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Atolls, Experiments, and the Origin of Islands

Science as a Way of Knowing the Pacific since 1766

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This chapter focuses on the knowledge tradition known as *science*, as it was practised in the Pacific during the two and a half centuries following Bougainville and Cook's voyages of self-consciously 'scientific' exploration in the late eighteenth century.[1] Rather than trying to summarize the full breadth of scientific activities in the Pacific across more than 250 years, I will focus on one continuous tradition of research – studies of how islands were formed – that brings into relief three broader themes characteristic of scientific ways of knowing Oceania: the significance of typological (or taxonomic) thinking c. 1770–1850; a shift in the effects of long-distance travel on scientific practices and theories from about 1820 to 1920; and the tendency to view individual Pacific islands as 'laboratories' for the development of scientific ideas from the late nineteenth century to the present.

Historians writing about Western science in the Pacific often emphasize the theme of 'science and empire', pointing out voyaging savants' reliance on resources of the imperial state, and, reciprocally, the contributions their activities made towards extensions of European and American power in the region.[2] Cook's three voyages highlight the contradiction between the then-common rhetoric of science as the pursuit of disinterested knowledge

[1] On the idea that science has been one among many knowledge systems in the Pacific, see D. Turnbull, 'Reframing science and other local knowledge traditions', *Futures* 29:6 (1997), 551–62. For a sharp criticism of efforts to analogize modern astronomy and 'ancient' Hawaiian knowledge, see I. Casumbal-Salazar, 'A fictive kinship: making "modernity," "ancient Hawaiians," and the telescopes on Mauna Kea', *Journal of the Native American and Indigenous Studies Association* 4:2 (2017), 1–30.
[2] Valuable surveys of the topic include R. MacLeod and P.F. Rehbock, *Nature in Its Greatest Extent: Western Science in the Pacific* (Honolulu: University of Hawai'i Press, 1988); D.P. Miller and P.H. Reill, *Visions of Empire: Voyages, Botany and Representations of Nature* (Cambridge: Cambridge University Press, 1996); R.M. MacLeod and P.F. Rehbock, *Darwin's Laboratory:*

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undertaken for the benefit of humankind and the underlying reality that scientific activities in the Pacific were often mutually constituted with imperial or commercial undertakings.

On one hand, each of Cook's three voyages investigated a fundamental question about the Earth that had fascinated savants of many nations. The publicly advertised reason for his first voyage to the Pacific (1768–71) was to be in position to witness the 'transit' of the planet Venus in front of the sun from the southern hemisphere, and thereby to help establish the Earth's distance from the sun.[3] His second voyage (1772–5) ranged widely across the Southern Ocean to investigate the existence of a hypothesized southern continent, and his third voyage (1776–9) sought a northern passage between the Pacific and Atlantic oceans.

On the other hand, Cook consciously undertook these voyages for the purpose of gaining useful knowledge and potentially acquiring new possessions. For example, the supplemental instructions for the first voyage, marked 'secret', directed Cook to sail south and west from Tahiti on an exploratory mission that would 'redound greatly to the Honour of this Nation as a Maritime Power, as well as to the Dignity of the Crown of Great Britain'. After three months sailing along the eastern coast of the continent now known as Australia he claimed the whole territory for Britain.

The legacies of outlanders' science in the Pacific are increasingly being contested by residents of Oceania, as evidenced recently by the critical reminiscences that emerged surrounding the 250th anniversary of Cook's entry into the Pacific and the ongoing protests of the proposed Thirty Meter Telescope atop Mauna Kea in Hawai'i. This chapter provides context to these important developments by documenting the origins and sustained power of a view that came to hold such sway among outsiders, that Pacific islands were remote and often interchangeable laboratories for the study of nature.

Evolutionary Theory and Natural History in the Pacific (Honolulu: University of Hawai'i Press, 1994); T. Ballantyne, *Science, Empire and the European Exploration of the Pacific*, Pacific World 6 (Aldershot: Ashgate, 2004); J.C. Beaglehole, 'Eighteenth century science and the voyages of discovery', *New Zealand Journal of History* 3:2 (1969), 107–23; S. Sivasundaram, 'Science', in D. Armitage and A. Bashford (eds.), *Pacific Histories: Ocean, Land, People* (New York: Palgrave Macmillan, 2014), 237–60; S. Kroupa, S.J. Mawson, and D. Brixius, 'Science and islands in Indo-Pacific Worlds', *British Journal for the History of Science* 51:4 (2018), 541–58; G. Williams, *Naturalists at Sea: Scientific Travellers from Dampier to Darwin* (Princeton: Yale University Press, 2015).

[3] The transit of Venus was a rare astronomical event, and the idea was that combining multiple observations from around the world would make it possible to calculate the physical distance from the Earth to the Sun.

Typological Thinking: From Low Islands to Atolls

Many commentators on eighteenth-century science have noted the ascendance of an urge to catalogue and classify, as exemplified by the taxonomies of Linnaeus and the *Encyclopédie* of Diderot and d'Alembert. This typological way of thinking guided naturalists' activities in the Pacific and, notoriously, resulted in Jules Dumont d'Urville's tripartite racial/geographical classification of Melanesia, Micronesia, and Polynesia. (Western classifications of Pacific Islanders are discussed in Chapter 48 by Bronwen Douglas.)

Many of the same voyagers who collected specimens and classified human groups also applied typological thinking to the character of the Pacific's islands themselves. The impulse to classify islands by their morphology went hand in hand with an assumption that islands of a given type must have had the same mode of formation. This meant that the localized surveys of *particular* islands undertaken by Pacific navigators in the decades around 1800 would be relevant to developing *general* theories of island formation. I show in this section that the peculiar threat posed by coral reef growth spurred a change in the practice of surveying, away from prioritizing the accurate description of specific locations towards seeing individual reefs as representative instances. This fostered survey practices that could produce broadly applicable *theories* of the coral reef formation, which in turn might help to predict where reefs would be found and how quickly new ones might arise.

Both Bougainville on his circumnavigation (1776–9) and Cook on his first voyage (1768–71) piloted through a vast group of reefs east of Tahiti, the Tuamotu Islands of present-day French Polynesia, consisting of what would later be called 'atolls'. The reefs formed narrow ring- or horseshoe-shaped arcs that encircled shimmering lagoons. Atop the reefs appeared to be low, sandy islands that scarcely hinted at the extent of treacherous shoals beneath them. Bougainville named this area *l'archipel Dangereux*, the Dangerous Archipelago. Because navigating among reefs was risky, and the land atop them appeared scant and unpromising, Bougainville was loath to devote much energy to surveying the individual reefs. Indeed, the Dangerous isles seemed so generic that Cook would struggle on his first voyage to determine whether he was naming new islands or duplicating ones Bougainville had already seen. One particular source of uncertainty was Hao atoll, which Bougainville called *Île de la Harpe* (Harp Island) and Cook unwittingly renamed Bow Island (each in reference to its roughly semi-circular outline).

