

Chapter 3

Island Origins and Environments

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Island origins

Islands in different parts of the world often show similarities in origin although, conversely, islands that appear superficially similar may sometimes have quite different origins. Commonalities of origin and physical development occur mostly among the community of ‘oceanic islands’, those islands that originated within the ocean basins (Nunn, 1994). Older ‘continental islands’ are parts of the continents that have become islands through submergence of continental margins.

Most oceanic islands develop either along convergent plate boundaries or in intraplate (mid-plate) locations. Convergent plate boundaries are places where one slab (or ‘plate’) of oceanic crust (or ‘lithosphere’) is being thrust reluctantly beneath another. The downgoing plate is eventually pushed so far beneath the Earth’s surface that it begins to melt, producing magma that sometimes finds its way back to the ocean floor where it erupts and may eventually produce a volcanic island. There are intra-plate locations (‘hotspots’) where the Earth’s crust is uncommonly thin and where liquid rock from the layer below may push its way to the surface to form a volcanic island.

Origins can not always be readily determined from examination of modern, above-sea islands. Often the key to an island’s origin lies buried deep beneath a thick cover of younger rocks, sometimes far below sea level, so the use of models of island genesis is common. For example, many atoll islands are made solely from superficial material that accumulated within the past few thousand years yet rest on ancient coral reef that, in turn, rises upwards from the underwater flanks of long-submerged volcanic

islands; it is from the geochemical character of these volcanic rocks that we can learn about the true origins of particular atolls.

This section discusses the origins of islands by appearance and composition, beginning with nascent ocean-floor islands – from which all oceanic islands developed – through mature above-sea oceanic islands and older sunken islands. These are not primarily age distinctions but developmental stages that may not be attained by every oceanic island. Most oceanic islands are younger than continental islands, the origin of which is that of the continental masses of which they are part.

Young under-sea oceanic islands

All oceanic islands came into existence as a result of volcanic activity on the deep ocean floor. Much ocean-floor volcanism is undramatic, often associated with upwelling of magma (liquid rock) along a fissure that has extended downwards to tap an underground magma source. As these early eruptions continue and the amount of lava produced increases, so parts of the fissure become blocked, and eruptions become concentrated at particular points. It is these point eruptions that then allow the growth of small volcanic edifices which may one day form giant oceanic islands.

The weight of the ocean water overlying eruptions on the ocean floor render them non-explosive. The principal material produced is pillow lava, so called because the magma is forced out of the volcano in discrete blobs, the outside of which immediately solidifies when it comes into contact with the cold ocean water. The inside, however, remains liquid for much longer while the blob rolls down the flank of the volcano, coming to rest at its foot and forming one of many ‘pillows’.



Figure 1: This image shows a 2002 eruption of the Kavachi undersea Volcano, located off the coast of the Solomon Islands.

Yet, as an undersea volcano grows upwards, its crestral vent will eventually rise to a point about 600 m beneath the ocean surface where there is no longer sufficient overlying water to suppress explosive eruptions. As the volcano grows above this level and into shallower water, eruptions will often be explosive – and spectacularly visible above the ocean surface (see [Figure 1](#)). Part of the reason why many shallow-water eruptions are explosive has to do with the reaction between liquid rock, heated perhaps to 1200°C, and cold ocean water which leads to the production of fragmental volcanic material. These ‘volcaniclastics’ commonly drape the core (made from pillow lavas and intrusive igneous rocks) of undersea volcanic islands, but may also float to the ocean surface to form often floating pumice mats, or even form an island.

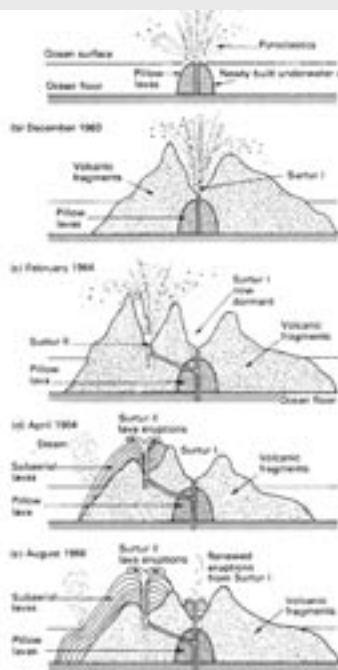
Islands made from newly-erupted volcaniclastic material tend to disappear through wave erosion once the eruption ends. Such ‘jack-in-the-box’ islands appear regularly in parts of the Southwest Pacific such as Solomon

Table 1. Shallow-water and island-building eruptions from underwater volcanoes (from data in Simkin et al., 1981).

| Volcano | Earliest record of eruption (AD) | Number of known eruptions | Number of island-building eruptions |
|-----------------------------------|----------------------------------|---------------------------|-------------------------------------|
| Fonuafo’ou (Falcon) Island, Tonga | 1781? | 11 | 5 |
| Karua, Vanuatu | 1897 | 10 | 5 |
| Kavachi, Solomon Islands | 1950 | 16 | 8 |
| Kick-‘em-Jenny, Lesser Antilles | 1939 | 10 | 0 |
| Metis Shoal (Late’iki), Tonga | 1851 | 8 | 3 |
| Myojin, Japan | 1952 | 6 | 1 |

Islands and Tonga (Table 1). For such an island to persist above the ocean surface, as has Surtsey off the south coast of Iceland in the North Atlantic, it is necessary for the eruptive vent(s) to be cut off from ocean water so that lavas will be produced instead of fragmental material (see Figure 2). Most older oceanic islands have been exposed above the ocean surface by sea-level fall or tectonic (land-level) movements.

Figure 2: Diagrammatic history of the 1963-67 eruptions of the Surtsey volcanoes (from Nunn, 1994).



A - The earliest eruptions visible above the ocean surface were explosive owing to mixing of ocean water and magma.

B - Pyroclastic and ash eruptions from the main eruptive centre of Surtur I built a cone of unconsolidated volcanic fragments.

