Geo-Tectonics, Geology, and Geo-Resources of the Southwest Pacific

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Geo-Tectonic Overview of the SW Pacific Region

The Pacific Islands region (Fig. 1) is predominantly located within the SW Pacific, and covers an area of c. 30 million km^2, or the equivalent of the area of the African continent. This region contains an incredible amount of geodiversity. The region is one of the best examples of a spectrum of oceanic tectonic phenomena in the world. This article provides details of the tectonic setting, geology, geological resources, and geoscientific highlights of six Pacific Island countries: Solomon Islands, Vanuatu, Fiji, Tonga, Samoa, and Cook Islands.

The SW Pacific ocean floor (Fig. 1) displays classic examples of ocean trenches, island arcs, ocean plateaux, ocean basins, seamounts, seamount chains, evidence of ocean plumes, and rifted submerged, aseismic continental material. The area is formed of the enormous Pacific and Australian plates, and a number of smaller, young ocean basins that constitute "micro-plates." The geometry of these oceanic-tectonic features presents a complex, yet understandable, ocean-tectonic architecture.

Perhaps the most obvious features are arc-linear archipelago chains of islands that characterize island arcs such as the Solomon Islands, Vanuatu and Tonga (Fig. 1). These islands are located on the subduction zone upper plate, adjacent to equally long curvilinear ocean trenches, up to c. 10 km beneath sea level. The trenches mark the sites of interaction between the Australian and Pacific plates and produce earthquakes to depths of c. 700 km, and magnitudes of up to >8 on the Richter scale. Island arcs form the largest Pacific islands which contain the larger human populations. Some trenches, such as the Vitiaz Trench, mark the sites of old trenches, although these are rarely fully extinct. Fiji occupies an unusual tectonic position as it is an arc without a trench: more recent tectonic movements have shifted the islands away from the subduction zones that once gave birth to them. Some of the island arcs

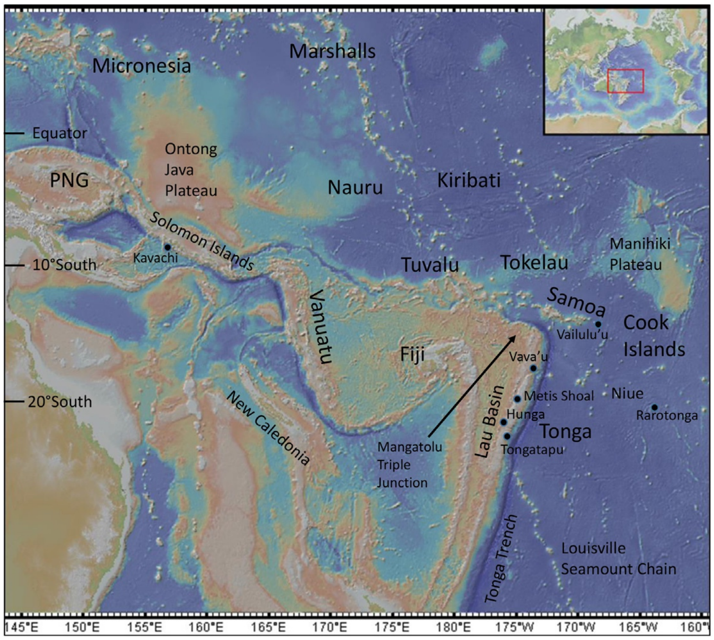

Fig. 1 Geo-tectonic map of the SW Pacific ocean floor, showing the positions of the six Pacific Island countries discussed in this article (Solomon Islands, Vanuatu, Fiji, Tonga, Cook Islands, Samoa). Two large continental sized ocean plateaux are the Ontong Java and Manihiki Plateaus. Trench systems marking the subduction of one plate beneath another include the South Solomon, Vitiaz, Vanuatu, and Tonga trenches. Solomon Islands, Vanuatu and Tonga are active island arcs with related volcanism and seismicity, and are located adjacent to trenches. Fiji has been tectonically removed from the subduction zones/trenches that originally produced the Fijian arc system. Cook Islands and Samoa are produced from deep mantle plumes: plumes also produce linear seamount chains such as the Louisville Seamount Chain.

are *not only* island arcs but also collages of geological terranes, with different origins and histories. Solomon Islands is part island arc, and part ocean plateau. Vanuatu marks the site of a subducting older continental ridge. Arcs and plumes interact with arc systems in a range of forms.

The SW Pacific region contains two of the world's largest ocean plateaux: the Ontong Java and Manihiki Plateaux (Fig. 1). These are analogous to submarine, basaltic oceanic continents, that rise over 2 km above the ocean floor and occasionally break surface to form atoll islands. They are thick and expansive crustal structures that likely formed as mushroom-shaped plume-heads broke the surface, after rising from the core-mantle interface, through the full thickness of the mantle, producing a thick sequence of high-volume, and rapidly produced, basalt lavas, and associated gabbros, sills, and dykes.

Underneath plume-heads are plume-tails which produce a series of volcanoes, such as the Louisville and Samoan Seamount Chains, over tens of millions of years, as the plates move across stationary mantle hot spots. These volcanoes form linear seamount chains, rising from the deep ocean floor, some of which form volcanic islands such as Samoa and the southern Cook Islands (Fig. 1). Some seamount chains produce lines of largely low-lying atoll-islands, such as Kiribati and Marshall islands.

Much of the SW Pacific region comprises the deep ocean abyssal plains, some 4–6 km deep.

Volcanism is evident throughout the region, and exhibits a range of styles. Island arcs are predominantly the more viscous, and more explosive, arc basalt and andesite stratovolcanoes, whilst seamounts and plume-related ocean islands are formed by shield-shaped, less-viscous alkali basalt volcanoes. A few volcanoes are in a transitional setting whereby during eruption they form subaerial islands, which then subside and erode to submarine depths between eruptions.

The SW Pacific contains the greatest volume of seabed minerals within nation-state territorial waters (Fig. 2). There are three main types of seabed minerals: seabed sulfides form in arc settings within hydrothermal environments, Manganese polymetallic nodules form as small-potato-sized concentric structures, within the depths of the abyssal plains, and polymetallic cobalt-rich-crusts form a carpet veneer deposit, some 5–15 cm thick on the tops and sides of seamounts and ocean plateaux. These minerals constitute high-value deposits which may, 1 day, form the foundation of a new mining industry in the region. Many islands exhibit geothermal heat, which could be used to generate geothermal energy in countries such as Fiji, Tonga, Solomon Islands, Samoa, and Vanuatu.

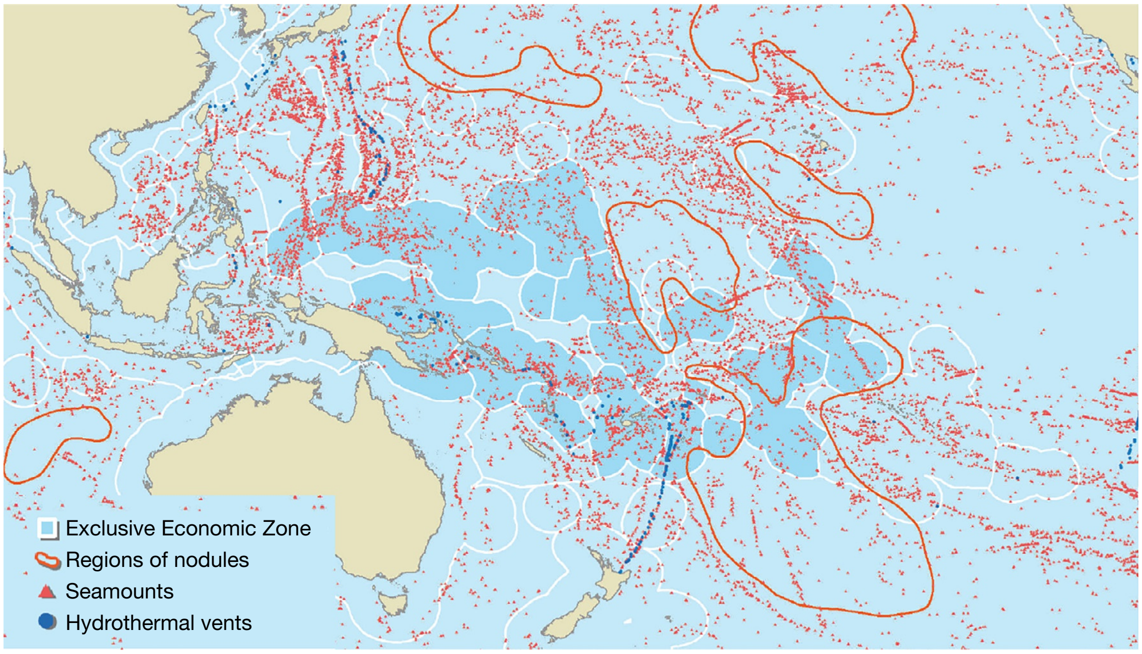

Fig. 2 The Pacific Ocean contains large expanses of seabed minerals. These are of three types: Polymetallic Seabed Sulfides are associated with island arc related submarine hydrothermal systems (shown as blue circles) and are rich in copper, silver, gold, and other metals; Seamount chains (red triangles) mark the position of extinct ocean volcanoes, many of which have a surface mineralized veneer, 5–15 cm thick, termed cobalt-rich crusts, containing a wide range of metals; and, Polymetallic, or Manganese Nodules fields are outlined by red continuous lines. Manganese Nodules are small-potato shaped, cauliform-like textured nodules, rich in a wide range of metals. From Volume 1A: SPC (2013) Deep sea minerals: Summary highlights. In: Baker E and Beaudoin Y (Eds). *Secretariat of the Pacific Community: Suva, Fiji*, second figure, p. 11, reproduced with permission of the Pacific Community, Suva, Fiji.

Solomon Islands

Geo-Summary and Highlights

Solomon Islands cover a land area of c. 28,000 km^2, an ocean area of 1.6 million km^2, with a total population of c. 680,000. The capital township of Solomon Islands is Honiara, situated in northern Guadalcanal, with a population of c. 90,000. Solomon Islands forms an archipelago between longitudes 156° and 170°E and latitudes 5°–12°S, over a distance of c. 1700 km of ocean, from NW to ESE (Figs. 1, 3 and 4). Geographically, there are two components to the Solomon Islands: a double chain of islands in the northwest extending from Shortland Islands to Makira, with a gap in subaerial islands eastwards from Makira to the Santa Cruz group of islands at c. 170°E (Figs. 3 and 4). Most of the Solomon Islands are located within the double chain of islands, with the Santa Cruz Islands representing a northern continuation of the Vanuatu island arc. The Solomon Islands comprises a collage of geological terranes of differing age and origin (Fig. 4). The geological timespan represented within the Solomon terranes is from Cretaceous to the present day (c. 125 Ma to the present day). The islands contain elements of primitive ocean crust, island arcs of differing ages, coral atoll islands, and obducted ocean plateaux. The region is an active tectonic region exhibiting subduction, obduction, basin subsidence, seismicity, and volcanism. There is a strong structural grain parallel to the main double chain (NW-SE), and, at a high oblique angle to this trend. This structural grain strongly controls a range of geological phenomena, including rhombohedral shaped submarine basins between the double island chain (Auzende et al., 1994). Geo-resources include precious and industrial metals (copper, gold, aluminium, nickel), geothermal energy, and a potential for hydrocarbons and micro-diamonds.