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In the narrative of his voyage, Bougainville asked of Harp Island, 'Is this extraordinary land rising, or is it in ruins?'[4]

The first naturalist to offer an answer to Bougainville's question was Johann Reinhold Forster, who saw the Dangerous Archipelago and many other Pacific island groups during Cook's second voyage to the Pacific (1772–5). Forster had been the translator for the English edition of Bougainville's narrative, and the contents of his journal from the voyage show that Forster arrived in the Central Pacific primed to contemplate the puzzle of island formation. After sailing through the Tuamotus, he was struck by the contrast with Tahiti and the other Society Islands, whose mountainous terrain made them utterly different from the islands comprising the archipelago to the east. Having seen low and high islands juxtaposed in such a short time, Forster began to think about them as two types exhibiting systematic differences, writing in his journal that 'we might account in a double manner for the formation of Isles. The high ones seem to be the work of fire [i.e. volcanic activity] & the low ones are the work of the Sea & its Inhabitants.' He noted that it was well known 'that all the low Islands in the South-Seas are surrounded to the South & South East by a reef of rocks', which, he discovered, 'when examined, are nothing else but immense lumps of rocks of the *Lythophyta Class*' – that is, corals. He conjectured that these stony plants (lithophytes) formed ring-shaped reefs 'by instinct'.[5] Forster was arguing, for the first time in the tradition of 'Western' science, that the oceanic reefs of the Pacific are *built by corals*. Indeed, the term 'coral reef' came into use as a response to Forster's work.

He published his taxonomy and corresponding theories of island formation in a book that vividly exemplified the late eighteenth-century scientific desire to classify phenomena into types. His *Observations Made on a Voyage Round the World* (1778) was unprecedented among Pacific travel reports in treating landforms *systematically*, rather than in the chronological order that they were visited.[6] Forster enumerated the differences between two great

[4] L. de Bougainville, *Voyage autour du monde, par la frégate la Boudeuse, et la flûte l'Étoile, en 1766, 1767, 1768 et 1769* (Paris: Saillant & Nyon, 1771), 182–3.

[5] Entry for 15 August 1773, J.R. Forster, *The Resolution Journal of Johann Reinhold Forster, 1772–1775*, 4 vols., ed. M.E. Hoare (London: Hakluyt Society, 1982), vol. II, 323–4.

[6] Forster organized his book in this manner at least in part because the British Admiralty denied him the assignment of writing the official history of the expedition and prohibited him from authoring a competing chronological account, although, as I have indicated, his journal from the voyage indicates that he was disposed to view islands taxonomically even before facing the obligation to publish in an unconventional style. On the book, see N. Thomas, 'Johann Reinhold Forster and his "Observations"', in N. Thomas, H. Guest, and M. Dettelbach (eds.), *Observations Made during a Voyage Round the World* (Honolulu: University of Hawai'i

classes of Pacific islands, the high and the low, and distinguished two subclasses of high islands: those encircled by reefs (e.g. Tahiti and the Fiji islands) and those (mainly outside the tropics) that were unprotected by shoals.[7] He attributed all the low islands to 'the polype-like animals forming the lithophytes'. These corals created prodigious structures towering from the ocean floor all the way to sea level, at which point they could build no higher but sand and shells would accumulate to form low islands atop the reefs.[8]

Like countless other naturalists who would travel the Pacific, Forster learned what he could from locals; to be sure, 'scientific' knowledge of Oceania did not develop independently of other knowledge systems. He considered his conjectures about the volcanic origins of high islands (even those with no active volcanoes) to be supported by his ethnographic work in the Society Islands. The Tahitians' descriptions of their God, O-Maoowe [Maui], 'who in his anger shakes the earth, and causes earthquakes', seemed to him 'to prove, that they are not quite strangers to this tremendous phaenomenon'. Moreover, he thought it plausible to interpret their story that 'O-Maoowe dragged a great land from West to East through the ocean [of which] their isles were broken off as little fragments, and left in the midst of the ocean' as a sign that 'they have not forgotten that their habitations formerly were parts of a great continent, destroyed by earthquakes, and a violent flood, which the dragging of the land through the sea seems to indicate'.[9]

When Forster's *Observations* was published, his claim that the low islands owed their origin to the labour of living creatures proved to be one of the most unexpected and widely remarked features of the book, and it led to widespread interest in coral growth in the late eighteenth and early nineteenth centuries. The idea that corals could produce significant changes to the (submarine) vertical relief of the Earth's surface suggested that these lowly creatures were in fact a major force reshaping the world. In France, the zoologist Jean Vincent Félix Lamouroux drew on reports from the Pacific to argue that the Earth might be entering a new geological age of corals,

Press, 1996), xv–xxii; M. Dettelbach, '"A kind of Linnaean being": Forster and eighteenth-century natural history', in *Observations Made during a Voyage Round the World,* lv–lxxiv.

7 Forster, *Observations Made during a Voyage Round the World*, 14–15.

8 Forster, *Observations Made during a Voyage Round the World,* 149–52.

9 Forster, *Observations Made during a Voyage Round the World*, 158–9. Forster also devoted a long section of his *Observations* to discussing the Raʻiātean navigator Tupaia's testimony about the locations of Pacific islands as part of his even longer review of the knowledge held by Society Islanders (511–28). (On the continued significance of Tupaia's exchanges with Cook, see Anna Johnston's Chapter 34, 'Europe's Other?' in Volume II.)

warning that reefs might one day grow so thickly in the tropical oceans that it would no longer be possible to sail between the northern and southern hemispheres.[10]

In 1816 and 1817, Otto von Kotzebue, a lieutenant in the Russian Navy, began using wintertime interludes between efforts to find a Northwest Passage to study low islands in warmer latitudes. Kotzebue was accompanied by two scientific gentlemen, the official naturalist, Adelbert von Chamisso, and the ship's physician and assistant naturalist, J.F. Eschscholtz. Kotzebue spent several months at the atolls of the present day Marshall Islands.[11] Because his vessel, *Rurick*, was very small for a ship of exploration at 180 tons burthen (roughly half the tonnage of *Endeavour*), he was able to navigate more closely near and between reefs than other navigators had managed.[12] Kotzebue's narrative of the voyage suggests that he was so fascinated with coral islands that he could not resist taking repeated risks to his ship. A striking feature of Kotzebue's account of surveying was to indicate the intense labour and extended time it could take for European voyagers to apprehend the form of islands whose 'type' would become obvious when fully plotted on a chart. For example, he was almost two weeks into his survey of a reef he named 'Romanzoff' before he perceived that it curved back on itself and supported a whole 'circle of islands'. Through the process of surveying and map-making, Romanzoff and other reefs in the group we now call the Marshall Islands were revealed to Westerners as 'low islands' (later 'atolls') that belonged to the same class as those in the Dangerous Archipelago.

Kotzebue's experiences reveal that Western cartography was not intrinsically necessary for recognizing the form of an atoll. The crew of the *Rurick* spent many weeks among the Islanders of Romanzoff, which turned out to be called Otdia [Wotje].[13] Among the benefits of learning to converse with the Islanders was receiving their descriptions of the other islands in what they called the

[10] J.V.F. Lamouroux, *Histoire des polypiers coralligènes flexibles, vulgairement nommés zoophytes* (Caen: F. Poisson, 1816), lix.

[11] O. von Kotzebue, *A Voyage of Discovery into the South Sea and Beering's Straits for the Purpose of Exploring a North-East Passage, Undertaken in the Years 1815–1818*, 3 vols. (London: Longman, Hurst, Rees, Orme & Brown, 1821), vol. I, 355.

[12] On the size of the ship, and advantages and disadvantages of a small ship for a voyage of discovery, see Krusenstern's discussion in Kotzebue, *A Voyage of Discovery*, vol. I, 13–14 and vol. II, 291–313.

[13] On interactions between Kotzebue, Chamisso, the artist Louis Choris, Lagediack, and a Caroline Islander named Kadu, see B. Douglas and E. Govor, 'Eponymy, encounters, and local knowledge in Russian place naming in the Pacific islands, 1804–1830', *Historical Journal* 62:3 (2019), 709–40; H. Liebersohn, *The Travelers' World: Europe to the Pacific* (Cambridge, MA: Harvard University Press, 2006).