C - Eruptions from Surtur I ceased and a new eruptive centre (Surtur II) came into being. Since the ocean still had access to this centre, mixing with the upwelling magma occurred and eruptions continued to be of an explosive character resulting in the accumulation of unconsolidated fragmental material easily eroded by the ocean.

D - Finally the Surtur II centre became isolated from the sea and lava eruptions replaced those of pyroclastic materials. Lavas armoured the surface of the existing cone rendering it significantly less vulnerable to marine erosion.

E - Eruptions renewed in the Surtur I area and lavas began to cover most parts of Surtsey. Lavas extruded on land which entered the sea gave rise only to steam clouds. No explosive activity would occur at this point owing to the existence of the already-cooled surface of the lavas, which eventually formed pillow lavas.

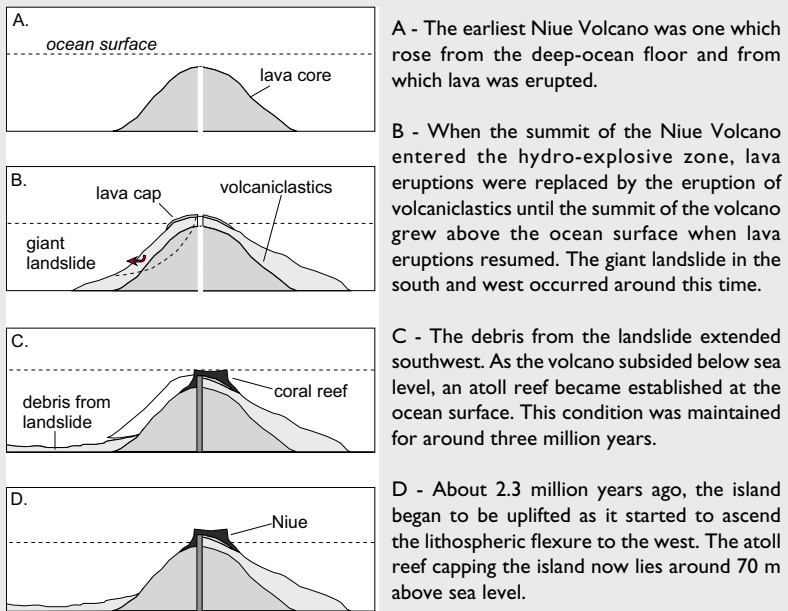
Mature above-sea oceanic islands

A newly-emerged volcanic island will commonly betray its origin although various processes soon conspire to begin to disguise this. Denudation – the physical wearing-away of the land – can erase the distinctive form of a volcanic island, even to the extent of reversing the original topography. Successive drowning and emergence associated with

climate changes, or long-term tectonic movements can also disguise very effectively the original form and origin of an oceanic island.

In the coral seas, generally those where ocean-surface waters remain above 20°C all year, the growth of coral reef around, sometimes even over, a subsiding volcanic island can transform it into an atoll island, one where the presence of a largely-submerged island edifice is manifested only by a ring of coral reef. Should an atoll island, or another such limestone-coated edifice, emerge, it will then appear as a high limestone island (see Figure 3).

Figure 3: Stages in the evolution of Niue Island:



Such transformations are relatively common in the most tectonically-active areas of the ocean basins, particularly near convergent plate boundaries, and relatively uncommon elsewhere. The island of Jamaica in the Caribbean is an oceanic island, despite being unusually large (11,500 km²). Slow steady sinking of Jamaica beginning around 55 million years ago led to deposition of the 'Yellow Limestone' around

its ancient volcanic core. The Yellow Limestone was overlain by the coral-reef dominated ‘White Limestone’ as subsidence continued, the entire island being submerged 40-25 million years ago. As a result of uplift associated with nearby plate convergence, the island subsequently emerged (Robinson, 1994).

As a general rule, above-sea oceanic islands will begin to subside once volcanic activity ceases. This subsidence commonly takes place because the island is being moved on an ocean plate from an area of shallower ocean in which volcanic activity is taking place to an area of deeper ocean where it is not. Thus islands that move away from a hotspot generally become both smaller in area and lower in altitude, as their bases are carried into deeper water; the northwestern islands in the Hawaii group, for example, are mostly atolls or low volcanic islands that were perhaps once are large as the islands Hawai’i (the “Big Island”) and O’ahu in the southeast of the group where the hotspot is located (see Figure 4).

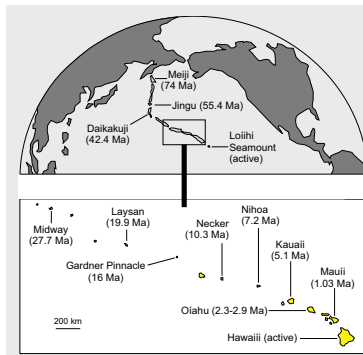


Figure 4: Ages of the most recent dated eruptions of shield volcanoes along the Hawaii-Emperor island-guyot chain (dates in millions of years ago (Ma)). The upper map shows the location of the Hawaiian Ridge within the North Pacific, the lower map the geography of the younger, largely emerged part of the island chain.

Old sunken oceanic islands

Many oceanic islands are being reduced in both area and elevation by processes of subaerial and marine erosion. In addition, the long-term tendency of many extinct volcanic islands is to subside. And while islands emerge as sea level falls at the start of an ice age, many are subsequently denuded to such a point that, when sea level rises again when the ice age is over, the former islands are drowned.

Many writers have drawn attention to contrasts in the form of undersea islands, distinguishing the conical 'seamounts' from flat-topped 'guyots'. Seamounts are generally thought to be the typical form of young undersea islands that have never emerged above the ocean surface, while guyots are older undersea islands that acquired their characteristic flat tops from wave bevelling of the island surface during the final stages of submergence.

Beyond Midway Island, the northernmost atoll of the Hawaiian Island chain, lies a line of guyots, the tops of which are composed of volcanic rocks marking the final stages of island formation. K-Ar (potassium-argon) dating of these rocks has allowed the times at which the islands ceased to be volcanically-active (that is, when they were moved away from the hotspot) to be determined precisely (see Figure 4). The linear relationship between island age and distance from the hotspot is well known for many such oceanic island chains (Richards & Lithgow-Bertelloni, 1996).