Geo-Tectonic Setting

The Solomon Islands are situated within the complex tectonic architecture of the SW Pacific (Petterson et al., 1999). By far the two largest plates are the Pacific and Australian plates (Fig. 3). The southern islands mark the subaerial boundary between the Pacific and Australian plates. Immediately south of the islands of New Georgia, Guadalcanal, Makira, and Santa Cruz, is a submarine trench that marks the subduction of the Australian plate, north-eastwards, beneath the Pacific plate. The deepest parts of the trench are the New Britain trench to the NW, and the San Cristobal trench to the SE. The Woodlark basin contains an active spreading center, which began extending from c. 5 Ma (Fig. 3): the Solomon Islands contain an example of a triple tectonic marginal contact, close to Simbo Island (Fig. 4), where three tectonic boundaries meet (called a Triple Junction). An older trench is situated north of the Solomon Island double chain, termed the Vitiaz trench (Petterson et al., 1999; Fig. 3). This marks the old site of subduction of the Pacific plate, southwest-wards, beneath the Australian plate. Southwards directed subduction mostly ceased from c. 12–6 Ma due to

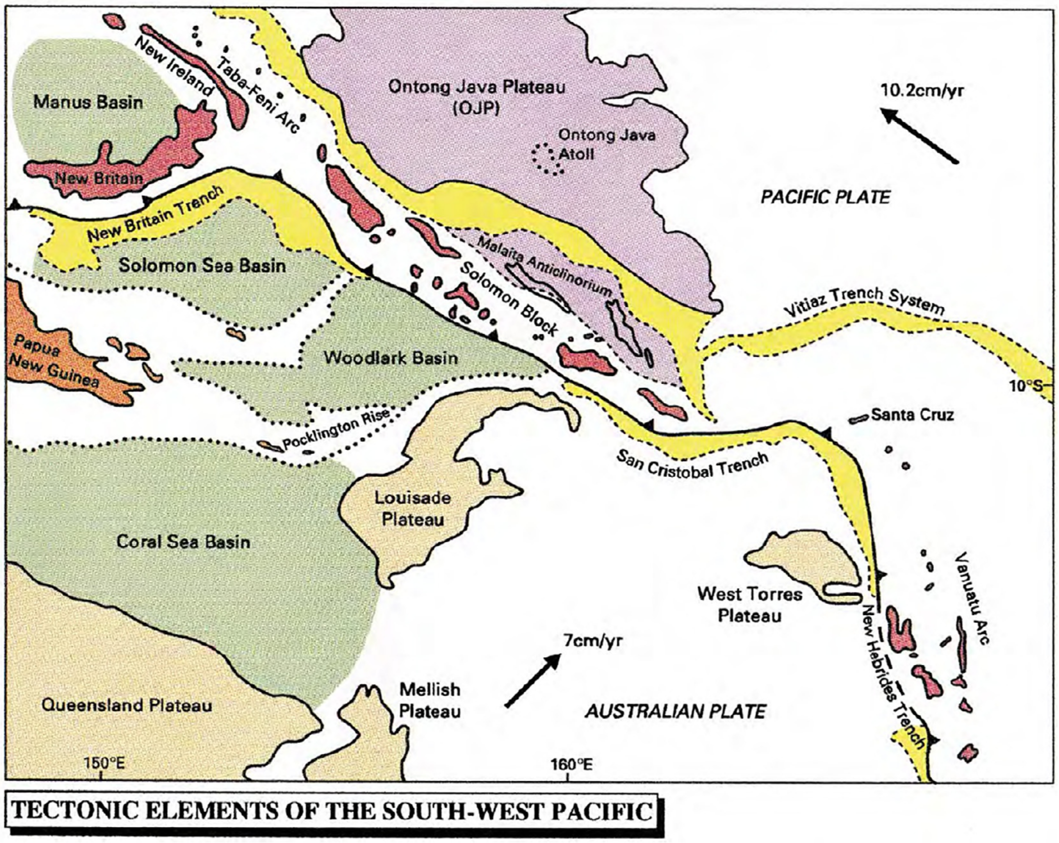

Fig. 3 Geo-tectonic elements of the SW Pacific region, outlining the positions and morphologies of the Ontong Java Plateau, the Vitiaz-New Britain-San Cristobal-New Hebrides trenches (also termed, in part, the South Solomon and Vanuatu trench systems—in yellow), actively spreading young ocean basins such as the Solomon Sea, Woodlark, Manus, and Coral Sea basins (in green), arc systems such as New Britain, the Solomon Block, and Vanuatu (in orange), and aseismic (continental arc material) submerged ridges such as the Louisade Plateau, West Torres Plateau, and Queensland Plateau (in tan). Arrows indicate key plate movements. Form Petterson MG, Babbs T, Neal CR, Mahonney JJ, Saunders AD, Duncan RA, Tolia D, Magu R, Qopoto C, Mahoa H and Natogga D (1999) Geological-tectonic framework of Solomon Islands, SW Pacific: Crustal accretion and growth within an intra-oceanic setting. *Tectonophysics* 301: 35–60, figure 1, reproduced with permission of Elsevier.

the collision between the c. 30–40 km thick Ontong Java Plateau, and the older Solomon arc terrane (Petterson et al., 1999). The largest ocean plateau in the world, the Ontong Java Plateau (OJP), is close to the size of Alaska in area and formed from the voluminous eruptions of thick, extensive basalt lavas, at 125–120 Ma and 90 Ma (Neal et al., 1997; Fig. 3). The OJP formed as a deep mantle plume surfaced, mainly under the ocean. The OJP can be compared to an ocean floor continent, with significantly greater crustal thicknesses and higher topographic elevations as compared to normal ocean crust. Seismicity is common along the southern Solomon trenches, with very deep (c. 700 km) earthquakes extending downwards from the San Cristobal trench, but less frequently along the Vitiaz trench. Volcanism was highly active in Miocene-Pliocene times. Today there are four active subaerial volcanoes: Simbo, Kavachi (a shallow underwater volcano, except when actively erupting), Savo, and Tinakula (San Cristobal islands), and numerous active submarine volcanoes (Figs. 3 and 4).

Geology

The oldest Cretaceous basement of Solomon Islands comprise two types of basalt and gabbro. N-MORB basalts and gabbros, typical of normal ocean floor material are present as the basement of Choiseul and Guadalcanal (Fig. 4). Basalts and gabbros that originate as plume-related ocean plateau material are present on the islands of Malaita, Ulawa, Santa Isabel, and probably Makira. Deep water sedimentary rocks, including cherts, deep marine limestones and mudstones, and distal turbidites overlie the basalts. Younger ultramafic alnöite intrusions, dated at 34 Ma, cut the Malaitan basement (Petterson et al., 1997). The presence of an active subduction zone on the southern margins of Guadalcanal and Makira uplift the islands, with most uplift in the southern part of the islands, resulting in the deeper exposure of older basement rocks. Basement rocks are metamorphosed and deformed. Rocks in Malaita and Santa Isabel have been thrust to the SW, on top of the Solomon arc, and exhibit asymmetrical folds indicating SW-vergence. An Eocene-Miocene arc sequence (Fig. 4) erupted upon, and intruded the Cretaceous basement. These arc sequences are exposed on islands such as Guadalcanal, Choiseul, Shortland Islands, the Florida Islands and southern Santa Isabel, and

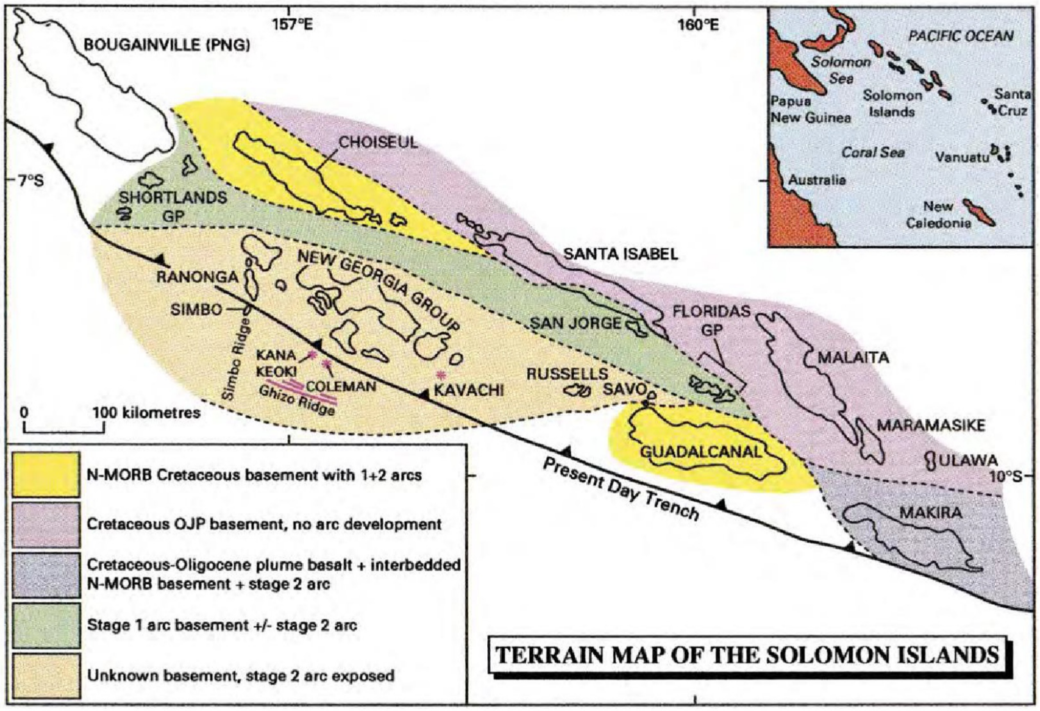

Fig. 4 Geo-tectonic subdivisions of the Solomon Islands. Purple regions represent obducted parts of the Ontong Java Plateau, including Makira. Other zones represent arc systems which have been produced from the Cretaceous period. Kavachi, Savo, Simbo, Kana Keoki, Coleman, and the Ghizo Ridge are sites of active arc volcanism. From Petterson MG, Babbs T, Neal CR, Mahonney JJ, Saunders AD, Duncan RA, Tolia D, Magu R, Qopoto C, Mahoa H and Natogga D (1999) Geological-tectonic framework of Solomon Islands, SW Pacific: Crustal accretion and growth within an intra-oceanic setting. *Tectonophysics* 301: 35–60, figure 2, reproduced with permission of Elsevier.

comprise basalts, andesites, rhyodacites, diorites, granites, and volcano-sedimentary/sedimentary rocks (Petterson et al., 1999). The older arc sequences are linked to the SW-directed subduction of the Pacific plate beneath the Australian plate. When subduction reversed an Upper Miocene-present day arc resulted, producing the islands of the New Georgia Group, Ranonga, Savo, Simbo, and volcanism in Guadalcanal (especially west Guadalcanal), Choiseul (Mount Maetambe area), Shortland Islands, and Makira (Fig. 4). Volcanic rocks span the full spectrum of compositions from basalt to rhyolite, and contain some rather unusual rock chemistries such as high-magnesian basalts in New Georgia, and high-sodium dacites in Savo (Smith et al., 2008). Intrusive and extrusive rocks are present. Alongside lavas, pyroclastic flow rocks, dominated by block and ash flows, are present in places such as west Guadalcanal and Savo. Active solfataric geothermal regions are well exposed in Vella Lavella (Paraso), West Guadalcanal, and Savo (Smith et al., 2008). The subsiding, submarine, rhombohedral basins, present in-between the double chain of islands, (sometimes termed "The Slot"), have accommodated high sedimentation rates, with up to 7 km of Eocene-Recent sedimentary material present in some basins, largely composed of eroded arc and ocean plateau material (Petterson et al., 1999). Examples of low-lying and upraised limestone atoll islands include Rennell, Bellona, and Ontong Java.

Geological Resources

There are a good number of mineral prospects that have been catalogued, particularly by the earlier systematic geological surveys of the 1930s–60s. Unfortunately, none of this resource information is easily accessible, and is largely in paper format in Honiara. Mineral exploration began in the early 20th century and was particularly active during the 1970s, and again during the late 1990s and early 2000s. Some mining and exploration interest remains today. The largest mine development has been Gold Ridge mine in Central Guadalcanal which mines an epithermal Cu-Au-Ag deposit, Petterson et al. (2004). The mine is closed at the time of writing. Gold Ridge is an example of mineralization formed during the Late Miocene-Recent arc activity (Petterson et al., 2004). Mineralization is of three main types: porphyry, epithermal, and placer. Guadalcanal hosts all three mineralization types. In addition to the Gold Ridge deposit, Koloula, in southern Guadalcanal, hosts the world's youngest porphyry copper deposit, dated at 1.7 Ma, and the flat Guadalcanal Plains host gold placer deposits within the Pliocene-Recent alluvial sediments (Petterson et al., 2004). Porphyry and epithermal deposits associated with Miocene-Recent gabbro-diorite-granitoid intrusions and andesite-rhyodacite volcanic rocks, have been investigated across the New Georgia islands, Savo, Shortland Islands and West Guadalcanal. Potential micro-diamonds and garnet-ilmenite resources are linked to ultramafic Eocene-Early Miocene alnöite intrusions on the island of Malaita. Residual nickel deposits are present in San Jorge, Santa Isabel. Bauxite deposits are exposed in Vaghena island, close to

Fig. 5 Photograph of the Paraso geothermal field, Vella Lavella, western Solomon Islands. This highly active and extensive geothermal field is an example of an area that can be utilized for the production of geothermal energy. Similar systems exist in Vanuatu, Fiji, Tonga, and Samoa. Photograph: M. G. Petterson.

