developed above subduction zones; the region was probably as complex as the western Pacific today. At the beginning of the Miocene, the arc–Australian continent collision began emplacement of arc and ophiolite terranes, which then moved west in a complex strike-slip zone. The Halmahera arc was one of these. Today, northern New Guinea is underlain by these arc and ophiolitic rocks, fragmented by faulting. In the Pliocene, subduction probably began at the New Guinea Trench (Fig. 1), as there is now a poorly defined slab dipping south that has reached depths of about 150 km. There was isolated, but important, magmatism associated with world-class copper and gold mineralization including the Grasberg and Ertsberg complexes. The rise of the New Guinea main ranges accelerated, and mountains reached their present elevations with peaks more than 5-km high (Fig. 2) capped by glaciers.

SEE ALSO THE FOLLOWING ARTICLES

Earthquakes / Eruptions, Laki and Tambora / Indonesia, Biology / Island Arcs / New Guinea, Geology / Philippines, Geology

FURTHER READING

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INSECT RADIATIONS

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Insect radiations on islands are the evolutionary product of diversification within an insect lineage on an island or a series of islands forming an archipelago. Radiations, by definition, represent in situ diversification and are often characterized by evolutionarily novel adaptations. Island radiations are one of the most important natural phenomena for evolutionary biologists, and, like other animal and plant groups, insects on islands have undergone radiations that range from a modest diversification of species to explosive radiations over a short period of time. Insect radiations vary not only in the numbers of species but in the rates of speciation and in the diversity of adaptive traits that evolve.

COLONIZATION, ESTABLISHMENT, AND DIVERSIFICATION

Island radiations are by definition the product of in situ diversification and the evolution of multiple species from a founding ancestor, producing a lineage of closely related island endemics. All islands represent habitable patches surrounded by uninhabitable environments. These can be terrestrial habitat "islands" such as shifting sand dunes in Namibia, where a lineage of *Scarabaeus* dung beetles has radiated into 12 endemic species, or "sky islands" in the Rocky Mountains, where *Melanoplus* grasshoppers have radiated into 37 species after isolation in multiple glacial refugia. More commonly, islands represent terrestrial habitats surrounded by water.

Insect radiations on islands necessarily begin with a stepwise process involving dispersal from a source population, establishment of a viable population upon colonization, and diversification into multiple species within an island or between islands in an archipelago. In many cases, the distances between source populations on continental land masses and remote oceanic islands (islands that are formed *de novo* and are not terrestrial fragments separated from a once-larger land mass) are great enough that active dispersal by insects (e.g., by flying) is ruled out and passive dispersal methods (e.g., by wind currents, attachment to migrating birds, or rafting with tidal debris) are considered more plausible means for insects to have traveled the distance. Four endemic flightless insect genera, including large flightless beetles, cave crickets,