Ancient continental islands

Islands of continental origin are generally larger and almost always older than oceanic islands. They may rise from continental shelves, as do the islands Sardinia and Tasmania, or from isolated pieces of continental lithosphere that have become (largely) detached from the main ones, such as Madagascar and New Caledonia. The origins of these islands are generally as diverse and as complex as the continents proper. Many well-studied structural alignments on continents are also exposed on offshore islands. For example, ancient Mediterranean islands (such as Minorca) appeared above the ocean surface at the same time and for the same reasons as the Alps, while the island Trinidad exhibits the same structures as the adjacent parts of northern South America.

Some continental islands that subsequently found themselves close to unusually active convergent plate boundaries have become draped with upthrust pieces of the ocean floor called ophiolites. Well-studied island ophiolites are the Troodos Massif of Cyprus (Robertson, 2002), those exposed on southern Aegean islands (Koepke *et al.*, 2002), and

much of the main island (La Grande Terre) of New Caledonia (Rawling & Lister, 1999).

Some continental islands show signs of having been islands – and therefore subject to the same processes as older oceanic islands – for a considerable time. Only when Australia collided with the Banda Arc about 3 million years ago did the island Timor begin emerging, a process that can be calibrated by the staircases of fossil coral reefs found along its coasts (Chappell & Veeh, 1978); a comparable situation obtains in northeast Sicily (Rust & Kershaw, 2000).

Island landscapes

Like other landscapes, island landscapes vary in character primarily because of geology and climate. Amongst the principal geological controls are age, rock type (lithology), structure and tectonic history. Traditionally the most important climate controls on landscape were regarded as temperature and precipitation but, as geomorphic studies of islands have shown increasingly in the last few decades, climate history, particularly climate extremes, has also had profound influences on the character of modern island landscapes (Lamb, 1982; Huggett, 1991). Whereas half a century ago, most scientists took a simple uniformitarian view of climate and discounted past variations when trying to explain the evolution of particular island landscapes, today the evidence of past climates is widespread, ranging from the evidence of former glaciation (such as u-shaped valleys) on islands like Arran in Scotland (MacDonald & Herriot, 1983) to evidence for glacial-period wetness on tropical Hawai'i Island (Gavenda, 1992). Yet it is the variations attributable to lithology and evolutionary complexity, both broadly defined, that are most visible in many modern island landscapes, for which reason they form the basis for the discussion in this section.

Volcanic island landscapes

Landscapes of active volcanoes vary in large part depending on the nature of the eruptive materials. Island volcanoes built solely from viscous lava often form dome-shaped edifices (cumulo-domes) while those built from both lavas and fragmental material (stratovolcanoes) are usually higher and have steeper, characteristically concave, flanks. The volcanoes

on the Caribbean island of Montserrat, that include the Soufrière Hills Volcano which erupted spectacularly in 1997, are stratovolcanoes, as are most of the active volcanoes in the Philippines including the highly-active Mayon on Luzon Island. Mt Egmont on the North Island of New Zealand is a mixture, its base being domed and representing an earlier phase of eruption to that involving mostly fragmental material that built the stratovolcano above. The largest volcanoes on Earth commonly form oceanic islands, such as those of the Hawaii Islands, and are known as shield volcanoes, from the shape of the edifice they form, which is built almost entirely from basalt lava.

Once a volcano ceases to be significantly active, its form will generally degrade in common ways. Around symmetrical volcanoes, a radial drainage pattern will normally develop and, through time as some streams are 'captured' by their neighbours, relict pieces of the flanks of the original volcano (planezes) will be isolated from erosion and may persist for much longer than the rest; planezes on the island of St Helena (South Atlantic), that last erupted some 7 million years ago, are used as pastures on this otherwise deeply-eroded volcanic island. Most oceanic volcanoes subside when activity wanes or ceases, resulting in drowning of island coasts and the formation of bays where there were once valleys; stellate (star-shaped) islands like Ono (southern Fiji) may form (Nunn, 1994).

Near the end of the active life of an island volcano, a caldera may form, either from explosion tearing out the heart of the old volcano or collapse of the summit into an empty magma chamber below. The landscape of the island Nisyros (Aegean Sea) is dominated by a 15 km² caldera. On Lihir (Niolam) Island in Papua New Guinea, formation of the Luise Caldera revealed a huge gold deposit (Corbett *et al.*, 2001).

Although an island comprising one or more extinct volcanoes may no longer pose a threat to its inhabitants from eruption, the steep-sided character of some oceanic volcanoes means that they are also notoriously unstable. The Hawaii Island chain, for example, is one of the steepest-sided structures on the Earth's surface and has experienced periodic catastrophic flank collapses. One of these, perhaps around 105,000 years

ago, may have created a wave more than 300 m high that washed back over the Hawaiian islands Lana'i and Moloka'i leaving behind gravels containing innumerable coral fragments (Moore & Moore, 1984; Moore *et al.*, 1994). The same wave may have crossed the Pacific, driving up onshore every coast it encountered (Young & Bryant, 1992).

Collapse of volcanic island flanks can occur with both active and extinct volcanoes. For example, the high volcanic islands of the Canary Islands have experienced enormous flank collapses many times in the past, some of which may have been caused only by gravity, others of which may have been triggered by the intrusion of magma deep within the volcanic edifice causing its flank to bulge and eventually collapse (Carracedo, 1994). Monitoring of the west flank of Cumbre Vieja Volcano on La Palma Island (Canary Islands) is seeking to predict its collapse which might produce high waves that could have devastating impacts on Atlantic coasts (Ward & Day, 2001).