Choiseul and Rennell Island (a raised coral atoll island situated c. 200 km south of Guadalcanal). Hydrocarbons may be present within the intra-arc basins, although no oil or gas plays are proven. Hydrocarbons linked to serpentinization of ultramafic rock have been discovered in SW Guadalcanal. There is potential for geothermal energy, particularly associated with the Savo and Paraso geothermal fields (Vella LaVella, western Solomons; Fig. 5, Smith et al., 2008). The Savo geothermal field was investigated during the 2010s with a view to geothermal power development. A submarine cable linking Savo to Honiara would be required to make any potential geothermal power scheme economic. Hydro-electric power potential (for Honiara) has been investigated since the 1970s with a focus on the Tina River, one of a number of rivers that are sourced in the south Guadalcanal highlands and have strong river flows northwards to the Guadalcanal plains.

Geoscientific Studies

The varied and complex tectonic setting of the Solomon Islands has generated geoscientific interest in a number of key scientific areas and has led to the deployment of a range of scientific methods (Auzende et al., 1994). Marine surveys utilizing a range of sonar, multibeam, sidescan, and seismic survey methodologies have been incorporated into research expeditions throughout Solomon waters, particularly associated with the young 5 Ma-Recent Woodlark Basin, the rhombohedral intra-arc basins between the island double chain, and parts of the Ontong Java Plateau. These surveys discovered ocean spreading activity and arc-like magmatism within the Woodlark basin, large thicknesses of sediment deposited within Solomon intra-arc basins, and the structure of the OJP (its thick basaltic character, and the deformation of its southern margins). Detailed mapping of obducted OJP rocks on Malaita, identified up to 6 km thick stratigraphic sections, allowing for the sampling of deep units within the OJP, as well as identifying structures that indicated the physical decollement and thrusting of parts of the OJP onto the Solomon arc (Petterson et al., 1999). Detailed trace element and isotopic geochemistry (Sr-Nd-Pb isotopes) led to the hypothesis that the OJP represents a massive melting event of the mantle with plume roots at the core-mantle boundary (Neal et al., 1997). Systematic studies of raised beaches and high-tide wave-cut rock-notches during the 1980s and 1990s, GPS land based instruments, and broadband seismometer readings in the later 1990s to the present day have demonstrated rapid, and differential, vertical and horizontal crustal motions in the western Solomon Islands, associated largely with the spreading of the Woodlark basin. Detailed, high-precision, U-Pb dating of zircon minerals, within central Guadalcanal plutons, and plutons related to the Koloula porphyry copper deposit, demonstrate the presence of ancient cratonic material (within central Guadalcanal) and repeated mineralizing-magmatic events that occurred within relatively rapid periods of time (with periods of tens of thousands of years between mineralizing events) (Tapster et al., 2014, 2016).

Vanuatu

Geo-Summary and Highlights

Vanuatu covers a total land area of c. 12,200km^2, an ocean area of 680,000 km^2, and a population of 276,000. The capital township is Port Vila, on the island of Efate, with a population of c. 44,000. The island archipelago is situated between longitudes 165° and 172°E and latitudes 13° and 20°S. There are around 15 larger islands, including Espiritu Santo, Malakula, Ambrym, Pentecost, Efate,

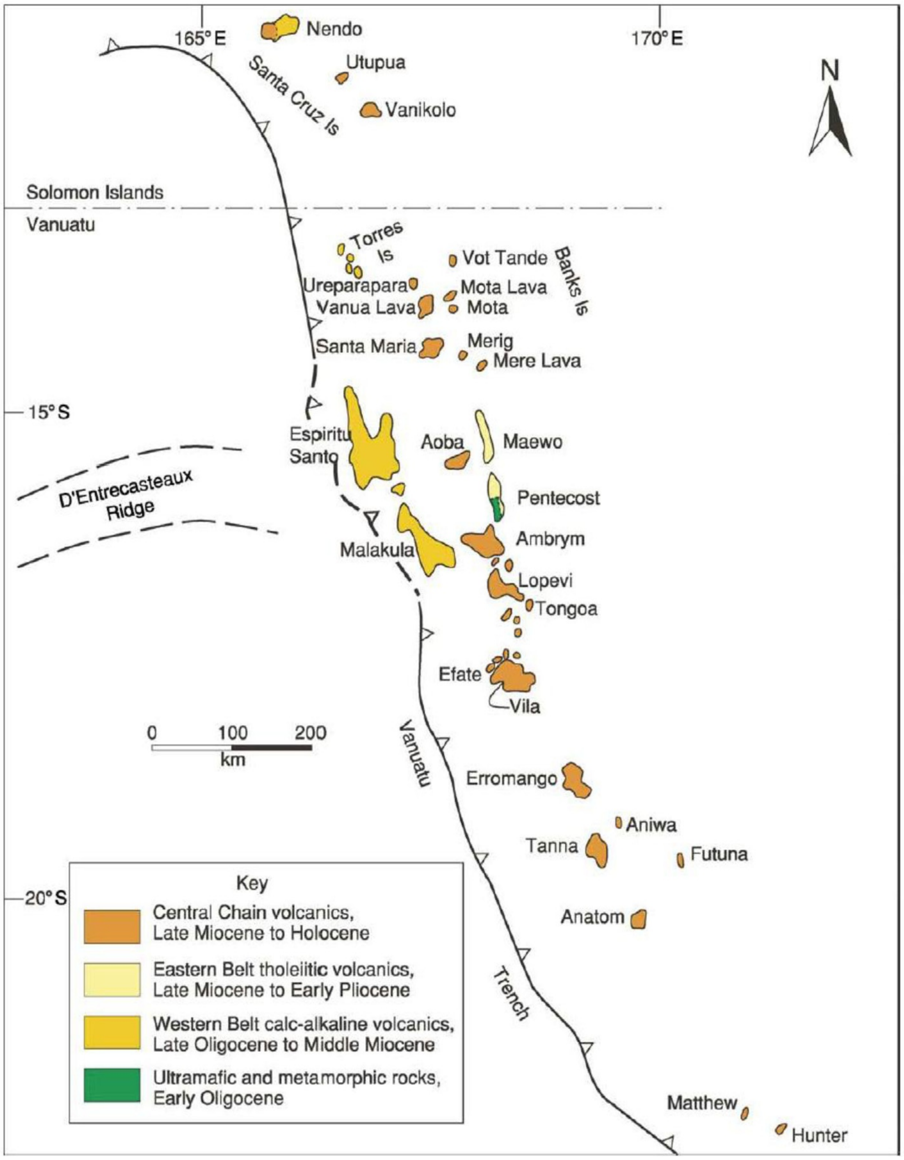

Fig. 6 Geological map of Vanuatu and eastern Solomon Islands (Nendo, Utupua, and Vanikolo). The Western Belt comprises older Oligocene-Miocene arc rocks. The oldest ultramafic rocks are exposed on Pentecost. The Central Chain of islands contains many active volcanoes such as Ambrym and Tanna (Yassur volcano). The Vanuatu trench marks the subduction of the Australian Plate (to the west) beneath the Pacific Plate. The D'Entrecasteaux Ridge is subducting beneath Vanuatu in the vicinity of Espiritu Santo and Malakula. From Davies H, Bani P, Black P, Smith I, Garaebiti E and Rodda P (2005) *Oceania chapter of Encyclopedia of Geology*. Elsevier, figure 5.

Erromango, and Tanna (Fig. 6). The northern Vanuatu islands form a double chain with Pentecost, Ambrym and Santa Maria toward the east, and Malakula and Espiritu Santo toward the west. The maximum width of the archipelago is c. 250 km. The islands extend mainly over c. 900 km, but extend to 1200 km including the small, southern, Matthew and Hunter islands (Figs. 1 and 6). The islands are volcanic in origin, forming a modern island arc as well as recording earlier arc volcanism. Predominantly andesitic composition islands vary in age from the Late Oligocene (c. 27 Ma) to the present day. Vanuatu is one of the more active south Pacific arcs in terms of present day volcanism. Vanuatu experiences frequent and widespread seismicity from shallow to very deep (c. 700 km), with magnitudes of the largest earthquakes exceeding 7.5. One shallow (c. 30 km) tsunamogenic earthquake, with an epicenter south of Ambrym, in 1999, resulted in tsunami waves almost 7 m high, the destruction of the village of Baie Martelli in southern Pentecost, and loss of life. The shallow nature of the earthquake was linked to the subduction of the D'Entrecasteaux ridge.

Geo-Tectonic Setting

Vanuatu is an island arc formed at the boundary between the Australian and Pacific plates. Like Solomon Islands, it has experienced a reversal in subduction polarity over geological time. The present day subduction zone accommodates the subduction of a sizeable positive topographic ridge, called the D'Entrecasteaux Ridge. The physical tectonic architecture of Vanuatu can be viewed as forming four geotectonic zones (Warden and Mitchell, 1971; Fig. 6): (1) the New Hebrides trench forms the western boundary to the islands, marking the site of present day subduction of the Australian plate beneath the Vanuatu arc; (2) the older-arc western islands of Espiritu Santo, and Malakula, formed at a time when the Pacific Plate subducted beneath the Vitiaz trench; (3) the eastern islands of Maewo and Pentecost, which record the earlier stages of subduction of the Australian plate beneath the Pacific plate; and (4) the central islands, including Tanna, Efate, Ambrym, and Vanua Lava, which were formed during the later to present-day stages of the modern arc. From the Late Oligocene to the Upper Miocene, the Pacific plate subducted beneath the Australian plate at the Vitiaz trench, creating the oldest Vanuatu arc. The Australian plate subsequently began subducting beneath the Pacific plate from Late Miocene times (c. 7 Ma), which mirrors the situation in the Solomon Islands. Vanuatu marks the site of the subduction of an aseismic oceanic ridge, called the D'Entrecasteaux ridge (composed of Eocene-Oligocene arc material). The subduction of aseismic ridges produces a number of impacts including the uplift of the arc at the point of ridge subduction, compressional tectonics that can lead to thrusting (e.g., east of Maewo and Pentecost), a slowing of subduction and/or change in subduction angle, and or polarity change in subduction (as the collision of the Ontong Java Plataeau with the Solomon arc produced), shallow seismicity, and a cooling of the mantle beneath the arc, leading to lower rates or cessation of volcanism, at least locally. The D'Entrecasteaux ridge first came in contact with the Vanuatu arc, south of Malakula, and has drifted northwards with time, presently situated west of Espiritu Santo (Hochstein et al., 1971).

Geology

The oldest rocks of Vanuatu (Early Oligocene) are exposed on southern Pentecost (Fig. 6). These are ultramafic serpentinites and peridotites, and gabbros, norites, schists and basalts. The older arc rocks exposed on the islands of Espiritu Santo and Malakula comprise Late Oligocene-Middle Miocene calc-alkaline volcanic rocks, including andesite and basaltic lavas, sills, dykes and tuffs, diorite plutons, and a range of volcaniclastic rock (Warden and Mitchell, 1971). The rocks are metamorphosed to low-grade zeolite facies. Rocks are block-faulted including normal and reverse faults, that were active mainly during Miocene-Pliocene times. Most faults trend W-NNW with throws of over 2 km measured locally. The Eastern belt islands of Maewo and Pentecost are dominated by Late Miocene-Early Pliocene early-modern-arc tholeiitic basalts and related rocks (Fig. 6). The central zone (Late Miocene to present day) comprises mature arc calc-alkaline basalts, andesites, pyroclastic, and reworked volcaniclastic rocks, together with more acidic rocks locally (e.g., on Efate), plus their plutonic equivalents (Warden and Mitchell, 1971). Young Pliocene-Pleistocene coralline and related sedimentary rocks locally overlie the arc igneous rocks, with much of the eastern part of Espiritu Santo, central-northern parts of Maewo, and most of Pentecost containing large expanses of coralline limestone rock. There are numerous active subaerial volcanoes in Vanuatu including Yassur (Tanna), Ambae, Ambrym, Epi, Hunter and Matthew Islands, and Lopevi (Fig. 7). These volcanoes have attracted modern studies related to their volcanic activity, the geohazards they pose, and their geochemistry and petrogenesis (Nemeth and Cronin, 2008).