Radack [Ratak] group (the eastern chain of the Marshall Islands). One Islander, whose name Kotzebue rendered as Lagediack, indicated that the rest of the chain also consisted of islets clustered into rings. After Kotzebue had indicated his desires by 'pantomime' and demonstrated how he recorded information on his charts, Lagediack drew several circular groups of islands and explained their distance in number of days' sailing. Kotzebue also described Lagediack's own 'very clever method' of depicting the 'geographical situation': 'he drew on the sand a circle, nearly in the form of the group Otdia [the atoll Wotje], placed round the edge of it large and small stones, which represented the islands; and . . . marked the channels', and 'explained [the other low islands] in the same sensible manner'.[14]

When Kotzebue saw, with the aid of Lagediack's directions, how the other low islands of the chain shared Wotje's annular form, he concluded that their 'uniformity . . . is probably not accidental; but this structure seems to be peculiar to the corals'.[15] Along with Kotzebue, the naturalists Chamisso and Eschscholtz wrote extensively about reefs, meditating on the degree to which the low islands all belonged to a single natural class of objects. Both remarked on the likelihood that the low islands and reefs of the Pacific 'belong[ed] to the same formation' – and thus the same 'type' – as similar ones reported in the Indian Ocean, though each separately emphasized that such opinions were based on 'imperfect and unsatisfactory accounts'.[16] Chamisso wondered how fast coral rock accumulated and how quickly low islands formed and changed. Any desire that he or other Europeans might have to settle the matter was constrained by the relatively brief duration of their visits to coral islands. Though he reported that 'the progressive growth of the reef does not seem to have escaped the natives' of the Sandwich Islands (Hawai'i), the rate of accumulation of coral rock could hardly be studied directly in a stay of a few weeks.[17] For this reason, Chamisso concluded his own discussion of reef formation with a call to action for naturalists who might follow him across what he called the Great Ocean: 'An accurate description of the state of these

[14] Kotzebue, *A Voyage of Discovery*, vol. II, 84.

[15] Kotzebue, *A Voyage of Discovery*, vol. II, 116–17. Kotzebue also offered extended reflections on the progressive formation of reefs, about which he wrote, 'It is a strange feeling to walk about on a living island, where all below is actively at work.' See vol. II, 27–8, 36.

[16] A. von Chamisso, 'Remarks and opinions of the naturalist of the expedition', in Kotzebue, *A Voyage of Discovery*, vol. III, 359; [J.F. Eschscholtz], 'On the coral islands', in Kotzebue, *A Voyage of Discovery*, vol. III, 331–6, at 334.

[17] According to Chamisso, the Sandwich Islanders 'who, at the king's order, fetched stones out of the sea, to build a wall, declared, while at their work, that it would grow, and increase of itself'; Chamisso, 'Remarks and opinions of the naturalist of the expedition', vol. III, 238.

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reefs at different periods, for instance, at an interval of half a century, if it were possible and really undertaken, must contribute to throw light upon many points of natural history.'[18]

By the end of the 1820s, the low islands of the Pacific were viewed as posing a double challenge to Western ambitions there. First, they were exceptionally hazardous to navigation because they sloped up abruptly from deep water and were difficult to see or anticipate when under sail. Second, the possibility that living corals were capable of extending existing reefs, or producing entire new ones in parts of the sea that had formerly been clear of obstruction, called into question the very enterprise of managing risk by the production of highly accurate charts.

Starting in 1831 the chief hydrographer of the British navy, Francis Beaufort, gave detailed instructions to study coral reef formation to all surveyors dispatched to the tropical Pacific.[19] This assignment differed from other parts of his instructions to hydrographers in a significant respect: they did not specify particular locations to be surveyed. Rather, they emphasized the importance of choosing a representative reef and using it to evaluate general theories of island formation. The first commander to receive such orders was Robert FitzRoy, in preparation for the voyage of the *Beagle* (1831–6). The main purpose of that voyage was to survey the coasts of South America, but Beaufort directed him to continue west toward the 'circularly formed Coral Islands in the Pacific', where 'a very interesting inquiry might be instituted respecting the formation of these coral reefs'.

The instructions explained the 'modern and very plausible theory [put forward by the French naturalists Quoy and Gaimard and endorsed by the British geologist Charles Lyell] that these wonderful formations instead of ascending from the [bottom of the] sea, have been raised from the summits of extinct volcanoes'. A submarine volcano crater would explain low islands' distinctive shape. Beaufort specified that FitzRoy should choose one such circular reef to survey with particular attention to documenting its submarine profile.[20] Four years later, Beaufort sent Frederick William Beechey to

[18] Chamisso, 'Remarks and opinions of the naturalist of the expedition', vol. II, 361.

[19] R. Cock, 'Sir Francis Beaufort and the co-ordination of British scientific activity, 1829–55', PhD thesis, University of Cambridge, 2003.

[20] F. Beaufort, 'Memoranda for Commander Fitzroy's orders', 11 November 1831. Archive of the United Kingdom Hydrographic Office [UKHO] MB 2, 2–24. J.R.C. Quoy and P. Gaimard's suggestion was published in 'Mémoire sur l'accroissement des polypes lithophytes considéré géologiquement', *Annales des Sciences Naturelles* 6 (1825), 273–90. See A. Sponsel, 'Coral reef formation and the sciences of earth, life, and sea, c. 1770–1952', PhD thesis, Princeton University, 2009.

the Pacific with a similar set of instructions and a 'boring apparatus used by miners' that he should use to study the foundation of 'any coral Island which may be well adapted to the purpose'.[21] Through these instructions, the practice of surveying began to draw on the typology of islands suggested by Forster and developed by other naturalists. FitzRoy and Beechey (and Edward Belcher, who replaced an ill Beechey as commander and oversaw the eventual boring) were dispatched to examine features that were irrelevant to navigation in the immediate term, but which promised to be important over the long term if they helped to explain where, how, and at what speed reefs were formed. Around the same time, the American naturalists and crew of the US Exploring Expedition (1838–42) to the Pacific under Charles Wilkes *also* received well-drilling apparatus and instructions to bore through a coral island as part of a larger investigation into reef formation.[22] It proved to be the case for both Belcher and Wilkes's lieutenant Robert Johnson that boring through coral rock was far more challenging than their superiors had anticipated. Nevertheless, the instructions they received indicate that what it meant to survey an island was becoming governed by theories of how it had been formed and, by extension, how it might change. In turn Pacific islands were becoming known by their generic features as much as their individual qualities.

The Effects of Distance: From Grand Theories to Annual Publications

Scientific practices and theories were materially affected by the scale of the Pacific, from its large number of islands to the long durations of travel in and to the region. This section shows how studies of atoll formation changed over a century when the speed and frequency of scientific travel in the Pacific increased significantly. I track Pacific science from the time when wooden sailing vessels carried naturalists on several-year surveying expeditions to an era when academic scientists could avail themselves of steam travel to carry out a season of field research during the northern summer vacation. I argue that the duration and rarity of those long voyages tended to produce broad and ambitious ideas, whereas quicker expeditions tended to produce shorter

[21] Beaufort, 'Memoranda for Capt[ain] Beechey's Orders', 19 December 1835, UKHO MB 2, 218–46, quotations from 241–2.