Limestone island landscapes

Limestone is permeable so that the surface landscapes of limestone islands are often slow to evolve and may continue to represent the form of the island when it emerged above the ocean surface long after this event occurred. An example is the island of Niue (South Pacific), a coral atoll before it began emerging about 600,000 years ago. Niue now lies 70 m above the ocean surface yet the former lagoon and the former ring reef (named the Mutalau Reef) are clearly visible in the modern landscape (Nunn & Britton, 2004). The fringes of emerging limestone islands in warmer ocean-surface waters are often marked by staircases of fossil coral reefs; those on the island of Choiseul (Solomon Islands) extend 800 m above sea level (Stoddart, 1969), those on Halmahera (Indonesia) to 1000 m (Hall *et al.*, 1988).

The surfaces of many limestone islands are low relief; areas of lower ground (sinkholes or dolines) mark the places into which surface water is concentrated before moving down below the surface. In certain limestones, funnel-like sinkholes may develop close together and extend downwards several metres, giving rise to particular types of karst landscape, such as the

cockpit country of Jamaica (Day, 1976). Long before humans arrived, the remote limestone island of Nauru (central Pacific) was home to millions of seabirds whose phosphate-rich excrement filled the sinkholes. Mining of Nauru for phosphate during the 20th century has re-exposed the original karst (pit-and-pinnacle) landscape (Weeramantry, 1992; see Figure 5).



Figure 5 - Contemporary pit-and-pinnacle landscape on Nauru island, west Pacific, created by phosphate extraction.

If the surfaces of limestone islands are commonly slow to change, then the same cannot always be said of subterranean parts. On many limestone islands, rain water percolates down from the ground surface and forms a freshwater lens that rests on top of limestone saturated with seawater. The unsaturated (vadose) zone above the freshwater lens is commonly riddled with cracks along which water trickles downwards; sometimes the cracks grow into narrow elongate and steeply-plunging caves; the ‘blue holes’ of the Bahamas and Caicos islands are vadose-zone caves formed during the last Ice Age drowned by subsequent sea-level rise (Mylroie *et al.*, 1995).

Within limestone islands, the surface of the freshwater (Ghyben-Herzberg) lens – the water table – is commonly dome-shaped, meaning that water that reaches it through the vadose zone usually then trickles through the limestone at an angle. The concentration of water flow down the dome of limestone-island water tables means that these are places where erosion (through solution and roof collapse) of the limestone is concentrated. Large water-table (or epiphreatic) caves often form in such places, leading downslope from the centre of an island to its coast, typically with a river, representing water flowing at the surface of the water table, running through it. Tatuba Cave in the interior of Viti Levu Island (Fiji) comprises a lower active part containing a river and several dry caves above, a result of the area’s uplift (Nunn, 1998). Similar emerged caves are found along the coast of Isla de Mona (Puerto Rico) where most

have developed along the contact between the principal reef-limestone/dolomite contact, an example of geological structure influencing processes of cave formation (Frank *et al.*, 1998).

Sometimes miniature archipelagoes are created when karst landscapes are drowned, as in the case of southern Vava'u Island (Tonga; Nunn, 1998) and Phang Nga Bay on the Krabi coast of Thailand (Harper, 1999).

About 66% of the continental Caribbean island of Cuba (111,000 km²) is covered by limestone and its landscape reflects this lithology, its great age, and its tropical climate (Iturralde-Vinent, 1997). Most tobacco fields in Pinar del Río province in Cuba are in areas dominated by collapsed limestone separated by isolated remnants of the original surface termed *mogotes* (residual limestone hills).

Composite island landscapes

Many islands cannot be readily classified as either volcanic and limestone. Many such composite islands have distinctive landscapes, at least in places, on account of their varied lithologies.

Larger islands of this kind, normally of continental origin, typically have an older core surrounded by rocks of younger age, often formed only after the landmass became an island. Typical of these is Jamaica (discussed above) and New Guinea, many fringing parts of which are formed by emerged coral reefs (Löffler, 1977; Pigram *et al.*, 1989). In a reverse of this situation, the sedimentary core of Shetland Island (Scotland) that dates back to the Cambrian Era (590-500 million years ago), has become fringed by younger (Tertiary) lavas and intrusive igneous rocks (Stoker *et al.*, 1993).

Among the smaller composite islands are the makatea¹ islands of many tropical oceans that comprise a volcanic centre fringed by uplands made

¹ *Makatea* is a Polynesian word for steep-sided hills of emerged reef limestone, and was adopted by Nunn (1994) for oceanic islands of composite type on which both such limestones and volcanic rocks are exposed.

of emerged coral reefs; several examples are found in the southern Cook Islands of the Central Pacific (Stoddart *et al.*, 1985).

Simple island landscapes

There are many, often smaller islands that have simple landscapes on account of their comparatively simple composition. Such islands can be divided into young coral islands, which owe their existence largely to the growth of living reef, and others, typically those formed from detrital material introduced to nearshore areas by large rivers. Other such islands include ice islands and islands made from floating vegetation and/or pumice which may have been important in the dispersal of certain organisms, known to biogeographers as waifs, from island to island (Stehli & Webb, 1985; Van Duzer, 2004). Waif dispersal is a common explanation for the arrival of certain organisms on particular islands, particularly when those are volcanically active (and have the capacity to produce pumice rafts) or in regions affected by tropical cyclones (which may wash 'mats' of vegetation and soil off the land). The distribution of lizards in the tropical Pacific Islands has been explained largely in this way (Austin & Zug, 1999).

a)- Young coral island landscapes

Islands exist on many broad coral reef flats and are composed primarily of reef detritus driven onto them by large (storm) waves and then concentrated in particular areas by normal wave action. On Funafuti Atoll (Tuvalu, central Pacific), a storm surge associated with Tropical Cyclone Bebe in October 1972 led to the creation of a 'rubble bank' along the edge of the reef off the island's east coast. Over the next few years, this rubble bank was moved slowly landward by wave action and became incorporated into the main island (Baines & McLean, 1976). Analysis of the geology of other such islands in Tuvalu show that they formed from the successive accretion and distribution of rubble banks of varying grade and size, and that on smaller reef platforms, the central lagoon-depression enclosed by these islands might eventually become infilled (McLean & Hosking, 1991).