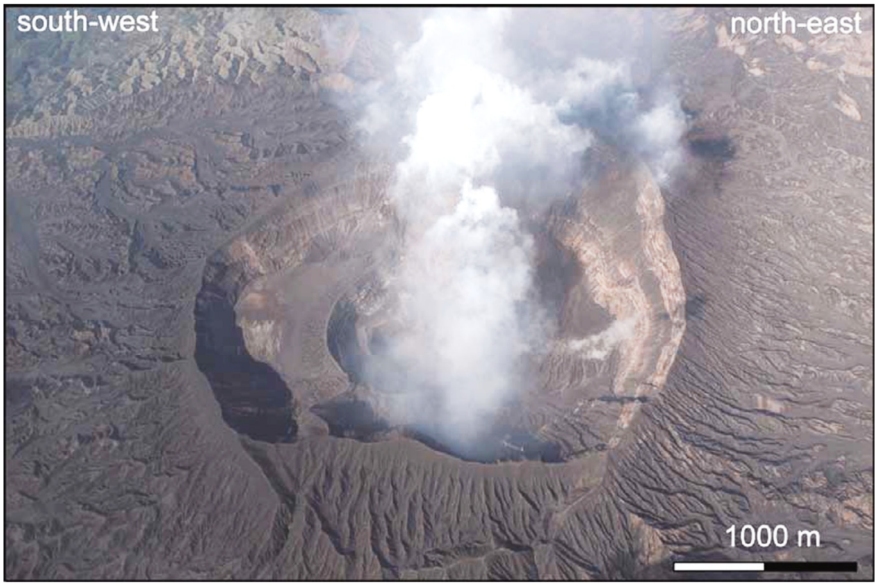

Fig. 7 Vanuatu is a highly active volcanic system. This volcano from Ambrym shows a complex series of concentric craters. A lava lake is present in the lowest crater below the erupting volcanic gases. From Nemeth K and Cronin SJ (2008) Volcanic craters, pit craters, and high-level magma-feeding systems of a mafic island-arc volcano: Ambrym, Vanuatu, South Pacific. In: Thomson K and Petford N (Eds) *Structure and Emplacement of High-Level Magmatic Systems*. London: Geological Society of London, Special Publications 302, pp. 87–102, figure 3.

Geological resources and geoscientific studies

At present there are no working metallic mines on Vanuatu although the potential exists for epithermal and porphyry copper-gold deposits. Seabed minerals are present within the submarine waters of Vanuatu's Exclusive Economic Zone, mostly in the form of hydrothermal polymetallic seafloor sulfides. There is abundant geothermal energy potential in Vanuatu. The Takara prospect on Efate has been seriously investigated for the development of geothermal energy. The government of Vanuatu have developed a renewable energy strategy with ambitious targets for the development of geothermal energy. Geochemical and petrogenetic studies of the Vanuatu arc examining trace elements, as isotope tracers show variations in composition with latitude (Peate et al., 1997). For example Sr^{87}/Sr^{86} initial ratios are lowest at the northern and southern ends of Vanuatu and highest in the arc regions that have experienced the subduction of the D'Entrecasteaux ridge. Sympathetic trends are seen with Pb and Nd isotopes, and with some trace elements. The mantle region beneath the island arc, which is the source of melting for the arc volcanic rocks, (termed *the mantle wedge*), is interpreted to be geochemically and isotopically heterogeneous (displays a wide variety of compositions) (Peate et al., 1997). The predominant Pacific mantle source is influenced by the introduction of fluids from subducted deep ocean sediment and the D'Entrecasteaux ridge. Vanuatu is subject to a wide range of geological and meteorological hazards, including earthquakes, landslides, volcanic eruptions, tsunamis, cyclones and storm surges. Port Vila is calculated to be the most dangerous capital township in the world for natural hazards. The impact of Cyclone Pam in 2015 cost the equivalent of two thirds of the economy. The prolonged eruption of Ambrym volcano in 2018–19 led to the relocation of several hundred islanders (Fig. 7). Yassur volcano on Tanna is continuously active. Research into geohazards and meteorological hazards using on the ground, and remote sensing mapping techniques, is leading to the development of better informed, and increasingly sophisticated, hazard maps and disaster and risk management policy.

Fiji Islands

Geo-Summary and Highlights

Fiji covers a land area of c. 18,000 km^2, and an ocean area of 1.26 million km^2, with a population of c. 900,000. The capital township is Suva, on the island of Viti Levu, with a population of c. 330,000 for Greater Suva (Figs. 1 and 8). Fiji comprises two larger islands (Viti Levu and Vanua Levu) the southern island group of Kadavu, the eastern Lau Island group, the small islands of the Yasawas, NW of Viti Levu, the island of Taveuni, SE of Vanua Levu, and the island of Rotuma, some 650 km north of Viti Levu. Most Fiji Islands are contained within a radius of 250 km from Ovalau, east of Viti Levu. The island archipelago nation extends from longitude 175°–186°E to latitudes 12°–24°S. Fiji Islands are largely composed of island arc rocks, predominantly of basaltic to andesitic calc-alkaline compositions, of Eocene to Quaternary age. Volcanoes on Kadavu and Taveuni are thought to be active. Fiji has a number of mines and mineral resources on-land, and potential for development of submarine seabed sulfide deposits, particularly within the Lau and North Fiji submarine basins.

Geo-Tectonic Setting

Fiji is located within a region of significant oceanic tectonic complexity (Fig. 8). Unlike island nations such as Vanuatu, which is mainly an island arc, or Samoa, which is the product of mantle plume activity, Fiji is more difficult to classify tectonically: in this respect it is similar to Solomon Islands which is a tectonic collage. Fiji is situated some 600 km east of the Vanuatu trench and 150–200 km east of the Tongan trench. The islands are the subaerial expressions of topographic ridges and platforms of arc or back-arc origin, rising from ocean depths of 4–5000 m to form islands. The central islands of Viti and Vanua Levu are part of the larger Fiji platform, with the Lau islands being attached to the north-south trending Lau arc (Colley and Hindle, 1984). Between the Tonga trench and the central Fiji platform lies the deeper Lau basin, an extensional marginal or back-arc basin relative to the Tonga arc (Tanahashi et al., 1991). The Fiji platform is bounded to the north by the Fiji Fracture Zone, and to the south by the Hunter-Kadavu-Fracture-Zone (Fig. 8). Another ENE-WNW trending lineament, called the Hazel-Holme-Fracture-Zone connects the northern Vanuatu arc, with Rotuma (Colley and Hindle, 1984). A series of oceanic ridges are present, called the Bounty Ridge, Peggy Ridge, and Nova Rise respectively. These ridges mark the central spreading centers (active or extinct) of marginal basins: the North Fiji Basin (or Fiji Plateau), the South Fiji Basin, and the northern Lau Basin (Fig. 8). The Lau Basin is the youngest, being active from c. 5 Ma. The Fiji Plateau/North Fiji Basin contains a triple junction with a spreading system to the south and active spreading from around 1.5 Ma (Chadwick et al., 2019). Some studies suggest that this complex area has been active since c. 10 Ma. The South Fiji Basin is the oldest of the Fiji basin features, with magnetic anomalies dating to 35 Ma. It has been inactive since Lower Miocene times. The Fiji island arc has had a complex history. Stage 1 (Eocene-Mid Miocene) saw the earliest arc form as the Pacific Plate subducted westwards beneath the Australian plate (Fig. 8). Stage 2 (Mid Miocene-Mid Pliocene) witnessed a subduction polarity reversal as the Australian Plate now subducted under the Pacific Plate, and the concurrent opening of the North Fiji Basin/Fiji Plateau. Stage 3 (Mid Pliocene-Recent) saw the further opening of the North Fiji Basin/Fiji Plateau, the opening of the Lau Basin, and movement along oceanic fracture systems, which moved Fiji away from its earlier arc position to the modern, mostly non-arc, position. Viti and Vanua Levu, and the host Fiji Platform, have rotated some 90–135 degree counter-clockwise, from c. 10 Ma to the present day (Taylor et al., 2000, Colley and Hindle, 1984). Rotation occurred because of the combined effect of the opening of the North Fiji Basin and movements along ocean fracture zones (left-lateral transform faults), particularly the Hunter-Kadavu-Fracture-Zone.

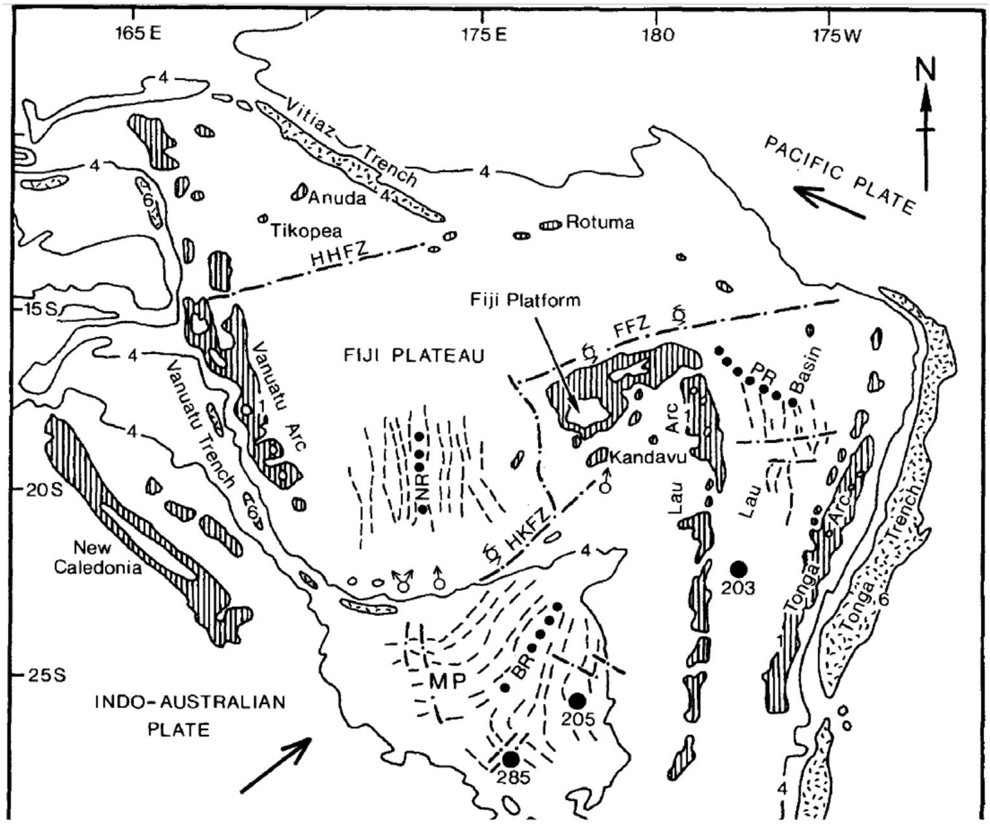

Fig. 8 Tectonic sketch map of the complex region around Fiji. Areas close to the ocean surface are shown in vertically lined ornamentation and include the Vanuatu Arc, New Caledonia, the Fiji Platform (also termed the North Fiji Basin), Lau, and the Tonga Arc. A series of large, continuous, fracture zones are shown, including HKFZ (Hunter-Kadavu Fracture Zone), FFZ (Fiji Fracture Zone), and HHFZ, (Hazel-Holme Fracture Zone). Back-arc or marginal basins include the Fiji Plateau (also called the North Fiji Basin), the Lau Basin, and the South Fiji Basin (marked with letters MP, and BR). Linear lines of black dots show the location of active/extinct spreading centers such as BR (Bounty Ridge), PR (Peggy Ridge) and NR (Nova Rise). Dots with numbers show locations of deep sea boreholes. From Colley H and Hindle WH (1984) Volcano-tectonic evolution of Fiji and adjoining marginal basins. In: Kokelaar BP and Howells MF (Eds), *Marginal Basin Geology*. London: Geological Society of London, Special Publications 16, pp. 151–162.