[22] C. Wilkes, *Narrative of the United States Exploring Expedition. During the Years 1838, 1839, 1840, 1841, 1842* (Philadelphia: Lea and Blanchard, 1844), vol. IV, 286.

publications containing narrower speculations. Grand theories of island formation became rarer, but scholars around the turn of the twentieth century seized the opportunities to pursue comparative and longitudinal studies that had eluded eighteenth- and early nineteenth-century savants.

Charles Darwin was FitzRoy's shipmate aboard the 1831–6 voyage of the *Beagle*. His activities during the voyage unexpectedly addressed Beaufort's instruction to study coral reefs, and they did so by imbuing Forster's typology of Pacific islands with dramatic new significance. By the time the ship had passed through the Pacific and into the Indian Ocean, Darwin had come to reject the prevailing crater-rim theory of low-island formation as 'a monstrous hypothesis', and in its place developed a theory arguing that Forster's three types of Pacific islands (high, reef-encircled, and circular 'low' islands – which Darwin proposed calling atolls) were actually three stages in a genealogical sequence.[23] While on an inland excursion at Tahiti in November 1835, he had gazed across from a steep mountainside to the equally rugged neighbouring island of Eimeo [Moʻorea], which – like Tahiti – was encircled by a barrier reef of coral. In his diary he wrote of being 'forcibly struck' with the idea that if the high island of Eimeo sank very slowly, until eventually it disappeared altogether beneath the sea, while the corals of the barrier reef continued to grow up and maintain the reef near sea level, then the result would be an empty lagoon surrounded by an atoll.

In a succession of private notes and essays and, eventually, in his first scientific treatise, *The Structure and Distribution of Coral Reefs* (1842), Darwin argued that atolls were 'monuments' standing above high islands that had sunk and drowned – which he thought they were likely to do because part or all of the Pacific sea floor was subsiding to compensate for an adjacent bulging of the Earth's crust that had uplifted the continent of South America. This came to be known as the 'subsidence theory' of reef formation, and it was one of Darwin's earliest claims to scientific fame.

[23] This account of Darwin's coral reef formation draws on my earlier work in A. Sponsel, 'An amphibious being: how maritime surveying reshaped Darwin's approach to natural history', *Isis* 107:2 (2016), 254–81; Sponsel, *Darwin's Evolving Identity: Adventure, Ambition, and the Sin of Speculation* (Chicago: University of Chicago Press, 2018). His use of the word 'atoll' (from the Maldivian word *atholhu*) as a general term for all such reefs, in both oceans, served to reinforce his argument that the circularly formed reefs of *both* the Pacific and the Indian oceans had been formed by subsidence of their foundations. Thanks to the wide discussion of his theory the usage became common practice, and in this manner a local term from the Maldives spread through scientific and geographical literatures and eventually became ubiquitous in the Pacific from the Tuamotus to Micronesia.

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Darwin's was a grand theory, linking the form of high and low Pacific islands to large-scale movements of the Earth's crust and, indeed, to the distribution and diversity of plants, animals, and people. Its scale transcended the scope of the half-decade voyage of the *Beagle*, for it purported to explain the origin of literally every coral reef on Earth even though Darwin had only studied three of them in person. After returning to Britain he had used the libraries of London to examine, so far as he knew, 'every original voyage and map' that contained information on the structure and distribution of coral reefs, and he consulted with correspondents who could provide him with geographical information or specialized knowledge that was unavailable in published works.[24] He spent the rest of his life with the reputation as one of the world's foremost scholars of coral reefs, even though he never returned to the tropics or revisited reef formation as a research topic.

The American geologist James Dwight Dana visited the Pacific as a member of the 1838–42 U.S Exploring Expedition. Like Darwin, he spent a handful of years as a young man travelling around the world and then spent a much longer time reaping the harvest from that labour by studying specimens and writing books. Dana visited scores of coral reefs throughout the Pacific, though he did not study any single atoll for as long as the eleven days Darwin spent at the lone atoll he visited (South Keeling in the Indian Ocean). Like Darwin, Dana returned home and devoted the following decade to producing grand treatises on geology and on corals and coral reefs, in which he offered a global-scale account for the origin of atolls and barrier reefs (very similar to Darwin's theory, but according greater significance to seawater temperature), as well as a related explanation for the history of the whole Hawaiian chain of high and low islands.[25]

[24] C. Darwin, *The Structure and Distribution of Coral Reefs* (Berkeley: University of California Press, repr. 1962 from 1842 original), 119.

[25] J.D. Dana, *Report of the United States Exploring Expedition,* vol. x, *Geology* (Philadelphia: C. Sherman, 1849), and *Report of the United States Exploring Expedition,* vol. vii, *Zoophytes* (Philadelphia: C. Sherman, 1846); D.R. Stoddart, '"This coral episode": Darwin, Dana, and the coral reefs of the Pacific', in R.M. MacLeod and P.F. Rehbock (eds.), *Darwin's Laboratory: Evolutionary Theory and Natural History in the Pacific* (Honolulu: University of Hawai'i Press, 1994), 24–48; D.E. Appleman, 'James Dwight Dana and Pacific geology', in H.J. Viola and C. Margolis (eds.), *Magnificent Voyagers* (Washington, DC: Smithsonian Institution Press, 1985), 89–118; D. Igler, 'On coral reefs, volcanoes, gods, and patriotic geology: or, James Dwight Dana assembles the Pacific Basin', *Pacific Historical Review* 79 (2010), 23–49; A. Sponsel, 'Pacific islands and the problem of theorizing: the U.S. Exploring Expedition from fieldwork to publication', in K. Anderson and H.M. Rozwadowski (eds.), *Soundings and Crossings: Doing Science at Sea, 1800–1970* (Sagamore Beach, MA: Science History Publications, 2016), 79–112.

Several coral reef scholars in the late nineteenth and early twentieth centuries deprecated Darwin's theory for having very little empirical basis, referring to the fact that he had spent relatively little time at coral reefs. This new generation travelled to remote field sites throughout their careers, and they drafted journal articles while in transit back to America and Europe and often published them before the next summer's trip. However, faced with the perennial expectation of returning to the field, they never published grand, synthetic treatises like Darwin's and Dana's – even though many claimed to have similarly ambitious plans to explain the origin of all the world's reefs.

Alexander Agassiz (son of Louis Agassiz and successor to his father as director of the Museum of Comparative Zoology at Harvard University) and Alfred Goldsborough Mayer (who had been a student of Alexander's at Harvard) adopted a pair of distinct approaches to studying reefs, neither of which ultimately resulted in a grand theoretical synthesis on reef formation, despite having been undertaken with a view to producing just that.

Agassiz's immense wealth allowed him to undertake a rather grand plan to visit every major coral reef group in the world. What Darwin had done by looking at maps, Agassiz would do by steaming around the globe in vessels such as the US Fish Commission's ship *Albatross*. He did publish a great deal about coral reefs: for example, an account of the Great Barrier Reef, a memoir on coral reefs in the Pacific, and another memoir on the coral reefs of the Maldives. 'In this, as in previous Reports', he wrote in the memoir on the Pacific, 'I have limited myself to an exposition and explanation of the observations made *in each of the coral reef districts examined*, and have only made such comparisons between the various groups as seemed essential.'[26] Agassiz long claimed that his fieldwork would yield a grand new theory, but when he died (of natural causes) at sea in 1910, not only had he never published the promised work synthesizing his coral reef observations, but his sons could not find traces of any such manuscript.[27]

Upon Agassiz's death, his former student Mayer commented:

> It is to be regretted that of the three great writers upon coral reefs Darwin saw only one atoll, Dana sailed past many but was permitted to land upon few . . . and Agassiz was compelled to cover such a vast field that certain of his

[26] A. Agassiz, 'The coral reefs of the tropical Pacific', *Memoirs of the Museum of Comparative Zoölogy, at Harvard College, Cambridge, Mass.* 28 (1903), 1–410, at 11. Emphasis added.