Newly-formed coral islands of this kind are known as cays and are transient islands that often migrate across reef flats, and even are sometimes removed from them in their entirety. Sometimes, cays persist long enough for conglomerates (such as beachrock) to form just beneath their surfaces, and these help armour the cays and protect them from erosion; well-armoured cays that have persisted for centuries rather than years are known as *motu*. Most inhabited coral islands in countries like Kiribati and the Marshall Islands in the western Pacific are *motu*, and attention in recent years has focused increasingly on their structure and how it might influence the impact of sea-level rise (Dickinson, 1999).

b)- Non-coral island landscapes

The unceasing denudation of the continents and larger islands is manifested by the suspended sediment load of large rivers. When these rivers reach the sea, much of this sediment is deposited on the ocean floor which then shoals rapidly in places to produce islands. At a later stage these islands often become incorporated into the mainland as they are subsumed by the prograding shoreline of the river delta.

In some places such islands may become colonized by dense mangrove forests that stabilize them and help them endure. While not always desirable places for humans to live, mangrove islands are places where other organisms often thrive, and the destruction of such habitats is frequently lamented. Some of the 54 islands in the Sundarbans, the 10,000 km² mangrove forest at the mouth of the Brahmaputra-Meghna-Ganges in India and Bangladesh, are the objects of conflict between local inhabitants and conservationists (Seidensticker & Hai, 1983). Owing to their isolation yet relative proximity to the mainland, such islands may also be important places of refuge or retreat; the 6th-century Irish saint Senan founded a succession of monasteries on islands at the mouths of rivers including one on Scattery Island in the Shannon Estuary.

Controls on long-term environmental evolution of islands

The environments of islands that we see today manifest the subtle interplay of nature and humans and it is consequently difficult to

generalize about the long-term evolution of island environments. Yet understanding environmental evolution is a necessary preliminary to appropriate and successful environmental management, increasingly a priority on many islands (Nunn, 2004). The principal controls on long-term environmental evolution of most islands are geology, climate (including changes in sea level), and extreme or rapid events. For those islands that have been inhabited by people for a significant length of time, pre-modern human impacts are often also a significant contributor to environmental development. Each of these four distinct controls is discussed separately below.

a)- Geological controls

The key element in understanding the evolution of island environments is time, specifically how much time has elapsed since that island appeared. Geological history can provide an answer to that, and also to the various earth-surface processes that have, from time to time, dominated in the moulding of island environments. For example, many island environments have been affected by volcanism, others have been pushed upwards from beneath the ocean without a hint of volcanic activity, while others have alternated between periods in which each of these processes occurred. Good examples of the latter are found where a former volcanic island sinks beneath the ocean surface, becomes covered with reef limestone, and then emerges; the island of Vava'u (Tonga, South Pacific) is composed of emerged reef limestone that covers an ancient caldera (Cunningham & Anscombe, 1985).

Many volcanic rocks are easy for natural denudational processes to mould whereas most limestones are more resistant and, on account of their permeability, comparatively unaffected by many of the processes of surface denudation. Most volcanic islands in Samoa (South Pacific) have deep-cut valleys, a consequence of the low-resistant lavas from which many formed. The massive peridotites (olivine-rich igneous rocks) that cover 30% of the main island (La Grande Terre) in New Caledonia have produced ultrabasic (very low silica) soils containing elements that are toxic to many plants (Jaffré & Latham, 1974); this explains why much

of this area is covered with *maquis*, a low, sclerophyllous heath that is easily cleared to expose the underlying regolith (weathered bedrock) to erosion.

The geological structure of some islands exercises the dominant control on their landscapes and the ways they have evolved. The island Iceland (North Atlantic) is one of the very few places on the Earth's surface where a mid-ocean ridge (divergent plate boundary) emerges above the ocean surface, and it is therefore cut by a 150-km wide rift valley within and on the high flanks of which there is considerable volcanic activity (Bott, 1985). Ancient fold belts around the eastern Mediterranean margins extend onto islands offshore; for example, Crete and Rhodes islands are parts of the Hellenic Arc that is exposed most broadly in mainland Greece (Barka & Reilinger, 1997).

Many islands, particularly oceanic islands, lie in tectonically-active locations, and their environments manifest the long-term effects of tectonic processes. Owing to their location in a compressive tectonic zone associated with plate convergence, Miocene coral reefs on the large island of New Guinea-Irian Jaya (Papua New Guinea and Indonesia) emerged and became covered with impermeable volcanic cap rocks creating hydrocarbon reserves (Hill *et al.*, 1996). On a smaller scale, the island of Moala in southeast Fiji is bisected by a rift valley that has opened progressively as the island has risen up a flexure in the ocean floor formed as a result of plate subduction nearby (Nunn, 1995). The removal of Last-Glacial ice cover from some islands has resulted in their emergence, marked in cooler ocean waters by staircases of 'raised beaches', as are common on islands such as Lasqueti Island off the coast of British Columbia, western Canada (Hutchinson *et al.*, 2004).

b)- Climate and sea-level controls

While geology may account for variations in the character of island environments, it is climate that largely drives the processes by which much of that change is accomplished. Weathering of islands in hot climates involves different processes – at commonly faster rates – than

in colder climates. High levels of mean annual precipitation, especially when that is concentrated seasonally and/or in storms, generally result in faster and more profound changes in the environments than occur in all-year drier climates. For example, ground-surface lowering is 3-4 mm/year in the wet New Guinea highlands (Pickup *et al.*, 1980) but only 0.04-0.19 mm/year in the Hawaiian Islands (Li, 1988), rates that are more representative of most islands.

The oscillating temperatures of the Late Cenozoic Era (last 10 million years), particularly during the Quaternary (last 1.8 million years), caused the Earth's climate to swing between cool ice ages (glacials) and warm interglacials, such as that (the Holocene) in which we are currently living. Changing temperatures forced vegetation zones to shift, and with them those organisms that could not adapt to the changed climate. Although the effects of these climate changes on certain islands may have been somewhat offset by the dominance of maritime influences in their climates, most high-latitude islands were subject to alternating glaciation and deglaciation during this period. Even high subtropical islands like Hawai'i experienced such climate changes and associated processes which have left their mark on the island's modern environment (Porter, 1979). In general, the temperatures of lower-latitude islands did not change much during the Quaternary although many experienced aridity, the legacy of which is visible today. The grasslands that exist in many parts of the Pacific Islands were once thought to be wholly anthropogenic - created only after humans arrived and began burning the native forests - although now many such grasslands are suspected to be far older, a relic ecosystem that developed during the arid Last Glacial Maximum about 18,000 years ago (Nunn, 1994).