Geology

The oldest basement rocks in Fiji are present in southern Viti Levu, and are classified stratigraphically as the Wainimana and Singatokka Groups (Fig. 9). These formations are Oligocene-Miocene in age. The Wainimana Group is an arc sequence of basalts, andesites, dacites, and volcaniclastic rocks, and their plutonic equivalents. They are metamorphosed to zeolite-greenschist facies (Colley and Hindle, 1984). The chemistry of the volcanic rocks indicates they are arc-tholeiites. The Singatokka Group has a faulted/thrusted relationship with the Wainimana Group and is a non-arc ocean floor sequence of pillowed/non-pillowed basalts, sills, dykes and gabbros, deep sea cherts and limestones, iron-manganese rich sediments, distal sediments and turbidites (Fig. 9). Basement rocks were compressed, folded and deformed during the Colo Orogeny, in Mid-Miocene times. The Colo plutonic sequence was intruded during *syn*-post Colo Orogenic times, sometimes within the cores of fold structures (Colley and Hindle, 1984). The Colo plutonic rocks, predominantly tonalities, gabbros, diorites and trondhjemites, are aged 7–3 Ma (Miocene-Pliocene). A Fiji-Platform-wide volcanic event followed the Colo plutonic intrusive period (Fig. 9). Volcanic rocks of this period (Mid Miocene-Mid Pliocene) were largely of a low-K calc-alkaline variety comprising basalts, andesites, dacites, rhyodacites, volcaniclastic rocks, and intrusive equivalents. Volcanic stratigraphic units of this era are called the Ba and Koroimavu Groups in North Viti Levu, the Namosi Andesites in southern Viti Levu, and the Natewa, Undu, and Nararo Groups, of Vanua Levu (this island was formed during this period, Fig. 9). Eruptions also took place on Ovalau, Gau, Beqa, and other smaller islands. Andesites and basalts exposed within the Lau Islands formed mainly at this time during two stages, 9–6 Ma and 3.9–3.5 Ma. The volcanic style changed again from Mid Pliocene to Recent times. Fiji was then situated in a less arc-like geotectonic setting, and, instead, was subject to extension along NNW and NE trending fractures which leaked more alkaline magmas, to produce alkali basalts in SW Vanua Levu, Koro, and Taveuni. Kadavu calc-alkaline volcanism may be linked to subduction along the Hunter-Kadavu-Fracture Zone (Fig. 9; Colley and Hindle, 1984). Alluvial and coralline reef deposits of Quaternary-Holocene age are present on many islands.

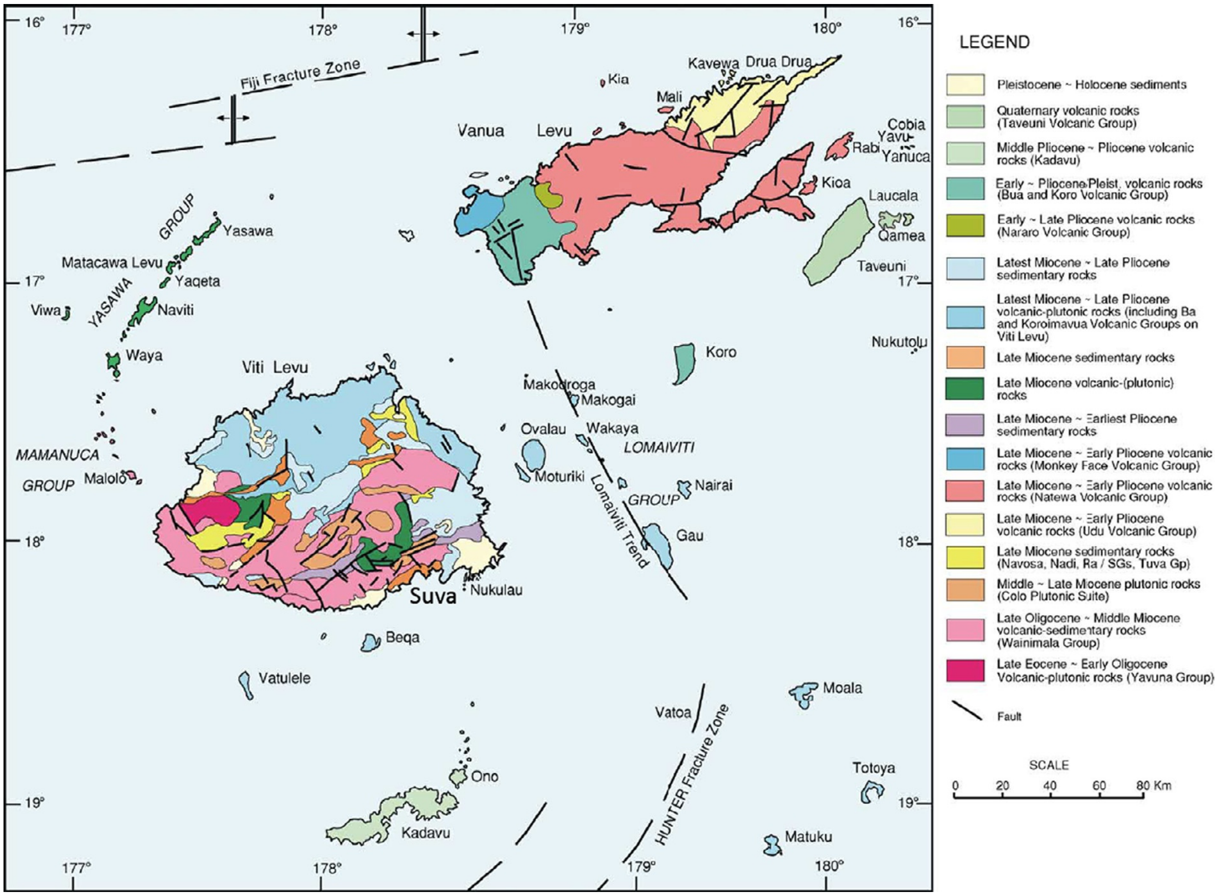

Fig. 9 Geology of the main Fiji Islands. Viti Levu exposes the oldest Eocene-Oligocene arc rocks towards the south of the island. These are intruded by the Mid-Late Miocene Colo plutonic unit. Younger Late Miocene to Recent arc rocks are exposed in northern Viti Levu and Vanua Levu. The youngest volcanic rocks (Quaternary-Recent) are located in Taveuni and Kadavu. Reproduced with permission from the Mineral Resources Department of Fiji.

Geological Resources

Fiji has significant geothermal potential, particularly around SavuSavu, in Vanua Levu, and in Kadavu, Taveuni, and northern Viti Levu. Around 60% of energy on Viti Levu is generated from hydro-power. Hydrocarbon deposits have been identified onshore and offshore in the Nadi area of western Viti Levu. There is an extensive aggregate and quarrying industry throughout the larger Fijian islands. Fiji has a mature mineral groundwater industry which has a global export reach, and earns a significant portion of Fiji's GDP. Fiji currently produces gold, silver, bauxite, and cement. The Pacific Islands region oldest gold mine is situated in Northern Viti Levu (USGS, 2018). The Vatukoula Mine has been producing gold and silver since the 1930s. There are a number of known epithermal and porphyry gold and copper prospects, which have had a significant history of exploration, some of which remain active. Prospects include Namosi (a large-scale, low-grade series of porphyry copper deposits in southern Viti Levu), the Tuvatu gold project, 50 km south of Vatukoula, the Ono gold prospect on Kadavu, and the Nadrau Gold Prospect in Viti Levu. Extensive bauxite deposits exist in a number of localities in Fiji. The Bua District of SW Vanua Levu is host to a number of bauxite mines. Cement is produced at Lami, close to the capital township of Suva (USGS, 2018).

Geoscientific Studies

Fiji has been the subject of a number of geological investigations, from the early 20th century and particularly from the 1970s. This research has developed insights into the nature of Fiji as an island arc, and the evolution of the many marginal basins within the oceans of Fiji. Some key research has focused around the location and origin of economic minerals. This work continues to the present day in the form of geological mapping, development of structural geological models, drilling, geophysical surveys undertaken to measure regional and local levels of gravity, magnetism, radioactivity, and electrical conductivity, and the generation of three-dimensional computer models of ore deposits, as well as evaluating mining environmental impacts. Other studies address the metallogenic origin of the deposits: how the metals have been incorporated into the ore via hydrothermal and magmatic processes (Pals and Spry, 2003). Ores and parental rocks are sampled to examine their overall geochemical composition (major elements, trace elements, and isotopes such as S, O, H, Sr, and Pb) and mineral content and composition (via optical microscopes, scanning electron microscopes, and electron micro-probes). Trapped gases within the rocks and minerals (called fluid inclusions) are examined to evaluate fluid chemical composition, and the ambient geochemical environment (e.g., acidity, oxygen activity) of ore deposition. Some of Fiji's deposits, such as Vatukoula and Tuvatu, are relatively rich in elements such as Tellurium and Bismuth, which are rare on Earth, and in increasingly high demand for applications such as the manufacture of solar panels, and a wide range of green-technologies (Pals and Spry, 2003).

Kingdom of Tonga

Geo-Summary and Highlights

The Kingdom of Tonga covers a land area of c. 749 km^2, and an ocean area of 660,000 km^2, with a population of c. 108,000. The Tongan archipelago nation extends from longitude 175°–178°W and latitude 15°–22°S (Figs. 1 and 10). The capital township is Nuku'alofa, on the island of Tongatapu, with a population of c. 24,000. Tongan islands form a double island chain, and extend in a c. NNE-SSW direction over a distance of c. 1000 km. The islands form the highest part of the Tongan Ridge, situated between the Tongan trench to the east, and Lau Basin to the west. Tongatapu, located in south Tonga, is the largest Tongan island, with an area of 257 km^2. Other islands include Eua, the Ha'apai island group, the Vava'u island group, and the northern islands of Niuatoputapu, Tafahi, and Niuafou. The islands and submarine edifices, including numerous active volcanoes, are all part of the Tongan arc, and comprise volcanic rocks and/or coralline and related sedimentary rocks.

Geo-Tectonic Setting

The Tongan islands are located on the western side of the Tongan-Kermadec trench, which extends for c. 2550 km, from Samoa in the NNE to New Zealand in the SSW, and is over 9 km deep for much of its length (Beier et al., 2017; Chadwick et al., 2019). The

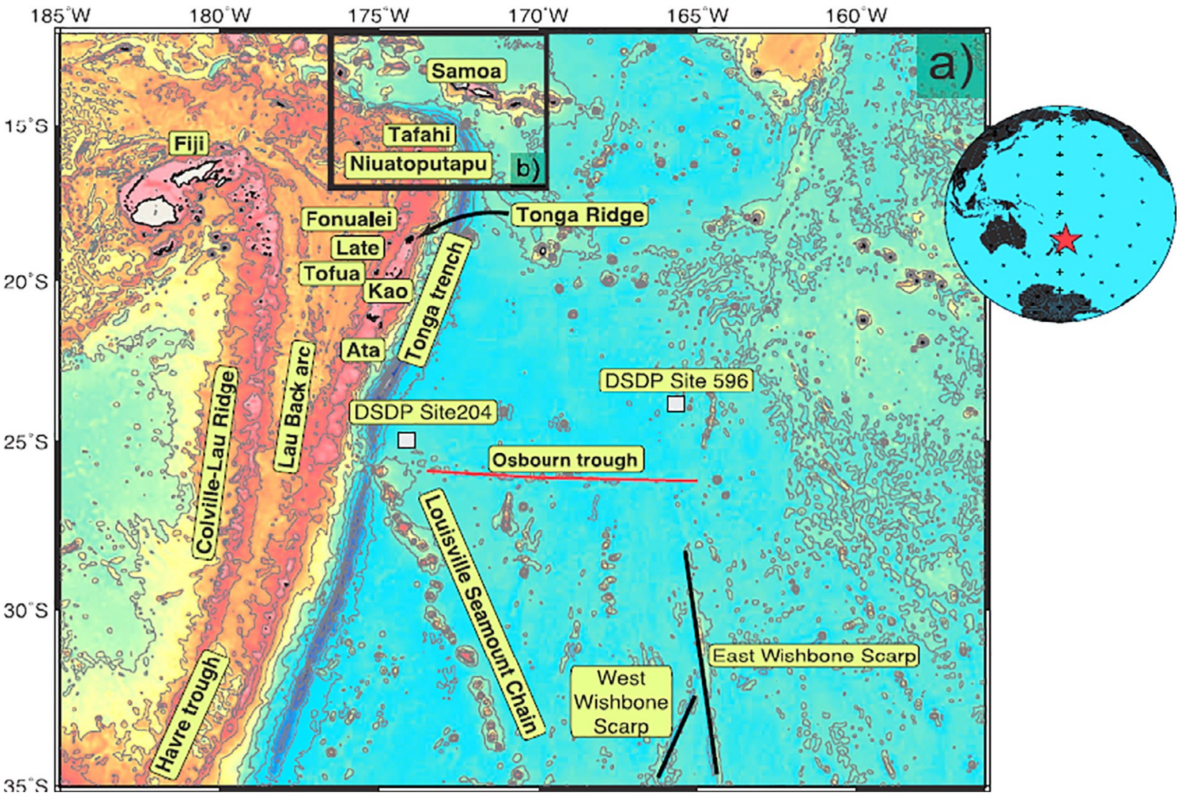

Fig. 10 Tectonic setting of the Tonga arc. The Tonga Ridge (located between the Tonga trench and Lau Back arc) hosts the Tongan arc. The Louisville Seamount Chain marks a line of plume-generated volcanoes, some of which are impinging upon the Tongan arc. The black box in the north of the diagram highlights the northern terminus of the Tongan arc system and the Samoan islands. From Beier C, Turner S, Haase KM, Pearce JA, Munker C, and Regelous M (2017) Trace element and isotope geochemistry of the northern and central Tongan islands with an emphasis on the genesis of high Nb/Ta signatures at the northern volcanoes of Tafahi and Niuatoputapu. *Journal of Petroleum* 58: 1073–1106; From Haase KM, Beier C and Kemner F (2019) A comparison of the magmatic evolution of Pacific intraplate volcanoes: Constraints on melting in mantle plumes. *Frontiers in Earth Science.* doi: 10.3389/feart.2018.00242, reproduced by permission of Oxford University Press.