[27] The comparison between Agassiz's work and Darwin's is the focus of D. Dobbs, *Reef Madness: Charles Darwin, Alexander Agassiz, and the Meaning of Coral* (New York: Pantheon, 2005). On Mayer see L.D. Stephens and D.R. Calder, *Seafaring Scientist: Alfred Goldsborough Mayor, Pioneer in Marine Biology* (Columbia: University of South Carolina Press, 2006).

> conclusions, as he states himself, are still tentative; for the solution of some of the questions presented by these problems demands a more intensive and prolonged study than he was able to devote to them.[28]

Mayer, instead, created a research laboratory *at* a coral reef, on Loggerhead Key in the Dry Tortugas (remote reefs at the very end of the Florida Keys), serving as director of the Carnegie Institution of Washington (CIW)'s marine biological laboratory from its founding in 1904 until his death in 1922. Gradually, Mayer came to believe that he would have to expand his field of operations in order to draw general conclusions about how coral reefs are formed. Mayer steamed to the Pacific *and back* in each of the years 1917, 1918, 1919, and 1920. He planted corals on reefs at Sāmoa in 1917, for example, and returned to track their growth, bringing with him successively larger teams of researchers until his untimely death at the age of 54. Between them, Mayer and his collaborators produced hundreds of publications on various aspects of coral reef growth in the first two decades of the twentieth century. Not one of these was a book that offered a globally applicable theory of coral reef formation.

Neither Agassiz nor Mayer ever believed that he had visited his last coral reef. By contrast, Darwin and Dana assumed, once they returned from the single voyages that occupied substantial portions of their respective lives, that they had seen all the coral reefs they would ever see (though in the end Dana did return once to the Pacific in his old age). Each man devoted years after his voyage to massive publishing projects that expanded on the work they had done on their travels, writing not just on coral reefs, but also multiple books on geology for both men, two on barnacles for Darwin, and one on molluscs for Dana, and each determined to do so because they understood this to be literally their life's work.

When frequent, or even annual, coral reef research expeditions became the norm it had several important consequences for reef science. Once excursions to even the most remote reefs of the Pacific and Indian oceans no longer needed to be several-year affairs, then for men like Agassiz and Mayer such trips did not need to be viewed as singular events of a lifetime. Unlike Darwin and Dana, they did not spend five years in transit accumulating observations, specimens, and theories before getting the opportunity to publish their work, and they could not afford to spend added decades

[28] A.G. Mayer, 'Alexander Agassiz, 1835–1910 . . .', *Popular Science Monthly* 76 (1910), 419–46, at 435.

preparing massive treatises. On the contrary, results could be written up on the steam passage home and in print within the year. Especially for Mayer and his contemporaries, the alternating intervals of fieldwork and publication were brief, most of their publications were correspondingly short, and the scope of each paper was consequently narrow. In this transition, speedier travel through the Pacific coincided with broader changes in standards of scientific specialization for individual researchers and shifts in the publishing landscape of science toward an emphasis on journal articles and away from the monographs favoured by Darwin and Dana. Yet, as we shall see, scientists' tendency to generalize from studies of individual Pacific islands continued to thrive in this new era, with updated language of experiments only thinly veiling the persistence of typological thinking.

Treating the Pacific as a 'Laboratory'

In this section I highlight the way an emergent trend of modern science – the heightened status of *laboratories* as sites of knowledge production from the mid-nineteenth century to at least the mid-twentieth century – affected the rhetoric and practice of science in the Pacific.[29] I have already shown how the late eighteenth-century idea that low islands were a distinct 'type' led surveyors to treat individual atolls as representative individuals, whose characteristics could shed light on all members of the group. In this section I show that this approach, seeking to derive general knowledge from studies at/of a particular Pacific island, intensified around the turn of the twentieth century in concert with more vivid use of terminology referring to tests, trials, and experiments. Eventually, the language of 'experiment', the broad rhetoric of science as a disinterested pursuit of knowledge, and even the specific tradition of research into the origins of atolls, were adopted by the military organizers of American nuclear weapons tests in the Pacific as ways of distracting from the damage caused by the blasts.

Charles Darwin's ideas and reputation loomed over these events. Darwin was popularly associated with the Pacific as a result of his post-*Beagle* publications, and his five weeks at the Galapagos Islands in 1835 eventually took on a mythic status for their supposed role in the development of his

[29] On the rise of laboratory-orientated language in conceptualizing field-based research in this period, see R.E. Kohler, *Landscapes & Labscapes: Exploring the Lab–Field Border in Biology* (Chicago: University of Chicago Press, 2002).

evolutionary theory.[30] Because Darwin's reef-formation and evolutionary theories both posited natural entities changing gradually from one 'type' to another over immense time scales, they were often discussed as component parts of a larger Darwinian worldview. Eventually, as historians Roy MacLeod and Philip Rehbock argue in their volume *Darwin's Laboratory*, 'the Pacific became a region of intellectual colonization by Darwinians, as evolutionary theory was called upon to explain the survival . . . of certain organisms and races and the disappearance of others'.[31]

Among the first large-scale scientific enterprises initiated with a view to shedding direct light on Darwin's evolutionary theory was a British initiative (1872–6) to study the great depths of the world's oceans using a specially fitted-out ship, HMS *Challenger*. The *Challenger* expedition did not turn up an ancient fauna of 'living fossils' from the presumably unchanging depths, but it yielded other insights that spurred further research in the Pacific. The *Challenger*'s dredging operations revealed that many parts of the ocean floor were blanketed with thick deposits of calcareous and silicious material composed of remains of microscopic plankton. This led one of the ship's naturalists, John Murray, to conclude that atolls might form atop banks of submarine sediments as they accumulated *upward* to depths where corals and other reef-building organisms lived.[32] If so, he argued, it was more parsimonious not to invoke large-scale geological subsidence, as Darwin had done in his explanation for the formation of barrier reefs and atolls. Although Murray's theory was disdained by many geologists, it was taken up by several vociferous advocates who saw it as a cudgel to criticize the increasing influence of Darwin's allies in British science.

Debates over what came to be known as 'the coral reef problem' spurred great interest in finding a way to subject the subsidence theory to a direct test.

[30] Darwin's private notes indicate that he became convinced of evolution (as a fact in the history of life) in the summer of 1837, about eight months after returning from the voyage, and developed his theory of natural selection to explain evolution the following year. See F.J. Sulloway, 'Darwin and his finches: the evolution of a legend', *Journal of the History of Biology* 15 (1982), 1–53, and 'Darwin's conversion: the *Beagle* voyage and its aftermath', *Journal of the History of Biology* 15:3 (1982), 325–96.

[31] R.M. MacLeod and P.F. Rehbock (eds.), *Darwin's Laboratory: Evolutionary Theory and Natural History in the Pacific* (Honolulu: University of Hawai'i Press, 1994), 'Introduction', 5.

[32] J. Murray, 'On the structure and origin of coral reefs and islands', *Proceedings of the Royal Society of Edinburgh* 10:107 (1880), 505–18. Murray argued that if detritus settled atop submarine mountains, calcareous sponges and other organisms would build the banks close enough to sea level that corals could colonize them, positing that atolls' ring-like shape could be caused by corals' growing vigorously on the outside of the reef and while coral limestone dissolved in acidic waters that accumulated within the reef.