Quaternary temperature fluctuations also drove sea-level changes that fundamentally altered the geography of the ocean basins and the islands they contain. During periods of low sea level (the 'ice ages'), island areas increased and islands became closer together, facilitating biotic dispersal. Island climates have altered because of the increased altitude. Conversely, during periods of comparatively high sea level (interglacials), islands were

smaller, farther apart, and many islands which were 'high' 18,000 years ago during the Last Glacial Maximum may today only poke a metre or two above the ocean surface.

c) - *Extreme or rapid events*

Viewed in the context of long-term environmental evolution, extreme or rapid events may in fact have lasted decades rather than days but still have left a profound and long-lasting signature.

A good example of a climatic event that was both extreme and rapid compared to times before and after is the Younger Dryas, an approximately 1000-year long reversion to almost full glacial climate that began around 11,000 years ago during the period of postglacial warming. It seems clear that tropical islands were among those affected by rapid temperature fall during the Younger Dryas; sea-surface temperatures 10,200 years ago in the Vanuatu archipelago were around 5°C cooler than today, a likely Younger Dryas signature (Beck *et al.*, 1992). Changes in the rates of upwelling around Caribbean islands during the Younger Dryas (Overpeck *et al.*, 1989) would probably have had significant impacts on their biotas.

A similar, more recent example is the 'AD 1300 Event', a period of rapid cooling and sea-level fall that affected the Pacific Islands (and perhaps elsewhere) for around 100 years beginning about AD 1250 (Nunn, 2000, submitted). Among the direct environmental effects were the emergence of islands made of surficial materials, the emergence of nearshore coral reefs, and degradation of lagoonal ecosystems.

More rapid, catastrophic events have also figured in the long-term evolution of island environments, although the identification of such events is often controversial. Giant waves, from storms or tsunamis, have sometimes left behind diagnostic deposits; an example comes from the Okupe Lagoon in New Zealand (Goff *et al.*, 2000). Collapse of island flanks, even entire islands, is an important process in their long-term collapse; such events have been isolated by geological survey, as in the case of Johnston Atoll in the Central Pacific (Keating, 1987), and by myth,

as with the now-vanished islands Tuanahi in the Southern Cook Islands (Nunn, 2001a) and that of Mamata in Vanuatu (Nunn *et al.*, 2006).

d) - Pre-modern human impacts

Owing to the vulnerability of most island ecosystems, the effects of human colonization are often regarded as having been immediate and massive. While there are many case studies suggesting that this is the case, such as the charcoal 'spikes' in swamp sediments on Mangaia island in the southern Cook Islands (Kirch *et al.*, 1991), there is considerable evidence to suggest that the connection is less straightforward (Nunn, 2001b). Much vegetation change that led to landscape change was brought about by human commensals, such as rats, or accidentally-introduced exotic plants. The origin of the singular gullies (named *lavaka*) on Madagascar was debated for a long time, with human impact as a leading explanation; it is now clear that *lavaka* have climatic origins although they may have been enlarged by human impact (Wells & Andriamihaja, 1993).

Several authorities have pointed to Easter Island and the 14th century collapse of its society as an example of its inhabitants committing 'ecocide' by cutting down all the island's trees in support of statue construction (Bahn & Flenley, 1992; Diamond, 2005). Such explanations, while salutary and more readily apprehended on smaller islands than on continents, are still contentious and alternatives have been mooted (Hunter-Anderson, 1998). Principal among these is the climatic explanation involving the AD 1300 Event, which sees sea-level fall (and water-table fall) reducing the amounts of food available to island peoples. This in turn forced lifestyle changes, sometimes what might be described as societal 'collapse', marked by conflict in many places (Nunn, 2000, submitted).

The AD 1300 Event led to people throughout the Pacific Islands abandoning their coastal settlements and establishing new ones inland, commonly in fortifiable locations such as hilltops and caves. This led to an abrupt impact on the inland parts of many islands, resulting in their degradation and often an associated response in downstream and coastal areas (Kumar *et al.*, submitted). Deliberate adaptations for the

enhancement of agricultural production also remain visible on many islands today. This is true especially of agricultural terracing, introduced to many tropical Pacific Islands during the arid Little Climatic Optimum (Nunn, 2003).

The beginning of plantation agriculture on many islands, often coincident with the start of their colonial history, resulted in major changes to their environments. Illustrative of this are the rates of erosion from various environments in the Philippines; areas under primary forest (largely undisturbed) lose around 3 tons/hectare/year, while areas of open grassland (converted from forest) lose 84 tons/hectare/yr, and overgrazed areas lose 250 tons/hectare/yr (Myers, 1988).

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Influences on contemporary island environments

Many island environments today bear little resemblance to their historical counterparts. Wholly urbanized islands like Manhattan (New York), Malé (Maldives) and some in Hong Kong are extreme examples of this situation. For most others, it makes sense to separate human influences from natural (non-human) ones. Among the latter, climate change and sea-level rise – often misguidedly regarded as ‘the’ problem confronting many islands (Nunn, 2004) – and catastrophic events are selected for discussion.

a) - Climate change and sea-level rise

Within the past hundred years or so, many islands have experienced ground-surface temperature warming and sea-level rise. This has caused a range of problems although it is sometimes difficult to separate non-

human from human causes. For example, most vegetation change during the 20th century on islands was most likely a consequence of direct human impact although some may have been due to warming and, particularly in low-lying coastal areas, to groundwater salinization resulting from sea-level rise.