Tongan trench marks the site of subduction of the Pacific Plate under the Australian Plate. Melting of the mantle wedge above the subducting Pacific Plate has produced the Tonga Ridge, the highest parts of which form the islands of Tonga (Fig. 10). Back-arc spreading west of the Tongan arc produced the Lau Basin, some 2000–2500 m deep, deepening to c. 3000 m further south (Chadwick et al., 2019). Seamount linear chains and clusters are situated east of the Tongan Trench, most notably the Louisville Seamount Chain which impinges upon the Tongan trench to the south of Tonga (Fig. 1; Beier et al., 2017). The northern part of Tonga contains the northern terminus of the Tongan Trench, adjacent to Samoa (Figs. 1 and 10) and an active spreading center (which includes the Mangatolu Triple Junction; Fig. 1). The Miocene Lau-Coleville ridge contains an older island arc. Rifting of the older arc commenced at c. 6 Ma and the new Tongan arc developed from c. 3–4 Ma. The Tonga Ridge forms an older basement to the modern arc. There is some local back-arc spreading west of the Tongan arc (e.g., around Mangatolu). The northernmost part of the Tongan Trench has witnessed the subduction of parts of the Samoan Ridge and plume-generated volcanic material.

Geology

Tonga forms a double chain of 160 islands. The western islands are mostly volcanic whilst the eastern islands are mostly composed of limestone. The oldest volcanic basement rocks dated on the Tongan ridge are Eocene basalts, gabbros, and andesites. The subducting Pacific basalt plate is Cretaceous in age. The northern islands of Niuatoputapu and Tafahi (Fig. 1, shown as Tafahi) are composed of arc basalts and andesites, with Niuatoputapu being formed of a predominant raised coralline limestone with a core of arc volcanic material, and Tafahi made mainly of lavas, some dated at $<$163 ka and $>$8 Ka (Beier et al., 2017). There are no historical records of volcanic eruptions on these islands. Most western Tongan islands are predominantly composed Pliocene-Recent island arc rocks, varying in composition from basalt, to andesite and dacite. There is a suggestion of an increase in potassium in the rocks from north to south (Beier et al., 2017). Islands such as Tongatapu and Vava'u expose raised coralline limestones. Tongatapu is composed of Pliocene-Pleistocene limestones, 130–235 m thick, which rest on top of volcaniclastic rocks (Harrison, 1993; Schofield, 1967). Tongatapu island reaches a maximum elevation of 65–70 m. Coastal cliffs with blow-hole features are present on the southern part of the island. Tonga contains a number of active volcanoes with eruptions recorded in historical times, including Curicoa, Fonafo'ou, Fonulei, Hunga Tonga-Hunga Ha'apai, Late, Metis Shoal, Niuafo'ou, Tofua and a significant number of submarine volcanoes (Chadwick et al., 2019).

Geological resources and geoscientific studies

Tonga has a number of working limestone quarries, mainly on Tongatapu but also on Vava'u and other islands with significant populations (Harrison, 1993). Oceanographic surveys have discovered a number of locations of submarine hydrothermal vents and related areas of ocean floor which contain high levels of gold and copper in the form of seabed minerals. The Kingdom contains a number of shallow submarine volcanoes that break surface when they erupt. These attract a significant amount of research attention from the volcanological and geochemical community, who undertake volcanological fieldwork, either on the ground, or via remote sensing techniques, and take samples for geochemical analysis (Price et al., 2013; Beier et al., 2017; Chadwick et al., 2019). Submarine volcanoes may grow high enough and erupt sufficient volumes of magma to form an island. There is a situation in such a volcano's evolution where the volcanic peaks change environments from submarine to subaerial. Shallow water volcanic eruptions can result in highly explosive eruptions with the interactions between hot magma and vaporized, highly-expanded water producing highly fragmented, *phreatomagmatic* eruptions. One such volcano is Metis Shoal situated between Tongatapu and Vava'u (Fig. 1) which, when erupting, produces a temporary island, and sometimes large areas of floating pumice. The islands of Hunga-Tonga-Hunga Ha'apai, about 100 km NNE of Tongatapu (Fig. 1) formed and co-joined, after an eruption which began under water in 2014, and is ongoing (Cronin et al., 2017). Kavachi, Solomon Islands, (Fig. 1), exhibits similar behavior producing a sizeable island every 4–8 years, which sinks beneath the waves when the eruptions end. Tongatapu hosts a number of coralline limestone erratic boulders (boulders removed from their original source position) 10–20 m above the present day shoreline and 100–400 m away from the present day coastline. The largest boulder measures 15 m $\times$ 11 m $\times$ 9 m. The dates at which the boulders were placed in their present position have been determined using ^{230}Th radiometric dating methods. These give emplacement ages of 120–130 Ka. The boulders are hypothesized to have been emplaced by a tsunami caused by a submarine landslide (Frohlich et al., 2009).

Cook Islands

Geo-Summary and Highlights

Cook Islands covers a total land area of 237 km^2 and an ocean area of 2 million km^2, with a resident population of c. 15,000. Avarua on the island of Rarotonga is the capital of Cook Islands (CI) with a population of c. 5500 (Petterson and Tawake, 2018). The ocean/land area ratio is one of the highest in the world. CI comprises 15 separate islands or island groups situated between longitudes 155°W and 168°W and latitudes of 5°S and 25°S (Figs. 1, 11, and 12. Islands are divided into a southern group (Rarotonga, Palmerston, Aitutaki, Mangaia, Atui, Manuae, Ma'uke, Miti-aro, and Takutea) and a northern group (Penrhyn, Suwarrow, Manihiki, Pukapuka, Nassau, and Rakahanga) (Figs. 12 and 13; Petterson and Tawake, 2018). Cook Islands are examples of two types of intra oceanic islands, far away from any continent. The southern Cook Islands attain significant heights above sea level (Rarotonga rises to 658 m for example, Fig. 13) and have reasonably large exposures of volcanic rocks whilst the northern islands are low lying coralline atolls. The southern islands form the upper parts of large intra-oceanic volcanic seamounts, which

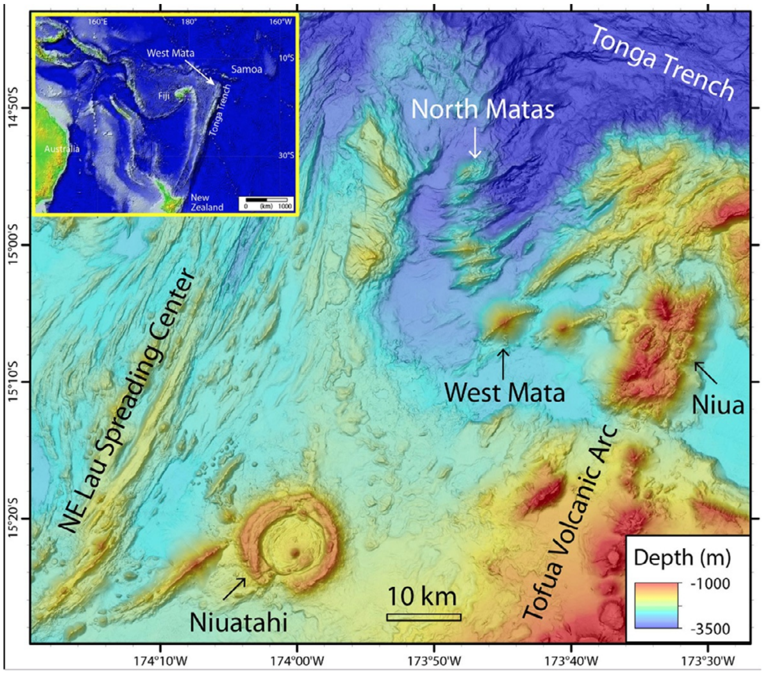

Fig. 11 Digital terrane model from remotely operated submarine data between Fiji, Samoa and northern Tonga. These rich data provide sharp detail of the Lau Basin spreading center, the Tofua arc, and submarine volcanoes such as West Mata, Niuatahi and Niua. From Chadwick WW, Rubin KH, Merle SG, Bobbitt AM, Kwasnitschka T and Embley (2019) Recent eruptions between 2012 and 2018 discovered at West Meta submarine volcano (NE Lau Basin, SW Pacific) and characterised by new ship, AUV, and ROV data. *Frontiers in Marine Science*. doi: 10.3389/fmars.2019.00495.

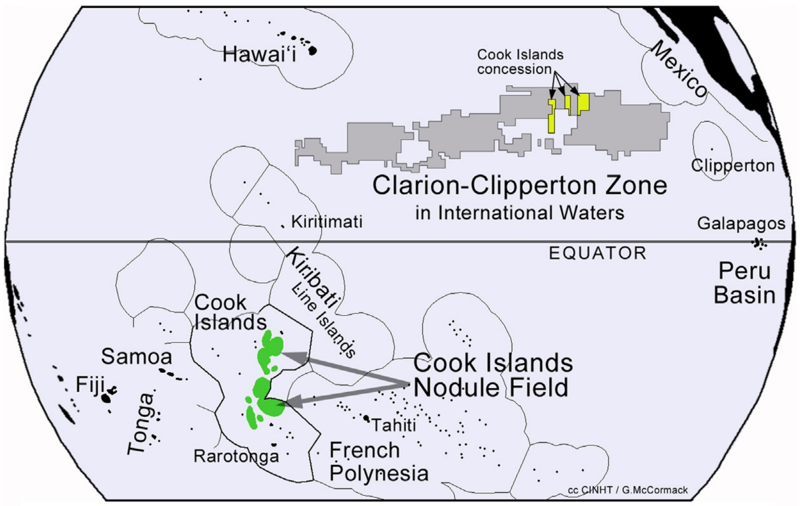

Fig. 12 Polymetallic Manganese Nodule fields around Cook Islands, extending to Kiribati and the Clarion Clipperton Zone. Manganese nodules form below 4–5 km ocean depth and could be the source of enormous metallic mineral wealth. The areas shown in green illustrate the highest Manganese Nodule Field grades for Cook islands. From Petterson MG and Tawake AK (2018) The Cook Islands (South Pacific) experience in governance of seabed manganese nodule mining. *Ocean and Coastal Management*. doi: 10.1016/j.oceoaman.2018.09.010, reproduced with permission of Gerald McCormack, and Elsevier.

extend to ocean depths of 4–>5 km. The northern Cook Islands are largely coralline, and coral-debris atolls, which rest upon the uppermost parts of the Cretaceous Manihiki ocean plateau (Taylor, 2006; Fig. 13).