The year before he died, Darwin himself had proposed a means for doing so. Writing to Alexander Agassiz about his reasons for doubting Murray's theory, Darwin told the wealthy American: 'I wish that some doubly rich millionaire would take it into his head to have borings made in some of the Pacific and Indian Atolls; and bring home cores for slicing from a depth of 500 or 600 feet.'[33] A decade later, after vigorous discussion was played out in the pages of several British scientific periodicals, participants on both sides came to agree that there were many valid reasons to try to bore down through an atoll for the first time since Beaufort's hastily planned effort of the 1830s. The idea would be to drill as deeply as possible into an atoll in an effort to determine, by bringing up cores, whether these formations were built up by shallow-water corals that had accumulated atop a subsiding foundation of volcanic rock (as Darwin argued) or if atolls were underlain by banks of sediment (as Murray predicted).

For many, the theories stood in as proxies for much larger visions of geology and zoology. As the British geologist J.W. Gregory wrote in the first issue of a new popular science magazine in 1892, 'Considering how much is involved by the coral reef question, with its bearings on the geological history of the whole Central Pacific area, on the permanence of oceans and continents, on zoological distribution, and on the relation of subsidence to volcanic action, it seems surprising that no attempt has previously been made to secure an adequate series of borings.' Gregory described boring as the sole means of reaching a 'final' adjudication between rival theories, but reported on the complications of selecting a single site that all sides would agree in advance served as an appropriate proving ground.[34]

The British navy's chief hydrographer William Wharton, in contrast to his forerunner Beaufort's willingness to let Beechey select his own circular reef for his boring attempt, worked hard by to help identify a specific reef that would best serve the purpose of the test. Ultimately the atoll of Funafuti, some 1,000 kilometres north of Suva, Fiji, was selected as the site where the history of the Pacific's islands would be put to the test. At the urging of William Johnson Sollas, the professor of geology at Trinity College, Dublin, a committee of the British Association for the Advancement of Science had

[33] Darwin to Alexander Agassiz, 5 May 1881. Darwin Correspondence Project, 'Letter no. 13145', www.darwinproject.ac.uk/letter/DCP-LETT-13145.xml. The letter became public just a few years after it was written when it was published in *The Life and Letters of Charles Darwin, Including an Autobiographical Chapter*, ed. F. Darwin (London: John Murray, 1887), vol. III, 183–4.
[34] J.W. Gregory, 'The exploration of coral reefs by borings', *Natural Science* 1:1 (1892), 50–2, at 50.

been created to investigate reef boring. Sollas's goal was to core to a depth of at least 100 fathoms (183 metres) and uncover once and for all what underlay the reef-building corals of an atoll.

In fact, the crucial test at Funafuti in 1896 turned out to be such a failure that a second expedition was dispatched to the atoll in 1897; and when that failed to settle the matter, a third boring mission travelled to Funafuti in 1898. That these three attempts could be planned and executed in successive years is a vivid illustration of my argument in the previous section: the cycle of researching and reporting on science in the Pacific quickened dramatically in the late nineteenth century. After commanding so much attention before departure, the 1896 expedition under Sollas proved to be a devastating anticlimax. Two bore holes were attempted, but the equipment was fouled repeatedly by loose material until it broke down, with the deepest bore reaching a depth of just 32 metres. The letters Sollas wrote from Funafuti reveal him to have been utterly mortified, despite the fact that the expedition had accomplished a valuable hydrographic survey of the atoll and accumulated significant natural history collections, and Sollas himself had gathered considerable ethnographic information from the Funafuti Islanders. To the reef biologist turned ethnologist A.C. Haddon, Sollas reported 'the boring is an ignominious failure . . . I am resigned like a dead man to death'.[35]

As historian Roy MacLeod has illustrated, the second and third Funafuti expeditions (1897 and 1898) were triumphs 'for Australian geology, and [for] Australian colonial nationalism in science'.[36] The Royal Society committee invited University of Sydney geologist T.W.E. David to lead the second expedition, which was funded largely by donations and grants from Australia. This time the bore hole exceeded the 100-fathom goal, recovering cores of chalky rock from 213 metres but seemingly failing to reach the foundation of the atoll. While the cores were sent to London for analysis, David appeared before the Australasian Association for the Advancement of Science and successfully stoked support for a third expedition, for it was not clear that even these improved results would resolve the theoretical dispute. As a review of David's announcement in the British journal *Nature* commented: 'Opinions amongst scientific men in Great Britain as to the conclusions to be drawn from the evidence of the Funafuti bore were at present

[35] W.J. Sollas to A.C. Haddon, 19 July 1896. Ms. Eng. lett. d 329.89, Bodleian Library, University of Oxford.

[36] R.M. MacLeod, 'Imperial reflections in the southern seas: the Funafuti Expeditions, 1896–1904', in Rehbock and MacLeod (eds.), *Nature in Its Greatest Extent*, 159–91, at 180.

divided. While the advocates of the Darwinian theory were inclined to congratulate themselves upon the results, Dr. Murray's supporters say that the evidence substantiates their views.'[37]

The reef-formation theories advanced by Darwin and Murray, along with a third by the American geologist R.A. Daly, remained viable when the Pacific was consumed by the hostilities of World War II.[38] Gaining knowledge of reef structures took on new urgency during this age of amphibious warfare, a fact made painfully clear on the American side at Tarawa in the Gilbert Islands (now Kiribati) in November 1943, when marines suffered heavy casualties when landing craft foundered on the reefs of this Japanese-held atoll. After the eventual US victory in grisly fighting at the Gilberts, the Americans occupied the Marshall Islands with decisive victories at Majuro, Enewetak, and Kwajalein atolls in the ensuing months.

Not long thereafter, a high-ranking scientist in the US Geological Survey named Harry Ladd was ordered to work on a pair of reports spelling out strategic and scientific objectives that might be served by War Department-funded research in the Pacific islands.[39] Drawing on his experiences doing geological and palaeontological fieldwork in Fiji before the war, Ladd advocated immediate mapping and assessment of mineral resources while the archipelagoes remained under US occupation, to be followed, if possible, by thorough surveys and wide-ranging basic science research after the war. The longer-term suggestions included 'bor[ing] through a living coral reef at a strategic location' in an attempt to determine how the reef had formed. This set the scene for the US Navy to place the metaphorical combat between different scientific theories at the forefront of its messaging about tests of newly destructive military technologies.

When the US Army and Navy jointly commenced detonating nuclear devices at Bikini Atoll less than a year after bombing Hiroshima and Nagasaki, the entire enterprise of the bomb 'testing' was suffused with scientific language.[40] The so-called Operation Crossroads was launched in

[37] 'The Australasian Association', *Nature* 57 (1898), 492–7, at 495.
[38] Daly's theory was known as the 'glacial-control' theory. R.A. Daly, 'Pleistocene glaciation and the coral reef problem', *American Journal of Science* 4 (1910), 297–308, and 'The glacial-control theory of coral reefs', *Proceedings of the American Academy of Arts and Sciences* 51:4 (1915), 157–251; Sponsel, 'Coral reef formation', chapter 5.
[39] See Ladd, 'Geologic investigations of Pacific islands' and Ladd, 'Suggestions for proposed long-term program of Pacific geology', Ladd Papers, Smithsonian Institution Archives (SIA), Box 1, folder 3.
[40] According to the official report of the first atoll test, Operation Crossroads, the requirements for any test site were 'A protected anchorage at least six miles in diameter . . . a site which was uninhabited, or nearly so . . . a location at least 300 miles distant from the nearest city . . . a

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the summer of 1946; it was the largest peacetime US military operation in history. Among some 42,000 personnel was a substantial scientific corps charged with documenting the 'effects' of the fission bombs that would be detonated at Bikini. The acknowledged purpose of the Crossroads operation was to assess how badly a 'target' fleet of nearly a hundred surplus vessels anchored in the lagoon would be damaged by the type of bomb that had been dropped on Nagasaki. The commander of the operation, Vice Admiral W.H.P. Blandy, described it as 'a scientific experiment by the United States Government'.[41] Not only did the test procedure explicitly lay out the terms of a 'controlled' experiment, but declarations made by individual officers and scientists also emphasized that they saw Bikini as a 'laboratory', and information put forward by the Navy's publicity department echoed long-established tropes about Pacific islands as proving grounds for scientific theories.