Warming has also affected ocean-surface temperatures, and this increase is implicated in recent changes to a number of shallow-water marine ecosystems, most notably coral reefs. When ocean-surface temperatures exceed 30°C for prolonged periods, as they have done increasingly over the past few decades, especially during El Niño events, corals will sometimes be stressed to the point that eject their symbiotic algae, thereby losing their colour (bleaching) and dying. This phenomenon of ‘coral bleaching’ is likely to affect island reefs more frequently in future decades if ocean-surface temperatures continue rising, and many coral reefs are likely to become barren (Hoegh-Guldberg, 1999).

Figure 6. - Adaptation to erosion along an island shoreline: Yadua Village, Viti Levu Island, Fiji.

A - The earliest response was to build a seawall, using largely rock from the fringing coral reef. The seawall was undermined by wave erosion, collapsed and was rebuilt repeatedly until it became clear that this was not an effective long-term option. This view shows part of the degraded seawall, and the land behind, into which storm waves penetrate and erode the coastal flat on which the village lies.



B - The villagers are now replanting a mangrove forest along the worst affected part of the shoreline. This option is sustainable, effective and will enhance the nearshore ecology. The only difficulty is that it may take 25 years for the mangrove fringe to reach maturity. Mangroves are grown in a nursery and then planted out at regular intervals when they are about 80 cm tall.



It is also likely that warming over the past few decades has contributed to both the increased frequency and intensity of tropical cyclones (hurricanes or typhoons) as these usually develop only in ocean areas where the surface temperature exceeds 27°C. In the tropical Pacific, the increased area where this condition is met has resulted in more frequent tropical cyclones that occur increasingly 'out of season' and affect islands farther east than what was long regarded as the cyclone-prone region. Tropical Cyclone Ofa that slammed into the islands of Samoa in 1990 was the first such storm to affect them for more than 35 years.

The problem with sea-level rise being portrayed as 'the' issue with which islands will have to cope in this century is that it encourages poorly-informed and cash-strapped island governments to overlook more pressing problems, both those associated with climate change (such as changes in precipitation regime) and those not linked to climate change (such as population growth) (Nunn, 2004). That said, sea-level rise represents an important challenge for many island communities, particularly those which are ill-equipped to meet it. In many poorer island countries, communities which are only marginally within the cash economy often raise huge sums to build seawalls, believing that these will protect against coastal erosion, both today and in the future. Most such seawalls collapse within a few years of and are often abandoned subsequently (see [Figure 6a](#)); a cheaper, more appropriate and more sustainable solution is to plant (often re-plant) the mangrove forest that once fringed these islands' coasts (see [Figure 6b](#)). As part of a multi-goal coastal rehabilitation programme on Marinduque Island in the Philippines, mangroves are being allowed to grow out over potentially toxic copper tailings in Calancan Bay.

b) - Catastrophic events

Owing to their youth and location, many islands are especially vulnerable to catastrophic events, and many island environments (and peoples) reflect their influence. Many islanders live in the shadow of active volcanoes, sometimes because there is nowhere else to go but often because of the fertile soils and dependable water supply characteristic of many such locations. Examples include the people occupying Tofua Island (Tonga) and those whose food gardens are scattered across the slopes of Merapi

Volcano (Java). In the modern age, volcanic catastrophes affecting islands are mostly containable in that they can be predicted and appropriate action taken to avoid unnecessary impacts. Yet some of the world's largest eruptions have occurred on islands and produced effects that were often felt around the world. The 1883 eruption of Krakatau Island (Indonesia) was audible around 57% of the Earth's surface; it produced devastating tsunamis and eventually destroyed the island (Simkin & Fiske, 1983). Yet it was considerably smaller than the AD 1452 eruption of Kuwae in Vanuatu – probably the largest in the past 10,000 years – that also destroyed the island producing a 72-km² submarine caldera (Eissen *et al.*, 1994) and ejecting so much ash into the atmosphere that northern-hemisphere weather was drastically affected for several years (Pang, 1993). The largest eruption of the past 2 million years occurred at Toba (Sumatra) and formed a 3000-km² caldera; pyroclastic flows covered an area of 20,000 km², and ash an area of about 4 million km² (Lee *et al.*, 2004); so many people were evidently killed by the eruption and the climate changes it produced that it has been cited as the cause of a bottleneck in human evolution (Ambrose, 1998).

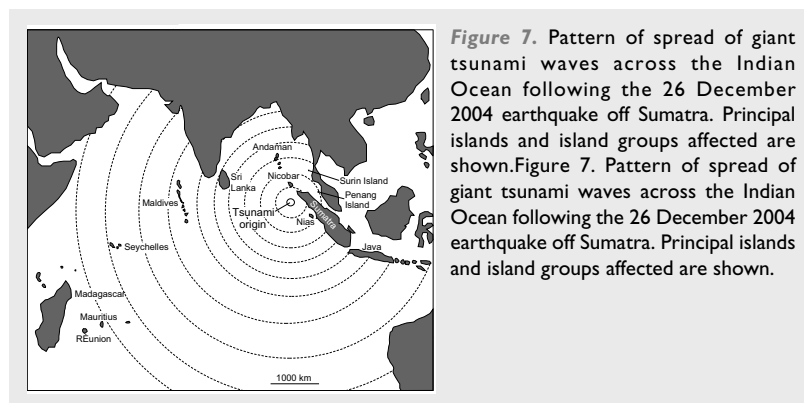
Large earthquakes may also have catastrophic effects on islands, sometimes causing them to rise, sink or tilt. Many islands close to convergent plate boundaries rise coseismically (when earthquakes are coincident with uplift). Parts of the coast of the island Taiwan are stepped indicating the effects of repeated coseismic-uplift events (Huang *et al.*, 1997). During the 1964 Prince William Sound Earthquake in the northeast Pacific, parts of Montague Island rose 11.3 m in a few seconds while parts of Kodiak Island sunk abruptly by more than 2 m (Plafker, 1972). Coseismic subsidence was also the cause of the destruction of Port Royal in Jamaica in 1692 (Gragg, 2000). Tilting is far less common, with the most compelling studies coming from smaller islands in Japan like Awashima and Sado (Ota, 1985).