Geo-Tectonic Setting

The southern group of islands are the highest parts of a linear seamount trail formed as the Pacific plate moved over a mantle hot spot/plume (similar to the situation with the Hawaiian-Emperor chain; Fig. 13; Petterson and Tawake, 2018). The Cook-Austral volcanic island chain forms a 1500 km long NE-SW trending chain of seamounts with the currently active hotspot volcanism being

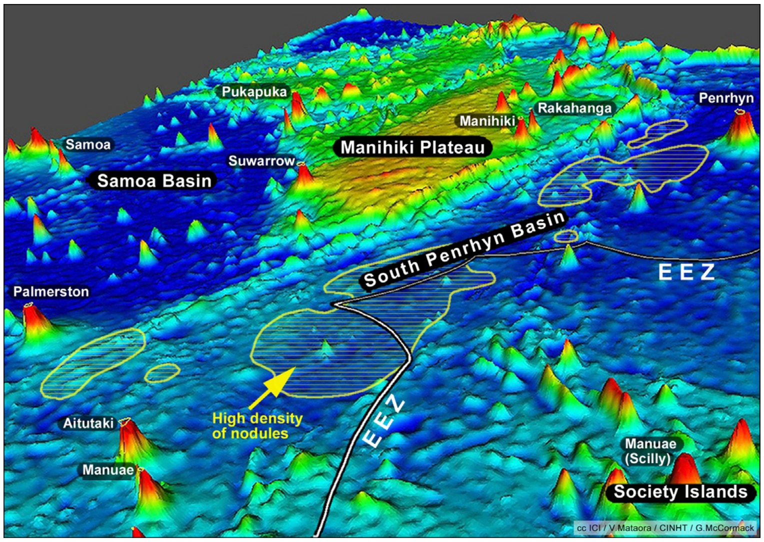

Fig. 13 Three dimensional model of the Cook Islands showing the large Manihiki Plateau to the north and the seamount islands to the south (alongside the Society Islands of French Polynesia). The highest densities of manganese nodules occur within the South Penrhyn Basin. EEZ marks the boundary of the Cook Islands Exclusive Economic Zone. Note that north is slightly NNE of vertical in this figure. Rarotonga is not included on the map but it's relative position is indicated by the arrow in the SW of the diagram. From Petterson MG and Tawake AK (2018) The Cook Islands (South Pacific) experience in governance of seabed manganese nodule mining. *Ocean and Coastal Management.* doi: 10.1016/j.oceoaman.2018.09.010, reproduced with permission of Gerald McCormack, and Elsevier.

located at Macdonald Seamount (c. latitude 29°S, 141°W). Seamounts rise from over 5000 m beneath sea level with foundations grounded upon a Paleocene-aged ocean floor (Fig. 13). The northern group of islands are mostly the uppermost parts of the very large volume, thick Manihiki ocean plateau (Taylor, 2006), formed from rapid, voluminous and rapid mantle melting as the large-scale Manihiki plume surfaced around c. 125–116 Ma during the Cretaceous period (Fig. 13).

Geology

The geology of Rarotonga is quite representative of many of the southern Cook Islands (Thomson and Smith, 1998; Wood, 1967). The surface parts of the volcano have been eroded and reasonably deeply dissected, allowing access to the stratigraphy of the upper parts of the volcanic seamount. Rarotonga rocks are dated from 2.3 to 1.1 Ma, and compare with ages of Aitutaki and Atiu island rocks (3–1 Ma), representing younger, rejuventated magmatic activity on the seamounts. Volcanic rocks form lavas, pyroclastic deposits, and dykes. Most rocks are alkali basalt and ankaramite in composition, with more acidic phonolites also present. Alkali basalts are typical products of plume-related volcanoes. Pleistocene to Recent alluvial sedimentary deposits of sands and gravels are present around parts of the periphery of Rarotonga, especially close to the larger river systems. The whole island is fringed by a modern coral reef system. The northern islands comprise coral reefs, cemented gravels, coralline-conglomerates, and lime sandstones, formed form the erosion and lithification of older, denuded, coral reef systems (Wood, 1967). Many islands have lagoons with intra-lagoonal sand and mud deposits. The Manihiki Plateau is c. 15–25 km thick, comprising large volume basalt lavas, sills, and gabbros, with a volume of 770,000 km^2. The Manihiki Plateau is cut by a rift valley which separates the plateau into eastern and western components. The deep Penrhyn and Samoa ocean basins, in parts almost 6 km deep, form the eastern and southern boundaries of the Manihiki Plateau.

Geological resources and geoscientific studies

The abundant presence of seabed minerals within Cook Islands waters is a good example of both a highly valuable economic resource, and a subject which has attracted significant geological study (Figs. 2, 11 and 12). Seabed minerals known as Manganese Nodules (or Polymetallic nodules) are situated on the ocean floor in much of the Cook Islands Exclusive Economic Zone. The nodules are mainly spherical/spheroidal, pancake, or irregularly shaped, with rough, often cauliform-like, exterior surfaces, measuring 8–80 mm in diameter. The nodules are formed by iron and manganese hydroxides precipitating concentrically around a pre-existing nucleus (such as a sharks tooth or rock fragment) (Hein et al., 2015; Petterson and Tawake, 2018). Cook Islands nodules are thought to have formed on the seafloor by direct precipitation from ocean waters (a process called hydrogenetic precipitation, probably assisted by the existence of the deep Antarctic Bottom-Water current which flows through ocean basins such as the Penryn basin, Fig. 12). The nodules grow very slowly (mainly 1–10 mms/million years for hydrogenetic nodules). The largest Cook Islands nodules are 14–18 Ma old. Analyses of Cook Islands nodules show that they are particularly rich in copper, cobalt, nickel, titanium, molybdenum, yttrium, and rare earth elements, with additional molybdenum, vanadium, tungsten, zirconium, manganese, and iron. Cook Island nodule abundances are up to 58 kg/m^2, making the deposits the fourth richest in the world (after the Clarion Clipperton zone in the East Pacific, the Peru basin, and the Indian Ocean). Oceanographic surveys undertaken during the 1960s–70s, and later from 1985 to the early 2000s generated data relating to the bathymetry and abundance of seabed minerals. Cook Islands nodules were first sampled during the 1970s. The nodules are relatively abundant and have been extensively studied for their geochemistry and metallogeny, as well as their mode of formation. Commercial mining and exploration companies are actively undertaking a series of environmental baseline, bathymetric, and nodule sampling expeditions in the Clarion Clipperton zone of the Pacific (between Mexico and Hawaii, Fig. 12). These surveys have discovered a plethora of new plant, animal, and fish species adapted to the great ocean depths, as well as data that provide information on the ocean floor character and structure, and modes of deposition of manganese nodules. Manganese nodules could represent highly valuable mineral deposits that, 1 day, may be mined. The value of the Cook Islands manganese nodule deposits is estimated at $10 trillion US (Hein et al., 2015).

Samoa

Geo-Summary and Highlights

Western Samoa covers a land area of c. 2800 km^2, an ocean area of c. 120,000 km^2 and has a population of c. 192,000. Its capital town is Apia, on the eastern island of Upolu, with a population of c. 38,000. Western Samoa comprises two main islands, Upolu and Savaii. The islands extend from longitudes 171° to 173°W and latitudes 13°–14°S (Figs. 1 and 14). Upolu and Savaii are part of a larger island archipelago oriented WNW-SSE that includes American Samoa, and a number of linear submarine seamount arrays. Samoa is dominated by alkali basalt volcanism, and rocks are young, aged Upper Miocene-Recent. One basalt lava eruption in the early 20th century partially buried a village on Savaii. The area has been of great interest to plume and isotope geologists. The islands are surrounded by deep water depths to c. 5000 m.

Geo-Tectonic Setting

The Samoan archipelago, including American Samoa, and a series of linear submarine volcanic seamounts (Figs. 1, 10, and 12) are part of a complex plume/seamount trail similar to Hawaii and the southern Cook Islands. The plume island volcanic chain varies in age from c. 13 Ma in the west to c. 0.3 Ma in the east, with historical post-shield volcanism recorded on the subaerial Samoan islands. The seamount and volcanic chain extend over a total distance of c. 1300 km. The Pacific plate moved in a WNW direction at a velocity of c. 7.1 cm/year. Volcanism (post-shield) rejuvenated on Upolu and Savaii from 0.4 Ma (Koppers et al., 2011; Hart et al.,

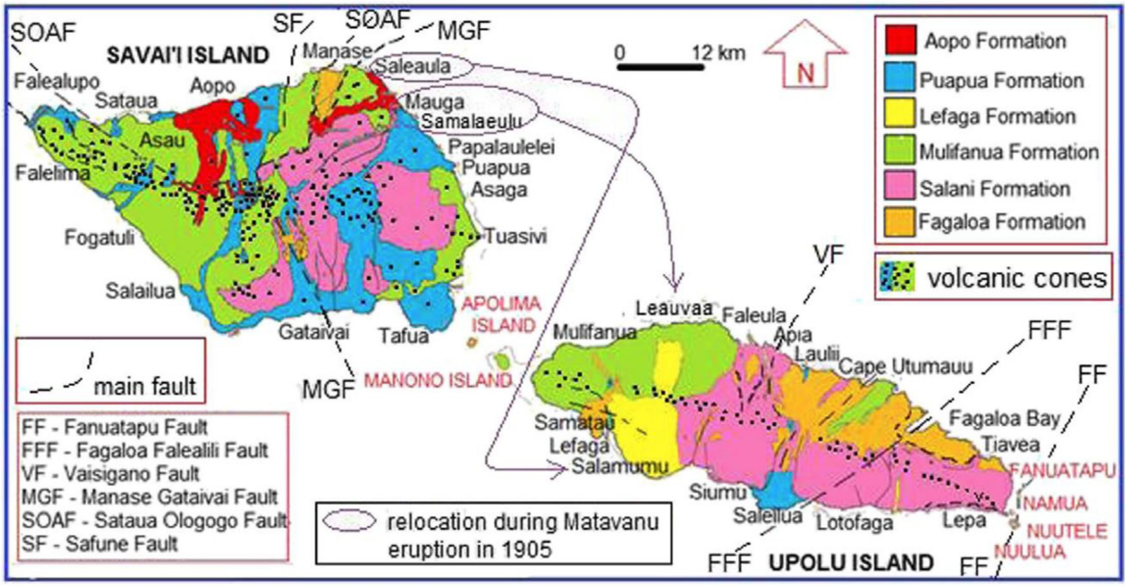

Fig. 14 Geological map of Samoa showing the locations of the six stratigraphic volcanic units. The lowermost four units form the bulk of the volcanic stratigraphy comprising Pahohoe and Aa basalt lavas and scoriaceous rubble. The Fagalo Formation has the lowest vesicle/void space and represent the exposed upper portions of the basaltic shield volcanoes. The Salani and Mulifanua Formations are lithologically similar, comprising vesicular basalts with zeolite coating many of the vesicles. The Lefago Formation comprises rubble-rich unweathered aa basalt flows. The Puapua and Aopo Formations are unweathered young basaltic volcanic units. Aopo historic lava flows have caused the relocation of several villages. Note the linear chain of younger volcanic centers that extends in a WNW-ESE line through the two islands (this line extends on the ocean floor as a linear chain of volcanoes). The shield volcanoes began to form from 5 to 3 Ma, whilst exposed rocks are mainly younger than 400,000 years. From Fepuleai A, Weber E, Nemeth K, Muliaina T and Lese V (2017) *Geoheritage* 9: 395–411, reproduced with permission from Springer.

2004; Strak and Schellart, 2018; Haase et al., 2019). Independent Western Samoa is also located close to the most NE segment of the Tonga trench, which marks the location of the Pacific plate subducting beneath the Australian plate. The currently most active part of the seamount trail, and the position of the present day Samoan hotspot, is at the eastern end, with the active volcano of Vailulu'u, some 3–400 km ESE of Upolu/Savaii (Fig. 1).