Before Crossroads was underway, the American physicist Lee DuBridge had complained in a new magazine, the *Bulletin of the Atomic Scientists*, 'wouldn't science and engineering be far better off if the 100 million dollars or so which the tests will cost could be devoted to laboratory research under controlled conditions?'[42] In fact, the Crossroads operation plan contained a strategy for making these field tests *into* controlled experiments – a strategy that depended implicitly on typological thinking about atolls. The scientific corps would make extensive baseline surveys and follow-up comparisons not only of Bikini, but also of other atolls that would serve as the 'control' subjects. For example, the biological team was ordered to catalogue the flora

location within 1000 miles of a B-29 base . . . freedom from severe cold and violent storms . . . predictable winds directionally uniform at all altitudes from sea-level to 60,000 feet . . . predictable water currents of great lateral and vertical dispersion . . . [and] control by the United States.' W.A. Shurcliff, *Bombs at Bikini: The Official Report of Operation Crossroads* (New York: Wise, 1947), 16–17. On scientific activity at the US nuclear proving grounds see N.O. Hines, *Proving Ground: An Account of the Radiobiological Studies in the Pacific, 1946–196*; J.M. Weisgall, *Operation Crossroads: The Atomic Tests at Bikini Atoll* (Annapolis, MD: Naval Institute Press, 1994); R. Rainger, 'Science at the crossroads: the Navy, Bikini Atoll, and American oceanography in the 1940s', *Historical Studies in the Physical and Biological Sciences* 30 (1999), 349–72, and '"A wonderful oceanographic tool": the atomic bomb, radioactivity and the development of American oceanography', in H.M. Rozwadowski and D.K. van Keuren (eds.), *The Machine in Neptune's Garden: Historical Perspectives on Technology and the Marine Environment* (Sagamore Beach, MA: Science History Publications, 2004), 93–131; E.J. Jessee, 'Radiation ecologies: bombs, bodies, and environment during the atmospheric nuclear weapons testing period, 1942–1965', PhD thesis, Montana State University, 2013; L.J. Martin, 'Proving grounds: ecological fieldwork in the Pacific and the materialization of ecosystems', *Environmental History* 23:3 (2018), 567–92; Sponsel, 'Coral reef formation', chapter 5.

[41] Blandy quoted in '"Operation Crossroads": the effect of the atomic bomb on naval power', *Bulletin of the Atomic Scientists* 1:5 (1946), 1–12.

[42] L.A. DuBridge, 'What about the Bikini tests?', *Bulletin of the Atomic Scientists* 1:11 (1946), 7–16.

and fauna of three atolls: Bikini, another one downwind (Enewetak), and one upwind of Bikini (Rongerik).[43] The main group of geologists did comparative studies of Bikini, Enewetak, Rongerik, and Rongelap atolls before the first blast, while marine geologist K.O. Emery did submarine studies of those four plus Ailinginae, in order 'to determine whether Bikini is a typical atoll and to provide controls for estimating bomb damage to organisms'.[44]

This notion of atolls as a type – as geologically and ecologically interchangeable with one another – also underpinned the American dealings with the Bikini Islanders during Operation Crossroads. In March 1946, the 167 people who lived on Bikini were relocated to Rongerik, an uninhabited atoll just east of Rongelap. Consistent with other publicity about the tests as scientific undertakings, the US military governor of the Marshall Islands had told the Bikinians that 'the United States government now wants to turn [the bomb] into something good for the benefit of mankind, and that these *experiments* here at Bikini are the first step in that direction'.[45]

Bikini and the control atolls were resurveyed during that summer of 1947 by an even larger scientific crew, which now faced the challenges and opportunities of studying contamination. They also pursued more of the initiatives the USGS geologist Ladd had proposed during the war. Indeed, it was Ladd himself who oversaw an ambitious attempt to solve the puzzle of atoll formation once and for all. On 18 July 1947 the Director of Public Information for the US Navy dispatched a press release that read:

> Drillers from the oil fields of Oklahoma began working around the clock on Bikini Island today in an operation that may settle a one hundred and ten year old argument among geologists. The core drilling operation being carried out jointly by the U.S. Geological Survey and the Navy Department is designed to definitely establish the origin of coral atolls.[46]

Why did the US Navy care about 'Charles Darwin, the famous British naturalist'? What was the purpose of obscuring the core drilling's relevance to the actual bomb tests (which, it had been feared, might seriously damage

43 'Oceanographic Survey Program for Operation CROSSROADS – Summary of.' Memorandum from Roger Revelle to Rear Admiral T.A. Solberg, U.S.N. and Dr. Ralph A. Sawyer, 15 February 1946. Subject Files, AC 6, Box 6, folder 27, Scripps Institution of Oceanography collection, UCSD.

44 K.O. Emery, 'Submarine geology of Bikini Atoll', *Geological Society of America Bulletin* 59:9 (1948), 855–60, at 856.

45 Wyatt is quoted in Weisgall, *Operation Crossroads*, 112. My emphasis added. This exchange with the Bikinians is also shown in the 1946 short film *Bikini, the Atom Island*.

46 'Bikini Scientific Resurvey Press Release No. 12', 18 July 1947. L.P. Schultz Papers, SIA, Box 26, folder 3, 'Bikini Scientific Resurvey, Correspondence, Press Releases, etc.'.

the deep structure of the atoll)? Given earlier accusations that the 1946 bomb tests were intended as sabre-rattling displays of military might, it is natural to wonder whether the conspicuous pursuit of pure scientific knowledge served some ulterior motive.

In fact, the (formerly classified) operation plan for the Bikini resurvey makes plain that its organizers were well aware of the public relations opportunities presented by solving a benign geological puzzle. The plan emphasized 'the importance of providing a continuing series of newsworthy press releases to the public' because '[i]nteresting, newsworthy stories from Bikini . . . will forestall much press criticism and speculation of a harmful nature'. Among the proposed topics of these press releases were the investigations into the structure of the atoll.[47] This section of the operation plan suggests that at least part of the value of conducting the resurvey was to create a venue for rehabilitating the 1946 tests, which had ended prematurely when the second blast – detonated beneath the surface of the lagoon – unexpectedly bathed the entire atoll in radioactive rain.