The history of Pukapuka Atoll (Cook Islands), passed down orally through generations, is dominated by one event named in the vernacular *te mate wolo* (the Great Death) that marks the time when a huge wave swept across the atoll carrying most of its inhabitants away to their demise

(Beaglehole & Beaglehole, 1938). Such waves sometimes obliterate entire islands, sometimes strip them to their unweathered sedimentary foundations, yet sometimes, paradoxically it might seem, create and enlarge such islands by driving reefal detritus onshore (see above). Much of the variation is attributable to the morphology of the ocean floor over which the wave approaches the island, and the amount of sediment it is carrying when it reaches the island coast.

c) The 2004 Indian Ocean Tsunami

The world was reminded of the destructive power of giant waves when, on 26th December 2004, a series of massive earthquakes triggered a series of landslides along the steep underwater flanks of the Sunda Trench off the northeast coast of Sumatra Island in Indonesia that produced a series



of tsunami. Around 260,000 people may have died in consequence, many on islands that lay in the direct path of the wave, such as the Andaman-Nicobar islands and the Maldives ([see Figure 7](#)).

Although high volcanic islands, the coastal environments of the Andaman and Nicobar islands were altered by the 2004 tsunami. Around 30% of Katchal Island in the latter group was washed away (www.andaman.org). Of widespread concern in these islands is the effect of saltwater having washed over the land, particularly productive agricultural land, and leaving a layer of salt behind that will inhibit crop regrowth.

The saltwater that covered the low atoll islands in the Maldives also affected agriculture but, more critically, has laid down a mass of saltwater on top of the islands' freshwater lenses which has drastically reduced ready access by many rural dwellers to drinking water, a situation that may endure for years (www.newscientist.com).

The lack of devastation in the Maldives has been attributed to the preservation of their offshore reefs which provide a formidable physical barrier to large waves; a similar situation pertained in the Surin Islands off the west coast of Thailand. Where mangroves fringed the coast, such as on Penang Island in Malaysia, it is also clear that far less devastation took place. Yet such ecosystems were not unscathed by the tsunami, with the physical structure of reefs likely to have been undermined and their health impacted by the overlaying of sediment (www.oceansatlas.org).

d) - Human influences

The least mistakable influences of humans on island environments are when these have been transformed for various human purposes, typically accommodation, recreation, infrastructure and commerce. Although some islands exhibit such influences clearly, the majority do not, and indeed islands are often perceived as places of refuge from the overcrowded and poorly-managed environments of continents.

Yet human influences on island tourism may sometimes be considerable, from the construction of artificial reefs to the creation of sand beaches of correct texture, in addition to the infrastructure and the challenges of waste disposal arising from introducing large numbers of visitors to environments that need to appear pristine (Howard, 2001).

As island populations have increased, whether this be in large cities or rural villages, there has often been a need to increase food production proportionately. Overfishing of island waters, overexploitation of reef foods, and the development of aquaculture have all, in their own way, raised questions about the future sustainability of island environments. On islands that are part of the 'developing world', the imperative of many people to produce food and earn money has resulted in negative

environmental impacts that national legislation is generally unable to stop. Similarly, the desire for foreign investment and foreign earnings in many such island countries often produces similar negative environmental effects. Owing to artificially-high prices for Fiji sugar resulting from a trade pact with the European Union, cane was planted on slopes of up to an inclination of 22° with soil loss equivalent to 90 tons/hectare/yr (Clarke & Morrison, 1987), a rate much greater than the tropical soil-loss tolerance level of 13.5 tons/hectare/yr (Hudson, 1971).

Among the most conspicuous environmental impacts on some islands are those related to mining, associated both with direct impact at mine sites and downstream effects, typically concerned with the disposal of mining waste. Many of the problems that led to the closure in 1989 of the giant copper mine on Bougainville Island (Papua New Guinea) were attributable to downstream pollution (Brown, 1974). Examples from the Philippines were described by Coumans & Nettleton (2000) and from the large island of New Guinea by Heffler *et al.* (1997).

On many smaller, more remote islands, the need for building materials, commonly sand and rock, has led to undesirable environmental impacts. Beach-sand mining on Dominica (Caribbean), a result of rapid population growth and tourism growth, has led to severe erosion of some beaches (Cambers & James, 1994) while the atoll islanders of the Maldives, lacking any other source of hard rock, excavate their coral reefs for building materials (see Figure 6a).

Island environmental futures

Many of those responsible for managing island environments are grappling with multiple environmental-related problems, almost all accentuated by islandness, with insufficient financial or human resources at their disposal, and often with little meaningful political backing (Liew, 1990; Granger, 1997; Hollinshead, 2001; Nunn, 2004). Most professionals who are managing island environments have also been trained in continental environments and assume – often with disastrous consequences – that islands are merely continents in miniature (Doumenge, 1987; Carpenter & Maragos, 1989; Baines,

1995). There is no shortage of bleak prognostications for the future of island environments, from the possibility of climate change causing the Gulf Stream to weaken bringing cold wet summers to the Western Isles of Scotland (thereby discouraging tourism; www.arct.cam.ac.uk), the flooding of Caribbean island wetlands with huge ecological consequences (Nicholls *et al.*, 1999), to the possibility that entire nations of low-lying islands like Tokelau and Tuvalu could disappear (Lewis, 1990). There is considerable cause for pessimism about the future of island environments (Zurick, 1995; Pelling & Uitto, 2001; Connell, 2003; Nunn, 2004).

A way forward is to recognize island environments – perhaps with isolated and archipelagic subsets – as distinct and requiring appropriate solutions to environmental problems devised and implemented by persons with the long-term interests of islands at heart. Many islands are regarded as economically ‘under-developed’ which explains why sustainable environmental development will always be considered secondary – despite many fine speeches – to income-generating activities by those island leaders. Hopefully the continuing deterioration of island environments – and with it the lifestyles of their inhabitants – will one day provoke drastic responses from those committed to their future.

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