Geology

Like most intra-oceanic volcanic islands of plume origin, the Samoan (and southern Cook) islands began their existence with the eruption of alkali basalt lavas and pyroclastic material that constructed a series of shield volcano structures, with a wide-diameter base, supporting a volcanic height of several thousand meters, which, in the case of Upolu and Savaii, have broken surface and formed subaerial islands (Fig. 14). Calderas may form, and become filled with more silicic magmas, and then experience caldera collapse. Once the shields are subaerial they are subject to subaerial erosion of the volcanic edifices. Subaerial volcanism takes over from the predominant shield-building submarine volcanism, and may cover large areas of the older shield-volcanic rocks, forming a cover volcanic sequence, overlying the shield-basement volcanic rocks. The two distinct stages of volcanism are dated at c. 5–2 Ma for the Shield stage, and from 0.39 Ma for the younger stage. Dated Savaii volcanic rocks range from 0.39 Ma to 1905 and 1911, with ^{14}C radiometric ages from 4150 to 3850 Ka, and between 1550 CE and 1820 CE. Upolu is highly dissected in parts with the younger subaerial volcanic rocks covering around one third of the island (Fig. 14). Savaii mainly exposes only the younger, subaerial volcanic rocks, with older shield-rocks exposed in the deepest valleys. Volcanism has been active on Samoa from Pliocene times. Some small volcanic cones on Upolu are located along an east-west rift lineament zone that span the width of the island and extend westwards into Savaii. Exposed Samoan basalts, basaltic tuffs and pyroclastic rocks are divided into six formations (Fagalo, Salani, Mulifanua, Puapua, Lefaga, and Aopo, Fig. 14). Island-wide faults are present on both Upolu and Savaii. The older shield volcanism is aligned along rift-fault structures. Post-shield volcanism emanates from small-volume scoria cones or fissure-fed spatter cones (see Koppers et al., 2011; Hart et al., 2004; Strak and Schellart, 2018; Haase et al., 2019 for details).

Geological resources and geoscientific studies

There are no known significant precious metal or hydrocarbon resources on Samoa. A range of rock types are extracted for aggregates, road building, and construction. There is the potential for geothermal energy, and hydro-electric power is generated on Upolu. Samoa, like other Pacific islands, has been the source of novel investigations that combine geology with oral history traditions. The Pacific people (Melanesians, Polynesians, Micronesians) occupied the Melanesian islands from c. 50,000 years ago, and the Polynesian/Micronesian islands from c. 4000 years ago. Pacific cultures have a rich story-telling and oral history tradition that can record events such as volcanic eruptions, earthquakes, floods and so forth. Researchers on Samoa have worked with the local people to write down key aspects of the oral history that may link to volcanic eruptions of the past. These stories have been combined with scientific volcanological studies, to develop volcanic hazard maps, and enrich the knowledge of the volcanic evolution of Samoa, during human occupancy times (Fepuleai et al., 2017; Nemeth and Cronin, 2009). As with other islands of mantle plume origin, Samoa and the larger Samoan island trails have been the source of intense research examining the age and geochemistry of mantle plumes with a view to developing a deeper understanding of mantle processes and chemical composition. Major and trace element geochemical studies (particularly examining elements such as REE, K, Rb, Sr, Pb, Nb, Y, Zr) geochronological studies using a variety of age-dating methods (e.g., U-Pb, K-Ar, Carbon 14), and the application of isotope systems (e.g., He, Nd, Pb, Sr,), have been used as tracers for the further understanding of mantle geochemistry and geodynamics. These studies characterize individual hotspots across the Pacific (e.g., the Samoan and Cook-Austral host spots) and allow for comparisons to be made between hot spots, plumes, and hot spot trails across the Pacific and globally. One interpretation of the Samoan hotspot is that it is a very deep seated plume with origins in the lower mantle. Other interpretations of the geochemistry of younger Samoan volcanic rocks include the hypothesis that the geochemistry is in part plume-derived, and, in-part, subduction-derived, with the influence of the Tonga trench (see Koppers et al., 2011; Hart et al., 2004; Strak and Schellart, 2018; Haase et al., 2019, for details).

References

Auzende JM, Collot J-Y, Lafoy Y, Gracia G, Ondreas H, Eissen JP, Larue MB, OLiskukulu C, Tolia D, and Biliki N (1994) Evidence for sinistral strike-slip deformation in the Solomon Island arc. *Geo-Marine Letters* 14: 232–237.

Beier C, Turner S, Haase KM, Pearce JA, Munker C, and Regelous M (2017) Trace element and isotope geochemistry of the northern and central Tongan islands with an emphasis on the genesis of high Nb/Ta signatures at the northern volcanoes of Tafahi and Niuatoputapu. *Journal of Petrology* 58(6): 1073–1106.

Chadwick WW, Rubin KH, Merle SG, Bobbitt AM, Kwasnitschka T, and Embley RW (2019) Recent eruptions between 2012 and 2018 discovered at West Meta submarine volcano (NE Lau Basin, SW Pacific) and characterised by new ship, AUV, and ROV data. *Frontiers in Marine Science*. https://doi.org/10.3389/fmars.2019.00495.

Colley H and Hindle WH (1984) Volcano-tectonic evolution of Fiji and adjoining marginal basins. In: Kokelaar BP and Howells MF (eds.) *Marginal Basin Geology*. vol. 16, pp. 151–162. London: Geological Society. Special Publications.

Cronin SJ, Brenna M, Smith IEM, Barker S, Tost M, Ford M, Tonga'onevai S, Kula T, and Vaiomounga R (2017) New volcanic island unveils explosive past. *Eos* 98. https://doi.org/10.1029/2017EO076589.

Fepuleai A, Weber E, Nemeth K, Muliaina T, and Lese V (2017) Eruption styles of Samoan volcanoes represented in tattooing, language and cultural activities of the indigenous people. *Geoheritage* 9: 395–411.

Frohlich C, Hornbach MJ, Taylor FW, Shen CC, Moala A, Morton AE, and Kruger J (2009) Huge erratic blocks in Tonga deposited by a prehistoric tsunami. *Geology* 37(2): 131–134.

Haase KM, Beier C, and Kemner F (2019) A comparison of the magmatic evolution of Pacific intraplate volcanoes: Constraints on melting in mantle plumes. *Frontiers in Earth Science*. https://doi.org/10.3389/feart.2018.00242.

Harrison DJ (1993) The limestone resources of Tongatapu and Vava'u, Kingdom of Tonga. In: *ODA R and D Programme, Project Number 91/4*, p. 38. British Geological Survey, NERC.

Hart SR, Coetzee M, Workman RK, Blusztajn J, Johnson KTM, Sinton JM, Steinberger B, and Hawkins JW (2004) Genesis of Western Samoan seamount province: Age, geochemical footprint and tectonics. *Earth and Planetary Science Letters* 227: 37–56.

Hein JR, Spinardi FF, Okamoto N, Mizell K, Thorburn D, and Tawake A (2015) Critical metals in manganese nodules from the Cook Islands EEZ, abundances and distributions. *Ore Geology Reviews* 51: 1–14.

Hochstein MP, Schofield JC, and Shor GG (1971) Geological evolution of the New Hebrides island arc. *Journal of the Geological Society* 129: 417–422.

Koppers AAP, Russell JA, Roberts J, Jackson MG, Konter JG, Wright DJ, Staudigel H, and Hart SR (2011) Age systematics of two young en echelon Samoan volcanic trails. *Geochemistry, Geophysics, Geosystems* 12: 7.

Neal CR, Mahoney JJ, Kroenke LW, Duncan RA, and Petterson MG (1997) The Ontong Java Plateau. Large igneous provinces: Continental, oceanic and planetary flood volcanism. *Geophysical Monograph* 100: 183–212.

Nemeth K and Cronin SJ (2008) Volcanic craters, pit craters, and high-level magma-feeding systems of a mafic island-arc volcano: Ambrym, Vanuatu, South Pacific. In: Thomson K and Petford N (eds.) *Structure and Emplacement of High-Level Magmatic Systems*. vol. 302, pp. 87–102. London: Geological Society. Special Publications.

Nemeth K and Cronin SJ (2009) Volcanic structures and oral traditions of volcanism of Western Samoa (SW Pacific) and their implications for hazard education. *Journal of Volcanology and Geothermal Research* 186: 223–237.

Pals DW and Spry PG (2003) Telluride mineralogy of the low-sulphidation epithermal Emperor gold deposit, Vatukoula, Fiji. *Mineralogy and Petrology* 79: 285–307.

Peate DW, Pearce JA, Hawkesworth CJ, Colley H, Edwards CMH, and Hirose K (1997) Geochemical variations in Vanuatu arc lavas: The role of subducted material and a variable mantle wedge composition. *Journal of Petrology* 38: 1331–1358.

Petterson MG and Tawake AK (2018) The Cook Islands (South Pacific) experience in governance of seabed manganese nodule mining. *Ocean and Coastal Management*. https://doi.org/10.1016/j.oceoaman.2018.09.010.

Petterson MG, Neal CR, Mahoney JJ, Kroenke LW, Saunders AD, Babbs TL, Duncan RA, Tolia D, and McGrail B (1997) Structure and deformation of north and Central Malaita, Solomon Islands: Tectonic implications for the Ontong Java–Solomon arc collision and for the fate of ocean plateaus. *Tectonophysics* 283: 1–33.

Petterson MG, Babbs T, Neal CR, Mahonney JJ, Saunders AD, Duncan RA, Tolia D, Magu R, Qopoto C, Mahoa H, and Natogga D (1999) Geological-tectonic framework of Solomon Islands, SW Pacific: Crustal accretion and growth within an intra-oceanic setting. *Tectonophysics* 301: 35–60.

Petterson MG, Coleman PJ, Tolia D, and Magu R (2004) Application of terrain modelling of the Solomon Islands, SW Pacific, to metallogenesis and mineral exploration in composite arc-ocean floor collages. In: Petterson MG (ed.) *Pacific Minerals in the Millenium, the Jackson Lum Volume*, 99–119. SOPAC Technical Bulletin No 11.

Price AA, Jackson MG, Blichert-Toft JB, Hall PS, Sinton JM, Kurz MD, and Blusztajn J (2013) Evidence for a broadly distributed Samoan-plume signature in the northern Lau and North Fiji Basins. *Geochemistry, Geophysics, Geosystems*. https://doi.org/10.1002/2013GC005061.

Schofield JC (1967) Notes on the geology of the Tongan islands. *New Zealand Journal of Geology and Geophysics* 10(6): 1424–1428.

Smith DJ, Petterson MG, Saunders AD, Millar IL, Jenkin GRT, Toba T, Naden J, and Cook JM (2008) The petrogenesis of sodic island arc magmas at Savo volcano, Solomon Islands. *Contributions to Mineralogy and Petrology*. https://doi.org/10.1007/s00410-009-0410-9.

Strak V and Schellart WP (2018) A subduction and mantle plume origin for Samoan volcanism. *Nature Scientific Reports*. https://doi.org/10.1038/s41598-018-28267-3.

Tanahashi T, Kisomoto K, Joshima M, Lafoy Y, Honza E, and Auzende JM (1991) Geological structure of the central spreading system, North Fiji Basin. *Marine Geology* 98: 187–200.

Tapster S, Roberts NMW, Petterson MG, Saunders AD, and Naden J (2014) From continent to intra-oceanic arc: Zircon xenocrysts record the crustal evolution of the Solomon island arc. *Geology*. https://doi.org/10.1130/G36033.1.

Tapster S, Condon DJ, Naden J, Noble SR, Petterson MG, Roberts NMW, Saunders AD, and Smith DJ (2016) Rapid thermal rejuvenation of high-crystallinity magma linked to porphyry copper deposit formation; evidence from the Koloula Porphyry Prospect, Solomon Islands. *Earth and Planetary Science Letters* 442: 206–217.

Taylor B (2006) The single largest ocean plateau: Ontong Java-Manihiki-Hikurangi. *Earth and Planetary Science Letters* 241: 372–380.

Taylor GK, Gascoyne J, and Colley H (2000) Rapid rotation of Fiji: Paleomagnetic evidence and tectonic implications. *Journal of Geophysical Research* 105(B3): 5771–5781.

Thomson GM and Smith IE (1998) Volcanic geology of Rarotonga, southern Pacific Ocean. *New Zealand Journal of Geology and Geophysics* 41: 95–104.

USGS (2018) *Minerals Yearbook*. Fiji: United States Geological Survey, US Department of the Interior11.1–11.4.

Warden AJ and Mitchell AHG (1971) Geological evolution of the New Hebrides island arc. *Journal of the Geological Society* 129: 501–542.

Wood BL (1967) Geology of the Cook Islands. *New Zealand Journal of Geology and Geophysics* 10(6): 1429–1445.