The 1947 press releases described the atoll in terms of the wealth of knowledge that the bomb test had sowed, which merely awaited harvest by opportunistic scientists, and they managed to portray Bikini as a benign paradise while still emphasizing what a high technical achievement the Crossroads tests had been. In the end, Ladd and his drill crew reached an unprecedented depth of more than 760 metres, although even this turned out not to be deep enough to reach the bottom of the reef. The next press release declared it 'the deepest hole ever drilled in a Pacific Atoll'.[48]

The idea of Pacific islands as pliant spaces for the production of generalized knowledge received some comeuppance – very much incomplete, but nevertheless striking – at Enewetak Atoll. In 1948, Enewetak too became an American nuclear test site. And it was at Enewetak, in 1952, that a drilling crew finally reached the foundation of a Pacific atoll. Under Ladd's supervision, a sample of volcanic rock was recovered from a depth of 1,280 metres, seven times deeper than Darwin had guessed would be necessary to find the remains of a sunken island beneath a reef.[49] The Enewetak result has been widely celebrated as a confirmation of Darwin's theory, for it did turn out to

[47] 'Operation Plan' for Bikini Scientific Resurvey, NARA II, RG 374, Defense Nuclear Agency, Entry 47B, Bikini Resurvey, Box 156, folder A3, 'Organization and Management'.

[48] 'Bikini Scientific Resurvey Press Release No. 21', [15?] August 1947. L.P. Schultz Papers, SIA, Box 26, folder 3, 'Bikini Scientific Resurvey, Correspondence, Press Releases, etc.'

[49] The argument that follows draws from my work in Sponsel, 'Coral reef formation', 411–52.

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be the case that the reef was made of a great thickness of shallow-water corals atop a sunken foundation.

However, Ladd preferred to point out a different lesson. Detailed analysis of the full column of core samples from Enewetak revealed that the atoll had been through a far more complicated geological history than the one Darwin predicted. The reef had not subsided steadily through the fringing reef, barrier reef, and atoll stages proposed by Darwin, but instead had for long periods been raised above sea level, and at others been 'drowned' beneath the depth zone occupied by reef-building corals. Indeed, the massive scaling up of scientific research at the irradiated atolls of Bikini and Enewetak turned out to have produced *such* detailed knowledge of these individual reefs that it was no longer plausible for any single, elegant theory such as Darwin's to encompass the origins of all atolls, let alone all coral reefs. In turn, there must be limits to how generalizable the knowledge would be that derived from any given island 'laboratory'.

If the uniqueness of individual atolls was a hard-won lesson for core-drilling geologists, it was more vividly and painfully evidenced in the plight of Islanders displaced from Bikini and Enewetak who found their new atoll homes lacking. And, in a bitter irony, the more deeply entrenched the American nuclear weapons programme became at Bikini and Enewetak, the more apparent it became that these atolls selected to serve as 'place-less' laboratories were also singular and irreplaceable to the US military.

These entanglements of the specific and the general, the Indigenous and the imperialist, came to a head at Enewetak in the wake of the 1963 limited nuclear test ban treaty by which the USA, the UK, and the USSR agreed to cease further above-ground testing.[50] In 1970, the US Air Force began planning a calibration test that would involve making new craters on Enewetak using conventional explosives. Seeking to develop a means for translating past data on bomb impacts on coral reefs into forecasts about bombs' effects elsewhere, this Pacific Atoll Cratering Experiment (PACE) would have culminated in a 500-ton TNT blast designed to leave the reef with another sizeable hole whose characteristics could be compared to those remaining from the nuclear test programme.[51]

[50] France did not sign on to the treaty; they conducted atmospheric and, until as recently as 1996, subterranean tests at Mururoa and Fangataufa.

[51] L.J. Circeo, 'Nuclear cratering experience at the Pacific proving grounds', Report, 10 November 1964, https://digital.library.unt.edu/ark:/67531/metadc100751/m1/1/; T.W. Henry and B.R. Wardlaw, *Introduction: Enewetak Atoll and the PEACE Program*, USGS

However, from the atoll of Ujilang just over 100 miles southwest, the exiled Enewetak Islanders invoked a new American environmental-protection law to try to halt the cratering 'experiments'. The Air Force pressed Harry Ladd and other scientific veterans of the earlier surveys of Bikini and Enewetak into service to produce an environmental impact statement that would comply with the 1970 National Environmental Policy Act (NEPA). It argued that PACE's objectives could not be achieved at 'other atolls, islands or reefs', because no other test site could be assured of having 'similar geologic conditions to the previous nuclear craters'.[52] As Ladd's own research had hinted, and as the Enewetakese knew all too well, there turned out to be limits to how satisfactorily one atoll might be made to stand in for another.

On 19 January 1973 the US District Court in Honolulu handed down an injunction against the PACE programme.[53] The decision was notable for several reasons. First, it declared that the new environmental law, NEPA, applied to territories administered by the US government even if they were not part of the USA proper. Second, it acknowledged that Marshall Islanders had standing to file for an injunction under the act despite not being US citizens. And third, of course, it was remarkable in actually granting an injunction against the US Air Force on behalf of the exiled population of Enewetak. The Air Force abandoned the remaining cratering plans intended for PACE's second phase, but resumed research on the existing Enewetak craters under a series of new acronyms.

Enewetak had not only been cratered and contaminated. Since its original subsidiary role downwind of Bikini in Operation Crossroads, it had also been transformed as a scientific object: from an interchangeable exemplar of its type – a literal 'control atoll' – into a unique artefact of both the physical impacts and the radiological effects of forty-three nuclear detonations. Bikini and its animals and plants had been similarly transformed from the very first blast, when it became possible to use the atoll to trace radionuclides from lagoon water to algae to fish. The same pattern has been true of many other Pacific-island 'laboratories', where a particular population of animals came to

Professional Paper 1513-A. US Government Printing Office, 1990; M.X. Mitchell, 'Offshoring American environmental law: land, culture, and Marshall Islanders' struggles for self-determination during the 1970s', *Environmental History* 22:2 (2017), 209–34; M. Smith-Norris, *Domination and Resistance: The United States and the Marshall Islands during the Cold War* (Honolulu: University of Hawai'i Press, 2016), chapter 2.

[52] A draft of the environmental impact assessment is preserved in the Joshua I. Tracey Papers, Smithsonian Institution Archives, Accession 02-021, Box 4, folder 'Eniwetok Active Corr. 74'.

[53] The people of Enewetak et al. v. Melvin R. Laird, Secretary of Defense et al., 353 F. Supp. 811.

stand in for the world's biodiversity, or Islanders became bodies of evidence for medical or anthropological research. These islands functioned as scientific microcosms not because they were sites of untouched nature (as if such a fantasy had ever been accurate), but because they were layered with traces of historical activity.

In closing, I note that this phenomenon is illustrated by one of the Pacific's most significant present-day sites for turning local investigations into general knowledge, the volcano Mauna Loa on Hawai'i Island. Using data from Mauna Loa, scientists are extending the world's longest continuous series of measurements of atmospheric carbon dioxide concentrations, recorded since 1958 at a station established by the US Weather Bureau earlier that decade. Mauna Loa data, as famously depicted in graphs of the upward-sloping 'Keeling Curve', demonstrated that the concentration of CO_2 in the atmosphere was steadily increasing.[54] This signalled the likelihood that emissions from human use of fossil fuels do indeed contribute to a warming 'greenhouse effect'.

The ongoing data series from Mauna Loa has become synonymous with 'global' carbon dioxide levels, cited by scientists and activists, including residents of Oceania's low islands, who find their homes threatened by rising sea levels. It is characteristic of the history of Western science in the Pacific that an iconic indicator of the whole planet's health owes its origin to the colonial infrastructure in Hawai'i and depends on the continuous presence of researchers there. At Mauna Loa and Mauna Kea, as at battle sites and bombing ranges, the knowledge produced by scientists in the Pacific acquired indelible traces of the not-so-placeless island 'laboratories' they visited, even as those islands became marked by the activities of science and its allied pursuits.

[54] The following reflections draw upon Madison Renner's work in progress on the history of the Mauna Loa measurements.